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ON THE VALUE OF LAND

Stefan Hellstrand

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Akademisk avhandling

som för avläggande av teknologie doktorsexamen i energi- och miljöteknik vid Akademin för ekonomi, samhälle och teknik kommer att offentligen försvaras onsdagen den 9 september 2015, 13.15 i Delta, Mälardalens högskola, Västerås.

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MÄLARDALEN UNIVERSITY
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Akademin för ekonomi, samhälle och teknik

Abstract

The issue of sustainable development is once again moving the production factor land into the focus of economic theory and practise. There are three production factors, capital, labour and land. Land is a synonym to ecosystems. During the major part of the 20th century land in economic theory has been handled as a peripheral issue. The sustainability context implies a challenge to take land in proper consideration. That means to in an adequate way consider system characteristics that result in complex systems, such as thresholds, resilience, irreversibilities, and interdependencies between systems and system levels.

The thesis examines

- how land can be understood and handled in the context of a sustainable development,
- the relations between land and society on a conceptual level and in operative terms,
- the relations between system levels and between the three sustainability dimensions ecological, economic and social,
- the importance of agriculture and animal production in a sustainable development.

The major findings are that in contexts such as economically profitable and natural resource-efficient milk production; methods to measure sustainability performance of production systems generally; and societal strategies for management of natural resources that support economic and social development within ecological sustainability limits, three "laws" need to be handled appropriate: Liebig's "Law" of the minimum, Shelford´s "Law" of tolerance, and the "Law" of diminishing return in biological-ecological productions systems.

The thesis identifies examples within dairy sciences, systems ecology, and engineering sciences that affect or may affect policies in real world systems from local to global level that can be substantially improved. In order to suggest relevant measures a tool-kit supporting a sustainable development have been generated, integrating contributions from agricultural sciences, systems ecology, economic theory, economic geography, applied environmental sciences and theories of complex systems. The thesis summarises around 30 years of professional experiences mainly within advanced consultancy, during which this tool-kit has been developed and applied. Evaluation of some applications afterwards shows relevance. For some of the examples analysed in the thesis, found weaknesses are such that global food security literally is threatened within one to twenty years.

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Sammanfattning

Hållbarhetsdiskussionen har ånyo fört produktionsfaktorn mark i fokus i ekonomisk teori och praktik. Det finns tre produktionsfaktorer, kapital, arbete och mark. Mark är synonymt med ekosystem. Under merparten av 1900-talet har mark i ekonomisk teori hanterats som en perifer företeelse. Hållbarhetsdiskussionen bär på utmaningen att på ett korrekt sätt hantera markresursen, vilket bl a handlar om att på ett adekvat sätt beakta systemkaraktärer som ger komplexa system, som tröskeleffekter, resiliens, irreversibiliteter och ömsesidiga beroenden mellan system och systemnivåer.

Avhandlingen studerar

- hur produktionsfaktorn mark kan förstås och hanteras i sammanhanget hållbar utveckling
- relationen mellan mark och samhälle konceptuellt och i operativa sammanhang
- relationen mellan systemnivåer och mellan hållbarhetens tre dimensioner ekologisk, ekonomisk och social
- betydelsen av jordbruk och animalieproduktion i en hållbar utveckling.

De viktigaste resultaten är att i sammanhang som ekonomiskt lönsam och naturresurseffektiv mjölkproduktion; metoder att mäta systems hållbarhetsprestation generellt; samt strategier för naturresurshushållning på samhällsnivå som främjar en god ekonomisk och social utveckling inom ekologiska hållbarhetsgränser, så finns tre ”lagar” att på ett korrekt sätt beakta: Liebigs “Lag” om första begränsande faktor, Shelfords “Lag” om ”lagom mycket”, samt ”Lagen” om avtagande utbyte i biologiska-ekologiska produktionssystem.

Avhandlingen identifierar exempel inom mjölkkornas utfodring och vård, systemekologi, och ingenjörsvetenskaperna som påverkar eller kan påverka policies i verkliga system från lokal till global nivå som kan substantiellt förbättras. För att kunna föreslå relevanta åtgärder har en verktygslåda för hållbar utveckling skapats och tillämpas genom att integrera bidrag från lantbruksvetenskap, systemekologi, ekonomisk teori, och teorier om komplexa system.

Avhandlingen sammanfattar drygt 30 års yrkesverksamhet, merparten inom avancerad consulting, där denna verktygslåda har utvecklats och tillämpats. Utvärdering i efterhand av några tillämpningar visar relevans. För en del exempel som analyserats i avhandlingen, är de svagheter som påvisas sådana att global livsmedelsförsörjning bokstavligen hotas inom ett till tjugo år.

Acknowledgments

On the 25th of August 1982 I started my professional career as the representative of the Swedish state at the Regional Agricultural Board in the county of Värmland, responsible for the implementation of the national agricultural policy at that time in the field of animal husbandry. In 1982 there were 1 621 dairy farms containing 22 124 dairy cows in Värmland. After two years I moved to a position within the farmers' economic cooperative in the same county, with responsibility for advanced consultancy in ruminant production. By 1986 the number of farms with dairy cows in Värmland had fallen to 1 231, and the number of dairy cows was 19 649. In a sense, this development was a function of the professional skill of my colleagues and me.

It was easy to see this as a rational development given the price relations at the time between labour and natural resources. The question was emerging as to whether this development was reasonable given the long-term capacity of natural systems from local to global level to support humanity. I use the words "rational" and "reasonable" here as put forward by the philosopher Henrik von Wright, where "rational" relates to the demand of internal logical consistency, while "reasonable" implies the same level of internal logical consistency and adds an ethical dimension. The concept of sustainable development implies a requirement for a sufficient level of justice within and between generations, and thus possesses a strong moral foundation.

This thesis summarises 30 years of professional experience in a number of positions in which I have examined the role of ruminant production in agricultural systems, the role of agriculture and forestry in society, and the role of society in its ecological context. Over the years, my awareness of the importance of sound methods has grown. Sound methods generate sound sustainability maps, which make sustainable development a real possibility.

A number of people have played important roles over the last 30 years. I thank them all. I especially want to thank my family Åsa, Elsa, Amanda, Agnes, Robert and Hillevi for their support during this period.

I am also grateful for the support from my supervisors at Mälardalen University, Jinyue Yan and Erik Dahlquist, and Lars Drake from the Swedish University of Agricultural Sciences.

David Ribé improved the English, for which I am also grateful.

Stefan Hellstrand

List of papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals. Reprints were made with permission from the respective publishers.

Journal papers

I. Hellstrand, S., Skånberg, K & Drake, L. (2009). The Relevance of Ecological and Economic Policies for Sustainable Development. *Environment, Development & Sustainability, 11*:4, pp. 853–870.

II. Hellstrand, S., Skånberg, K & Drake, L. (2010). A biophysically anchored production function. *Environment, Development & Sustainability, 12*:4, pp. 573–596.

III. Hellstrand, S. (2006). A Multi-Criteria Analysis of Sustainability Effects of Increasing Concentrate Intensity in Swedish Milk Production 1989–1999. *Environment, Development and Sustainability, 8*:3, pp. 351– 373.

VI. Hellstrand, S. (2013). Animal production in a sustainable agriculture. Environment. *Development & Sustainability, 15*:4, pp. 999–1036.

Conference proceedings accepted following the peer review process

V. Hellstrand, S. & J. Yan (2009). The potential to increase sustainable global green energy production through increased efficiency in milk and cattle production: a Swedish case. *First International Conference on Applied Energy, January 5–7, 2009 Hong Kong*.

Manuscript

IV. Hellstrand, S. A simulation model of animal production and its results in production biological and economic terms when applied on an ecological and a conventional system.

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Acronyms and abbreviations

BAPF	Biophysically Anchored Production Function
DM	Dry matter
ECM	Energy corrected milk
EEA	Ecological Economic Accounts
GHG	Greenhouse Gases
Gt	Gigatonnes ($1*10^9$ tonnes)
IEA	International Energy Agency
LCA	Life Cycle Assessment
ME	Metabolizable energy
MEA	Millennium Ecosystem Assessment
SEK	Swedish Crowns
SUAS	Swedish University of Agricultural Sciences

1 Introduction

1.1 Background

In classical economic theory, the production value was described as a function of inputs of labour, capital and land. Land was a synonym for nature and ecosystems, including all natural resources (Daly and Cobb 1989; Nanneson et al. 1945).

Neoclassical economics focused on the relationship between production value and inputs of labour and of capital, while the importance of land was devalued. As a consequence, environmental impacts of production were classed as something external to the core of the analysis (Daly and Cobb 1989; SOU 1991).

In recent decades, the issue of sustainable development has brought the importance of land back into the focal plane of economic practice and theory, which is expressed in contributions such as Daly (1990), Daly and Cobb (1989), Hall et al. (1986), MEA (2005), Odum (1988), Odum (1989), OECD (2001).

There are unsolved gaps in the scientific knowledge in this area, including

- how land can be understood,
- the relations between land and society on a conceptual level and in operative terms,
- the relations between system levels and between the three sustainability dimensions ecological, economic and social,
- the importance of agriculture and animal production in sustainable development.

These gaps are the main aspects investigated in the thesis.

These scientific gaps are not as wide on a general conceptual level. The OECD has stressed that these gaps are concerns in the implementation phase of policies to enhance sustainable development.

The general foundations for the understanding of sustainable development were laid during the late 1980s and the early 1990s. What has remained an issue is: how does one actually achieve sustainable development?

The thesis mostly focuses on problems in the implementation phase, where representatives from different fields try to solve the new problem of sustainable development using the internal logics of their own disciplines. Giampietro (2003) elaborated on this. Trying to solve new problems by applying old solutions is seldom fruitful. A particular problem is the strong influence of engineering-based approaches, concepts, methods and incentives in the efforts to implement measures for sustainable development. This is a problem as engineering sciences do not represent greater competence than any other unrelated field with regard to ecological, economic and social sustainability. However, this is not commonly understood.

Proposals based on systems ecology that by analogous oversimplification and misrepresentation of integrated ecological-economic systems are just as problematic, and could cause actions that may threaten global food security within a few years.

Common denominators between such engineering-based approaches and proposals within systems ecology, are

- the weaknesses in the representation of agricultural systems, such as animal production systems, especially ruminant production systems, compared to known properties of these systems, and
- the low priority allocated to expertise regarding these systems, and thus to known properties of these systems.

This is a concern from a scientific quality perspective, since for hundreds of years, scientific knowledge has been founded on empirical evidence. The thesis provides examples of these implementation problems and suggests how they can be overcome.

To the discussion above regarding relevance of some contributions from engineering sciences and systems ecology, there is a need to add problems in changes in feeding standards systems to dairy cows in Sweden since 1991, and feeding standard systems to dairy cows common internationally.

Closer examination reveals a great deal of similarity between the constructed models of real world systems in the examples examined by engineering sciences with their knowledge gaps, and the feeding standard systems to dairy cows common internationally.

Basic concepts in economic theory such as capital, pecuniary and property originate from early economies based on agriculture and cattle production. The word ‘fee’ has a similar origin. Of a total area of 13 billion ha of land globally, 3.4 billion ha (26%) are classed as permanent pastures, where ruminants are the dominating path to convert the sunlight captured in biomass to food. This suggests that there are substantial relations between efficient cattle production and general principles for efficient natural resource management.

On a higher level, the issues discussed are

- the importance of using relevant methods for the issues and systems under consideration,
- the problem of extrapolating methods from one area where their relevance has been sufficiently well probed and approved, to other issues and systems where different disciplines represent the state of the art,
- the need for good empirical evidence as a foundation for sustainable development, whether we are discussing feeding standards to dairy cows, or general market-based incentives in the economy.

1.2 Scope

The scope of the study is to contribute towards an operative toolkit for sustainable development, bridging the implementation and knowledge gaps acknowledged by OECD (2001).

This toolkit consists of contributions on the conceptual level, or what we might call a macro-ecological-economic level. The contribution on the conceptual level supplies the major elements and relations to consider in implementing sustainable development. The macro-ecological-economic contribution supports the evaluation of the rationality of policy measures given the context of sustainable development.

This toolkit provides a methodological contribution to the field of Participatory Multi-Criteria Multi-Level Analysis. This contribution provides an example of how to analyse systems that possess mutual dependencies between systems and system levels, exemplified by an application in animal production sciences. While the contribution on the conceptual level focuses on the relations between the ecological, economic and social dimensions of a sustainable development on the macro level, the later contribution focuses on the relation between very high and very low system levels. An example is the relation between the performance of an individual cow and her marginal impact on food supply as well as climate on the global level. When analysing relations between the three sustainability dimensions, and between high and low system levels, it is of crucial importance to pay the respect due to the system characteristics that describe the complexity of systems where sustainability is an issue. If this is solved sufficiently well, it can contribute to systems of ecological economic accounts that are valid at individual firm level, where the ecological, economic and social contribution added per firm can be summed up to regional, national and international systems of ecological economic accounts, considering carrying capacity limits of affected ecosystems from low to global level. This can also help when adjusting the accounting rules regarding the climate issue from IPCC to the accounting rules in the international system of national accounts. It can also improve the subsystem of sustainability performance analysis within systems of sustainability/environmental certification such as the ISO 14 001 system.

Finally, among these tools an example is presented where traditional management tools within agricultural and animal production sciences are integrated, thus increasing the capacity to explore potentials to increase the efficiency of utilisation of the variation in global agro-ecosystems for production of goods and services supporting human needs and desires. The traditional management tools integrated are feeding plans in ruminant production systems such as milk and meat from cattle, plans for nutrient supply in crop production, and the system of production branch calculus in agriculture. The resulting tool supports evaluation of how to increase the long-term contribution to societal needs from combined plant-ruminant production systems in agro-ecosystems that otherwise have a low capacity to produce food. Around 70% of global agricultural land (3.4 billion ha) is classed as permanent pasture. Ruminants are a prerequisite for food production from permanent pastures. Of the remaining 30% of agricultural land classed as arable land (1.4 billion ha), a substantial fraction produces feed for animals. The tools mentioned above are needed to optimise the use of land for different societal purposes from local to global level.

1.3 Thesis outline

Section 2 presents the methodology of the thesis. **Section 3** gives an overview of the results of the six papers. **Section 4** analyses vital aspects of the results in relation to the knowledge frontier, and discusses policy implications of the results. **Section 5** provides conclusions and a short summary of the degree to which the thesis has increased knowledge about the sustainability aspects considered therein (see 1.1).

Figure 1 shows a model of the global system based on the contributions in systems ecology by H.T. Odum. The different papers in the thesis relate to different parts of this system.

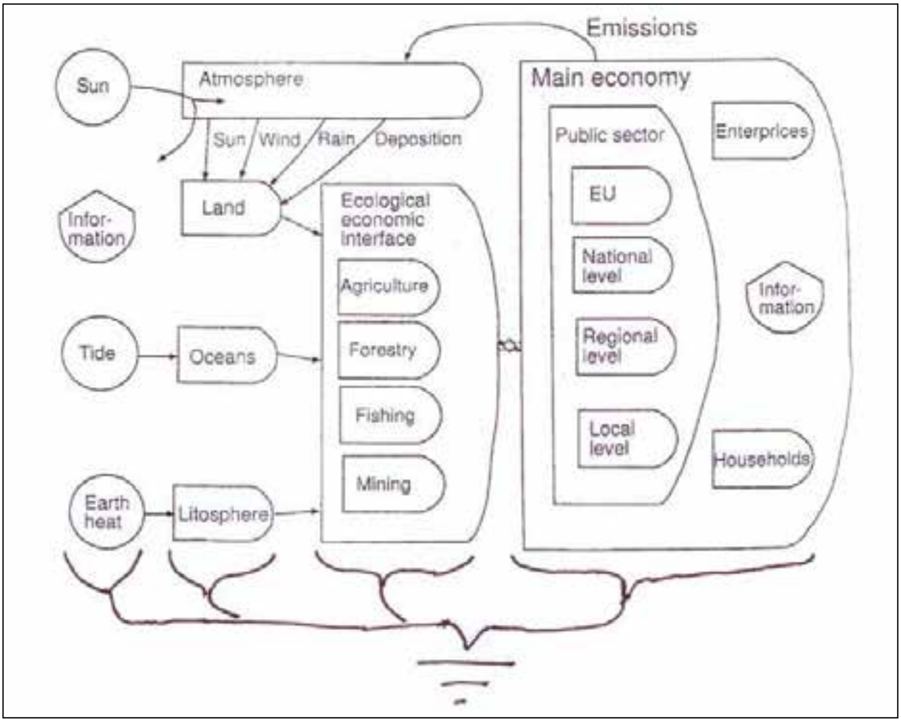

Figure 1. **A model of the global ecological economic system based on the contributions by Odum (1988, 1996).**

Paper I presents a version of the conceptual model shown in Figure 1, where the concepts, symbols and relations have been translated into the language of economics

Paper II treats the same system. Here, the conceptual model is transformed into a mathematical logical structure by which the output in a production process is related to the inputs of renewable and non-renewable natural resources, and the impact of production on the environment.

Figure 1 indicates the hierarchical structure of global systems, where e.g. in the economy, important system levels are the enterprise and household level (in principle the same level), local level, regional level, national level, EU, the global economy, and the global economic-ecological system.

Paper III focuses on the subsystem concentrate feeding of dairy cows in Sweden and evaluates how it affects other parts of the global system through emissions of ammonia contributing to acidification and eutrophication of aqueous and terrestrial ecosystems, the nutritional supply of members of households that may affect global food security, and the economy of the group of enterprises constituted by Swedish milk producers.

Paper IV goes deep into the animal production system in Sweden and its production biological and economic aspects. It relates the outcomes from animal production to the quality of the input of feeds into animal production. This provides a necessary link in a chain that joins animal production systems to the agro-ecological context provided by nature through e.g. the bedrock, soils and weather conditions of each individual production site.

Paper V goes further in an analysis of how decisions made in animal production systems in Sweden and globally affect the different subsystems in Figure 1, thereby affecting economic and ecological resources appropriated in animal production systems, as well as the capacity to fulfil human needs and desires, focusing on food and bioenergy potentials.

Paper VI takes a global perspective of the animal production system and its capacity to fulfil human needs while minimising the appropriation of mainly ecological resources. The role of animal production systems in a sustainable development is defined from the system ecological perspective in Figure 1. Used in a relevant way, animal production systems are important means within "Agriculture" in Figure 1 to enhance global sustainability through the capacity to convert biomass from terrestrial ecosystems ("Land" in Figure 1) to high quality food. Through such production, there may be mutual benefits in agricultural soils through impacts on the humus and nutrient content, on atmospheric carbon dioxide levels, on the aesthetic and recreational values of the agricultural landscape, and on biodiversity associated with agro-ecosystems. Used poorly (given the context of sustainable development), animal production systems may cause substantial sustainability costs in the ecological, economic and social dimensions through direct and indirect impacts on agricultural, forestry, water, and atmospheric systems. Based on the logics of Figure 1, such impacts are investigated in the context of four measures in global animal production systems. One of these evaluates the global relevance of the findings in Paper III regarding feeding trends in Swedish milk production for sustainable development.

Papers V and VI build on the methodology developed in Paper III regarding analysis of causal chains in a complex ecological-economic production-consumption system with mutual interdependencies between systems and system levels.

1.4 A common thread

A common thread through the thesis is identification of the gap between the characteristics of real systems according to the best available knowledge and the characteristics of the models of real systems used in different analyses.

LCA (Life Cycle Assessment) is widely used in Sweden to evaluate the sustainability of agricultural production systems. One problem with LCA is that it is a methodology that was developed in the engineering sciences thus it scope is limited and excludes vital features of systems where life is a key systems characteristic, as shown in Figure 2.

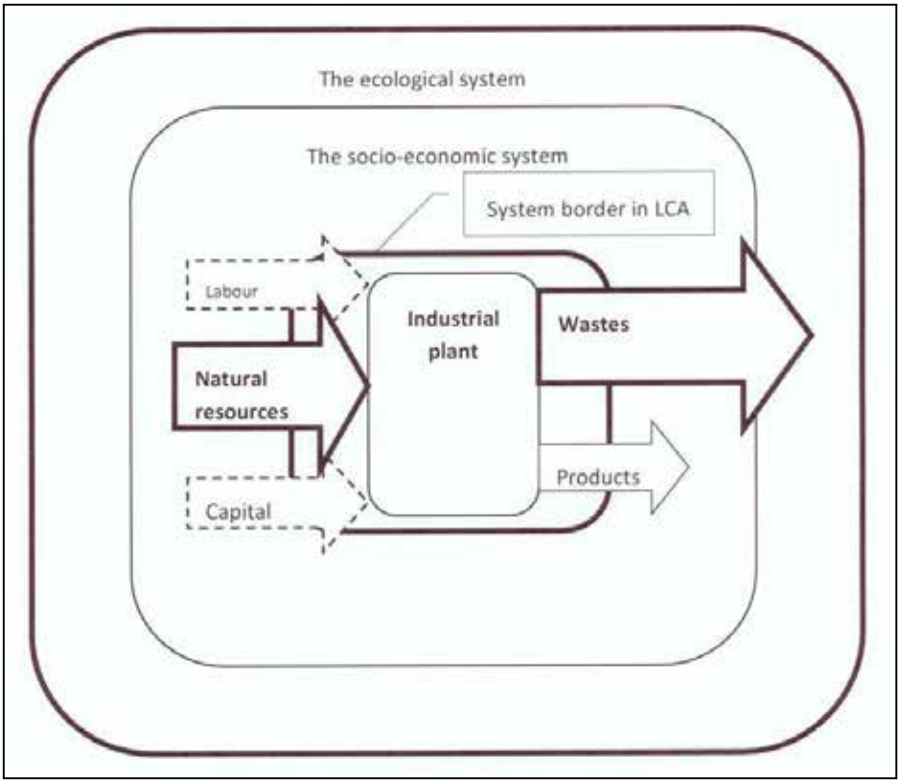

Figure 2. LCA and the sustainability context.

The engineering-based conceptual model of the production system is the industrial plant. The importance of labour and capital (using their traditional meanings) is ignored. Furthermore, the model suggests that there are no natural resources costs behind humans, labour, and capital. The focus is on influxes of natural resources, and effluxes in the form of wastes. Products and product quality in relation to their usefulness in the socio-economic system are typically treated with substantially less accuracy.

With its background in engineering sciences, LCA has its strengths in analysis of the technical aspects of industrial production processes (see Baumann and Tillman 2004). Inputs of natural resources into the production system and emissions out of the production system, where the industrial plant is the mental model used, are handled easily. Problems arise because engineering sciences do not provide expert knowledge regarding the ecological, economic and social process restrictions that define the level of sustainability in specific production situations. To overcome this limitation in the understanding of the total sustainability, different assumptions are made, providing analytical shortcuts. For example, it is commonly assumed that there are no time and space dependent variations whatsoever in conditions in ecological systems. Furthermore, ecological carrying capacity limits are not considered. With these assumptions, the concept of ecological sustainability becomes irrelevant as there is no longer any ecological process restriction that can be affected, and thus no ecological carrying capacity limit that can be trespassed. Such assumptions devalue the results obtained, given the sustainability context. This illustrates the scientific problems of extrapolation, here on the methodological level. Methods that have proved useful within the boundaries of engineering sciences are applied outside these boundaries, generating results that carry a high risk of being inaccurate.

Important and related aspects considered in the thesis relate to

- the relevance of engineering-based concepts, methods and incentives in general as promoters of sustainable development,
- the relevance of the theoretical models behind current protein evaluation and standards systems in milk production, and
- the relevance of the theoretical models behind current energy evaluation and standards systems in milk production.

There are similar issues regarding the gaps between the characteristics of the real world systems treated in these three groups of examples and the simplified models, as previously mentioned regarding LCA.

The thesis provides arguments supporting these conclusions. It also suggests how these models may be complemented so that their advantages are retained while their weaknesses are eliminated.

The following section presents a number of quantitative estimates. A high level of logical consistency is prioritised in the chain of operations leading to the final estimates. This reflects the view that when handling complex systems the quality of the numeric analysis is vitally important. However, the final results should not be viewed as the definite truth. Often the best that can be achieved is a reasonable estimate of the magnitude of impacts, given specific assumptions.

2 Methodology

2.1 General description

The thesis follows a long tradition in agricultural science in Sweden, where Nanneson et al. (1945) made contributions to agricultural economics with deep roots in the biology of crop production and animal husbandry, Renborg (1957) and Johnsson et al. (1959) developed methods from linear algebra to maximise the profits of individual farms for particular economic and production biological conditions. Wiktorsson (1971, 1979) explored the law of diminishing returns in relation to feed allowances in milk production. Hellstrand (1989) based on the relation between feed intake and milk output of Wiktorsson, evaluated whether the energy feeding standards at the time corresponded to the level that yielded the maximal economic result per cow, taking into account the price relations between concentrate feeds and milk.

Renborg (1957) and Johnson et al. (1959) provided the foundation for management and analytical tools regarding the economics of agriculture at farm level in Sweden from 1960 onwards. The contributions from Wiktorsson (1971, 1979) linked production functions in milk production in biological terms to economic analyses such as those developed by Renborg and Johnson et al. Hellstrand (1989) refers to corresponding contributions regarding biological production functions in cattle production for meat, gestation and maintenance for different types of cattle. Drake (1999) developed and applied a methodology to evaluate external values in the agricultural landscape, where one point of departure was methods based on Renborg (1957).

SLU (1989a,b; 2006; 2009) summarises this information in tools for extension services that are updated versions of the methods and relations developed by the authors mentioned above.

This forms the methodological backdrop for Paper IV, in which a simulation model of animal production is developed and applied. The model is based on the relations between feed intake and milk output found by Wiktorsson (1971, 1979) and how they are expressed in the system of budget sheets for Swedish agriculture (SLU, 1989a,b; 2006; 2009). Essentially, Paper IV presents the results from the toolkit that guided the work of the regional authorities “Lantbruksnämnden”, which was an important organisational body supporting the implementation of rational agriculture in Sweden from 1967 to 1990. “Rational” in this context refers to the logics of the economic models guiding the general economic policy at that time, as it was expressed in the agricultural policy. In Paper IV, this methodological approach is used to investigate economic and ecological outcomes of two different objectives of animal production. The first is to maximise profit given the prevailing price relations in the economy and the agricultural sector. The second is to maximise sustainable production levels, assuming that ruminants consuming 100% forages would support this goal.

Paper III focuses on a minor part of the system described in Paper IV. Ecological, economic and social effects of changes in the concentrate feeding of dairy cows from 1991 to 1999 in Sweden were evaluated from the low system level to the global level. The methodological core of the analysis was based on methods that were commonly used in extension services in animal production in the 1980s, when I worked in the field. Hellstrand (1988) summarised these experiences in a model to be applied in advanced consultancy in milk production, improving the economic results by more efficient utilisation of the biological production capacity of the cows. Hellstrand (1989), in a background to a major revision of the official feeding table for ruminants in Sweden with feeding standards, further elaborated on the basic principles to handle economically competitive and natural resource efficient milk production. In these early contributions regarding milk production, the same three basic principles that play a major role in Paper VI are of vital importance, namely Liebig´s "Law" of minimum, Shelford´s "Law" of tolerance, and the "Law" of diminishing returns.

From this common core in Papers III and IV based on traditional methods supporting evaluation of the efficiency in animal production systems in biological and economic terms, the analysis was expanded in an evaluation of the sustainability impacts of the increasing level of concentrate feeding per kg of milk produced in Swedish milk production from 1991 to 1999 (Paper III). The analysis of sustainability impacts from low to global system level in Paper III follows the methodology of Impredicative Loop Analysis (ILA) (Giampietro 2003) on a conceptual level. ILA is a contribution within multi-criteria multi-level analysis and is thus a method for integrative assessment.

The core of the methodology applied in Papers III and IV lies among traditional analytical methods that have been applied for several decades within agricultural sciences in Sweden, as well as in extension services. It implied that in repeated probing against reality, methodological flaws have been removed through trial and error.

Papers III and IV articulate a movement away from traditional analysis in animal production towards contributions that take their point of departure from a high abstract system level.

Paper I makes a contribution at the conceptual level. Animal nutrition, physiology, economic theory, and systems ecology are integrated into a conceptual model of the economy in its ecological and social context. In Paper

II this model of the economy in its ecological and social context forms the platform for the construction of economic production functions that not only show the value of the outcome of production as a function of inputs of labour and capital, but also of natural resources, including environmental effects. This was partly motivated by a need to express the dependence of the economy on the ecosystems in which it is embedded, in a widely understood language, such as the language of economics. Papers I and II were inspired by early contributions of e.g. Costanza and Daly in ecological economics and in systems ecology from around 1990 (e.g. Costanza 1994; Costanza and Perrings 1990; Daly 1990; Daly and Cobb 1989).

Papers III and IV expand analytical approaches from a concrete and low system level to higher levels. Paper I starts at a high abstract level, and performs an analysis that moves towards a methodological contribution for quantitative analyses of sustainability performance. This methodological contribution is made in Paper II, in which its relevance is anchored by statistical analysis.

Thus, Papers III and IV express a bottom-up approach in the evaluation of the role of land in the economy within a sustainability context; whereas Papers I and II represent a top-down movement in the investigation of the same issue. The same issue is thus illuminated from two independent perspectives.

Papers V and VI take as their departure point Paper III, and broaden the analysis towards a contribution in Paper VI regarding the role of animal production in sustainable agriculture in a sustainable society.

Taken together, the papers describe original contributions where a substantial part of the work has been to develop new methods to investigate new issues. In this context, the work has followed the methodology of post-normal science as described by Giampietro (2003). The contributions can also be described as a stepwise enlargement of the system boundaries of traditional contributions within economics and agricultural sciences.

2.2 Data gathering and analysis

Paper I contains qualitative analysis regarding a basic conceptual model of the economic system in its ecological and social contexts, and thus does not include data gathering and quantitative analysis. Paper II solidifies some of the steps in the conceptual model laid out in Paper I, in terms of a production function where production value is defined as a function of inputs of

- natural capital, renewable and non-renewable, including the impact of the life-support systems,
- man-made capital, and
- human capital.

The function obtained is named a Biophysically Anchored Production Function (BAPF).

Data from IEA are used to evaluate the value and significance of some parameters in the BAPF for Sweden, USA, EU, and Japan 1962-1997. Official national statistics in Sweden are used to evaluate some relations on a more detailed level for the period 1970-2000. Data from Lindmark (1998) made it possible to relate some emissions to air, water and of solid wastes to GDP for the period 1900–1990. The obtained R^2-values and significance levels varied substantially for the different emissions.

The BAPF was used in a non-numerical analysis of the pattern of welfare losses of forcing an ecologically limited economic subsystem to act as if exponential growth trespassing carrying capacity limits was possible.

Paper III describes a relatively uncomplicated analysis of a spectrum of sustainability impacts of an increase of crop protein feeds in Swedish milk and cattle production from 1991 to 1999. The analysis performed was of basically the same type that formed the backbone of economic and production biological analysis in agriculture for decades, with some additional steps. The challenge here was to ensure that the law of constancy of mass and energy were not violated, i.e. that effluxes of energy and matter from one subsystem was equal to the influxes into the next subsystem.

In Paper IV traditional methods to plan the production system at farm level in order to balance available production resources such as labour and land, is used in an analysis of sustainability performance of different management strategies.

Paper V examines sustainability impacts of three measures within animal production systems,

- substitution of ruminant products with products from pigs,
- increased feeding efficiency in milk production with constant yield per cow, and
- increased milk production per cow.

Within animal production sciences and from experience as a professional in animal production, these examples are quite straightforward. The results follow quite logically when the points of departure for the analysis are known.

Paper VI mainly builds on the results in Papers III and V.

The following paragraphs describe potentials for improvements. It should be borne in mind that the estimated potentials are a function of set assumptions. The degree to which the discovered potentials can actually be realised depends on a number of factors that need further studies for clarification.

2.3 Validation, use and uncertainties of data

When working with models of complex systems there are three levels where the relevance of a model should be probed (Giampietro 2003).

The first is whether the model is at all relevant for the systems and issues at hand.

The second is whether the subsystems and relations within the overall model are relevant.

The third is whether the numerical values of constants associated with different relations are good enough. The expression "good enough" is chosen to stress that when dealing with complex systems there is always an element of arbitrary choice involved.

In all contributions in the thesis, models and tools have been constructed from the literature within disciplines that offer expertise in the systems and issues described. Concepts and structures from different disciplines have been integrated into new concepts and tools appropriate for the questions at hand. The ambition has been to keep a high level of internal logical consistency.

This ambition is reflected in the timespan for the PhD thesis, which has enabled studies and professional experiences within different fields of knowledge of importance for the understanding of the value of land within human geography, economy, systems ecology, forestry sciences, agricultural sciences, applied environmental sciences and theories of complex systems. At the same time, networks offering complementary skills have been developed and utilised.

The expansion of the relevance boundaries of already established models, the integration of complementary contributions from different disciplines, and the ambition to meet high standard of internal logical consistency contribute to the relevance of the tools and models used on the two highest system levels.

When possible, the relevance of proposed models has been evaluated through regression analysis against data from the best public sources available from authorities and/or scientific publications. This contributes to the probing of relevance on the lowest of the three levels.

The methods and tools presented in the thesis have been applied during more than 30 years of professional experiences as a consultant in different contexts. This experience has enabled the possibility to evaluate the relevance of the results delivered in real world systems. In a sense, this means that my experience as a consultant has acted as a laboratory for testing methods and concepts developed in the scientific context.

If, for example

- the analysis in Paper VI suggesting that a new system for feeding standards in Swedish milk production will increase the use of concentrates, reduce the economic returns, and result in a lower efficiency in the use of natural resources,
- the analysis is supported by theoretical contributions in the thesis itself, and
- work as consultant at five dairy farms from 2011 to 2013 which shows that
    - this actually happened when the new system was introduced,
    - when farmers adjusted their feeding rations, there were positive impacts on economic results and increased efficiency in the use of natural resources per kg milk produced of the same magnitude as anticipated by the theoretical analysis,

then the evaluation of the relevance of models and tools have elements that are not usually found in scientific contributions. There are two different aspects to this test of relevance. It demonstrates credibility among dairy farmers, who take the risk of changing their feeding strategy against the dominant system. This is not an easy step to take. The second aspect is that the proposed potentials for improvements were realised.

The methods and models regarding milk production and feeding strategies in Papers III, IV, V and VI have been evaluated throughout using this scheme. Thus the relevance of models and tools has been tested at all three system levels simultaneously.

The contributions in Papers I and II have been evaluated in the role of consultant to local, regional, and national authorities regarding the issue of how a sustainable development can be understood from the customer in question, and utilised for the benefit of their mission. The acceptance of this work as consultant indicates a perception among people outside the scientific context that issues around data quality, relevance, and uncertainties have been handled satisfactorily.

Later parts of this thesis present a collage of real world trends that is itself a test of relevance of the contributions in the thesis. Do these trends pose questions about where the toolkit for sustainable development presented in the thesis can contribute to needed answers, or do these trends suggest that the toolkit is irrelevant? These trends contribute to a probing of relevance at the three levels mentioned above.

In Papers I and II, the basic structure of the conceptual model of the economy in its ecological and social contexts and the biophysically anchored production function derived from it agree well with

- the OECD model of the economy in its ecological and social contexts (2001),
- the goal structure expressed in the UN Millennium Development Goals of sustainable development (UN 2008), and
- the perspectives and methods of the Millennium Ecosystem Assessment (MEA 2005).

The contribution within Participatory Multi-Criteria Multi-Level Analysis in Paper III is consistent with the same three sources. This structure is also an important part of Papers V and VI, and expresses the general structure of the thesis itself.

This suggests that if these contributions in the international policy-sphere are relevant in the relation to a sustainable development, then this thesis with its contributions is as well.

3 Results

3.1 Overview

This presentation of results has the following structure: Table 1 gives a summary of research questions, materials and methods, and results from the first five papers of the thesis. Paper VI has a somewhat different character, as it is a review of the current knowledge regarding sustainable animal production on a global scale. Papers I–V are summarised after Table 1.

The papers are included in Appendix I–VI.

Table 1. Research questions, system levels, sustainability dimensions, materials and methods, and results in Papers I–V.

Issues	System levels	Dimensions	Material/ method	Found answers	Paper
1. Conceptual model of the economy in its ecological and social context.	From physiological cellular and sub cellular level to global level regarding, e.g., global food security.	Ecological, economic and social.	The procedure by which research question 2 and 3 were answered gave as a result the conceptual model.	The conceptual model.	I
2. Strength and weaknesses of natural resource concepts.	From physiological cellular and sub cellular level to global level regarding, e.g., global food security.	Ecological, economic and social.	Analysis of internal logical structure; comparison with known properties of ecological, economic and social systems, with a focus on their key characteristics given by the importance of life of microbes, plants, animals and humans in the sustainability context.	Natural resource concepts from economic theory, nutritional physiology and systems ecology had a substantial potential to contribute towards sustainable management of natural resources, including consideration of impacts on ecosystems life-supporting systems. Strengths and weaknesses was a function of the part of ecological economic systems focused within each theory. Central resource concepts within physical resource theory were found to have a limited capacity to contribute, as they were defined under such conditions, that those process restrictions that defines ecological, economic and social sustainability limits are ignored. As a result, the application of these resource concepts, such as exergy and/or entropy shows that the size of the human economy in terms of the flux of natural resources feeding the process in the biosphere is very small, around 1 part of 10 000 compared to the influx through solar radiation. The magnitude of the environmental disturbances due to human use of natural resources is substantial. In practice, thus, vital sustainability components in the evaluation of natural resources quality are ignored when applying resource concepts from physical resource theory. In the simplest form this	I

Issues	System levels	Dimensions	Material/ method	Found answers	Paper
				conclusion can be stated in the following way. Life is a key system characteristic in ecological, economic and social systems. In physics, life is not. Thus, physics does not have the tools relevant for analysis of the sustainability of systems where sustainability is an issue.[1]	
3. How to integrate between natural resource concepts, expanding their domain of relevance.	From physiological cellular and sub cellular level to global level regarding, e.g., global food security	From physiological cellular and sub cellular level to global level regarding, e.g., global food security	Analysis by which assumptions the different natural resource concepts are defined; exploring to what degree they can be unified by modifying the assumed assumptions; deciding which that can be integrated, and which that has a limited potential to contribute, given the complexity of systems where life is a key-feature.	The basic structure of systems ecology, nutritional physiology, and economic theory was found to be complementing, not contradictory. Thus, the integration implies that the system borders are expanded so that the connections can be explicitly expressed.	I
4. Construction of Biophysically anchored production functions (BAPF).	Those system levels where production functions are relevant, i.e., from single industrial plant to national economic level.	Ecological and economic.	From the internal logic of the conceptual model, see research question 1, and the work used as input in its construction, a BAPF was constructed. More specified, important inputs in that process were the production functions used by the Swedish Productivi-	It was possible to construct it; when through statistical analysis estimating the historical predictive power, strong R2-values was found. That relates to how much variation over time in quality corrected energy use explained variation in GDP, for four economies. Also, the change in energy use from one year to another explained a substantial part of the change ion GDP from one year to another. The latter measures decreases the risk that a hidden third factor is the independent one where energy use and GDP both are dependent ones,	II

1. This is not to say that physics lack value in the context of a sustainable development. The point is that physics is not suitable as modus operandi in the evaluation of ecological, economic, and social sustainability.

Issues	System levels	Dimensions	Material/ method	Found answers	Paper
			ty Commission (SOU 1991:82); the so called Hubbert curves used in analysis of the exploitation pattern of fossil oil, earlier studies regarding the conversion efficiency from energy to GDP, and the resilience concept with organising and disorganising forces.	with no causal relations between them. Thus, the statistical analysis supports the relevance of the BAPF.	
5 Trends, levels and explanatory power of key parameters in the proposed BAPF.	National level.	Ecological and economic.	Statistical analysis of long term trends and levels of key-parameters in the proposed BAPF for different economies.	Se above.	II
6. What are the costs of unsustainable economic material exponential growth.	All levels (the issue is general).	Ecological, economic and social.	An logical analysis based on the BAPF constructed (see 4).	The costs follow the pattern of quadruple exponential growth. The reason is that a materially growing economy increases the demand on natural resources and increases the amount of land appropriated, and emissions made, everything else equal. At the same time, with exhaustion of the most valuable stocks of renewable and non-renewable natural capital first (supports the optimisation of profit in recent time), an over time increasing amount of natural resources exploited is needed to (i) upgrade mined natural resources to the previous quality level and (ii) take care of wastes that per unit natural resource delivered of a standardised quality, increases with decreasing resource quality.[2]	II

2. By mathematical logic, decreasing ore grade implies increasing wastes per unit metal produced, everything else equal.

Issues	System levels	Dimensions	Material/ method	Found answers	Paper
7. Method to measure sustainability effects of an over time increased concentrate feeding in milk-production.	From individual cow to global food security-level.	Ecological, economic and social.	Based on (i) methods and approaches used in advanced consultancy in milk production, (ii) integrated with methods of participating integrative assessment, (iii) and expanding systems borders to also include sustainability impacts in the three sustainability dimensions from single cow to global food supply level.	A method was developed, which made it possible to relate the increased use of purchased feeds to increasing sustainability costs in ecological, economic and social terms.	III
8. Results delivered by the method developed in 7.	From individual cow to global food security-level.	Ecological, economic and social.	A combination of the methodology developed in 7 and official data regarding number of cows, their production level, and consumption of purchased feeds to cattle and dairy cows.	Such results were performed, showing substantial and negative effects in ecological, economic and social terms from individual cow level to global food supply level. For the numerical values, see paper III.	III
9. Analysis of the quality of the description of animal production in some studies of the sustainability of animal production.	From rumen microbe ecosystem to global food supply and climate change.	Ecological, economic, and social, with a focus on rumen production biology and economy.	Compared (i) LCA-studies of Swedish milk production; (ii) the Food Phytomass Demand-model; and (iii) an study of integrated cattle and sugarcane production for ethanol-purposes with common knowledge within rumen animal production sciences, and the perspectives on	The analysed examples provide results that to a substantial part were artefacts, due to the gap between the analytical approach they applied in their analysis of rumen animal production systems and (i) common knowledge within rumen animal production sciences, and (ii) the interpretation of a sustainable development expressed by the mentioned sources, respectively. Thus, there is a demand for such methods as the simulation model constructed, see research question 10 and 11.	IV

Issues	System levels	Dimensions	Material/ method	Found answers	Paper
			sustainable development expressed by UN, OECD, and Millennium Ecosystem Assessment.		
10. Construction of a simulation model of animal production.	From physiological level within individual animal up to national animal sector level.	Nutritional physiology, production biology and production economy within animal production.	Based on own (i) experiences as extension officer and (ii) findings when contributing to a major revision of the official Swedish table of feeds and nutrient requirements for ruminants; integrated into the system of production branch calculus and planning of the production at farm level provided by the Swedish University of Agricultural Sciences.	That was constructed, and used, see 11 below.	IV
11. Result of simulation model when assuming that the first management priority was maximum profit, and maximum (ecological) sustainability, respectively.	From physiological level within individual animal up to national animal sector level.	Nutritional physiology, production biology and production economy within animal production.	Run the simulation model, see 10.	The Con-system achieved a good result in economic terms, given the price-relations at the time. Substantial potentials for improvements in production biological and economic terms was identified. In the Eco-system the assumed manager managed to produce quite high milk yields by cows only consuming forages. No grains were used in the feeding, only pasture and forages. In this system, a stock of cows only producing calves for meat-production had the same function as the pig-production system in the Con-system.	IV
12 What are the potentials to increase land avail-	From feeding efficiency per kg milk produced to global	Ecological, energetic, economic and			V

Issues	System levels	Dimensions	Material/ method	Found answers	Paper
able for food and bioenergy purposes through improved milk production by:	demand of bio-energy and food security on global level.	social.			
12.1 Increased feeding efficiency with constant production level in a nation with high production levels.	From feeding efficiency per kg milk produced to global demand of bio-energy and food security on global level.	Ecological, energetic, economic and social.	Based on method, material and results from research question 7-8, combined with an analysis of its possible significance on global scale, through a comparison of feeding efficiencies in Sweden compared to some other nations with high milk yields per cow.	Given the Swedish case it was estimated that 160 000 hectare of tropical land can be released if the higher feeding efficiency3 of 1991 was re-achieved from the lower one of 1999. This would at the same time increase farmers' revenues with 1.2 billion SEK. The results scaled up to global level would correspond to 32 million hectare, and 240 billion SEK4. The relevance of scaling up the Swedish results to global scale was supported by data suggesting generally lower feeding efficiencies in milk production in USA, Denmark, and the Netherlands.	V
12.2 Improved production per cow globally	From feeding efficiency per kg milk produced to global demand of bio-energy and food security on global level.	Ecological, energetic, economic and social.	FAO-data on number of cows and their production levels globally over time, and corresponding data for Sweden, and applying Swedish energy requirements for dairy cows provided information about the decreased appropriation of feeds, thus of land, for a constant total production of milk globally, when	By increasing global average milk production per cow to the current Swedish level, and produce the same total amount of milk, 150 million hectare crop land and pasture is released for other purposes.	V

3. To avoid misunderstanding, the feeding efficiency measure is a partial one, where milk output is related to inputs of purchased feeds. The fractions of feeds produced on farms and feeds traded between farms are not included.
4. On 1 January 2013, 1 US$ = 6.51 SEK, and 1 € = 8.58 SEK. From http://se.rateq.com/, 2013-01-01.

Issues	System levels	Dimensions	Material/ method	Found answers	Paper
			average milk yield increases.		
12.3 Expanding milk production in a developed nation to otherwise, with regard to food-production, marginal agro-ecosystems.	From feeding efficiency per kg milk produced to global demand of bio-energy and food security on global level.	Ecological, energetic, economic and social.	Applying the production biological competence as was the basis of the analysis regarding research question 7-11, combined with actual data on areas of agricultural land, distribution of crops, ley and pasture, and average yields per hectare made it possible to estimate what milk production that area could supply.	Current areas of agricultural land in the northern part of Sweden used for grain and forage production, 400 000 hectare, including pasture, with current production levels could supply the total energy requirements of 3.5 times more dairy cows. They produce high quality food, milk products, from agro-ecosystems with otherwise marginal capacity to deliver high-quality food products. If the same amount of protein was to be produced by pigs, it was estimated that this would require 290 000 hectare of good agricultural land in southern parts of Sweden or somewhere else in the EU for grain production, and 130 000 hectare tropical land for soya production. The number of people whose total protein needs could be satisfied by the grain and soya produced from these areas summed to 14.1 million people. However. The cows emit methane, contributing to global warming. If instead taking all cows away, the contribution towards a reduction of the global climate change, would sum to 718 million kg, That implies a climate change cost of approx 50 kg CO_2 more, per human life that can be sustained through increased production of high-quality protein.5	V

5. This analysis is restricted to the question of using the land to milk production or not. In reality, the alternative of no milk production in the northern parts of Sweden could imply that most of the agricultural land is transformed to forestland. That would increase carbon sinks, which is positive. That is counter-balanced by negative impacts on national level related to national environmental objectives such as conservation of cultural landscape and biodiversity where grazing cattle is a critical limiting factor in northern Sweden. On global scale, increased pig production increases pressure on tropical forests where the climate change impact per kg meat from pigs more is estimated to around 230 kg carbon dioxide, following the feeding rations in the production branch calculi from Swedish University of Agricultural Sciences for fattening pigs the production year 2007, the content of protein feeds in purchased feeds to fattening pigs (Lindberg, 2008, personal communication), and the routes of calculating the impact of land use change in tropical areas of FAO

Issues	System levels	Dimensions	Material/ method	Found answers	Paper
				Global area of pastureland is 2.5 times the area of cropland. Thus, the potential to through ruminants utilise these areas, that way reducing the pressure on more productive cropland for food and fuel purposes is substantial.	
13. What are the associated sustainability effects of the measure that research question12.1 relates to?	From feeding efficiency per kg milk produced to global demand of bioenergy and food security on global level.	Ecological, energetic, economic and social.	Applying the same method and data as used in 7, modified to this task.	12.1 showed that re-achieving the feeing efficiency of 1991 from the lower level of 1999 decreased the appropriation of land for a constant production level within animal production. Revenues increased. Through a more efficient use of protein feeds, the nitrogen content in manure decreased. All effects were substantial. Increasing nitrogen efficiency provide benefits in parallel to the ones reported in 12.1 with regard to environmental objectives such as climate change (decreased emission of N_2O) from manure-handling decreased emissions of ammonia contributing to eutrophication and acidification of terrestrial and water-ecosystems decreased eutrophication of surrounding seas.	V

(2006). In analyses of the climate change impact of ruminants based on life-cycle analysis, the issue of relevant reference values are normally not considered. Some researchers have provided results suggesting that the total methane emissions from the megafauna on all continents before their fast decline, sometimes extinction, coinciding with the arrival of humans dependent on hunting and gathering might well be of the same magnitude of order as current total methane emissions from farm animals and wild animals together. Another aspect is that the same analyses do not normally consider carbon sink potentials in integrated feed-ruminant production systems, which are significant accordion to FAO. For details, see Paper VI.

A brief summary of the contributions follows.

3.2 Tool-kit for sustainable development

The thesis summarises professional experiences from 25 of August 1982 and onwards. During this course a major ambition has been to develop methods increasing the understanding of land and its importance for humanity. This has resulted in a tool-kit supporting choices that contribute to a sustainable development. The individual tools are

1. A conceptual model of the economic system in its ecological and social contexts, in which natural capital, man-made capital, human capital and social capital are considered, see Paper I and II, and Figure 1.
2. Biophysically Anchored Production Functions (BAPF), where production value in the economic production process are expressed as a function of inputs of natural capital, man-made capital, human capital, and the environmental impact of the production process through impact on the life-support capacity. Goods and services measured in the adjusted GDP-terms suggested are means to support the maintenance of social capital, see Paper II.
3. A contribution within participatory multi-criteria multi-level analysis for evaluation of how a specified subsystem contributes to a hierarchy of sustainability objectives in the ecological, economic and social dimensions from low to high system levels considering typical features of complex systems such as thresholds, resilience, irreversibilities, mutual dependencies between systems and system levels (Paper III).
4. System of ecological economic accounts (EEA) obtained when specifying BAPF in time and space, where capital stocks and their changes can be focused, or the flux of economic and ecological goods and services. EEA can be used to measure the performance of any system in ecological, economic and social terms and in relation to affected systems sustainability limits, if sufficient knowledge about them is available. Table 3 and 4 present results from evaluation by means of EEA, where it is shown how the EEA measure contributions to a majority of the 16 national environmental quality objectives in Sweden decided by the Parliament, as well as to Millennium Development Objectives from the UN. Table 7 gives outcomes on local community, regional and national level. Hellstrand (2003a,b; 2007) used EEA to measure sustainability performance on regional level. Hellstrand and Yan (2010) in an evalutaion of whether China is an option when Sweden and EU reduces their contribution to climate change.

5. A simulation model of animal production systems with supporting crop production where EEA for specified agricultural production subsystems are developed with included biological-economic production functions based on Hellstrand (1988, 1989). The simulation model is a development of common tools within agricultural sciences used to optimise the use of available resources of land, labour and capital. The simulation model can be used to generate data for further analysis of sustainability performance of animal production systems based on a genuine professional understanding of animal production systems, and of how balanced agricultural production systems shall be constructed where in- and effluxes in biophysical and in monetary terms between systems are constant. It is also an example of and suggestion for how on societal level find solutions supporting a sustainable development through the combination of different stocks of capital mentioned in 1. Hellstrand (2009) elaborates on this possibility in connection with an job concerning physical planning for sustainable attractiveness in Gothenburg on behalf of Göteborg Stad. The task was to develop new methods to measure values from agriculture in a landscape dominated by urban and industrial elements utilising the concept of ecosystem services, and then apply them. In this context EEA was used as a means for urban planning for sustainability.

3.3 The value of land

Paper I examines the value of land on a conceptual level. The relevance of central natural resource concepts in physical resource theory, systems ecology, nutrition physiology, and economics is probed. By integrating the relevance domains of these disciplines, strengths and weaknesses within the disciplines and their resource concepts are identified and broader, more general natural resource concepts are generated. The conceptual model is consistent with the perspectives of sustainable development within systems ecology and ecological economics around 1990, and the perception of sustainable development by OECD about ten years later. It harmonises well with the perspective in the Millennium Ecosystem Assessment (MEA 2005) regarding the importance of ecosystems and ecosystem services for human wellbeing, and ways of describing dependencies, often mutual, between socioeconomic and ecological systems, and between scales.

The latter follows as Paper I provides the conceptual framework for the other papers. For example, one of the major contributions in Paper III within this frame is the general methodology that is developed relating a specific step in a production system on a low system level and its significance to a hierarchy of sustainability sub-goals in the ecological, economic and social dimensions from a very small to the global scale. This framework ensures that the typical features of systems (given the complexity challenges typical of systems relevant to sustainable development which are difficult to deal with in a formalised methodological manner) are considered, while maintaining the speed and resource (in monetary terms and in terms of intellectual power appropriated) efficiency (in monetary and intellectual terms) of the analysis and relevance given the conditions of real world systems.

Paper I expresses the same goal hierarchy regarding sustainability as is expressed in the UN Millennium Development Goals (UN 2008).

The main findings are that:

- Exergy, a central resource concept in physical resource theory, is useless as a resource concept, according to its strict definition. It is defined under the assumption of thermodynamic ideality. With thermodynamic ideality a flux from system A to system B cannot exist. If anyhow such a flux was possible from A to B, the condition of thermodynamic ideality states that no process where a resource could make a difference can occur in system B. In thermodynamic ideality, all process restrictions defining ecological, economic and social sustainability are ignored. Thus, given the conditions in its definition, exergy is a useless resource concept.

- The result when estimating resource constrains to the global economy by resource concepts in physical resource theory closely related to exergy, suggests that the global economy is infinitesimally small, around 1 part in 10 000 of global natural resource metabolism. Paper I suggests that this result is not a measure of the potential for material growth of the global human economy within the limits of the solar energy flux, but rather a measure of the gap of relevance when measuring environmental resource restrictions by measures that relies on concepts that places e.g. sustainability limits outside the system borders.

- Resource concepts relevant to sustainable development can be improved by integrating contributions from systems ecology, economics and nutrition physiology.

A comment is needed here. The total supply of primary energy globally in 2008 was 492 EJ6. Global technical potential for renewable energy (RE) is estimated to lie in the range 1 895 to 52 721 EJ7. The estimates of technical

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6. EJ = 1018 J.

7. The source for these three estimates is IPCC 2011. Special Report on Renewable Energy Sources and Climate Change Mitigation: Summary for Policymakers. A report of working group III of the IPCC and Technical Summary. Eds: Edenhofer, O., Pichs-Madruga, R: & Y. Sokona. The values are from “Figure SPM.4”. The figure summaries data presented in chapters 2–7 in: IPCC. 2012. Renewable Energy Sources and Climate Change Mitigation. Special Report of the Intergovernmental Panel on Climate Change. Eds: Edenhofer, O., Pichs-Madruga, R: & Y. Sokona.

potential for RE are thus 3.9 to 107 times the total supply of primary energy. In 2008 it was estimated that RE contributed 12.9% of the total primary energy supply, i.e. 63.5 EJ. Thus, the estimates suggest the potential to increase the supply of RE by a factor of 30 to 830 times the contribution in 2008. To put these figures into perspective, total biomass production in agriculture globally adds up to around 230 EJ chemical energy annually (Paper V) when agricultural land comprises the most productive terrestrial ecosystems, and covers around 38% of global land area.

Without anticipating the rest of the results, Papers II and VI explore weaknesses in analyses of environmental performance focused on the climate impact based on the rationality and relevance provided by engineering sciences on an operative level. Some of the examples evaluated directly affect the estimates provided above regarding future RE potentials. On an operative level they are shown to suffer from the same problems as the proposals in Paper I based on physical resource theory, i.e. the problems of extrapolating methods and concepts outside the relevance boundaries where they have been probed. The results in Paper I motivate the following question: to what degree do the potentials for RE proposed by IPCC reflect real sustainable potentials, and to what degree do they express a gap between the constructed maps of the terrain and the terrain itself, given known properties of the systems concerned within the disciplines that represent the expertise regarding these systems and issues? For example, is it possible that the estimates to some extent express the same or similar weaknesses described in Paper I in relation to basic resource concepts in physical resource theory?

I am not stating that there is a problem. The point is to evaluate whether there is a problem or not, through competence that is independent of the competence that generates these estimates. Paper VI demonstrates that the contributions regarding renewable energy from the IPCC rely on contributions from physical resource theory. This issue is therefore not only motivated by principally academic reasons. The importance is stressed by the obvious competition for land use for RE and for food production, and the fact that the first UN Millennium Development Goal concerns global food supply while climate change is one aspect of three in one of four sub-goals in the seventh of a total of eight UN Millennium Development Goals. In total there are 15 aspects of the four sub-goals in the seventh UN Millennium Goal. Thus, the UN through the UN Millennium Development Goals values food production from land higher than RE production. The energy supply for humans is valued higher than the energy supply for machines.

3.4 How to anchor the economy in land

A biophysically anchored production function (BAPF) is derived in Paper II from the conceptual model in Paper I. The BAPF is a tool that supports the evaluation of the sustainability performance on a macro-economic-ecological level. The BAPF is used to analyse the welfare costs of forcing an economic system to trespass ecological sustainability limits, focusing the resilience aspect. It supports measures that enhance sustainable development in harmony with the perceptions of sustainable development within systems ecology, ecological economics, OECD, Millennium Ecosystem Assessment, and UN Millennium Development Goals.

The main outcomes are that:

- The increase of GDP has historically been closely associated with growth in use of energy in Sweden and in other countries.
- The Swedish economy has a lower level of eco-efficiency, measured as GDP obtained per unit energy used, compared to Japan and the EU over the period 1962–1997, and showed a smaller increase in eco-efficiency than Japan, the EU and the USA over the same period.
- The major remaining environmental issues are related to energy use (the importance of changed land use was not examined).
- Forcing an economy to follow the path of exponential material growth may eventually lead to a situation where the welfare costs increase in a pattern of exponential growth raised to the second power, when ecological carrying capacity limits are trespassed.

3.5 Sustainability impacts of feeding trends in milk production

Paper III develops a methodology which supports analyses of sustainability impacts of production systems from low to global system levels within the ecological, economic and social dimensions. The perspective in Papers I and II is integrated with a methodological approach in agro-ecology with a basis in complex system theory, supporting sustainable land management strategies, and traditional management tools within dairy production sciences and agricultural economics. The system levels covered span from the conditions of rumen microbes in physiological terms to global sustainability impacts due to the skill in managing the complex system comprising feeds, rumen microbes and the dairy cow.

The methodology is used to evaluate the sustainability impacts of the increase in use of crop protein feeds by a factor of 2.7 in Swedish milk production from 1991 to 1999 and the associated increase in the use of purchased feeds. The increased feeding intensity for constant milk production equates to decreased feeding efficiency, i.e. decreased economic efficiency and natural resource efficiency. The major impacts were:

- Inferior economic results, by 840 million SEK[8] in 1999 which corresponds to 23% of total payments for labour and capital within the entire agricultural sector.
- An increase in national ammonia emissions by 15% compared to the officially reported level.
- Reduced global food security capacity by 6.6 million people, as the increased amounts of soymeal and other crop protein feeds used in excess of feeding requirements could otherwise have been used to fulfil human nutritive requirements.

It was found that the increase in use of crop protein feeds had not resulted in a greater increase in milk yield than otherwise expected. Nor did changes in price relations between milk price and costs of purchased feeds motivate the increased use of concentrates. The estimate of increased costs for purchased feeds considered the increase in quantities but did not consider the price effect of the substantial increase in the share of the more costly protein feeds in purchased feeds.

Paper III stresses the importance of methods within animal production sciences that formalise the relations between feeds and animals on low system levels, up to appropriation of natural capital, man-made capital, human capital, and the impact on social capital on a high system level.

3.6 A simulation model of animal production

Paper IV presents a simulation model of animal production that meets a major part of the demand of methods that formalise the relations between feeds and animals on low system levels, up to appropriation of natural capital, man-made capital, human capital, and the impact on social capital on a high system level. The simulation model covers milk and meat production from cattle and pigs, i.e. the majority of animal production in Sweden, as well as of agricultural production.

On the global scale, animal production accounts for 40% of agricultural gross domestic product (GDP). It employs 1.3 billion people and creates livelihoods for one billion of the world's poor. Animal products provide close to 40% of humanity's protein intake (Paper VI). On the global scale, ruminants and pigs provided 72% of the feed energy consumed by humans from animal products in 2003, and 52% of the protein consumed from ani-

8. On 1 January 2013, 1 US$ = 6.51 SEK and 1 € = 8.58 SEK, accessed from http://se.rateq.com/ 2013-01-01.

mal products[9]. Of the total area of agricultural land, 70% or more produces feeds for ruminants.

These figures indicate the global need for this type of well probed analytical tool, reflecting the importance of animal production systems as a mediator in enhancing the capacity to use land for sustainable fulfilment of human needs and desires.

The analytical tools here discussed are the system of ecological economic accounts proposed during the 1950s combined with linear algebra and differential functions as means to find optimal production designs on farm level taking into consideration the biophysical and socioeconomic context at hand for the individual farm. The ambition was to find the optimal combination and use of land, labour and capital available. These tools are presented by Nanneson et al. (1945), Renborg (1957), Johnsson et al. (1959), Arbrandt (1971), Wiktorsson (1971, 1979), Østergaard (1979), Hellstrand (1988, 1989).

A feeding plan program was developed and integrated with a common management system in agricultural economics, the system of production branch calculus with associated methods to optimise the production on farm level with consideration of available resources of land, labour and capital (SLU 1989a,b; 2006; 2009). This system has its roots in agricultural management systems from the early 20th century in Sweden (Nanneson et al. 1945), as well as in the management systems developed to support the productivity improvement in European agriculture within the Marshall plan that were inspired by the system used to steer the economy of the USA to meet the demands of the Second World War and the civil society (Renborg 1957).

The simulation model formalises the impact of changes at the low physiological level on overall system performance. The simulation model is based on mathematical expressions of animals' nutritive physiological requirements. All costs in the production branches behind the cattle and the pig production systems are included. In this way, the impact of e.g. increased energy content in forages fed to dairy cows by 1.0 MJ metabolizable energy per kg dry matter on all revenues and costs in a system producing a fixed amount of milk and meat from cattle and pigs can be estimated. This is a quite complex issue, as increased energy content per kg dry matter affects the production of milk per cow as well as the amount of feeds needed for a fixed milk production. Increased production of milk per cow affects the number of cows needed to produce a certain amount of milk. A change in the number of dairy cows affects the amount of meat produced from the stock of dairy cows through cows, heifers and bulls. Thus, it also affects the complementary meat production system. With changes in the structure of the animal

9. Own processing of data from FAOSTAT, http://faostat.fao.org/site/610/DesktopDefault.aspx?PageID=610#ancor, accessed 2009-07-16.

production in terms of number of animals in different production branches, the structure of supporting crop production systems is affected. The crop production system is also affected through another path; increases in nutritive quality per kg dry matter of silage, for example, reduce the amount of feeds needed per kg of milk and meat produced.

Since 1997 I have analysed a huge number of studies related to the environmental and sustainability profile of animal production systems, especially ruminant and dairy production systems. None of the studies that I have analysed has captured the importance of the skill by which e.g. the physiological requirements of the complex dairy cow rumen ecosystem in interaction with the host animal are considered in the socioeconomic and biophysical context of the farm. As shown by Hellstrand (1988), the skill by which farmers manage to do precisely this has a major impact on their economic results as well as the natural resource efficiency of their production. I therefore propose that Paper IV fills in a gap in the available methodological toolkit used to improve the capacity of land to fulfil human needs in Sweden and internationally.

Increased energy value of forages is a major means of improving ruminant production. Substantial improvement can be achieved within existing technological solutions, simply by doing things in a more skilful way. To be able to evaluate this potential, tools are needed that capture the causal chains from nutritive values of feeds to overall system performance for integrated animal production systems, including supporting crop production systems. The simulation model captures fluxes in biophysical and monetary terms. It relates to the appropriation of natural capital (renewable and non-renewable), man-made capital such as buildings and machines, and human capital (labour). The products are food items that have a substantial importance for the maintenance of social capital in society. By this type of analysis, a platform is provided that supports evaluation of environmental (positive and negative) effects of animal and agricultural production systems (results in Papers III, V and VI are based on this type of analysis) as well as human health impacts. The latter are needed when evaluating cost-efficient policy measures regarding food-mediated human health impacts. Hellstrand and Landner (1998; 2001), Hellstrand and Drake (2008) and Drake and Hellstrand (1998) utilised this approach in an evaluation of social costs related to food intake of cadmium. This had an impact on cadmium policies in Sweden and on the debate in the EU.

The social costs of fractures related to the impact on the skeleton of cadmium intake through food in Sweden are 4.2 billion SEK annually. Total costs for fracture annually are 39 billion SEK (Kemikalieinspektionen, 2012). One of the major conclusions of this report was that there are large social benefits to be gained by reducing cadmium intake through food. The implementation of cost-efficient policy measures for this task demands the type of analysis of cadmium fluxes and factors affecting human exposure to cadmium in the food system that Hellstrand and others produced (references above). The consistency regarding influxes and effluxes and the general methodological approach in traditional management tools in agriculture discussed above is a prerequisite for this task.

The simulation model supports a mutual evaluation of natural resource and economic efficiency in the production. It fills a gap as a tool that supports the development of ecological, economic and social contributions to a sustainable society from animal production systems generally. The output in production biological and economic terms provides information about impact on the appropriation of renewable natural capital, non-renewable natural capital, assimilative capacity, human capital, man-made capital and social capital. For some impacts the effects are shown immediately. For others, the outputs of the model are vital inputs for subsequent analyses of impacts on aspects of the aforementioned stocks of capital, as illustrated in Paper III.

The contextual factors referred to above were common knowledge in agricultural sciences in Sweden during the 20th century up to around 1990/95. However, a major research program with the ambition of supporting sustainable food production systems (FOOD 21) was initiated in 1997. Together with the changes in feeding standards systems during the 1990s, FOOD 21 was symptomatic of a significant loss of awareness of this perspective, which is discussed in Papers IV and VI. The results imply that there were significant scientific problems with the changes in the feeding standards systems in 1991 and 1995, and that these made a large contribution to the falling sustainability performance of Swedish milk production from 1991 to 1999 as reported in Paper III (see also Section 4). For this reason, the simulation model of milk production is based on the feeding standards that were valid until 1990.

The simulation model is applied in an evaluation of one conventional and one ecological production system. The potential for improvements in production biological and economic terms are analysed in relation to application of good agricultural practice in animal production.

The most important outcomes were:

- The simulation model itself.
- The identification of weaknesses in the way animal production systems and agricultural systems were treated in engineering-based approaches such as
    - a model of the global food system developed within the frame of physical resource theory (Wirsenius 2000; 2003a,b),
    - an integrated model of ethanol and milk production in Brazil with major inputs from physical resource theory (Sparovek et al. 2007; Egeskog and Gustafsson 2007), and

    - LCA studies delivered from the Swedish University of Agricultural Sciences (SUAS) and the FOOD 21 program regarding sustainability in milk production systems (Cederberg and Flysjö 2004; Cederberg et al. 2007; Gunnarsson et al. 2005; Sonesson 2005).

- The identification of the deep nutrition physiological problems in Totfor, a program from SUAS that was used to provide production biological and economic data for milk production for Swedish authorities and the milk sector from 1996 onwards.
- The results from the comparison of the two production systems, which
    - are valuable inputs for further studies of the sustainability profile of animal production systems, and
    - inform about potential for improvements in economic results and natural resource efficiency within each system.

3.7 Sustainability impacts of measures in animal production

Paper V evaluates sustainability contributions of three measures in animal production systems based on the contributions in Papers I to IV. The evaluated measures are:

1. increased production level per cow on the global scale,
2. increased feeding efficiency in milk production at constant production level, and
3. the importance of utilising ruminants as ruminants, converting biomass from otherwise marginal agro-ecological systems to high quality food.

The major results were

(i) that increased milk production level on the global scale by a factor of 4 up to the current level in Sweden would

- reduce energy requirements per kg milk produced from 13.7 to 7.7 MJ metabolizable energy, i.e. by 44%, and
- as a result reduce the agricultural land area appropriated for a fixed amount of milk produced globally by 150 million ha, and decrease the appropriation of gross energy by 6.7 EJ[10].

(ii) Increased feeding efficiency globally was estimated to

10. EJ = 1018 J.

- increase the revenues from milk production by approximately 40 billion US$ per year,
- reduce nitrogen emissions to air and water by approximately 4 000 million kg nitrogen per year, and
- decrease the pressure on forests in Brazil to produce soya bean meal by approximately 32 million ha or increase global food security through an increased capacity to fulfil human need for protein by 1.3 billion people.

(iii) Utilising the current production area of 400 000 ha in Northern Sweden would support milk production that

- provided the total protein supply for 3.7 million people,
- released 293 000 ha of good arable land for grain production and 131 000 ha of tropical arable land for soymeal production, that otherwise would have been appropriated to produce the same amount of protein from pigs. The utilisation of 400 000 ha of otherwise marginal agricultural land would enable use of 424 000 ha of good agricultural land, and
- increased global food security potential by 14.1 million people with respect to protein supply (the number of people whose protein requirements could be supplied if not using up barley and soymeal for the corresponding pig protein production).

Paper V explores a combined ecological-agricultural-social perspective in the analysis. The ecological, economic and social impacts identified are typically not covered in engineering-based analyses of milk production, as in the references provided above in the presentation of Paper IV.

3.8 Animal production and global sustainability

Paper VI analyses the contribution to a global sustainable society of four measures in animal production systems. It provides measures of the significance of animal production systems in economic, ecological and global food security terms. The most important results in Papers III and V were utilised, together with results from other sources. The impact of consuming 1.7 g less chicken meat per capita and day in developed nations was considered alongside the three measures evaluated in Paper V. The most important additional findings as a result were that:

- Reduced consumption of chicken meat would reduce the amount of appropriated arable land by 16.0 million ha of which 9.1 million ha was tropical forests, increase global food security potential by 470 million people, or[11] as a one-off event[12], reduce emissions of climate change gases by 5.2 Gt CO_2-equivalents.

- Increased feeding efficiency at constant milk yields per cow and constant total production globally would reduce the appropriation of agricultural land by 51 million ha of which 32 million ha are tropical forests, increase global food security by 1.3 billion people, or decrease climate change impact by 22.4 Gt as a one-off event.
- Increased feeding efficiency in Swedish milk production from 1999 levels to 1991 levels (as reported in Paper III) would reduce discharges of nitrogen to the Baltic Sea by around 6 million kg, while saving the milk producers an estimated 1.21 billion SEK.

The reason for the estimate of savings being 370 million SEK higher than the 840 million SEK estimated in Paper III is that in Paper VI, the impact of the increased quality of the purchased feeds is accounted for and added to the impact of the increased use of purchased feeds.

The eutrophication issue is interesting. As Paper VI shows, it was decided that Swedish national discharges of nitrogen to the Baltic Sea should be reduced by around 10 million kg more than earlier objectives. Sweden has problems in meeting the current objectives regarding reduced discharges to the Baltic Sea, especially in the south-west of the country. In this context Kattegatt, outside the south-western part of Sweden, is defined as a part of the Baltic Sea. On the margin, the cost for reducing nitrogen discharges is around 1 000 SEK/kg. The set objectives are not being met, and thus the marginal price to fully cope with the objectives is increasing. Here, a previously unidentified measure has been found that through increased nitrogen efficiency in milk production improves farmers' economic results by 1.21 billion SEK, reduces nitrogen discharges to the Baltic Sea by around 6 million kg, reduces the contribution to climate change through deforestation in Brazil and through emissions of nitrous gases from manure (due to decreased nitrogen content), and reduces contributions to acidification and eutrophication through ammonia emissions.

Paper VI found that the welfare economic impact of the possible increased nitrogen efficiency in Swedish milk production was a net societal gain of 9.8 billion SEK (slightly more than 1 billion €) given the environmental preferences of Swedish society. This corresponds well with the value of the total milk production in Sweden, suggesting that the negative external

11. Either tropical forests, that on the margin are appropriated for soymeal production, are converted to agricultural land producing soymeal with the capacity to support human protein requirements, or they remain, thus the contribution to climate change by deforestation is avoided.
12. I use the expression "one-off event" to stress that when forests are cut down, the storage of carbon in wood will eventually be oxidised and released as carbon dioxide.

effects of Swedish milk production in 1999 in terms of the aspects discussed here were close to the same size. The welfare value of reduced nitrogen discharges of 9.8 billion SEK, corresponds to a negative cost of 1 600 SEK per kg of nitrogen less discharged.

Applied to the global scale, the three measures mentioned (i) reduced the appropriation of agricultural land by 217 million ha of which 41 billion ha were tropical forests; (ii) improved global food security potential by 1.8 billion people (protein supply); (iii) reduced the contribution to global climate change as a one-off event by 27.6 Gt, where the total annual anthropogenic contribution is estimated at 40 Gt. Effects (ii) and (iii) are of the either/or type.

The next part of Paper VI analyses the mechanisms that explain why these potentials were not yet utilised. This knowledge enables measures to be taken that contribute to eliminating current implementation gaps in sustainable development, with a focus on animal production systems globally. For this reason, a detailed examination was carried out on the quality of methods and concepts that underpin current

- energy standards in milk production,
- protein standards in milk production, and
- evaluation of sustainability impacts of production systems generally and of agricultural and ruminant production systems specifically.

The results indicate substantial potentials for improved sustainability performance on the aggregate level through measures at the low system level, by changing common practice. This is a result of a partly new and more efficient methodological approach, whose foundations are presented in Papers I-VI. The combination of the significant potentials and the novelty of the approach motivates further discussion of some important aspects in Section 4, in order to probe the relevance of the results.

4 Discussion

This section discusses in detail some of the most critical aspects affecting the relevance of the contributions in Papers I to VI and the thesis.

Papers I and II are relatively straightforward in their approach, content and delivered results. Papers III to VI treat animal production systems in a sustainability context. There is a need to discuss some aspects of the results in more detail. For instance:

- Provided the official data from Statistics Sweden, Swedish Board of Agriculture, Eurostat, FAO, and OECD are correct, they suggest substantial sustainability improvement potentials in the dairy production sector in Sweden, the Nordic Countries, the EU, and globally, which influence overall sustainability in ecological, economic and social terms.
- Current theoretical foundations for feed evaluation and feeding standards systems for dairy cows in Sweden, the Nordic Countries, and internationally may be a major factor.
- Analyses of general sustainability potentials based on engineering sciences and systems ecology have identified substantial potentials through measures within agriculture, animal production, and ruminant production systems. Papers I, II, IV, V and VI suggest that the relevance of these analyses may be questionable.
- If the relevance is not sufficient when probed against
    - known properties of relevant systems within the disciplines in which there is expertise regarding concerned systems and issues,
    - traditional scientific criteria regarding e.g. internal logical consistency and a sound empirical probing,

  there is a risk that advocated measures may in fact harm vital sustainability assets.
- Thus, if the logic of these analyses guides real world actions and their relevance is weak as suggested by the results in Papers I–VI, within a time frame of 2–20 years they could severely
    - reduce the productivity of global agricultural systems and thus human food supply,

- reduce the effectiveness of Swedish environmental policies including those on climate change from local authority level to contributions in international contexts,
- diminish Swedish competitive power given major economic, energetic and environmental trends from local to global level,
- reduce the ecological sustainability basis for urban and industrial systems,
- harm rural development.

- Few people are in a position to be aware of these problems, as it would require the capacity to follow causal chains from the level of the physiology of rumen microbes to global food security, taking into account socioeconomic and biophysical contexts and variations in time and space.
- Thus, there is a real risk that actions that are currently being taken to secure sustainable development within, e.g.
  - dairy production in Sweden and internationally, or
  - biofuel production,

  will actually harm the objectives of sustainable development.

This section, on a meta level, treats the importance of complying with traditional scientific quality criteria as one aspect of supporting good quality in societal decision-making processes.

The systems under consideration are complex. The presentation is based on my own understanding of the issues, with all the strengths and weaknesses that this implies. One purpose of this section is to present my perception of the situation with supporting arguments. The most important effect of doing so is the invitation to the reader to address those parts of the presentation that the reader perceives as having the most important flaws. With this exchange of information I can either improve the arguments, or thanks to the feedback adjust and improve the analysis.

4.1 Increasing nitrogen influxes for constant milk production

Papers III and VI imply that the nitrogen influxes to cattle production though purchased feeds in 2006 were 2.5 times higher than in 1991, 48.2 million kg compared to 19.0 million kg. Swedish production of beef and milk was 137 099 and 3 200 000 tonnes respectively in 1991, and 137 404 and 3 172 000 tonnes respectively in 2006. Thus, changes in production did not motivate this increase in nitrogen influxes and nor did the price relations between milk and purchased feeds. Fixed prices for purchased feeds and milk fell by a similar degree from 1991 to 1999, thus the price relation was constant (Paper III).

This raises five questions in parallel:

1. Could the changes of the energy standards to dairy cows in Sweden during this period (1991–1999) explain these trends?
2. Could the changes of the protein standards to dairy cows in Sweden during this period (1991–1999) explain these trends?
3. Why were these trends not detected in national environmental monitoring systems regarding ammonia emissions from and nitrogen balances of the milk production sector?
4. Why were these trends not detected in the research regarding sustainable food production at that time?
5. What is the international relevance of the Swedish case?

These questions are discussed in the following paragraphs. Without anticipating the results from this discussion, the answer to 4 generates a sixth question:

6. Are engineering-based approaches intended to support sustainable development counterproductive, due to their limited capacity to detect the ecological, economic, and social process restrictions that define sustainability limits and opportunities?

While questions 1–5 focus on the animal production level, addressed in Papers III to VI, question 6 has a more general relevance for sustainable development, and thus applies for all papers in the thesis.

Paper VI was accepted in October 2012. Questions 1–5 were not discussed in detail in the submitted version. Rightly, one of the reviewers strongly criticised this omission, as the submitted version did not present sufficient arguments to support the conclusions. Thus, the final revision was rewritten in the first weeks of October 2012 to provide some of the answers to questions 1–5. I am aware that the following paragraphs repeat some of the information in Paper VI. There are five reasons for deciding to do so:

1. The information in this section and in Paper VI is complementary in parts.
2. If the analyses in Papers I–VI are mainly correct, they imply that only by improving the way in which the feeding requirements of dairy cows are estimated globally and then feeding the cows in accordance with the results can major ecological, economic and social sustainability improvements be achieved globally (see Table 1 and Paper VI).

3. If the analyses in Papers I–VI are mainly correct, then there are major problems, for instance in the climate change policy from regional level in Sweden, through national to the IPCC level, that ultimately risk global food security (Paper VI).
4. This is new knowledge that is not yet available in national and international policy contexts.
5. Before major changes in important policies are made, new proposals should be scrutinised; with this presentation I invite readers to do their best to show that the presented analysis is false.

Regarding 2, examples of contributions to sustainability are improvements in the capacity to support human protein requirements corresponding to 1.3 billion people, or reducing the global land area for soymeal production by 32 million ha, i.e. close to half the total global area for soymeal production (FAO 2006).

Regarding 5, this forms part of a relevance test of scientific contributions that aim to support sustainable development. This kind of transparency is needed due to the complexity of the issue.

4.2 Energy standards to dairy cows

This section is mainly an extraction of Paper VI and a draft of a longer report from which Paper VI is extracted. As most readers of the thesis are not experts in animal nutrition and animal production theory, major issues in the scientific basis of current energy standard systems in Sweden and internationally are outlined below, followed by a more detailed discussion of some of the most important aspects. This is because these issues have a major influence on the natural resource efficiency in the major animal production branch in Sweden (Paper IV) and globally (Paper VI), and that there may be major problems with current systems in Sweden, Denmark, and the USA (Paper VI). Furthermore, this is one area where there are critical problems with engineering-based approaches in the analysis of sustainability of animal production systems when compared to known properties of the systems studied. This discussion also serves as preparation for an analysis of the relevance of the way in which animal production systems have been treated in some engineering approaches discussed in Section 4.7.

The first question is the accuracy of how metabolism of ruminants is presented. Problems in this field imply sustainability costs in ecological, economic and social terms. Here lies a paradox. The higher the identified costs the better, as past flaws imply future options for savings.

Since 1995 energy standards to dairy cows in Sweden have been based on the objective that they predict yield from feed intake on the commercial herd level. Paper VI and the underpinning report show that this is flawed as:

- The aim on the commercial herd level is to achieve a good economic result. This happens when the marginal cost for feeds equals the marginal income from milk.
- On the commercial herd level, both feed intake and milk yield depend on the sum of the quality of the management, in terms of the degree to which it allows the herd to express its full genetic capacity for milk production. This is closely related to Liebig´s "Law" of the minimum concerning the first limiting factor for production in biological systems, and Shelford's "Law" of tolerance (Paper VI). The effect is that the apparent (not true) relation between feed intake and yield among commercial herds is linear.
- The statistical method applied introduces problems. Regression analysis was applied on trial averages of milk yield and feed intake where
    - in many trials the cows had free access to high quality forages[13],
    - none of the trials were designed to provide information about the response curve to increasing feeding intensity

  Consequently,
    - feeding levels above economic optima in feeding trials were transformed to general feeding standards to be applied to commercial herds, steering the feeding levels of basically all herds in Sweden to excessive feeding rations considering economic and environmental impacts,
    - pure chance decided the values for maintenance and milk production requirements; this was a function of the trials that were selected for the meta-analysis, where there was no obvious guiding principle for the selection process.

13. As an example; in the probing of the relevance of different feeding standard and evaluation systems for the new Nordic Norfor system, trial 16 (of a total of 26) had an average intake of forages of 10.0 kg dry matter for a production of 3 kg ECM. With average forage quality, this implies an energy allowance of 9.6 MJ ME (Metabolizable Energy) per kg milk, where the official standard in Sweden since 1995 is 5.55 (Spörndly 1995), and before 1995 it was 5.0 (Hellstrand 1989; Spörndly 1989). This raises the question of whether it is reasonable that such a trial, with such a significant average deviation from commercial production conditions, is used as a criteria by which the relevance of different energy standard systems are probed (see Table 4.1.b in Norfor 2004). A consequence is that this trial will steer the Norfor system to feeding intensities above the economic optimal level.

- The reason given for the change of the energy standard, that the relation between feed intake and milk output is curvilinear, was not addressed by the measure taken; one linear relation was replaced with another. This indicates that the combined physiological, mathematical, logical and statistical competence applied was not sufficient.
- A new physiological principle was introduced. For lactating cows, the maintenance needs were now assumed to be a function of the life-weight and an added constant, -13.6 MJ[14]. Previously, it was only a function of the life-weight. No reason was given for the introduction of this principally new physiological approach.
- The work was performed at too low a scientific level. Energy standards to dairy cows are among the most important relations in agriculture from combined economic, natural resource, environmental and social sustainability perspectives. The sustainability impacts of increased feeding intensity reported in Paper III express precisely this point. The fundamental change regarding the guiding principle in 1995 was based on a student's work that contained substantial internal inconsistencies[15] (Paper VI and supporting report).

During most of the 20th century, the feeding standards regarding energy allowances in milk production in Sweden were based on three ruling principles:

- The purpose is to support a feeding intensity that maximises the economic result at commercial farm level;
- Based on this, the law of diminishing returns was utilised to arrive at the average energy allowance per kg milk where the value of a marginal increase in milk yield is equal to the feeding costs that produce it;
- On commercial herd level, the apparent relation (not a true one) between milk yield and feeding levels is constant.

The last point is explained by Liebig's "Law" of the minimum (Liebig 1840) and Shelford's "Law" of tolerance (Shelford 1913). Together, these early contributions present the chemical, physiological, biological and ecological foundations for relations behind the concept of resilience later introduced..

When the quality of the total environment of the animal is enhanced, the capacity of the cow to utilise her production capacity increases. When this happens both milk yield and feeds consumed increase. Both yield and feed intake are in this situation dependent factors and the quality of the total envi-

14. This implies an assumption that very small cows have no maintenance requirement.
15. This is not a critique of the work of the student. The issue is whether a student's work should have this much influence on national feeding standards to dairy cows.

ronment is the independent factor. This explains why in nations like Sweden where the use of artificial insemination is widespread, and the genetic capacity of cows in all herds is therefore similar, production can vary by a factor of 2 between herds, while the amount of feeds for production of a kg of milk is constant.

The methodological approach to achieve feeding standards that conform to these rules involved long-term production trials (three years) in which the feeding intensity was varied while all other factors were held constant. By doing so, the marginal response to increasing feeding intensity was estimated.

This perspective was expressed and supported by contributions from Nanneson et al. (1945), Wiktorsson (1971, 1979), Arbrandt (1971), Østergaard (1979), Hellstrand (1989) and Spörndly (1989, 1991, 1993).

In 1995 the guiding principles in the energy standards system in Sweden were fundamentally changed (see Andresen 1994, Spörndly 1995). With this change it was assumed that:

- Energy standards would predict milk yield from energy intake.
- Due to the law of diminishing returns[16] high yielding cows are assumed to request more feeds per kg milk produced, consequently on average the energy requirement for milk production per kg milk is higher in high-yielding commercial herds.
- The relationship between milk yield and amount of feeds consumed is curvilinear on both individual cow level and among commercial herds.

It is noteworthy that the production economic aspects were no longer considered (see Andresen 1994, Spörndly 1995).

Figure 3 illustrates the curvilinear relationship between feed intake and milk yield on the individual cow level in trials where variations in factors other than the feeding intensity are minimised.

The figure shows diminishing returns at individual cow level with increasing feeding levels, when all other factors are held constant.

16. Expressed in physiological terms as lower utilisation of nutrients per kg feed consumed at higher production levels, as every kg of feed then passes through the digestion tract more quickly, as more feed is processed per time unit, and thus the time for digestion processes per kg is decreased.

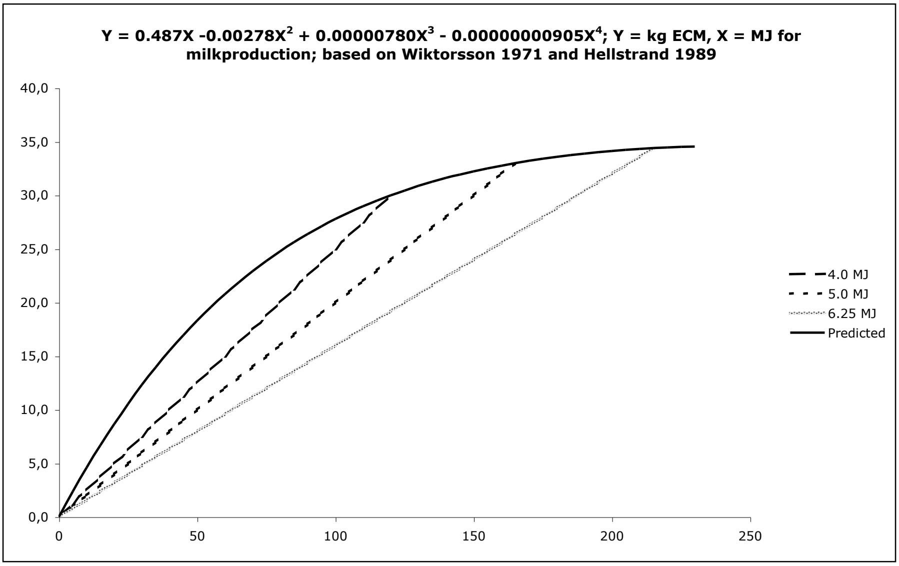

Figure 3. The principal relation between energy intake for milk production in MJ Metabolizable Energy (MJ ME, x-axis) and milk output in kg ECM (y-axis), assuming a curvilinear relation of the fourth order.
Adapted to the marginal output in Wiktorsson (1971) as interpreted by Hellstrand (1989).

The significance of Figure 3 for commercial feeding is in the challenge to find the average feeding intensity that causes the maximal result, i.e. where the value of a marginal increase in production exactly matches the costs for the marginal increase in feeds causing it. For many decades this was the ruling principle for feeding standards in Sweden (see Nanneson et al. 1945; Hellstrand 1989), but it was abolished in 1995 (Andresen 1994; Spörndly 1995). The basic principles discussed, ruled during the major parts of the 20th century in Swedish dairy science, based on theoretical and empirical supporting evidence. It is surprising that these principles so easily were withdrawn with that level of scientific justification.

It is notable that in Swedish crop production science, the same principal approach using dose-response in biological-economic production systems is still used to recommend fertiliser application rates in response to varying market prices (Jordbruksverket 2008a). It is also noteworthy that when the approach regarding energy standards was changed to the present Norfor system, a mutual Nordic[17] system for feed evaluation and feeding standards, Danish researchers reacted as though it was no longer possible to identify the feeding intensity that maximised the economic result on the commercial herd level utilising the combination of the “laws” of diminishing returns, first

17. Except Finland.

limiting factor, and of tolerance[18]. This resulted in a longer report that led to a Scandinavian research program with the aim of correcting for this limitation - see Østergaard et al. (2009) for the report.

Figure 4 shows the relation between energy intake, milk yield and economic results among commercial farms in Sweden for five different years.

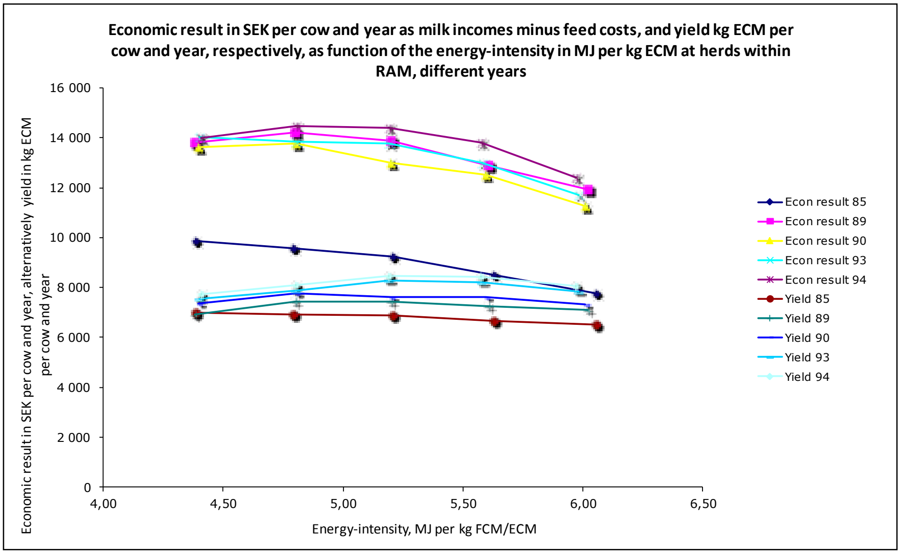

Figure 4. Average yield and economic result in RAM, measured as payments for milk – costs for feeds, per cow and year for herds with different feeding energy intensities, for 1985, 1989, 1990, 1993, 1994.
Source: SHS (1986, 1991, 1994, 1995).

Figure 4 present results from RAM. RAM is an acronym for ResultatAnalys i Mjölkproduktion, i. e. Result-Analysis in Milk Production. It was a tool offered to dairy farmers to analyse the production biological and economic efficiency. From 1984 to 1986 I was responsible for that system with about 30-35 farmers as customers. A substantial part of Hellstrand (1988) is a synthesis of these experiences.

At commercial herd level, with increasing energy intensity per kg milk (i.e., amount of feeds consumed per kg milk produced), the production level and the economic result per cow decreases at a certain point. Thus, the feeding intensity that results in the highest milk production for the five years investigated was in the range 4.4–5.6 MJ per kg ECM. The highest economic result per cow was achieved at a feeding intensity in the range 4.4–4.8 MJ ME per kg ECM.

18. Shelford´s "Law" of tolerance is not commonly known within agricultural sciences. I propose that the way the "Law" of first limiting factor is handled, e.g. in Wiktorsson (1979) and Hellstrand (1988), it actually represents an integration of the contributions of Liebig and Shelford.

Figure 4 supports three important arguments that bring into question the relevance of the guiding principles behind the change in energy standards in Sweden in 1995:

1. Among commercial herds, the amount of energy for milk production per kg milk is not always higher in high-yielding farms than in low-yielding farms.
2. The farms with highest production levels reported energy intakes per kg milk produced that was centred around 5.0 MJ ME per kg milk (ECM), i.e. the energy standard that operated until 1995.
3. In commercial farms, the primary objective of milk production is not to maximise milk production per cow but to achieve a high and durable economic result in relation to inputs of own labour and capital. Figure 4 clearly shows that farms with the best economic result per cow operated at an energy intensity equal to or below the official energy standard at the time.

Figure 4 provides empirical arguments that suggest that the ruling principles behind the changed energy standards for dairy cows in Sweden in 1995 should be rejected, and that the previous ruling principle was still valid. Figure 4 suggests that in the construction of the new energy standard system, a relation between feeds consumed and milk yield on the individual cow level, when all other factors were held constant (Figure 3), was mistakenly used to describe the relation between average milk yield and feed consumption between commercial herds with different production levels. If so, the changed ruling principle for the energy standard showed a decreasing understanding of the complexity of the milk producing dairy cow in commercial herds.

Figure 5 shows the relation between milk yield and economic result measured as revenues for milk minus feeding costs among commercial herds in Sweden for eight different years. The yield at herd level accounted for all of the variation in economic results. The relation between feed intake and economic result is completely linear, as the data that Figure 5 is based on are standardised prices for feeds and milk, which support this type of comparison. Thus, Figure 5 shows an apparent linear relation between feed intake and yield at commercial farm level.

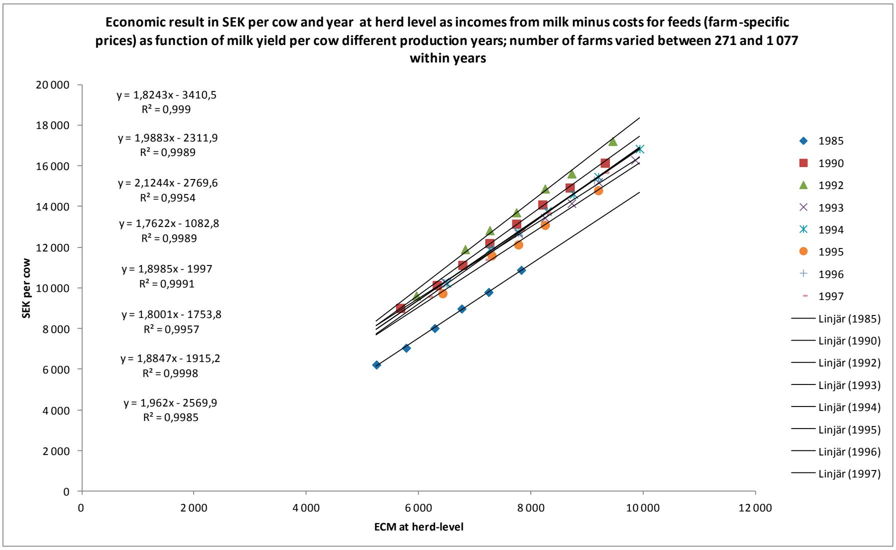

Figure 5. The relation between milk yield and economic result as milk incomes minus feeding costs on herd level.
The regression function for the trend each year is presented to the left in Figure 5, with the function for 1985 at the top and for 1997 at the bottom.
Source: Own calculations based on SHS (1986, 1991, 1994, 1995; results for 1992, 1995, 1996, 1997 are based on internal material which the author obtained from SHS).

The reason that the relation is apparent is that both are a function of a third factor, the total environment of the cow (excluding feed intake). Figure 5 provides strong arguments that Liebig's "Law" of the minimum and Shelford´s "Law" of tolerance are valid at the commercial herd level. This results in an "apparently" linear relation between feed intake and milk yield. Figure 5 points towards the double challenge of commercial milk production: to simultaneously optimise the total environment of the dairy cow and provide the amount of feeds of the right quality that optimises the economic return taking into account the principle of diminishing returns.

The reason to call this relation "apparently" is that when comparing averages of milk production and feed intake between farms, which is what Figure

5 actually does, it is not so that the difference between farms regarding average milk production is because they differ in the feed rations. The difference relate to the capacity to provide a good environment for the dairy cows. When this environment is good, the milk production of the cows is closer to their genetic capacity. Then they milk more and eat more. The underlying independent factor “environment for milk production” affects the dependent variables milk production and feed intake. In this situation they are independent of each others. The result is an “apparent” linear relation between milk production and feed intake.

The situation here described is hard for the human mind to understand. It contradicts what as intuitively appears as quite a simple system to understand. The reason is that when discussing commercial milk production the number of feed-back loops to understand, and subsequently the degree of self-reference is substantially higher than when performing controlled feeding trials.

I suggest that Andresen (1994), NRC (2001) and Norfor (2004) have not understand the difference between the real curvilinear relation between feed intake and milk production in controlled trials, and the “apparent” linear relation when comparing average feed intake and milk production between commercial herds.

During most of the 20th century until 1995 the combination of the law of diminishing returns and Liebig´s law of the minimum provided the foundation for the official energy standard system in Sweden (see Nanneson et al. 1945; Wiktorsson 1971, 1979; Arbrandt 1971; Østergaard 1979; Hellstrand 1989; Spörndly 1989, 1991, 1993) and the basis for the official nitrogen application recommendations (Jordbruksverket 2008a). Why Sweden now applies two fundamentally contradictory approaches to basically the same issue in plant production and milk production is unclear. Figure 5 provides strong empirical evidence that the assumption of a curvilinear relation between feed intake and milk yield at commercial herd level in milk production is false.

The changed ruling principles behind the energy standards in 1995 reduced the feeding efficiency in Swedish milk production through two paths:

1. The adjusted energy standards increased the amount of concentrate rations at high production levels.
2. The disconnect between economic efficiency and feeding standards communicated on false grounds to farmers that the task was no longer to feed their cows economically optimal amounts of feeds.

The basic argument for the change of energy standards was that due to a curvilinear relation (Figure 3) between feed intake and milk yield, on the margin more feed was required per kg milk at high production levels than at low production levels. However, the enforced change implied that the energy requirement in MJ ME estimated by the older system for milk production and for maintenance was multiplied by 1.11, reducing the result by 13.6 MJ ME (Spörndly 1995). Thus, in order to create a curvilinear relation, a linear relation was transformed by multiplication and subtraction of constants, i.e. the linear relation was replaced by another linear relation. This characterises the lack of logical consistency behind current Swedish feeding standards to dairy cows. A mathematical expression of the relationship between feed intake and milk production was sought based on a false assumption regarding the physiology of milk production at commercial herd level. The statistical method applied resulted in the rejected mathematical expression being replaced by another expression of exactly the same form.

This mistake has remained unrecognised by the organisations and experts in charge since 1995.

Against this background, it is not surprising that the major changes in the energy and protein standard systems (see next section) in Sweden during the 1990s contributed to a 2.7-fold increase in the use of crop protein feeds to cattle between 1991 and 1999 as reported in Paper III (see also Paper VI).

These findings are of fundamental importance for the issue of increasing the sustainability of global milk production. Feeding standards in the USA, Denmark and the Netherlands (Paper VI) are based on the same logic as the one behind Swedish feeding standards since 1995. The governing assumption is that at high production levels in commercial herds the demand on feeds per additional kg milk is higher than in herds with lower production levels. The curvilinear relation from controlled dose-response trials at individual cow level (Figure 3) provides the results that form the basis of the energy standards that are applied at commercial herd level.

Figure 6 shows this relation as it relates to the USA standards. It is based on the relations in NRC (2001) regarding the energy content in feeds and energy requirements of the dairy cow.

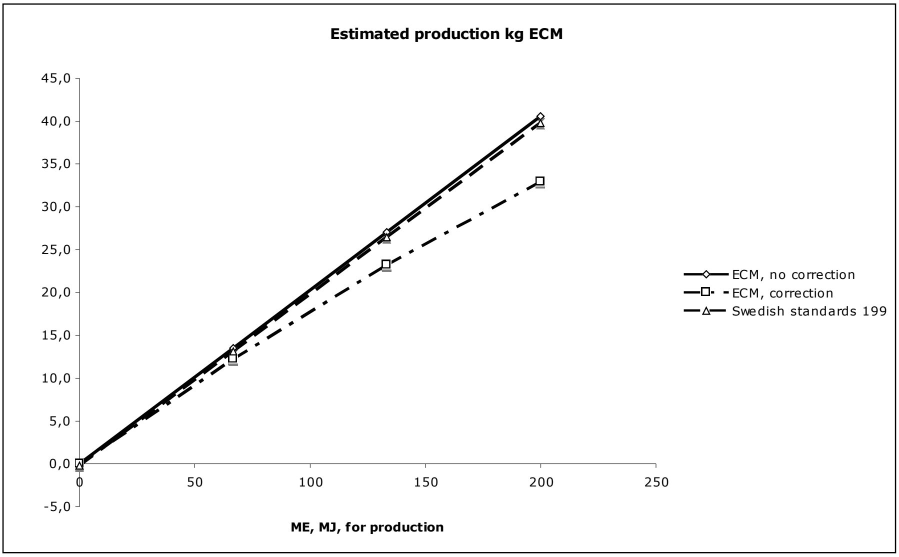

Figure 6. **Estimated production capacity at different energy supply levels according to NRC (2001) with and without correction for decreasing utilisation of nutrients in the feeds at increasing consumption level; assuming a live weight of 680 kg, no gestation, and no weight changes.**
Digestible Nutrients are 77% of feeds.

NRC (2001) assumes decreasing capacity of cows to utilise nutrients in feeds at higher production levels, i.e. at higher feed consumption levels. A consumption of 200 MJ ME above maintenance requirements would, according to the pre-1995 Swedish standards, support production of 40 kg milk (ECM). The NRC system gives a similar result before correcting for an assumed decreased utilisation rate at high consumption levels. After the correction is applied, the NRC system suggests that the same amount of feed would support less than 35 kg milk. The consequence is that at these production levels, the NRC system estimates that the cows need an additional 3–4 kg of concentrates per day, compared to the pre-1995 Swedish system. This difference can be converted directly to increased sustainability costs ecologically, economically and socially as shown by Hellstrand (2006). The results in Figure 6 are in agreement with Huhtanen and Hristov (2009), who found in a comparison of feeding trials between North America and Western Europe, that the average feeding intensity per kg milk was higher in North America for the same production. They interpreted this as an expression of different customs regarding feeding at commercial herd level in North America and Western Europe,

Figure 7 shows the corresponding curves for Denmark, Norway and Sweden based on Norfor (2004; p. 51), which gives the relations that predict milk production from energy intake according to Danish, Norwegian, and Swedish feeding standards at the time.

The assumed live weight is 600 kg, and barley is used as “currency” when converting the different energy qualities used in the Swedish, Danish and Norwegian energy standard systems to the same energy base.

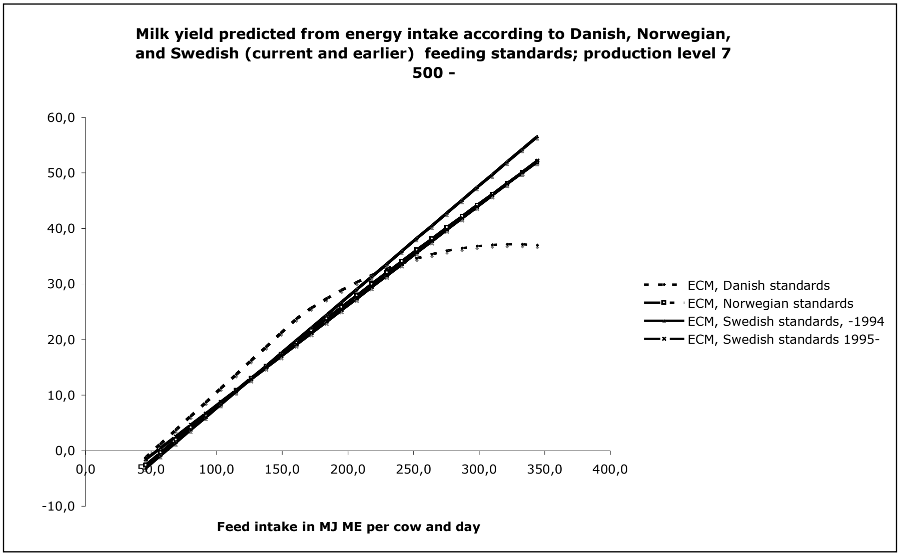

Figure 7. Production levels in kg milk (ECM) per cow and day predicted from energy intake according to feeding standards in Denmark, Norway and Sweden. Assumed annual production level is in the interval 7 500 to 10 000 kg milk (ECM) per cow.

The Danish feeding standard implies that milk yield peaks at a consumption of 24.4 kg dry matter (DM), with a predicted production of 37.2 kg ECM, whereas using the Swedish feeding standard as described by Hellstrand (1989) (“ECM, Swedish standards, –1994” in Figure 7), predicted production would be 52 kg ECM.

Note that the dry matter intake here is related to an energy concentration of 13.2 MJ ME per kg dry matter, as in barley. This is higher than common energy concentrations at commercial herd level, where roughly half of the dry matter intake is forage and half is concentrate. However, the principal point is not affected. The consequence for feeding on commercial herd level is that if using the Danish approach, a substantially lower feeding efficiency is assumed at production levels of 35 kg ECM and above. The Danish system gives a similar outcome as the NRC system (Figure 6). ME on the X-axis in Figure 6 relates to energy for milk production after maintenance requirements are met, while in Figure 7 it relates to the total energy intake.

The consequences from a sustainability perspective are that the NRC standard in the USA and the Danish feeding standard for herds with high production levels recommend substantially higher feed rations per kg milk produced compared to herds with lower production level. The reason is that they have mistaken an apparent linear relation between feed intake and milk production between herds with different average production levels, with the real curvilinear relation on individual level in controlled trials when other factors are hold constant, without realising that these are two fundamentally different situations as a function of different contexts.

This causes the kind of unnecessary ecological, economic and social costs that emerged in Swedish milk production from 1991 to 1999 due to increased concentrate intensities as reported in Paper III.

Andresen (1994) compared the outcome of different energy standard systems. While the Danish system underestimated the production capacity by 6.8 kg milk, the system from the Netherlands underestimated the production capacity by 3.9 kg milk. This implies that on real high-yielding farms, these cows would be fed around 3 and 2 kg concentrates more per day during a long part of the lactation period respectively. The Netherlands also had a system that presumed that a curvilinear relation was preferable in energy standards for commercial herds.

Figure 8 shows the results of four different applications of the same basic assumptions and analytical approach in the statistical analysis as the one that governed the changed energy standards in Sweden post-1995. The difference between these examples is the selection of data on which essentially the same methodology is applied. If based on good science, the results should be reproducible and the influence of randomness would be minimised. Figure 8 shows a significant variation in the estimates of energy requirements for maintenance needs and milk production when applying the same methodology on different datasets.

Regarding Norfor, the results are based on the assumption that the energy content of concentrates was 13.5 MJ per kg dry matter, and 10.5 MJ per kg dry matter for forages, and that the cows weighed 600 kg. A regression between production of milk in ECM and energy intake was done, based on the averages for these parameters in the investigated trials. The source for the data used is Norfor (2004). At a 20 kg ECM production level, the Norfor system gives an input of 5.75 MJ ME per kg ECM (15/20) (Figure 8), at 30 kg ECM the input is 5.9 MJ ME per kg ECM, at 40 and 50 kg ECM it is 6.0 MJ ME per kg ECM. This is what as would be expected from the feeding intensities in the trials that were chosen to probe the method when evaluating the relevance of different systems of feeding standards when constructing the NorFor system. A common denominator of these trials was that none was constructed with the purpose of finding the economic optimal and/or natural resource optimal feeding level. These two optimal levels are the same when adding external effects such as higher emissions per kg milk and higher appropriation of tropical forests per kg milk at the margin at higher feeding intensities, i.e. lower feeding efficiency per kg milk.

The consequence when taking a societal perspective is that the optimal feeding intensity decreases when considering negative environmental externalities.

When considering the variation in the total environmental and human health load for different locations, consideration of external effects will apply pressure for a structural redistribution of animal production from areas with high concentrations of humans and animal production to areas where the load is lower and more environmental space is available, see Figures 12 and 13 and the associated discussion. Stokstad (2014) elaborated on this issue, and Hellstrand commented on this contribution[19].

Hellstrand (1989) made a major revision of the official Swedish feedstuff table and feeding standards for ruminants. The feeding standards were presented as equations when possible.

The lines in Figure 8 show the difference between the energy requirements at different yields using the same statistical method described by (Andresen 1994) and the pre-1995 method (Hellstrand 1989). These alternatives were used in the search for the correct feeding standards with respect to energy.

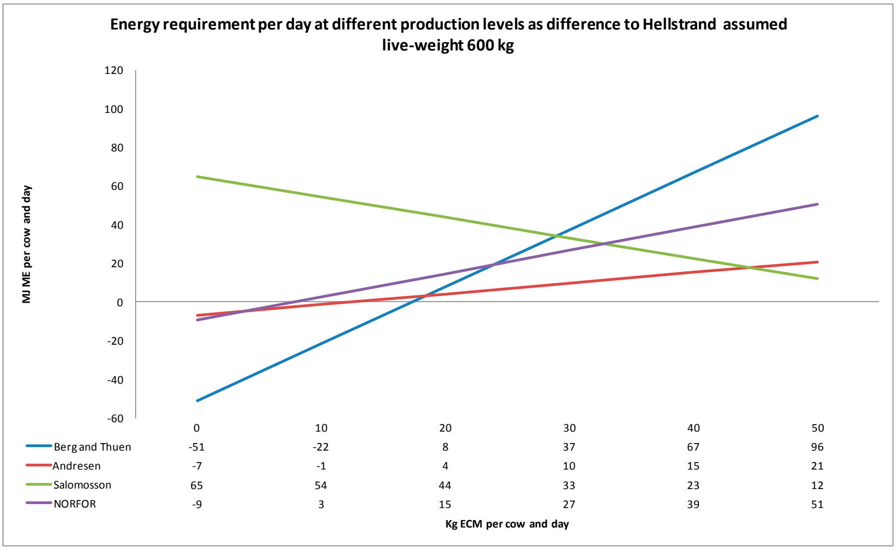

Figure 8. The difference between the alternative energy feeding standards and the one of Hellstrand (1989).
Source: Own calculations based on Andresen (1994), Berg and Thuen (1991), Norfor (2004) and Salomonsson et al. (2003).

19. See http://comments.sciencemag.org/content/10.1126/science.343.6168.238#comments, accessed 2014-02-15.

Hellstrand (1989) provides the background with commentaries and references to the original sources to a new official table of feedstuffs in Sweden for ruminants, including feeding standards. As far as possible the requirements for different physiological functions are given as mathematical expressions. This is the latest official report from the Swedish University of Agricultural Sciences that treat feeding standards to milk production, where the ruling principle is to arrive at that average amount of energy per kg milk produced that precisely results at that output of milk at the margin, which value equals the cost for the marginal increase in feeds applied.

The point that Figure 8 makes is that in four examples where

- the same basic assumption for the purpose of feedings standards are assumed; that the overall objective is to predict milk yield as a function of feed intake, and where
- the feeding standard that shall generate this answer is calibrated against average milk yields and feed intakes, respectively, in different trials connected by two common factors;
    - none is designed to capture actual marginal output of milk at a marginal increase in feed-intake
    - on average, the consumption of feeds are above the level that gives maximal net economic result, as in most trials the cows have free access to feeds of good quality;

the resulting feeding standard results in feeding intensities that on the average are above the level that is economically motivated; with a huge variation in whether the greatest gap compared to Hellstrand (1989) is at low or high production level.

Thus, on average this approach results in lower feeding efficiency in natural resource terms, higher levels of feeds per kg milk produced; and the result to a substantial degree expressed a random factor introduced when picking trials to calibrate with.

As a result, due to these circumstances, there are significant variations between the different studies with respect to energy requirements for maintenance purposes and for milk production. Pure chance determines the results with respect to energy requirements for maintenance and production. There is insufficient understanding of real causal chains in the considered systems. Figure 8 suggests that the statistical approach used to achieve the numerical values of the variables in the energy standards in Sweden post-1995 is incorrect.

From the information in Figures 3 to 8 the following can be concluded.

- The scientific basis for the changes in the foundations of Swedish energy standards for dairy cows in 1995 applied to commercial herds is weak.

- The changes have reduced the feeding efficiency, thus partly explaining the increase in sustainability costs reported in Papers III and VI between 1991 and 1999 (and 2006) due to increased concentrate intensities in Swedish milk production.
- The Swedish trend is towards a lower feeding efficiency which is common internationally.
- Other nations have similar problems, where there are indications that the level of sustainability costs are higher in nations such as the USA, Denmark, and the Netherlands, than currently in Sweden.
- The relevance of the pre-1994 ruling principles and the way they were interpreted with respect to the law of diminishing returns, Liebig's "Law" of the minimum, Shelford´s "Law" of tolerance, and how to set up trials and analyse them statistically in order to support economically and natural resource-efficient feeding strategies is supported.
- In a Scandinavian context, the results are concerning. There are indications that the feeding standard system Norfor recently introduced in Denmark, Iceland, Norway and Sweden will contradict national efforts to increase the economic and environmental efficiency of milk production. This needs to be investigated further by independent and competent researchers.

Figures 3 to 8 provide empirical evidence that suggests that the ruling principles for the fundamental change of energy feeding standards in Sweden in 1995 should be rejected, while they support the relevance of the principles that were accepted until 1995. They question the relevance of the ruling principles behind the NRC system in USA, and the Norfor system now introduced in the Nordic countries, excluding Finland. The magnitude of the results is such that it supports the conclusion that as a first estimate, the increase in sustainability costs in Swedish milk production from 1991 to 1999 can be used as a measure of the potential for sustainability improvements through increased feeding efficiency at constant production levels per cow globally.

The model for analysis of production biological and economic performance presented by Hellstrand (1988) was applied at five farms in 2012-2013. The results are interesting.

According to reports from the farmers they have increased their economic results by an average of 3 500 SEK per cow and year (Table 2).

Table 2. Economic outcomes at five dairy farms applying a model for evaluation of production biological and economic performance (Hellstrand, 1988) in 2012/2013, based on information from the farmers (Hellstrand, 2014).

	Improved economic result, SEK per year					
	Total		*Aspect*			
Farm	Per cow	Per herd	Production	Purchased feeds	Age first calving	
A	3 936	551 000	193 000	197 000	161 000	Con
B	3 060	404 000		404 000		Eco
C	7 950	349 800	349 800			Eco
D	2 375	166 250		166 250		Eco
E	0	0	-107 310	122 640		Eco
Average	3 470					

Half of the impact was due to increased feeding efficiency, by reducing the feeding intensity by around 0.5 MJ ME (through decreased rations of purchased feeds) per kg milk. On average, the feeding rations suggested by the Norfor system corresponded to an allowance of 6.2 MJ ME per kg milk (ECM) (Hellstrand 2014).

A system of ecological economic accounts called Hellstrandmetoden® has been generated from the toolkit supporting sustainable development presented in this thesis, and has been applied in a number of tasks in advanced consultancy. Table 3 shows the results when applied to farm D to estimate some important aspects of its sustainability performance in 2012. Table 4 shows the result of the increased feeding efficiency through decreased amount of purchased feeds (Table 2).

Table 3. Ecological economic accounts Höglunda gård (2012)
Source: Hellstrand (2014).

Aspect	Value
Social	
Food security	
Protein supply, total yearly requirement, no of people	1 210
Landscape with aesthetical and recreational values, SEK	430 000
Ecological	
Resource	
Food security, see above	
Forest biomass, tonne	905
Energy, MWh energy captured in forests minus own consumption	4 170
Uranium, kg (through use of electricity)	-0,28
Biodiversity	
Sustains a landscape formed by thousands of years of pasture, ha	184
Assimilative capacity	
Carbon dioxide equivalents, tonne	1 600
Carbon dioxide equivalents, value for society, SEK	2 453 000
Water, kg nitrogen	1 210
Water, value of purification of nitrogen, SEK	300 000
Release of oxygen , tonne	1 200
Economy	
Contribution to GDP, SEK	
Without value of ecosystem services	1 188 000
With value of ecosystem services (assimilative capacity)	3 979 000
Employments	
Based on non environmentally adjusted contribution to GDP	2.5
Public welfare	
Taxes to local and regional authorities	250 000
Environmental space for ecological footprints, Stockholm-equivalents, no	
Carbon dioxide	250
Nitrogen	115
Sulphur	510

Table 4. Improved sustainability performance due to improved feeding efficiency at farm D in Table 2, effects per year unless otherwise stated.

	On milk herd level	Per tonne milk
Influx of nitrogen, kg	-1 250	-1.88
Economic effects		
Economic result, SEK	166 000	250
Social effects		
Increased food security, protein demand, no of people	361	0.55
Taxes to local and regional public authorities, SEK	35 000	53
Ecological effects		
Decreased pressure tropical deforestation, ha	8,7	0.014
Decreased emissions of ammonia, kg	456	0.69
Decreased emissions of GHG, kg CO2equiv		
• Nitrous oxide	96 000	145
• Tropical deforestation, allocated on 20 years	307 000	460
• Decreased eutrophication -Kattegatt, kg N	330	0.50
Societal benefits, SEK		
Ammonia emissions, SEK	92 000	140
GHG, nitrous oxide	144 000	217
GHG, tropical defor, allocated on 20 years	460 000	700
Eutrophication Kattegatt	330 000	500
Sum societal benefits	1 192 000	1 800
Economic result the farm of total societal value of taken measure	0.14	0.14

Tables 3 and 4 may look quite simple, but they are not. They present tabulated values representing the difference between two point estimates of a biophysical production function describing the milk production system at farm D in Table 2. Everything is held constant in the two alternatives expect the amount of purchased feeds per kg milk. The outcome of this comparison is analysed within the ecological economic social context of the farm. The structure and the estimates in Table 3 and 4 are a function of the methods and results in Papers I to VI. The challenge is not to deliver values in a table, but to find those values that reflect important features of real world systems.

Multiplying the values in the right hand column by 3.3 million provides an initial estimate of the national impact in Sweden based on the impact at this farm. Typically, the other farms using this method showed similar levels of improved contribution to ecological, economic and social sustainability objectives, from local to global level. These first estimates of national impacts show

- reduced influxes of nitrogen by 6.2 million kg N,
- less pressure for tropical deforestation by 46 000 ha,
- improved food security by 1.8 million people (protein supply),
- improved economic results for Swedish milk production by 825 million SEK, and
- increased taxes to local and regional public actors by 173 million SEK.

Hence, here at cow and herd level roughly one fourth of the suggested sustainability improvements through increased feeding efficiency, i.e. measure 4 in Table 2 in Paper VI, have been achieved.

The Swedish national environmental quality objectives[20] are

1. Reduced Climate Impact.
2. Clean Air.
3. Natural Acidification Only.
4. A Non-Toxic Environment.
5. A Protective Ozone Layer.
6. A Safe Radiation Environment.
7. Zero Eutrophication.
8. Flourishing Lakes and Streams.
9. Good-Quality Groundwater.
10. A Balanced Marine Environment, flourishing Coastal Areas and Archipelagos.
11. Thriving Wetlands.
12. Sustainable Forests.
13. A Varied Agricultural Landscape.
14. A Magnificent Mountain Landscape
15. A Good Built Environment
16. A Rich Diversity of Plant and Animal Life

20. See http://www.miljomal.se/sv/Environmental-Objectives-Portal/, accessed 2014-02-17.

The increased feeding efficiency in this example results in substantial contributions to numbers 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, and 16. Objective 4 is influenced as increased feeding efficiency reduces the amount of crops required, thereby reducing the amount of pesticides used. A similar reasoning explains the contribution to objective 6, as less feeds to handle and process implies reduced use of electricity, reducing the demand for nuclear power.

The same measure has contributed to the UN Millennium Development Goal 1 – to eradicate extreme poverty and hunger, and 7 – ensure environmental sustainability, where aspects explicitly expressed are reducing loss of forests and biodiversity respectively, increasing access to safe drinking water, and addressing climate change.

The outcome in Tables 3 and 4 can be compared to the criteria for public procurement from SEMCO (Miljöstyrningsrådet in Swedish)[21]. SEMCO proposes three criteria regarding impacts on ecosystems on the highest ambition level for dairy:

- phosphorus, "has the amount of livestock effluents on producing farms not exceeded a level corresponding to a maximum of 22 kg phosphorus per hectare and year, calculated as an average over five years?";
- nitrogen, "has the amount of livestock effluents spread by producer farms not exceeded the limit set forth by the Nitrates Directive of 170 kg nitrogen per hectare and year?"; and
- emissions of GHG, "can the supplier provide information about the product's carbon footprint from a lifecycle perspective, reported in CO_2 equivalents?".

In the Swedish version, the criteria regarding GHG are linked to LCA provided by the rules set by ISO 14 040 and 14 044. The limits of the sustainability relevance of a number of LCAs of dairy production following ISO 14 040 ad 14 044 are analysed in Papers III, IV and VI.

The limits suggested for influxes of phosphorus and nitrogen though manure are quite high. This is one of many influxes, and the balance per ha land is more interesting if the purpose is to link the criteria to real impacts on ecosystems. If that is the purpose, the total environmental load of affected ecosystems should be considered: The same environmental load from one ha of agricultural land can have substantially different environmental and human health consequences depending on the context, see Figures 12 and 13 and Stokstad (2014). Stokstad shows that as well as nitrogen applied to the field, ammonia emissions are also important, and may cause substantial human health impacts in areas with high densities of people and farm animals.

21. SEMCO´s procurement criteria for dairy, accessed 2014-01-17 at http://www.msr.se/sv/.

Hence, the methodology presented in the thesis can support public procurement to achieve the objectives put forward in SOU 2013:12 regarding public procurement. It can increase the efficiency of public procurement when it is used as a tool to enable national environmental objectives and global sustainability goals such as the UN Millennium Development Goals, by providing objective grounds to facilitate selection of offers with lower external costs and higher external benefits.

Figure 8 suggests that already at the stage when the feeding trials were chosen that were the prober stones for the candidates of established systems of feeding standards to build the new Nordic feeding standard system around, the project group made a choice to increase the feeding intensity from the level of 5.0 MJ ME that resulted in economic rational feeding levels (Hellstrand 1989), see also Figure 4 and 5, to around 6.0 MJ ME per kg ECM..

Causes behind impacts at farm level are hard to determine with scientific precision. So far, these experiences at these farms support the relevance of the analysis above and in Paper III and IV. An improved economic result with 3 500 SEK per cow with 350 000 dairy cows in Sweden in 2012 corresponds to 1.2 billion SEK at national scale.

The outcome when switching from the new system to the one used in 1991 at these farms is that Norfor presupposes an energy requirement measured in ME terms of 6.1–6.3 MJ per kg ECM. This corresponds to the line representing an average allowance of 6.25 MJ ME per kg milk (ECM) in Figure 3. According to this figure, the biological return on an extra unit of feed at this intensity is low, if any. A decrease in the feeding intensity at this high level will have little negative impact on milk production, positive impact on economic result, and a substantial impact in terms of decreased appropriation of renewable natural resources (feeds) and decreased emissions of e.g. nitrogen. The positive contribution to Millennium Development Goals regarding food security and ecological sustainability is substantial, so is the contribution to national environmental quality objectives.

4.3 Protein standards for dairy cows

A fundamental change in Swedish protein standards systems was made in 1991, and was followed by a major revision in 1995. Some of the problems with the changes are that (see also Paper VI and Hellstrand 2008):

- In the 1991 change it was assumed that
  - the maintenance requirements increased in g protein per cow despite the fact that the protein content in most feeds was substantially reduced with the new protein measure,

- protein content in forages was no longer a function of the crude protein content, but was a strong function of the energy content. Thus in practice the energy value of forages was counted twice, while their protein content was not accounted for,
- the protein value of forages with high crude protein contents was reduced to greater degree than for other feeds.

As a consequence, the estimate of the requirement for crop protein feeds increased, and the assumed feeding value of forages decreased. The nitrogen efficiency thus decreased. This follows the logics of how feeding rations are constructed. An assumption of higher protein maintenance requirement increases the estimate of the amount of soymeal[22] required to balance energy and protein demands and reduces the amount of coarse grain. Assuming decreased protein content in forages increases demand for soymeal, everything else being equal. Thus, the changes in 1991 implied that the value of soymeal increased relative to grain and forages.

- In the 1995 revision, the assumed protein requirement for maintenance was increased further, as was the protein requirement for low lactating cows, while it was reduced for high lactating cows.
- This was based on a fundamentally new physiological principle, i.e. that the requirement of protein in g per unit energy was constant and the same for very low and high production levels. Arguments for this fundamentally new principle were not delivered.
- The scientific basis for these major changes in such an important relation regarding the economic and ecological efficiency of Swedish agriculture is not available. The reference in the official publication presenting feedstuff tables and feeding standards (Spörndly 1995) is to a PM at a department at the Swedish University of Agricultural Sciences. The PM cannot be found at the department (Hellstrand 2008).
- The same competence at the Swedish University of Agricultural Sciences that is responsible for the feeding standards has supported the Swedish Environmental Protection Agency, the Swedish Board of Agriculture and the Swedish Dairy Association with feeding plans to be used in official contexts from 1996 to 2006. Surprisingly, these feeding plans are not congruent with the official feeding standards that the same source is responsible for, and the deviations are substantial.

22. I use "soymeal" as a synonym for crop protein, for three reasons: (i) soymeal dominates the global crop protein feeds market; (ii) Soymeal can be used for all animals; and (iii) thus on the margin, changes in use of all other types of crop protein feed affect the supply and demand on soymeal.

- In the instances mentioned in the previous point, there are substantial deviations from basic animal physiology, and no supporting arguments have been provided. Together, these changes increased assumed protein requirements, resulting in decreased nitrogen efficiency.
- The full extent of the deviations from basic physiological knowledge can only be seen when examining the content in the individual Excel cells of the supporting data. Hellstrand (2008) and Paper IV illustrate its consequences.
- There are two problems with this from a sustainability perspective. (i) The contributions from the responsible competence at the Swedish University of Agricultural Sciences in these two contexts (definition of official feeding standards and the application of the same feeding standards in influential contexts) contain a substantial internal inconsistency. (ii) This can only be fully appreciated through the expressions at the level of individual cells in the supporting spreadsheets. This conflicts with the demand for transparency in the analysis supporting well-informed decision processes for sustainable development, as expressed by Giampietro (2003) and OECD (2001).
- The Swedish Dairy Association, which is responsible for most of the extension services to dairy farmers and the production of recommended daily feeding rations on individual cow level, recommend a substantial increase in protein requirements compared to the official standard for high-yielding cows. This increases assumed protein requirements, which results in decreased nitrogen efficiency. The scientific basis for this deviation is unclear.
- In the system for feeding rations control in order to secure high nitrogen efficiency, the Swedish Dairy Association chose a system from the USA. OECD statistics and FAO statistics indicate that the USA has the lowest nitrogen efficiency in milk production globally among nations with high production levels[23]. The rules chosen allowed animals to be fed substantially more nitrogen than the level corresponding to the official Swedish protein standards. Thus the control measure chosen with the aim of improving nitrogen efficiency in milk production was set at such a high protein level that it allowed a substantial decrease of the nitrogen efficiency.
- The choice of a rule expressed in a different protein measure than the official feeding standards system is odd (previous point). There should either be trust in the official system, or it should be changed. Working

23. This is treated in Section 4.7 in the thesis.

with two fundamentally different systems in parallel does not support efficiency in management.

The basic construction of the protein standards system is questionable. It expresses a belief that the true complexity of a system with complex feedback loops such as the rumen digestion system can be captured by computer based models with long chains of calculations, presupposing only linear causal relationships. I propose that regarding milk production, the human mind is better suited to handling this kind of complexity than computer programs.

Thus, the changes in the protein standards systems in Sweden in 1991 and 1995, and the praxis in the way it has been applied explains an important part of the increase in use of purchased feeds to dairy cows in Sweden from 1991 to 1999. This is further shown in Paper VI and Hellstrand (2008).

The increase in nitrogen influxes via crop protein feeds in Swedish cattle production from 1991–2006 (Paper VI) implies increased use of soymeal equivalents of 450 million kg in milk production and 81 million kg in other cattle production systems. In November 2012 the price of soymeal on the Chicago market was 490.6 US$ per tonne[24]. This implies an increased cost in Swedish milk production in 2006 of 1 435 million SEK compared to a situation with 1991 levels of crop protein feeds. In 2006 the number of dairy cows was 387 530, corresponding to an increased cost for crop protein feeds of 3 700 SEK per dairy cow and year in 2006.

4.4 Environmental monitoring systems

One reason that the rapid increase in the use of crop protein feeds and the associated significant sustainability costs in Sweden between 1991 and 1999 were not detected is as follows: Authorities with the responsibility of monitoring trends regarding the environmental pressure from agriculture (Statistics Sweden and Swedish Environmental Protection Agency) in the official reporting of ammonia emissions and nitrogen balances in agriculture, mainly base this reporting on so-called soil surface balances, see e.g. Statistics Sweden (2009a,b). These analyses, from 1995 and onwards, are based on the assumption that the feeding of the cows is constant over time at the same production level. With increased production, the feeding was changed in accordance to fixed feeding rations constructed in 1996 (Paper VI). There was no capacity to reflect real national feeding trends. Thus, these balances do not reflect the substantial and fast increase of nitrogen influxes in cattle

24. http://www.indexmundi.com/commodities/?commodity=soybean-meal, accessed 2013-01-02.

production due to the increase of crop protein feeds in purchased feeds to cattle from 1991 to 2006 (see Figure 2 in Papers III and VI respectively).

The Swedish Board of Agriculture is responsible for the programme Focus on Nutrients (Greppa näringen in Swedish)[25]. This is a major means of dealing with eutrophication issues in agriculture. Regarding milk production, they rely on the contributions and competence of the Swedish Dairy Association. For 701 dairy farms that participate in the program, three years participation did not result in any increase in the nitrogen efficiency of their milk production measured on the cow level (Jordbruksverket 2008b).

Possible explanations are

- there was no focus on the nitrogen efficiency in the animal production subsystem, and/or
- the methodology used was not relevant, i.e. the issue could not be solved within the logics of the feeding standards system applied.

Regarding the third point, the Swedish Dairy Association and their member organisations have a dominant role in the production of feeding rations for commercial herds. They are also in charge of feeding standards. In Focus on Nutrients, they are responsible for the revision of the very same advice and recommendations regarding the feeding of dairy cows that they themselves are responsible for. Thus the same organisation that may have caused a problem in the first place are supposed to evaluate the outcome of their own work and eventually correct it by applying the same methods that caused the problem.

This is not an efficient organisation of evaluation and revision.

Furthermore, the impact on milk production on the farms in terms of increased milk production per cow was the same as in the official milk recording program in the same period. Hellstrand (1988) showed that the most important way to improve the economics of milk production and feeding efficiency among commercial herds is to increase the capacity of the farm to utilise the genetic capacity for milk production, i.e. increase milk production. The second most important measure is to improve feeding efficiency. Hellstrand also presented a production biological and economic model for how to do this. This model provides the frames for the feeding plan subsystem in the simulation model in Paper IV. Actual impact of the model on economy and milk yield after around two years of application was shown for two real farms in the same report. The positive impacts were substantial.

According to the mentioned report, in the milk production subsystem, the Focus on Nutrients program had no impact on either milk yield per cow or on the feeding efficiency measured as nitrogen efficiency on the cow level.

25. http://www.greppa.nu/ovrigt/kontakt/english.4.1c0ae76117773233f780001230.html, accessed 2009-11-05.

This can be compared to the positive sustainability impacts of advanced consultancy based on the methods of Papers I to VI at five farms according to information from the farmers reported in Tables 2 and 3.

Another problem with this program is that it subsidises inputs of advanced consultancy to farms in intensive animal production areas with high eutrophication problems, at least indirectly, by farms that do not have these problems.[26] Thus, this reflects a new environmental policy: The Polluter Subsidy System. This distorts the competitive conditions in a way that disfavour sustainable production in favour of unsustainable production.

4.5 Research regarding sustainable food production

The major research program in Sweden regarding sustainable food production since 1997 is FOOD 21.[27] In their synthesis work, the evaluation of environmental impacts was based on LCA, a method developed within engineering sciences. Paper IV (see also section 4.7) identifies major problems in their model of the ruminant production system given its social and ecological context in the studies regarding milk production (Cederberg and Flysjö 2004; Gunnarsson et al. 2005; Sonesson 2005). More specifically, there were major weaknesses in

- the animal production system constructed,
- the model of environmental systems supporting the production system with natural resources, and taking care of emission/discharges, and
- the social system, with regard to the evaluation of the social and economic needs and desires that the production satisfied.

The severity of these problems was such that it restricted the capacity to detect the substantial negative sustainability impacts due to the reduction in nitrogen efficiency in Swedish milk production from 1991–1999 (Paper III). Consequently, these effects were not reported.

These findings suggest that there is reason to evaluate the relevance of applying engineering-based approaches as means of supporting sustainable development. Section 4.7 presents 25 such applications, and evaluates their usefulness for supporting sustainable development. The examples from FOOD 21 mentioned will be examined further in this context.

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26. This is the consequence when looking at regional level. Agriculture in areas with low discharges of nitrogen to the sea per kg milk produced are outside this system, while agriculture in areas with high discharges per kg milk can utilise the opportunity of subsidised consultancy.
27. http://www-mat21.slu.se/eng/, accessed 2010-01-18.

The discussion about the shortcomings of these applications of engineering tools by no means reduces the importance of engineering science. This is an example of the principal problem of methodological extrapolation.

Before the examination of the 25 applications, the international relevance of the results will be discussed first.

4.6 International relevance

Paper VI shows that

- the same basic approaches govern energy standard systems in Sweden, Norway, Denmark, the USA and the Netherlands (see also Figures 6 and 7);
- similar protein standards systems are used in Denmark, Norway and the USA as in Sweden;
- there are theoretical and empirical indications that the feeding efficiency is lower in Denmark, the Netherlands and the USA compared to Sweden; and
- available theoretical and empirical evidence suggests that the new feeding standards system introduced in the Nordic Countries (excluding Finland) will deteriorate the feeding efficiency further compared to the current Swedish system.

This suggests that the findings regarding sustainability trends associated with Swedish milk production from 1991-1999 may well be representative

- on a global scale, and
- for the Nordic countries (excluding Finland) in the future.

The findings in Sections 4.2 and 4.3 support this conclusion. Figure 9 illustrates the possible international relevance.

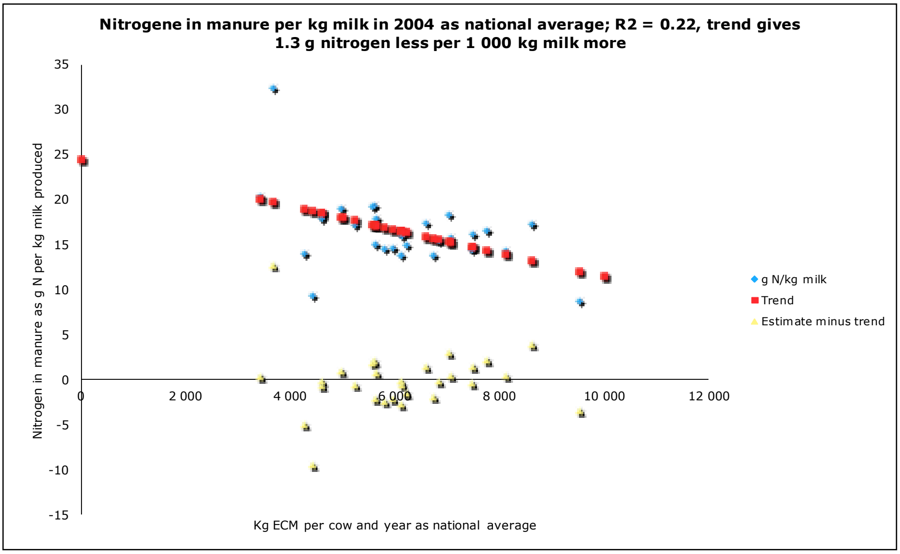

Figure 9. Nitrogen content in manure from dairy cows per kg milk produced at different production levels among OECD nations.
Source: Own calculations based on OECD data regarding nitrogen balances, and FAO data regarding production levels[28]. Turkey excluded as their data were not included in the reports.

The nitrogen balances reflect both the nitrogen/protein content in the feeding ration, and the total amounts of feeds consumed (Huhtanen and Hristov 2009). Thus, they relate to both energy and protein standards and their impact on feeding regimes.

Figure 9 shows a trend of increasing nitrogen efficiency with increasing yields, but the trend is not strong. Other factors explain 78% of the variation. The values for Korea and the USA are interesting. Korea combines a high production level, around 9 500 kg per cow, with high nitrogen efficiency. The amount of nitrogen in manure is 8.8 g per kg milk, which is 3.3 g less than the expected value due to the high production level. The USA has a somewhat lower production, 8 600 kg per cow and year, with 17.3 g nitrogen in manure per kg milk, which is 4.0 g more than expected due to the milk yield level. The measure for Korea is thus 8.8 kg nitrogen in manure per 1 000 kg milk, and the corresponding measure for the USA is 17.3 kg nitrogen in manure per 1 000 kg milk, i.e. 8.5 kg more than in Korea. Among nations with high production levels (> 7 000 kg per cow and year), the Netherlands and Denmark have low nitrogen efficiencies, i.e. 3 and 2.3 g more nitrogen in manure per kg milk than expected respectively. Finland is the

28. From FAOstat, http://faostat.fao.org/default.aspx, and Environmental Performance of Agriculture in OECD countries since 1990, http://stats.oecd.org/Index.aspx?datasetcode=ENVPERFINDIC_TAD_2008, respectively. For further details, see Hellstrand (2010).

only nation with a lower value than the level predicted from the yield in the group with high production levels, 0.3 g below the trend.

With a global production of 578 million tonnes of cow milk in 2008[29], the estimate for Korea suggests the possibility of a nitrogen efflux in manure of 5 100 million kg, while the efficiency of USA milk production suggests a nitrogen efflux in manure of 10 000 million kg, i.e. 4 900 million kg higher. The estimate 4 900 million kg nitrogen in terms of nitrogen in soymeal corresponds to around 35 million ha of soybean production. This is half the global acreage used for soymeal production for feed purposes (FAO 2006). From this measure the possible impact on climate change, global food security and on farmers' net income can be estimated through the same route as in Paper VI.

However, before continuing with a process for possible global policy implementation of Korean feeding strategies, there is a need to probe the accuracy of the nitrogen balances data from OECD.

Figure 10 shows nitrogen influxes to dairy cows from 1991 to 1999 through purchased feeds as kg N per cow in Sweden.

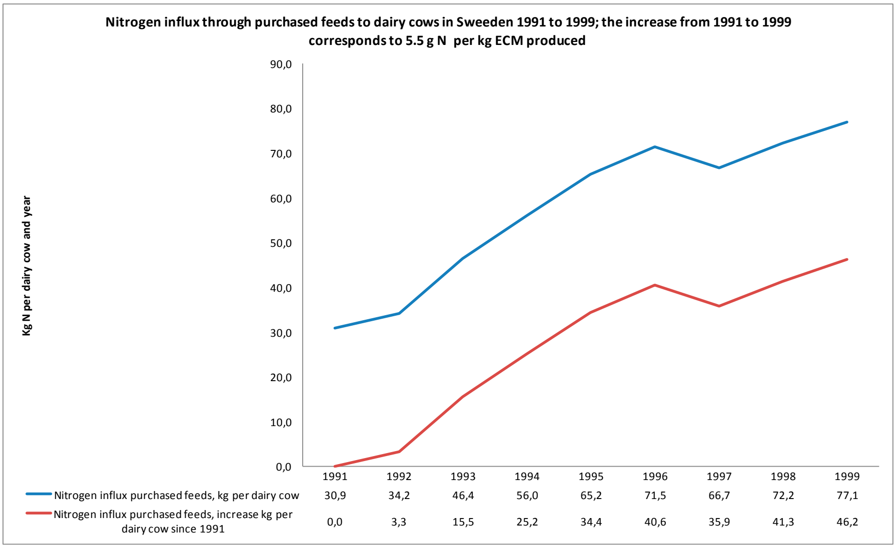

Figure 10. Nitrogen influx from purchased feeds to dairy cows in Sweden, 1991–1999.
Based on materials, methods and results in Hellstrand (2006).[30]

29. http://faostat.fao.org/site/569/DesktopDefault.aspx?PageID=569#ancor, accessed 2010-01-19.

30. The nitrogen influxes from purchased feeds to cattle were estimated by multiplying the amounts of feedstuffs within purchased feeds by their crude protein content. Division by 6.25 gives the amount of nitrogen. Here the same operation has been performed for the fraction of purchased feeds to cattle that is reported as feeds to dairy cows. Division by the number of dairy cows gives the amount of nitrogen influx per dairy cow (Hellstrand, 2006).

The nitrogen efficiency in milk production decreased substantially during the decade as major changes were enforced in the protein standards system (Figure 2; Paper III).

The increase in influx by 46 kg from 1991 to 1999 should be compared with the 117 kg nitrogen in manure per dairy cow that OECD uses as a constant in their nitrogen balances for Sweden from 1985–2004. Considering this increase in nitrogen influx, the value of nitrogen per kg milk for Sweden would increase by 5.5 g to 19.9 g per kg milk, the highest level of all nations with a production of 7 000 kg milk per cow and year or more (Figure 9).

These facts in combination with Paper VI (see beginning of this section) imply that it is relevant to use the Swedish values as starting values in a first evaluation of global potentials for increased feeding efficiency in milk production. Figures 9 and 10 raise a concern, as they indicate that among nations with high production values Sweden may now have an internationally low nitrogen efficiency level in milk production. This question is open as available official data is not sufficient to determine the answer. Other data from official sources (see Hellstrand 2008) suggest that the Swedish trend is towards a lower value that is common internationally. Even so, the Swedish trends since 1989 imply that there is a huge potential to improve the sustainability performance in Swedish milk production. Other facts presented earlier in this thesis as well as in Paper VI and in Hellstrand (2008) suggest that this is of international relevance.

The fact that the environmental monitoring systems regarding nitrogen balances in agriculture and ammonia emissions in Sweden do not consider this flux (see Section 4.4) is a concern. A relevant question is whether monitoring systems and systems for evaluation of environmental performance in dairy production in the EU and FAO have similar weaknesses.

4.7 Approaches in engineering sciences

There is a multitude of examples where engineering-based approaches form a toolkit with the ambition of supporting the implementation of sustainable development. In the following 25 such examples are analysed. This analysis informs about possible obstacles for sustainable development, and provides an indirect evaluation of

- the relevance of the toolkit for sustainable development that this thesis presents,
- the degree to which the thesis contributes to bridging the knowledge and implementation gaps of sustainable development identified by OECD (2001), and
- the level to which the thesis increases the understanding of the value of land.

Examples of engineering-based approaches for analyses of (ecological) sustainability of economic production systems that have been examined are shown in Table 5.

Table 5. Examples of efforts based in engineering sciences to support sustainable development.

Physical resource theory	Environmental and national accounts	Industrial sector	LCA in general and applied on milk production
1. Kåberger and Månsson (2001)	8. Statistics Sweden (2009)c	10. The IPPC-directive with the BAT-principle (EIPPCB 2014)	15. Baumann and Tillman (2004)
2. Månsson and McGlade (1993)	9. Engström et al. (2007)	11. EU-directive[31] governing technical solutions sewage treatment plants	16. Stern et al. (2005)
3. Kåberger (1991, 1999)		12. The Integrated Product Policy (IPP) (Wijkman 2004)	17. Gunnarsson et al. (2005), Sonesson (2005)
4. Azar et al. (1996), the Natural Step (2014), the Forom For the Future (2014)		13. Application of IPP, Williams et al. (2008)	18. Cederberg and Flysjö (2004), Cederberg et al. (2007)
5. Egeskog and Gustafsson (2007), Sparovek et al. (2007)		14. SWENTEC, SOU (2004)	19. LRF (2002)
6. Wirsenius (2000)			20. SNFA (2008), Lagerberg Fogelberg (2008)
7. Swedish Environmental Advisory Council (2007), Lundqvist et al. (2007)			21. SBA (2008)
			22. The Swedish Dairy Association (2009) work with climate change issues
			23. IDF (2009), GDAACC (2009)
			24. A cooking book titled Food and climate, by Björklund et al. (2008)
			25. The sustainability work by one group of Swedish hamburger-restaurants (MAX 2009)

4.7.1 Contributions from physical resource theory

Examples 1–7 concern contributions from physical resource theory. Example 1 is on the most general level, and is treated in Paper I. Here, natural re-

31. EU directive (91/27/EEG).

source concepts are defined using assumptions such that even the word ‘resource’ loses its meaning. Exergy is defined assuming thermodynamic ideality, implying that no fluxes occur. Resource is thus a meaningless concept. As a consequence, the definition presupposes freedom from all process restrictions that define ecological, economic and social sustainability. Not surprisingly, based on these resource concepts, the authors estimate a potential for the growth of the human economy in physical terms by a factor 10 000 from the current level, fed by energy fluxes from the sun.

In Example 2, the authors perform an analysis of the relevance of contributions in systems ecology. They base their analysis on four criteria delivered by O´Neill et al. (1986). They chose physics as their modus operandi. What they do not realise is that this choice violates their own criteria. They do not show why it is relevant to apply physics in an evaluation of the relevance of contributions within systems ecology regarding the characteristics of ecosystems. Rather, Example 1 shows that physics is not relevant in such contexts. Basically, this is an example of extrapolation error, here on an abstract, methodological, scientific level.

Example 3 concludes that energy values in nutrition theory are basically measures of gross energy. This is fundamentally wrong. This assumes that the physiological complexity of humans and animals is equivalent to that of a combustion engine or wood stove. Energy evaluation in animal and human nutrition theory expresses an intricate understanding of energy transformations in a complex physiological web that defines energy metabolism in living organisms. This conclusion in Example 3 is thus a good measure of the gap between expert knowledge regarding energy metabolism in living organisms, and the level of understanding delivered from physics. The perceptions of the economy in Examples 2 and 3 are problematic.

The scientific basis for the system conditions for sustainability of The Natural Step (Example 4) is a contribution within physical resource theory (see Azar et al., 1996). When relating to Figure 2, one can conclude that the consideration of process restrictions in economic and ecological systems is poor. The system conditions imply that agriculture is impossible, as it raises the level of nutrients in water systems to unnaturally high levels. If implementing these system conditions, the majority of the human population would vanish. Thus, the consideration of vital social process restrictions is also poor.

Example 5 implies that local socio-economic conditions will be severely depressed, and that the gender profile is strongly negative. This follows because the results that state that the local socio-economic conditions would be improved are based on the assumption that women in the local society milk 7 times more milk by hand than in the reference alternative, i.e. up to 100 tonnes of milk per year, without payment. The net impact on climate change may be negative, as the marginal impact on deforestation and on methane emissions of a 7-fold increase in milk production are not considered. It is interesting that this is found when the details and footnotes in Egeskog and Gustafsson (2007) are analysed. Still, Sparovek et al. (2007) present it as a case study illustrating how certification schemes for good ethanol including climate change impacts and local socioeconomic development can be constructed. Lundqvist et al. (2008) in a policy brief to decision makers in the international community and nationally, also present this example, where due to their lack of competence in animal production science and practice, they did not notice that if actually implemented, the proposed measure would most probably increase contributions to climate change and depress local socioeconomic conditions.

In Example 6, the FPD-/ALBIO model, a global model of food production from crops to human intake is constructed. The model includes an energy conversion efficiency measure which follows the same logic as in Example 3. Thus, it is the ratio between gross energy in food consumed and gross energy in biomass appropriated. The same critique is relevant as for Example 3. The physiological complexity of humans is reduced to that of a wood stove. One problem of this efficiency measure in the way it is used in the FPD-/ALBIO model is that it defines fluxes of manure and crop residues back to agricultural land as a waste, as if there were no feedback loops fertilising the top soil layer enhancing the productivity of agricultural land. Another is that it is ignorant to the quality aspect of energy in food given the physiological context of humans and how it may vary.

Furthermore, the variation in ecological conditions is reduced to zero. In reality the agro-ecological as well as agro-social conditions provide contexts that must be considered when evaluating efficiency and durability in agricultural production. Regarding the social dimension, in many economies cattle production provides a multitude of values outside food production. FAO (2006) is clear about this. In Example 6, these social values are ignored. This implies that the low efficiency in ruminant production systems that the author report substantially reflects an ignorance of real values related to ruminant production systems in their ecological and social contexts.

Thus, ruminant production systems are classed as having extremely low efficiency.

In the FPD-/ALBIO model, agricultural soils are not included. Around 50% of biomass appropriated in food production from agricultural land ends up in feedback loops back to agricultural land through fluxes of manure and crop residues. According to the FPD-/ALBIO model, society would be better off if these useless fluxes (according to the model) were steered so that they supported the energy metabolism of society. In reality, this measure would deplete one of the most important stocks of natural capital for human societies, the humus content of 4.9 billion ha of agricultural land, where this is a prerequisite for future yields and thus food production. This is one example of how the theoretical analysis in Paper II regarding the pattern of welfare costs of forcing an economic system to exhibit such a growth in physical terms that biophysical sustainability limits are trespassed, can become relevant in the understanding of real world policy failures and their causes. Paper VI shows how this model now influences the IPCC strategy for bioenergy.

Example 7 proposes precisely this, where about 50% of current refluxes should instead feed the energy metabolism of society. It concludes that this measure will have no ecological consequence whatsoever. Considering all agricultural land globally, this implies a reduction of the reflux of 600 kg dry matter (DM) organic matter per ha and year, or if considering all arable land, it corresponds to 2 100 kg DM per ha and year. In reality, this will reduce the humus and plant nutrient content of agricultural soils, reducing soil fertility and global food supply capacity while increasing carbon dioxide emissions. The context is a study that aims to inform the Swedish Government about the conflict between growth and the environment. In this example, physical resource theory was chosen as the relevant competence for analysis of sustainable production potentials in agriculture and forestry. However, as shown above, physical resource theory is not suitable for this task. Other problems are that energy conversion issues in agriculture and society were treated in quite odd ways, and that estimates of acreages needed for bioenergy purposes were not based on real production potentials, considering real agro-ecological conditions affecting production levels.

Examples 1–7 illustrate a consistency in the way contributions from physical resource theory ignore real conditions that define ecological, economic and social sustainability, from highly abstract conceptual contributions, to non-scientific analyses of animal production systems. If such studies influence policy decisions, the sustainability cost can be devastating.

The reason to class it as non-scientific is that the way data here are generated is in conflict with the second principle in ”Fundamental Principles of Official Statistics”[32] of UN:

“Principle 2. To retain trust in official statistics, the statistical agencies need to decide according to strictly professional considerations, including scientific principles and professional ethics, on the methods and procedures for the collection, processing, storage and presentation of statistical data.”

Here data are processed in conflict with established principles in scientific disciplines that represent the excellence of competence regarding systems and issues focused.

4.7.2 Environmental and economic national accounts

The Swedish system of environmental economic accounts (Example 8) is not a system of environmental accounts, since it is basically an accounting sys-

32. http://unstats.un.org/unsd/dnss/gp/FP-New-E.pdf, adopted by the General Assembly on 29 January 2014. Accessed 2015-03-31.

tem that handles aspects of economic and natural resource use. The conditions of ecosystems and impacts of production on ecosystems are largely ignored.

Example 9 makes an effort to evaluate the environmental impact of Swedish agriculture on national environmental objectives. With some simplification the approach is a hybrid between LCA and some of the methods behind the system of environmental economic accounts. Two unacknowledged problems arise: only negative environmental impacts are considered, while agriculture is also the limiting factor for other environmental objectives where maintained agriculture is crucial. The focus on negative impacts is surprising, given that the objective of the paper is to evaluate environmental impacts, and not only negative impacts. The evaluation of environmental impacts is not based on an investigation of environmental impacts in affected ecosystems using suitable methods in natural sciences. Instead it is based on different approaches to measure preferences among groups of citizens. This becomes problematic if "scientific" contributions influence decision-makers, when the scientific material actually reflects preferences of certain groups.

Examples 8 and 9 are biased in their treatment of land and agriculture. Positive contributions through production of ecosystems services are not considered, while environmental costs are.

4.7.3 Sustainability in the industrial sector

Examples 10–14 treat the issues of methods and means supporting the development of more sustainable production processes and products in the business sector. All are examples of production-oriented approaches. The environmental policy discussed in these treatments is not an environmental policy, as the criteria are defined in terms of natural resource use and emissions per unit product (see Figure 2). The real impact on ecosystem carrying capacity limits is largely ignored.

Example 13 illustrates the weak environmental consideration within Integrated Product Policy (IPP) and the weak regional anchoring. Here it is presented in some detail in a discussion regarding problems of the EU-based IPP in its implementation as a tool supporting sustainable regional and national growth. IPP and similar approaches play a major role in the EU, Sweden and in Swedish regions in the ambition to improve competitive power through the environmental factor.

The study is a scientific outcome within the field of environmentally driven businesses in a strategy for sustainable growth in Värmland within the regional growth program. This area, together with IPP, was prioritised in this growth program under the heading environment and production (Länsstyrelsen och Region Värmland 2004). The article treats the importance of food packaging well. The pulp and paper industry are important in Värmland, and production of packages is an important part of this industry. Nevertheless, this is a minor fraction of the total production in Värmland. The "environmental analysis" is not an environmental analysis. It is a review of some LCA studies from regions other than Värmland or other system levels, in which production related aspects such as the capacity to protect food, the environmental impact of the production of food packaging, the capacity of the package to support efficient transport solutions, environmental impact of wastes generated by the packages, material, process energy, transport and loss of food are classed as environmental aspects. These aspects affect the environment, but they are not aspects of the environment per se. This results in the same principal problems as in all typical LCA studies, with one added element. All studies with the character of a meta-study have the problem of varying contexts for the individual exploited studies, and how to deal with them. The article does not treat the impact of the production systems on the environmental systems in Värmland. The gap between what is called environmental aspects and real impacts on the carrying capacity limits of ecosystems that would be affected is significant. Because

- the small fraction of the regional production treated,
- the non-existent relation between the analysis in the article and the ecosystems in Värmland, and
- the substantial gap between the performed analysis with respect to what are called environmental aspects and real world impacts expected on physiological processes in microorganisms, plants, animals, and/or humans that define carrying capacity limits,

the capacity of this type of scientific contribution to support sustainable growth on the regional level is limited.

This critique should be seen in context. The definition of environmentally driven businesses from NUTEK, the national authority in the area at that time, relates to environmentally adopted products and services (NUTEK 2003). The criterion provided is that they should have a better environmental performance than existing alternatives on the market. Taking the definition literally, this implies that all alternatives belong to the class of environmentally adopted products and services, even those that cause severe environmental damages, if there is at least one alternative that is worse. The definition is so broad that its value is minimal.

The regional growth programs were viewed by the government as a major tool to achieve a sustainable development in Sweden (p. 117, Regeringen 2004). The origin of the definition of environmentally adopted products and services by NUTEK was from earlier definitions by Eurostat, OECD, and the EU (NUTEK 2003, p. 4). It is similar to the IPP concept of the EU commission, which was criticised by the EU parliament (Example 12). This illustrates how definitions and concepts on high system levels such as

EU/Eurostat/OECD that have “environment” in their name, by setting such system boundaries as in Figure 2, often ignore the characteristics of affected ecological, economic, and social systems. The sustainability issue is interpreted as mainly an issue of numerical values of natural resource use and emissions per unit product while ignoring

- whether the total appropriation of natural resources and of assimilative capacity is within available ecological carrying capacity limits,
- a major part of the economic aspects of production and consumption including impacts on the environment and human health and
- the social consequences of natural resource use and emissions made.

With this definition of environmentally adopted products and services, the decision by the Värmland growth program to base its sub-strategy regarding environment and production on IPP and environmentally driven businesses implies a decision to ignore the values delivered by the ecosystems of Värmland.

Following methods and prices used by Swedish authorities, the value of the assimilative capacity of the ecosystems in Värmland in 2006 was around 20-40 billion SEK[33] compared with a total contribution to GDP of around 70 billion SEK. The Stockholm urban region had a net deficit in assimilative capacity worth several billion SEK. On a national scale, the value of Swedish production of ecosystem services is in the range of 300 to 600 billion SEK from a total GDP of around 3 000 billion (2006 prices). These figures are deliberately presented as round figures. For a detailed presentation see Hellstrand (2003a). Section 4.9 presents some further information regarding this issue.

There is a principal difference between these analyses, however. The values presented here are based on the assumption that when felling a tree, not all of its carbon content is oxidised to carbon dioxide immediately. Hellstrand (2003a) followed the common convention of only considering the change of the storage of carbon in living trees. The values presented here are based on the assumption that climate accounting rules should be based on the best available knowledge regarding important processes. The photosynthesis in forests in Värmland and globally is one such important process. This assumption is in accordance with what could be termed good accounting practise as expressed by ”Principles governing international statistical activities” from the United Nations Statistics Division.[34]

33. Given as ranges as SIKA recommend the use of two prices for carbon dioxide, 1.5 and 3.5 SEK per kg.
34. See http://unstats.un.org/unsd/methods/statorg/Principles_stat_activities/principles_stat_activities.htm, hämtad 2012-09-23.

These values were obtained by specifying the biophysically anchored production function in Paper II, which is derived from the conceptual model of the economy in its ecological and social context (Paper I) in time and space, and with such a focus, that the obtained system of ecological economic accounts was well suited to the purpose of estimating the production and consumption of ecosystem services in one rural and one urban region, and on the national scale. In the operation, information from traditional management tools in forestry and agriculture was integrated with the perspectives of sustainable development of Giampietro (2003) and OECD (2001).

The definition of environmentally adopted products and services by EU/Eurostat/OECD on the international level and by the responsible Swedish authority NUTEK, combined with the decision of the regional authorities in Värmland to base their strategy for sustainable growth on this concept, resulted in a regional strategy for sustainable growth that lacked the capacity to translate unique environmental values including a substantial production of ecosystems services to improved economic results for firms in Värmland.

This illustrates how definitions on high policy levels may have substantial impacts on a low operative system level. This is one example illustrating causes behind the combined knowledge and implementation gap for a sustainable development that OECD (2001) stressed. The consequences of this are that information needed for incentives

- to increase capacity of rural regions to produce ecological goods and services that define the sustainability basis of urban regions,
- to increase capacity of agriculture and forestry to produce ecological goods and services that define the sustainability basis of industrial sectors,
- to adopt urban regions to available ecological carrying capacity delivered from surrounding rural areas and
- to adopt industrial sectors to available carrying capacity from agriculture and forestry,

is blocked. “Environmental” policies that ignore known key features of environmental systems are dominating in the operative mode. This follows as the environmental systems are located outside the system boundaries of the performed analysis. This may cause human health problems and environmental disturbances and degrade sustainable attractiveness in urban and rural regions, compared to policies based on methodologies and knowledge from the disciplines that represent the state of the art knowledge in the systems concerned.

One key aspect here is that most if not all sustainability effects imply impacts on the physiological level for microbes, plants, animals and/or humans.

Evaluations of sustainability impacts that ignore the physiological level may have a limited value.

This is another example that supports the message from the analysis of feeding standards of dairy cows. The understanding of the causal chains between high and low system levels is crucial in the sustainability context. The feeding example regarding cows shows how assumptions on the rumen physiological level have major sustainability impacts on the global level. In this latter example, definitions made on a high policy level internationally have a major impact on the relevance of regional strategies for sustainable growth with regard to their capacity to handle the ecological sustainability dimension.

Example 11 concerns sewage plants, and is not related to businesses. However, it resembles Example 10 as specific technical solutions are decided by authorities, where the consideration of local conditions could be better.

The discussion above concerns outcomes from policies in Sweden and the EU around 2003–2004. A Swedish strategy for environmental technology was launched in September 2011 (Regeringen 2011). Environmental technology was defined as “all technology that causes less harm to the environment than available alternatives”. It follows the definition used by the EU Commission in the Environmental Technologies Action Plan (2004). The definition of environmental technologies that they use includes all technologies whose use is less environmentally harmful than relevant alternatives.

Problems with this definition have been discussed above. It is so broad that its value is minimal. The steering definition does not address ecological, economic, or social aspects.

The first lines in the communication from the EU Commission (ibid.) are:

> Sustainable development – development that meets the needs of the present without compromising those of future generations – is at the core of the European Union’s (EU) objectives. In 2001, the Göteborg European Council launched the EU strategy for sustainable development. This set ambitious objectives and called for a more integrated approach to policy making in which economic, social and environmental objectives can be achieved at the same time. It therefore complemented the Lisbon strategy to make the EU “the most competitive and dynamic knowledge-based economy in the world, capable of sustainable economic growth with more and better jobs and greater social cohesion”.

This shows both the importance of sustainable development within EU objectives and the high ambition level in the Lisbon strategy. The communication in the following paragraphs underlines the importance of the action plan for environmental technologies for these overall objectives. However, major policies for sustainable development steered by definitions that ignore vital aspects of ecological and economic sustainability can cause problems in the context of sustainable development, as it is understood and interpreted by e.g. the UN Millennium Development Goals (UN 2008), OECD (2001), and Millennium Ecosystem Assessment (MEA 2005). These definitions conflict with the interpretation of sustainable development in the scientific context of this thesis.

Section 4.9.3 present some trends that show the degree to which these policies have contributed to an increased awareness of ecological resources measured in terms of economic contribution to GDP in Sweden and in different parts of Europe, and to the objective of being the most competitive and dynamic knowledge-based economy in the world, capable of sustainable economic growth with more and better jobs and greater social cohesion.

4.7.4 LCA in general and applied to milk production

The remaining examples (15–25) are related to LCA. Example 15 is a textbook case of LCA. Even in the analysis of technical systems, the methodology shows severe scientific shortcomings. The authors explicitly mention 11 different ways to solve the allocation problem. This concerns how to divide natural resource use and emissions among a spectrum of co-products. This introduces a significant level of arbitrariness into the methodology. The internal consistency is low, thus LCA does not pass one of the criteria that O'Neill et al. (1986) put forward for when application of a theory or method is relevant in analysis of ecosystems. The conclusion that the internal consistency is low follows, as the optional space for the "experimenter" to steer the results is large, due to the multitude of options available regarding the allocation issue.

In example 16, the evaluation of the environmental impact is done in accordance with the logics of Figure 2, see also Example 18 below.

In Example 17 the authors presuppose that the manager in the scenario that resembles organic milk production is substantially less skilful than the manager in the conventional scenario. The latter feeds the cows according to feeding standards, while the former provides 40–50% more feeds than required per kg milk. As most resources and emissions in milk production are related to the feeding intensity, this causes significant errors in all the delivered results.

Example 18 requires a more detailed presentation for two reasons. It concerns the core of the thesis – the sustainability contribution of milk production – and is influential in Sweden and internationally. It essentially relates to two studies performed in the same way in the southern and northern parts of Sweden respectively. A number of dairy farms were analysed, where some produced conventional milk and others produced organic milk. There are major flaws both in the description of the animal production system and in the evaluation of the environmental impacts.

In the description of the animal production system, roughly 50–75% of the dry matter intake was measured through the amount of diesel used on the farm, according to the accounts. The nitrogen content in manure, which is a function of nitrogen influxes in feeds minus effluxes in meat and milk, was not estimated in this way. Instead, the STANK program from the Swedish Board of Agriculture was used in these two studies from 2004 and 2007. The value for nitrogen in manure in STANK is based on a feeding plan for conventional milk production from 1996 that assumes protein overfeeding. Thus, the estimates of ammonia emissions for the organic farms were based on data that were about ten years old for conventional milk production with protein overfeeding.

The same data was used to estimate nitrous oxide emissions from manure, an important climate change gas that also contributes to decreasing stratospheric ozone levels.

The environmental profile of the major protein feed in the organic system was not evaluated due to methodological issues within LCA (the allocation problem, see also comment regarding Example 15). Instead, data for conventional soymeal was used despite the fact that soymeal is not accepted in organic production. The soymeal equivalent of the other protein feed was estimated through the crude protein content. The crude protein levels are quite similar for the two protein feeds. The problem with this is that according to the official protein evaluation system of the time, the nutritive value of the crude protein differs substantially between the two feedstuffs. Thus, given that the protein evaluation system is relevant, the amounts of the protein feeds assumed to be equal, was far from equal in physiological terms.

Thus major parts of the evaluation of the environmental profile of organic milk were based on data for conventional milk production. With some surprise it was noted that the environmental profiles obtained for organic and conventional milk production was quite the same...

In these studies 1 kg of organic milk was assumed to be equivalent to 1 kg of conventional milk. This is not correct as the sum of the premium payment from consumers and society for the organic system results in a value per kg milk that is about 30% higher compared to conventional milk. Thus, the two products differ and cannot be compared in this way. The differences between the two systems are further illustrated by Table 4 and 5, Paper VI.

With regard to the evaluation of environmental performance, the default assumption is that there is no variation in the environmental conditions between winter and summer and geographically. Any substance emitted in the production chain anywhere in the global production network that has a capacity to contribute to, e.g. eutrophication, is assumed to do so. Thus, strict additive relations are assumed between compounds and between ecosystems around the globe. From an agricultural perspective, this equals an assumption that application of 100 kg of nitrogen in the Pacific Ocean will have the same fertilising effect on the farm in Kil in Värmland as applying the same 100 kg on the fields of that farm. Furthermore, to that effect on that farm in Kil shall be added the fertilising effect of 100 kg of phosphorus applied in the middle of Sahara. And if we solely look at the farm, the ruling assumption in LCA is that a further increase of the application of nitrogen by 100 kg per ha, repeated an infinite number of times, will always have the same marginal impact on biological production. Thus, the law of diminishing returns does not exist in LCA, the way it is normally performed.

Furthermore, the impact on biological production of nitrogen is assumed to be indifferent to the phosphorus status of the soil. Thus, the relevance of Liebig's Law of the minimum is also rejected. The eutrophication of terrestrial ecosystems, of lakes, and of seas is principally the same issue as the issue of plant nutrient supply in agriculture. When an agricultural university in its major research program regarding sustainable food production moves the knowledge frontier regarding the biological significance of plant nutrients from that of around the year 2000 to that from 160 years or more earlier in this way, there should indeed be a concern, not only for the university, but for the citizens that ultimately pay the bills. This implies that at least in this context, the work performed at the agricultural university regarding the conditions for sustainability, which implies an ambition to reintroduce the importance of land as a production factor, in the main ignores the importance of land.

Impact on climate change through deforestation due to increasing amounts of soymeal is not included in these studies. The possibility of production of ecosystem services is also excluded. Thus, the substantial carbon sink capacity in crop rotation systems with ley and pasture is not accounted for. According to FAO (2006), the mitigation options in global animal production systems, mainly within ruminant production systems with supporting plant production, equal total emissions of climate change gases. This capacity is ignored in Example 18.

The assumption is that all relations are linear. Humans can only damage ecosystems; all impacts considered are appropriation of natural resources or emissions that cause harm. Consider a thought experiment where all activities in the Baltic Sea Drainage Basin were evaluated by means of LCA. The goal function regarding discharges of nitrogen and phosphorus would then be zero discharges to the Baltic Sea. If achieved, the ecosystems of the Baltic Sea would starve to death.

In these applications LCA has major problems in

- representing economic values (compare the assumed equal value of one kg of organic and conventional milk),
- representing the animal production system, assuming that for all conventional and organic farms in the study, vital environmental aspects were best estimated through data for conventional production from other contexts in time and space,

- that the evaluation of environmental effects moved the knowledge frontier regarding the biological effects of plant nutrients at least 160 years back in time,
- that the evaluation of environmental impacts was based on assumptions that implied major conflicts with known properties of ecosystems.

Examples 20–23 draw heavily on the studies in Examples 5 and 6, and thus the same weaknesses in those studies are reflected in Examples 20–23.

The recommendations in Examples 24 and 25 regarding design of climate-friendly meals are based on the results from several LCA studies.

4.7.5 Summary of examples 1–25

The consequence of the examination of Examples 1–25 is that none of them comply with the principles for sustainable development with respect to its ecological dimensions as expressed by the Millennium Ecosystem Assessment (MEA 2005), OECD (2001) and the UN Millennium Goals (UN 2008). Aspects not considered are the limitedness of renewable and non-renewable natural resources; the limitedness in ecosystems assimilative capacity; the typical features of thresholds, irreversibilities, and resilience in ecological-economic systems; and the mutual dependencies between systems and system levels. The capacity to reflect the value of land is highly restricted.

Examples 1–25 affect measures that directly or indirectly aim at increased ecological sustainability as well as design of environmental policies and strategies among actors in the private and public sphere from the enterprise level to the international community. It is not possible to explore this further within the frame of this thesis. What can be concluded is that at best the cost efficiency of these measures/policies/strategies could be improved. At worst they may increase the speed at which the sustainability of our society is eroded.

The examples all express the problems of methodological extrapolation. They reflect an insufficient understanding of the value of land, and of agriculture and animal production systems in a sustainable development. However, this is not only an issue within engineering sciences. The next section presents an example from systems ecology where the thesis has the capacity to make a contribution in increasing the understanding of the conditions for sustainable development.

4.8 A safe operating place for humanity

An article in Nature (Rockström et al. 2009) discusses the natural boundaries for a safe operating space for humanity over the next 1 000 years. The ambition of the paper is good. Having a background in agriculture, I have closely examined the planetary boundaries relating to the use of phosphorus and nitrogen. The results are disturbing. With the trends in (i) population growth; (ii) increased welfare per capita causing a shift in food intake towards more animal products; (iii) urbanisation; (iv) globalisation with more and more agricultural products traded over increasingly longer distances; (v) the increasing demand for bioenergy; and (vi) the limitations of the available land area, we have an increasing demand on biological production per ha land with time. Since the Second World War, mineral fertilisers such as nitrogen and phosphorus have been major means of increasing yields per ha globally. This was a major element in the so-called Green Revolution.

During the 18th and 19th centuries Sweden suffered from starvation. The introduction of crop rotation systems in which nitrogen fixation by leguminouses was utilised contributed to eliminating these food shortages.

The food supply perspective related to the biophysical conditions of the planet is not considered in the article. On the subject of plant nutrients it focuses on the wellbeing of water systems, while allocating a lower priority to the biophysical preconditions for the wellbeing of people, including the food supply. Regarding phosphorus, it is the wellbeing of oceans over the next 1 000 years that defines the set boundary, while possible restrictions in agricultural production affecting global food security due to a lack of phosphorus are ignored. The estimate of global available reserves quoted in the paper is not referenced. It is up to 9.6 times higher than the reserves estimated in U.S. Geological Surveys, and 3.1 times higher than the reserve base estimated by the same source. Estimates suggesting that the phosphorus reserves will be used up within 100 years are quite common within agricultural sciences.

Regarding nitrogen, the concern is once again the quality of water systems. The planetary boundary suggested implies that the amount of mineral nitrogen fertiliser used globally should be reduced from an application rate of an average of 57 kg per ha arable land to 13 kg per ha. This reduction cannot be compensated by increased use of leguminouses. On the contrary, their contribution should be reduced from 29 to 7 kg nitrogen per ha arable land and year. Thus, in total an average supply of 86 kg nitrogen per ha and year should be reduced to 20 kg per ha and year. This reduces global agricultural production substantially in a short time while demands are increasing.

The provided estimate of annual use of nitrogen fertilisers is 80 million tonnes; once again, this is not referenced. A check with FAOstat (2009-11-17) showed that the actual global consumption in 2007 was 111 million tonnes, i.e. close to 40% higher. Thus, the reduction in application rates discussed above is based on conservative and inaccurate estimates. When working with extension services to farmers, it is important to use relevant figures. This is equally important when considering the issue of the management of land on the global level, with the ambition to affect real world policies.

The natural boundary presented regarding biodiversity is that the rate in loss of species should be reduced to 1–10% of current rate. This will effectively restrict the possibility to increase food production from ecosystems other than agricultural ones. Habitat loss may be the most important factor driving loss of biodiversity, thus the consequence of successful policies regarding biodiversity is that substantial parts of global terrestrial ecosystems are removed from production purposes.

The restriction related to global climate change will substantially increase demand for biofuels. Given that around 80% of the global energy budget is provided by fossil fuels, and current socioeconomic trends suggest that total energy use will double or more in 35 years (2% yearly growth), the climate change boundary will increase the competition for land, reducing the area of agricultural land available for food purposes. The combined demand for biomass from agricultural land for food and fuel purposes will increase substantially.

Combining the natural boundaries proposed due to biodiversity loss, climate change and eutrophication implies that more biomass should be produced from less remaining productive land, while nitrogen influxes to arable land as the sum from nitrogen fertiliser and leguminouses are reduced from 111 to 21 kg per ha and year, assuming no such influxes to permanent pastures, gardens or forests.

If these planetary boundaries regarding plant nutrients were actually introduced, then the number of starving people would increase substantially within a year. Within ten years, the global population will have fallen significantly. Lack of energy and food will increase social disorder among people, regions and nations. The biophysical constrains for humanity proposed in the article, if they were effectively implemented, would soon deteriorate the socioeconomic foundations for a safe operating space.[35]

This shows that the integrated eco-agro-social perspective of the thesis also has a contribution to make in this context, increasing the understanding of the importance of land and our land management skills to maintain a safe operating space.

One reason for the limited usefulness of Rockström et al. (2009) is that the article does not consider the importance of land and agricultural expertise when discussing global food security. Agriculture is possibly the most important system that mediates global biophysical conditions, defining a safe operating place for humanity (see Figure 1). Thanks to agriculture, this operating space has been enlarged by a factor of 100 to 1 000 times (Paper I). Animal production systems play a major role in this (Paper VI). This insight regarding the importance of agriculture is reflected in the Millennium Development Goals of the UN and the order by which MEA (2005) presents

35. See http://blogs.nature.com/climatefeedback/2009/09/planetary_boundaries_1.html, accessed 2009-11-15, contribution dated 20th of October 2009.

ecosystem services that support human wellbeing. Here, I conclude that the biophysical limits for humanity that Rockström et al. have defined are flawed due to the fact that (i) they have not included the significance of agriculture and food for humanity in their analysis, and (ii) they have not utilised competences within agricultural sciences in the process of generating the biophysical boundaries.

Moreover, the system perspective could have been stronger. For three boundaries they conclude that critical thresholds have been trespassed, regarding climate change, eutrophication, and loss of biodiversity. Their message is that we need to tether global society to these boundaries in order to have the possibility to continue a positive social and economic development. However, according to their analysis, the combined measures that are needed in order to achieve a safe operating space regarding these three aspects would instead increase the threats to global sustainability by substantially reducing global food security.

This shows that the performed analysis has provided results that conflict with the very purpose of the work. Boundaries proposed with the aim of securing human wellbeing will severely damage human wellbeing within a few years if converted into efficient measures. With a stronger system perspective, humanity and agriculture had been considered in the analysis. The current analysis focuses on the conditions of global biophysical and ecological systems within a time frame of 1 000 years, while the impacts on humanity over the next ten years if the proposed boundaries are enforced are not analysed.

This is not merely an academic discussion. In different contexts in Sweden and internationally, the findings of this article are being presented as something that has to be addressed in its entirety and in an integrated manner, to secure global social and economic development within ecological sustainability limits.

The thesis makes a contribution regarding both the knowledge of agricultural systems and the system perspective on biophysical conditions, humanity and a safe operating space, compared to the way these aspects were treated in Rockström et al. (2009).

4.9 Some applications and their implications

The thesis and its papers make contributions in two fields, the design of feeding rations to dairy cows that support the economic result and natural resource efficiency, and methods for evaluation of systems sustainability performance. On a high system level the findings contribute and agree well with policy contexts such as the UN Millennium Development Goals, the principles for sustainable development put forward by OECD, Millennium Ecosystem Assessment, the initiative “Beyond GDP”, FAO and its perception of the role of animal production in a sustainable future, “The Economics of Ecosystems and Biodiversity” (TEEB), and the risk analysis of the global economy launched at World Economic Forum[36]. Thus, on a general policy level there is no major tension between the thesis and the current discourse.

There are substantial tensions between the findings presented and methods and approaches that dominate on the operative level. This section presents some applications of the methods presented and their consequences in different contexts. The applications are sometimes in the role as consultant. This means that the following information may suffer from self-reporting bias. No scientific proofs are presented. However, it still contributes to a test of the relevance of the applied methods and the ways in which they have been applied in real world situations. When dealing with such complex systems as are typical when the issue concerns aspects of a sustainable development, the relevance of the work for the system and issue at hand is equally important as high standards of the work in relation to traditional scientific criteria (Giampietro 2003). In the following, the information is based on official statistical sources when possible in order to reduce the space for subjective bias.

The following tables and figures provide some information supporting a relevance test of the thesis and some of its central parts.

4.9.1 Dairy production and environmental objectives

Table 6 shows the results from a regression between number of dairy cows and time based on data from the Swedish Board of Agriculture for the period 1981–2010.

36. Most of these contexts are presented earlier in the thesis or in the included papers. Regarding Beyond GDP, see http://www.beyond-gdp.eu/; TEEB, see http://www.teebweb.org/wpcotent/uploads/Study%20and%20Reports/Reports/Synthesis%20report/TEEB%20Synthsis%20Report%202010.pdf; and the risk report from World Economic Forum, see http://www.weforum.org/reports/global-risks-2012-seventh-edition; all accessed 2013-01-02.

Table 6. Regression between number of dairy cows and time based on data from the Swedish Board of Agriculture for the period 1981–2010.

	Regression		Predicted year for the vanish of last dairy cow
County			
Stockholm	y = -319.92x + 13001	R^2 = 0.969	2020.6
Västmanland	y = -366.53x + 15191	R^2 = 0.9852	2021.4
Värmland	y = -516.51x + 22907	R^2 = 0.9865	2024.3
Södermanland	y = -609.41x + 1E+06	R^2 = 0.9751	2024.8
Örebro	y = -437.71x + 19835	R^2 = 0.9768	2025.3
Dalarna	y = -415.49x + 19040	R^2 = 0.9875	2025.8
Västernorrland	y = -407.11x + 18714	R^2 = 0.9603	2026
Norrbotten	y = -340.16x + 15906	R^2 = 0.9647	2026.7
Gävleborg	y = -464.18x + 21767	R^2 = 0.98	2026.9
Blekinge	y = -237.83x + 11185	R^2 = 0.985	2027
Västra Götaland	y = -2338.3x + 125310	R^2 = 0.9731	2033.6
Skåne	y = -1423.3x + 79975	R^2 = 0.9797	2036.2
Västerbotten	y = -459.74x + 25925	R^2 = 0.9322	2036.4
Jämtland	y = -301.52x + 17200	R^2 = 0.9752	2037
Kronoberg	y = -430.38x + 24991	R^2 = 0.9273	2038.1
Östergötland	y = -532.62x + 40059	R^2 = 0.9208	2055.2
Uppsala	y = -491.31x + 997288	R^2 = 0.971	2056.3
Jönköping	y = -549.12x + 45338	R^2 = 0.9293	2062.6
Halland	y = -342.4x + 34680	R^2 = 0.7933	2081.3
Gotland	y = -195.39x + 21608	R^2 = 0.8944	2090.6
Kalmar	y = -380.2x + 50002	R^2 = 0.8693	2111.6
Dairy cooperative			
"Milko"	y = -2104.8x + 99628	R^2 = 0.9923	2027.3
"Norrmejerier"	y = -799.9x + 41832	R^2 = 0.9506	2032.3
"Skånemejerier"	y = -1423.3x + 79975	R^2 = 0.9797	2036.2
Sverige	y = -11559x + 674451	R^2 = 0.9786	2038.3
"Arla"	y = -7231.1x + 453016	R^2 = 0.971	2042.6

x in the equations refers to the number of years after 1980.

The information in Table 6 should not be interpreted literally. It is not a prediction of when the last dairy cow will disappear in different regions. Instead, it shows what will happen if the same trends that operated from 1981 to 2010 were to continue. Nobody knows whether they will.

Figure 11 illustrates these trends.

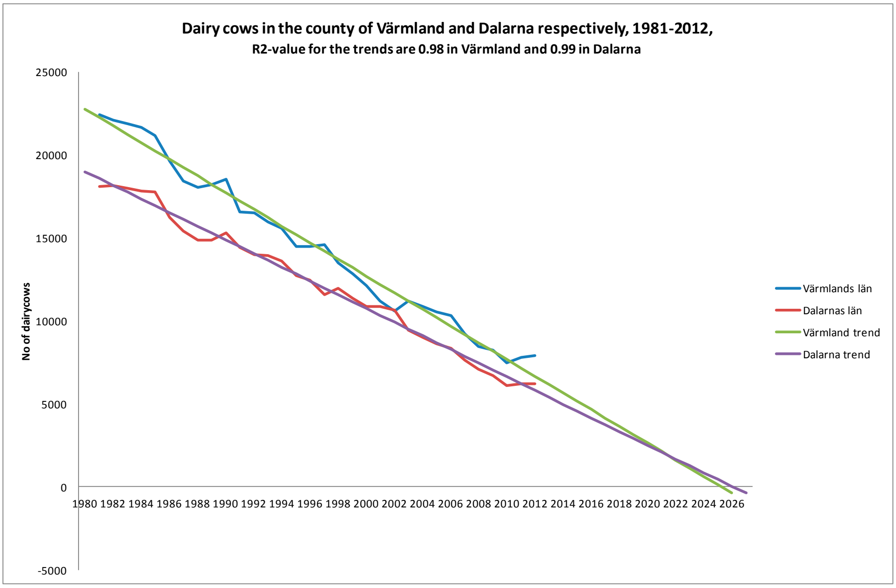

Figure 11. Number of dairy cows in the county of Värmland and Dalarna, 1981–2012.
Data from http://statistik.sjv.se/Dialog/Saveshow.asp, accessed 2014-02-17

The results in Table 6 and Figure 11 are concerning. Dairy cows are of crucial importance for achieving four of the sixteen national environmental objectives[37], namely

- Number 1, reduced climate impact, where the first paragraph explains its meaning as "In accordance with the UN Framework Convention on Climate Change, concentrations of greenhouse gases in the atmosphere must be stabilised at a level that will prevent dangerous anthropogenic interference with the climate system. This goal must be achieved in such a way and at such a pace that biological diversity is preserved, food production is assured and other goals of sustainable development are not jeopardised. Sweden, together with other countries, must assume responsibility for achieving this global objective." [38]
- Number 8, flourishing lakes and streams: "Lakes and watercourses must be ecologically sustainable and their variety of habitats must be preserved. Natural productive capacity, biological diversity, cultural heritage assets and the ecological and water-conserving function of the land-

37. See http://www.miljomal.nu/sv/Environmental-Objectives-Portal/, accessed 2013-01-02.
38. See http://www.miljomal.nu/sv/Environmental-Objectives-Portal/, accessed 2013-01-02.

scape must be preserved, at the same time as recreational assets are safeguarded."

- Number 13, a varied agricultural landscape: "The value of the farmed landscape and agricultural land for biological production and food production must be protected, at the same time as biological diversity and cultural heritage assets are preserved and strengthened."
- Number 16, a rich diversity of plant and animal life: "Biological diversity must be preserved and used sustainably for the benefit of present and future generations. Species habitats and ecosystems and their functions and processes must be safeguarded. Species must be able to survive in long-term viable populations with sufficient genetic variation. Finally, people must have access to a good natural and cultural environment rich in biological diversity, as a basis for health, quality of life and well-being."

One kg of milk produced in Sweden maintains 1–2 m^2 agricultural land in production forms that support environmental objectives related to biodiversity and the preservation of the cultural landscape.

Society has decided on these environmental objectives, with the ambition to achieve them in one generation. It is a policy failure when current trends in one agricultural production branch crucial for their success, dairy production, are such that in those regions where this production is vitally important for success, linear trends are unbroken since 1981, suggesting that the last dairy cow will disappear within half a generation. The counties within the area of the former dairy cooperative Milko, i.e. Värmland, Dalarna, Västernorrland, Gävleborg and Jämtland, had a higher rate of annual decline of dairy cows compared to the counties whose farmers delivered to the three largest Swedish dairy cooperatives in 2011.

Papers V and VI showed that increased milk production in the former Milko area makes a substantial contribution to vital global sustainability goals such as food security. Paper VI also showed large positive societal welfare effects of milk production in this area compared to other areas in Sweden with substantially higher contributions to eutrophication of the Baltic Sea per kg milk delivered.

Thus, milk production in these counties is competitive in its delivery of the ecosystem services that society demands, expressed through national environmental quality objectives. The problem is that these farmers are not paid for the societal value of their production.

Based on current trends, the last dairy cow will leave a number of counties in 10 to 15 years. In many of them, continued dairy production is necessary to reach four of the environmental objectives decided by the national parliament. Furthermore, in the same areas the contribution per kg of milk to the eutrophication of the Baltic Sea is substantially lower than in other areas that have benefited from subsidised extension services in the program Focus on Nutrients for a long time. The societal value of the lower contribution to eutrophication is in the range of 30–60 000 SEK per dairy cow in some of these regions, following the calculation route laid out in Paper VI.

An interesting initiative was undertaken by local retail stores in Jämtland in the summer of 2012. They offered customers the option to pay more for their milk, on the condition that the extra money was transferred to local milk producers. The customer demand for the more expensive milk increased. This indicates that people are concerned about current trends and are willing to pay to maintain local milk production. The initiative was communicated via the motto "Milk is thicker than water" ("Mjölk är tjockare än vatten"), to underline the situation where water is more expensive in shops per litre than milk. This situation was already noted in 1970 (Jansson 1970).

Finally, maintaining dairy production contributes to a landscape which is attractive for permanent living as well as for tourists. Many of the regions in Table 6 such as Dalarna, Värmland and Jämtland are dependent on tourism.

These aspects, added to the environmental objectives underline the severity of this policy failure. Despite the delivery of a spectrum of ecosystems services of societal importance, the total impact of the incentives that society provides are such that the objectives that society has decided on cannot be reached.

4.9.2 Value of ecosystem services and the 4P principle

It is not certain that the main policy failure is within agricultural policy. Ecosystems deliver ecosystem services. As around 75% of terrestrial land in Sweden is classed as agricultural land or forests, most of the total production of ecosystem services originates from agriculture and forestry. Globally, the corresponding value is 70%. A sustainable situation is at hand when the total consumption of ecosystems services is within the sustainable production level. One major incentive towards achieving this is to adjust the prices of goods and services so that they reflect the value of positive and negative ecosystems and human health impacts (OECD 2011). FAO (2006), Millennium Ecosystem Assessment (MEA 2005), and TEEB[39] make similar proposals.

Hellstrand (1998) suggested a solution based on the Precautionary Polluter Pays Principle (the 3P principle) (Costanza and Perrings 1990; Costanza 1994). The 3P principle integrated the precautionary and the polluter pays principle into a market based insurance solution. The 3P principle made it rational for enterprises to reduce (the risk of) human and ecosystem health

39. http://www.teebweb.org/wp-content/uploads/Study%20and%20Reports/Reports/Synthesis%20report/TEEB%20Synthesis%20Report%202010.pdf, accessed 2014-02-18.

damages caused by production. It also provided incentives where enterprises benefitted from actions that reduced the uncertainty regarding possible negative external impacts of production. However, one piece of the puzzle was still missing. The 3P principle did not link the consumption of environmental space to its production, i.e. it did not link consumption of ecosystem services to production. The 4P principle (the Precautionary Polluter Pays the Preventer/the Polluted Principle) however does this, within production levels set by affected ecosystems carrying capacity limits (Hellstrand 1998). The potential contribution of the 4P principle was discussed in relation to aspects such as cadmium fluxes in the food system with its impacts on human health, the depression of photosynthesis and thus production in forestry and agriculture as a result of ozone close to the ground due to emissions from society, carbon sinks in forestry, and production permits to the forestry industry based on the so-called best available technology principle.

The 4P principle stresses the importance of not only utilising environmental fees and taxes but also reward systems when actors take measures to improve the environment and the production of ecosystem services[40]. In theory, with this kind of principle an insurance solution is enforced where environmental as well as human health risks of production systems are internalised in the price. Actors that harm the environment or/and human health are forced to pay those that bear the costs. Finally, in this system actors that produce ecosystem services that enhance the sustainability basis of society are paid for this production. In fact, the 4P principle provides a frame where for example, trading systems for emissions are anchored in the carrying capacity limits of affected ecosystems. By doing so, the market mechanism is used to enhance social and economic development in affected systems within ecological and human health limits. Solutions that provide low satisfaction of human needs per unit emissions will then be outcompeted while solutions that provide high satisfaction of human needs per unit emission are favoured. At the same time, this system suggests how the total amount of emissions can be captured within the carrying capacity of affected ecosystems. It provides incentives where managers of ecosystems are encouraged to improve the production of ecosystem services, and it provides incentives favouring technological development and innovation favouring social and economic development within sustainability limits of affected ecosystems[41]

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40. The issue of externalities and how to price them has been discussed for a long time within economics.

41. This concept has been treated at a conference and a workshop at the Swedish Royal Academy of Forestry and Agriculture. The exercises are documented in separate reports, see Jakten på den gröna marknadskraften, samt Jakten på den gröna marknadskraften del 2 in separate issues of KSLAs Tidskrift. The first report is also available in English, The Search for green market forces. Links to these reports are http://www.ksla.se/publikationer/kslat/kslat-1-2006/; http://www.ksla.se/publikationer/kslat/kslat-6-2008/; http://www.ksla.se/publikationer/kslat/kslat-1-2006-eng/, all accessed 2013-01-03.

The Swedish ecological-economic system combines industrial sectors with high resource and emission efficiency, and ecosystems/recipients with higher remaining assimilative capacity compared to most other developed nations. The latter aspect is mainly a function of the low concentration of humans per ha of biologically productive ecosystem. The share of land area where deposition of nitrogen exceeds critical thresholds is substantially lower in Sweden compared to most EU countries (Figure 12).

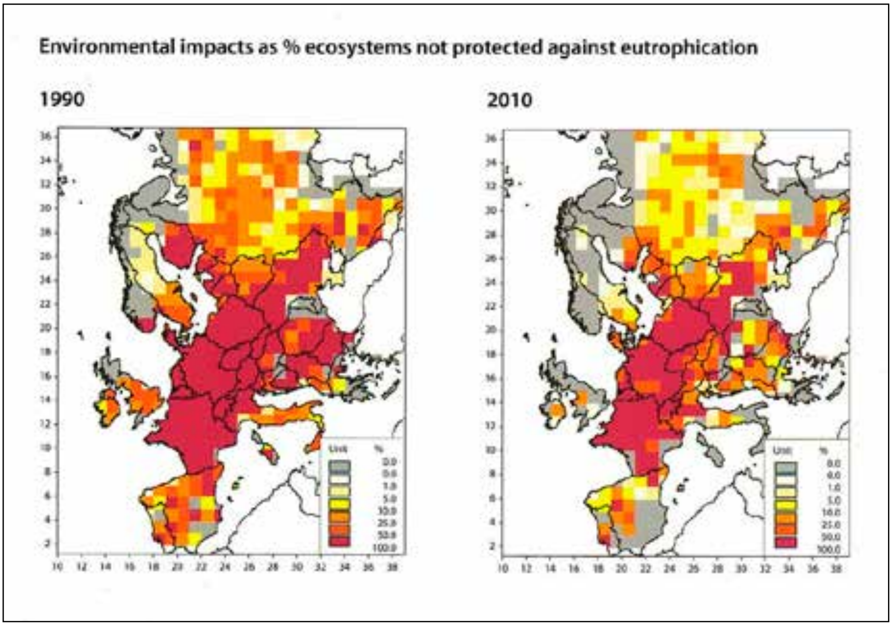


Figure 12. The exceedance of critical loads for eutrophication around Europe for the base year 1990 and target year 2010 of the Gothenburg Protocol. Source: Pleijel (2007).

Figure 12 shows a huge variation in the degree to which critical loads, i.e. assimilative capacity limits, are trespassed in Europe. In the most densely populated areas, which also have the highest economic activity per area unit, the critical load is trespassed for 100% of the area of ecosystems.

Emissions to air also have human health impacts. They were estimated to cause around 400 000 deaths in the year 2000 in the EU. The annual cost to society of this level of health impacts has been estimated at 270 to 880 billion € (EU-Commission 2005).

The spatial variation in air emissions is similar to the one in Figure 13. Thus, in the most densely populated areas with the highest economic activity, the expected lifespan is expected to be reduced by 1–3 years due to emissions to air. In the three largest cities in Sweden the reduction is 6–9 months, while in the majority of Sweden it is 0–4 months (personal communication; Grennfelt 2009).

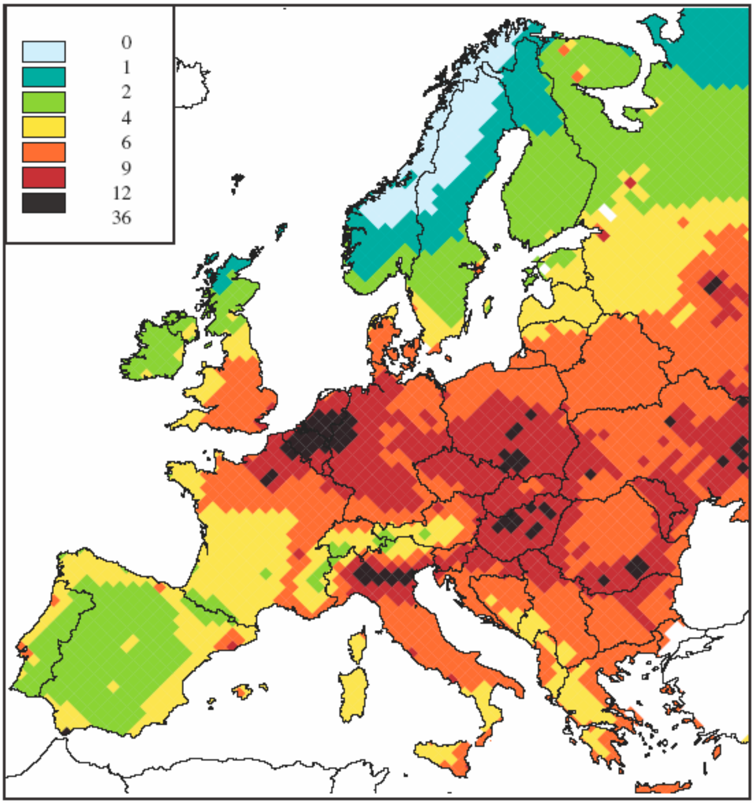


Figure 13. Loss in statistical life expectancy in Europe in 2000 due to emissions of particles (PM2.5) in months.

The concentration of ecosystem and human health impacts in areas with the highest level of economic activity per area unit in combination with the high economic costs in terms of e.g. human health impacts suggests that economically efficient policies for sustainable growth in Sweden and the EU would improve the competitive power in rural areas in Sweden in two ways:

1. Through payment for the production of ecosystems services such as the annual sink of around 170 million tonnes of carbon dioxide via photosynthesis in Swedish forests.
2. Through the competitive advantage of industries via the combination of resource and emission-efficient industrial plants located such that the negative pressure is zero or significantly lower compared with identical industrial plants located in areas with high economic activity per area unit with a corresponding high environmental and human health load (see Figures 12 and 13; Hellstrand 1997 and 1998 treat this issue).

Incentives with the characteristics of the 4P principle would work via these two paths. At the same time, they would favour cost-efficient measures that help the adaptation of those urban/industrial regions to human health and ecosystems carrying capacity limits where they are now trespassed. This implies that the costs of such measures are allocated in those urban areas where the contribution to GDP will be somewhat lower when the ecosystem and human health impacts are internalised in the price mechanism, improving the environment and increasing expected average lifetime.

Table 7 shows the impact of economic development, from local to national level, of incentives internalising external environmental and human health effects.

Table 7. Sustainability accounts regarding climate change gases in the local community Kil, the county of Värmland, Stockholm, and Sweden.

	Million kg		*Balance*		
	Assimilative capacity (i)	Consumption (i.e. emissions caused by final energy use (ii))	Million kg (i minus ii)	Value, million SEK	Value, SEK per inhabitant
Kil	194	44	150	225	19 206
County of Värmland	11 849	2 013	9 837	14 755	53 995
County of Stockholm	2 814	4 277	-1 462	-2 194	-1 068
Sweden	168 545	63 347	105 198	157 798	16 759

The assimilative capacity of carbon dioxide in forests is estimated via the chemical formula for photosynthesis, where sunlight + 6 molecules of water + 6 molecules of carbon dioxide result in 6 molecules of oxygen released to the atmosphere, and the production of biomass via the molecule of sugar that result from this process. The total annual forestry photosynthesis is estimated via annual growth of Swedish forests according to official statistics. It is assumed that the total biomass production is 1.7 times the estimate of annual growth, which is measured in m^3sk. This volume measure is converted to weight considering the distribution of different types of trees with their different densities.

Every kg of biomass (dry matter) stores the equivalent of 1.8 kg of carbon dioxide and contains around 17 MJ of chemical energy. Thus, on the national scale in Sweden, photosynthesis in forests produces 92 million tonnes of biomass, converts solar energy to 434 TWh of chemical energy, and releases 123 million tonnes of oxygen to the atmosphere, making life on land possible for humans and other animals. In the same process, 169 million tonnes of carbon dioxide are captured. As a comparison, total final use of energy in Sweden in 2009 was 376 TWh[42].

Emissions of climate change gases are estimated from emission factors for different types of energy carriers from the Swedish Environmental Protection Agency, and data on final use of energy are estimated from data on different energy carriers from Statistics Sweden. One major point that Table 7 communicates is the structure of the analysis where production of environmental services is compared to consumption, resulting in a sustainability balance, where this follows the same structure as when construction e.g. feeding plans in animal husbandry and fertilisation plans in crop production.

Official measures of total emissions of climate change gases in Sweden are 55–60 million tonnes carbon dioxide equivalents annually[43]. The estimate in Table 7 of a carbon sink of close to 170 million tonnes in Swedish forest annually suggests that in fact Sweden now have a substantial negative climate gas balance that neutralises emissions from nations that are net-emitters.

The estimate of 55–60 million tonnes carbon dioxide emitted in Sweden should however be increased. The estimate of 170 million tonnes as a sink considers the total photosynthesis in forests. In order to treat related subsystems with internal consistency, all the emissions when using e.g. biofuels should be considered. When doing so and using the best data I can find in 2014, total emissions in Sweden is increased to around 100 million tonnes of carbon dioxide equivalents. Still, the negative balance is substantial.

Thus, current climate policies in Sweden aiming at achieving climate gas neutrality within some decades, reflects an unawareness of the nature of the systems discussed.

The value is estimated from the price of 1.5 SEK per kg carbon dioxide. This is a measure used by Swedish authorities when estimating welfare effects of emissions (SIKA 2009).

The sustainability accounts for climate change gases follow the structure of analytical and management tools that have been used and developed for decades and centuries in agriculture and forestry in Sweden, capturing combined biological/ecological and economic performance. They follow the logic of the biophysically anchored production functions developed in Paper II and the system boundaries and rules of aggregation in conventions regarding systems of national accounts. This is a contribution to systems of "cli-

42. The two estimates cannot be directly compared as not all of the chemical energy produced via photosynthesis can be utilised by the economy because of economic and ecological restrictions. Furthermore, correction for different energy qualities has not been made. Still, this provides a basis for the first step in an evaluation of the sustainable capacity of our forests to produce energy to substitute fossil fuels.

43. See e.g. Swedish Environmental Protection Agency, National Inventory Report 2012 Sweden, Submitted under the United Nations Framework Convention on Climate Change and the Kyoto Protocol (SEPA 2012).

mate change accounts"[44] which supports an adoption of current dominating modes to known properties of forestry and the forestry industry, where there is no longer a need to assume that when a tree is cut down, all of its carbon is immediately and completely oxidised to carbon dioxide. If that were the case IKEA could not sell any wooden furniture, and there would be no houses built from wood. Table 7 indicates that it may be a smart option to include wood products in society as a carbon sink among systems for Carbon Capture and Storage (CCS). In so doing, Sweden and its forest sector and forest industry could sell three functions in the same product, the traditional function of a table made of wood, the 1.8 kg of carbon dioxide stored in every kg of wood (dry matter) and the 17 MJ of renewable energy also stored in every kg.

Table 7 and Figures 12 and 13 suggest that when positive and negative external effects are adequately considered in the price, regions and nations that combine a high production of ecosystems services with resource and emission-efficient industries will have a good development. Regions and nations that are worse off at the beginning, is stimulated by a price internalising external effects to find cost-efficient measures improving their situation.

Recently, Sveaskog and LKAB, with support from Pricewaterhouse-Cooper, have developed a system for payment for ecosystem services. The mining company LKAB is increasing its production due to the increasing demand from China. Their carbon dioxide emissions will therefore also increase. At the same time the emissions permits within the EU trading system are being reduced. One way to deal with this is to pay for measures that increase the carbon sink in the forest of Sveaskog[45].

This is in line with concepts introduced in the environmental report of AssiDomän for the year 1997 (AssiDomän 1998). Hellstrand et al. (1998) performed a study in which the environmental space of the forest of AssiDomän generated by the production of ecosystem services was estimated. At that time, the company owned over 3 million ha forest land, i.e. more than 10% of the total forestry area in Sweden. The production of environmental services in the forests was reduced by the consumption due to actions such as felling and the transporting of trees and the activities in pulp and sawmills. This work delivered the first estimates of the company's eco-efficiency. That work was one element inspiring the proposal of the 4P-principle in Hellstrand (1998), which then resulted in one conference and

44. See e.g. Swedish Environmental Protection Agency, National Inventory Report 2012 Sweden, Submitted under the United Nations Framework Convention on Climate Change and the Kyoto Protocol.
45. See http://www.sveaskog.se/press-och-nyheter/pressmeddelanden/2011/lkab-koper-koldioxidkrediter-av-sveaskog/, accessed 2013-01-04.

one workshop at the Swedish Royal Academy of Forestry and Agriculture (2005 and 2007) under the title the Search for Green Market Forces[46].

Sveaskog now owns the majority of these forests. The initiative between Sveaskog, LKAB and PWC follows the logics outlined in the work by Hellstrand (1998) and Hellstrand et al. (1998).

4.9.3 Do economic trends show increasing value of land?

This section presents a number of economic trends. Its purpose is to investigate whether an increasing value of land is expressed, i.e. an increased value of ecological resources. One reason that this could be the case is that a sustainable development within affected ecosystems carrying capacity limits is a general objective within UN, OECD, the EU, Sweden, and its region from around the year 2000 (Hellstrand 2005b).

Figure 14 presents the development of the contribution to GDP from different sectors in Sweden from 1993 to 2012.

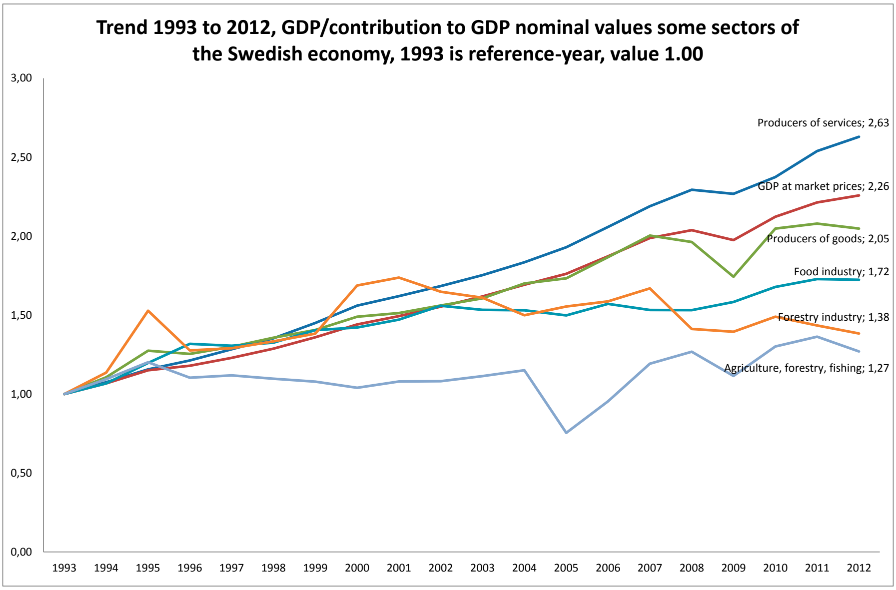


Figure 14. Contribution to GDP in Sweden from acreage-dependent sectors, forest industry, food industry, production of goods, production of services, and GDP, 1993–2012.
Data from www.scb.se, accessed 2014-02-19.

In nominal prices, the contribution to GDP from acreage-dependent sectors in Sweden from 1993 to 2012 has increased by a factor 1.27, in the mean-

46. For documentation from these events, see http://www.ksla.se/publikationer/kslat/kslat-1-2006/, http://www.ksla.se/publikationer/kslat/kslat-6-2008/, and http://www.ksla.se/publikationer/kslat/kslat-1-2006-eng/, the last in English, all accessed 2013-02-19.

time the the forest industry sector and the food industry grew by 1.38 and 1.72-fold respectively. In total beneficial production increased by 2.05 times, and GDP increased 2.26-fold. Service sectors increased by a factor of 2.68.

Figure 14 shows that since around 1995 the acreage-dependent sectors in Sweden have not grown in nominal prices, and that from around 2000 the forestry industry has substantially decreased its contribution to GDP. The food industry has also shown low growth similar to the acreage-dependent sectors since around 2000.

This can of course be understood as an example of what happens in growing economies, where the importance of acreage-dependent sectors in the economy decreases first, followed by industrial sectors, while the importance of service sectors increases.

At the same time, the sustainability issue suggests that this trajectory of developing economies has hidden external costs where the economy may eventually move outside a safe operation space for humanity as defined by Rockström et al. (2009). According to Odum (1989), OECD (2001), FAO (2006), MEA (2005), TEEB (2010), a prerequisite for sustainable development is that external effects are considered, including payments for ecosystem services that constitute the ecological sustainability of society.

From this perspective, if efficient incentives for sustainable development were implemented around 2000 when sustainable development emerged as an overall societal goal, then they would have had an impact on economic trends. Growth of acreage-dependent sectors would have increased due to their production of ecosystem services, and forestry and food industries would have increased in size due to their combination of "embodied" environmental values[47], often resource- and emission-efficient production systems, and their location where remaining assimilative capacity is high.

The trends in Figure 14 show that this did not happen. It may be that current societal development in Sweden is quite sustainable. The trends may also reflect that current incentives do not efficiently promote sustainable development in which positive and negative external impacts are internalised. This issue requires further studies.

Figure 15 shows the relation between the share of the regional economy that comes from the production of goods in 1993, and the regional economic development from 1993 to 2009.

47. Forestry products are also a carbon sink. Every kg of milk typically contributes around one square meter of agricultural land supporting biodiversity.

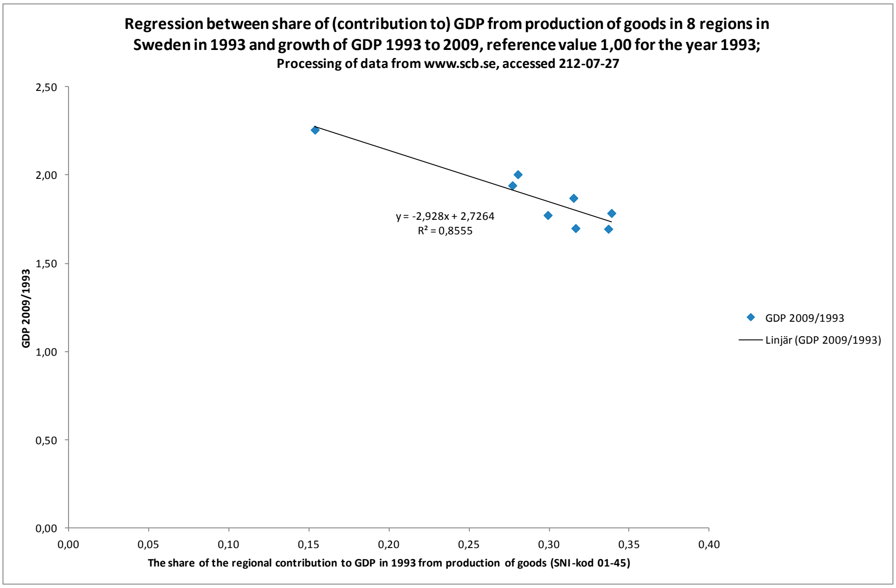


Figure 15. The relationship between share of (contribution to) GDP from production of goods in 8 regions in Sweden in 1993 and growth of GDP 1993–2009, reference value is 1.00 for the year 1993.

From 1993 to 2009, the growth in those regions in Sweden that in 1993 had a regional economy with a high share of production of goods was substantially lower compared to other regions.

The regions in Figure 15 with the lowest growth from 1993 to 2009 are the northern parts of Svealand and the southern and middle parts of Norrland. These regions combine a high production of ecosystem services per inhabitant (because they have a large area of productive ecosystems per inhabitant), low environmental load of ecosystems (Figure 12), low decrease of expected lifespan due to emissions to air (Figure 13), and an economy where the base industry, such as forestry, mining and steel industry is more important than in other regions.

I suggest that if efficient incentives internalising positive and negative environmental and human health effects had been implemented, then the economic development in these regions had been better. Thus, the trends in Figures 14 and 15 suggest that there is an implementation issue in Sweden regarding sustainable development. The trends in Figures 14 and 15 are not surprising given the outcome of the analyses in Papers II, VI and section 4.7, regarding the lack of capacity of different methods to evaluate real impacts of production in real ecosystems, where this lack of capacity is converted to environmental policies based on the logics of these methods.

Figure 16 presents the contribution to GDP from acreage dependent sectors from 1970 to 2011 in Sweden, Northern Europe, Western Europe, Europe, North America, Asia, Africa and the world.

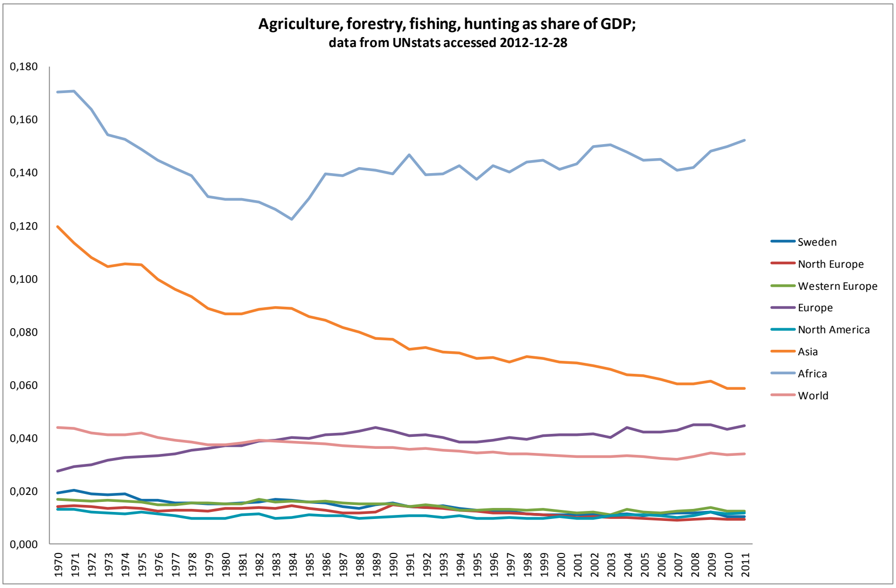


Figure 16. The contribution to GDP from acreage-dependent sectors 1970–2011 in Sweden, Northern Europe, Western Europe, Europe, North America, Asia, Africa and the world as shares of GDP.

Figure 16 shows that the general trend in the economies investigated is that the share of acreage-dependent sectors in GDP is decreasing. Europe and Africa follows a somewhat different pattern. It does not support the conclusion that policies for sustainable development in general have increased the value of the fluxes of ecosystems services from the stock of natural capital land. Ecosystem services (MEA 2005) are e.g. clean water; food; forestry products; capacity to take care of emissions and discharges to water, air and land; aesthetic values.

Figure 17 shows the development over time of the contribution to GDP from acreage-dependent sectors in Sweden, Northern Europe, Western Europe, Europe, North America, Asia, Africa and the world.

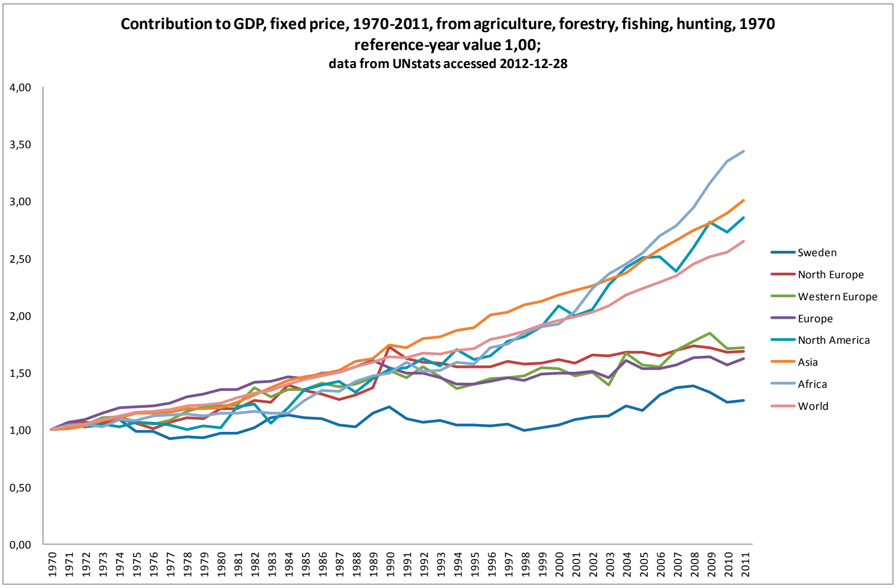


Figure 17. Contribution to GDP from acreage-dependent sectors in Sweden, Northern Europe, Western Europe, Europe, North America, Asia, Africa and the world 1970–2011, fixed price. Relative to a value 1.00 in 1970.

The lowest growth in the contribution to GDP from acreage-dependent sectors in this period was in Sweden, followed by different regions in Europe, while Africa, Asia, North America, and the world had a substantially higher growth (Figure 17).

The information provided in Tables 6 and 7 and in Figures 12–17 support the following conclusions:

- Global trends do not reflect an increased value of land due to incentives effectively internalising positive and negative human health and environmental impacts.
- There are substantial welfare economic advantages in rural regions in Sweden and in their agriculture and forestry due to human health and environmental aspects.
- When discussing the Northern parts of Svealand and the southern and middle parts of Norrland the following can be added. The environmental load is lower than in other areas, the human health impact of emissions is lower, the positive contribution to national environmental objectives is higher, and the environmental load in terms of eutrophication of the Baltic Sea per kg milk produced is lower than in other regions. Despite this the development of the regional economy and of milk production, the most important agricultural production branch, is weaker/more negative in these areas than in other areas of Sweden.

- In Sweden and in Northern and Western Europe, the contribution to GDP from acreage dependent sectors is low and falling as a share of the economy as a long-term trend.
- One explanation is if policy measures in the private and the public sphere aiming at sustainable development from regional and national to EU level express substantial weaknesses in their capacity to capture the relations between ecological, economic and social systems.
- The results presented above suggest that the overall incentive structure may still neglect vital aspects of the production factor land. If so, the fast decline in the number of dairy cows in regions in Sweden where their marginal contribution to
    - global food supply (Papers V and VI), and to
    - the fulfilment of national environmental objectives is substantial,

  can to a significant degree be a function of policies on higher levels than the European Agricultural Policy, such as general economic policies, environmental policies, and policies for sustainable development.

The tables and figures presented here may reflect policy failures on higher policy levels, impairing the capacity of agriculture and rural areas to make their full and important contribution to the ecological sustainability basis of society.

4.9.4 ISO 14 001 and ecosystems

In 2010, organisations behind the ISO 14 000 system initiated the first major revision since it was introduced in 1996. ISO 14 040 and ISO 14 044 give rules regarding how to perform Life Cycle Assessments (LCA). The approach of LCA and the method itself are influential in environmental policies in Sweden and the EU, not least within agriculture.

Eleven challenges are to be handled, concerning environment management systems (EMS)[48]:

1. EMS as part of sustainability and social responsibility
2. EMS and (improvement of) environmental performance
3. EMS and compliance with legal and other external requirements
4. EMS and overall (strategic) business management
5. EMS and conformity assessment

48. ISO/TC 207/SC 1 Future challenges Study group N 9. Final report on the future challenges of EMS and ISO 14001.

6. EMS and the uptake in small organizations
7. EMS and environmental impacts in the value/supply chain
8. EMS and engaging stakeholders
9. EMS and parallel or sub systems (GHG, energy)
10. EMS and external communication (including product information)
11. Positioning of EMS in (inter)national policy agendas

The text explaining these challenges shows that future credibility is dependent on a capacity to actually contribute to a better environment in the future. The focus of ISO 14 001 from 1996 is the efficiency in the internal administration of internal environmental policies. There has been a demand to actually perform an analysis of the environmental performance of the ISO 14 001 system. However, no criteria have been put forward regarding the content and quality of this analysis. Knowing this, and given the influence in public and private spheres in Sweden and in the EU, the low capacity to actually translate unique environmental assets to improved economic results in agriculture as well as enterprises in other sectors areas where the environmental factor implies a competitive advantage given effective policies for sustainable development is not surprising.

This is a concern because since around the year 2000 there has been an ambition in the EU, Sweden, and Swedish regions to secure future international competitive power and domestic economic growth via policies for environmentally driven businesses. As shown in previous sections, a number of policies aimed at environmentally driven growth are based on LCA and the information this methodology provides about systems sustainability-performance.

One example is the criteria for public procurement from SEMCO (Miljöstyrningsrådet) of dairy production, where in the Swedish version the criteria proposed regarding climate change are results from analyses in accordance with the IS0 14 040 serie. Another example is the research program FOOD 21 in Sweden which started in 1997, which used LCA in accordance with ISO 14 040 and ISO 140 44 as the methodology to evaluate sustainability performance of animal production systems. This program now influences climate change policies in Sweden regarding ruminants as well as the IPCC strategy for bioenergy. Section 4.7, Paper II and Paper VI analysed weaknesses of LCA and the way that it analysis impacts of production in affected ecosystems.

The consequence is that current climate change policies regarding animal production systems in Sweden and internationally, as well as policies for environmentally driven growth, are based on the logic and results from a methodology from 1996 onwards, where the organisation responsible for the guidelines regarding how to perform the analysis is now concerned with its lack of capacity to credibly handle environmental impacts of production.

To avoid any misunderstanding, I do not argue that agriculture should always be the major economic sector measured in GDP terms. My argument is that when going from an economic system that ignores the value of land, i.e. the ecological dimension of the economy, towards a sustainable economy where economic and social development are within affected ecosystems carrying capacity limits, it is probable that trends that have dominated for several decades in developed nations, with declining contribution to GDP from acreage dependant sectors will be influenced, and that this will be expressed in the type of analyses presented above. Furthermore, if the ambition of society to facilitate sustainable growth is to a significant degree based on methods that lack the capacity to capture the characteristics of ecosystems and the potentials for sustainable development that they provide, then this may explain the lack of such signs in overall economic trends.

4.9.5 Relevance for local communities

Figure 2 in Paper I and Figure 1 in Paper II show the economic system in its ecological and social contexts. It follows the logics of economic theory when the system boundaries are broadened and more of the ecological system is located inside the system boundaries. Figure 1 in this thesis shows what is basically the same system with symbols from system ecology and emergy analysis.

These figures stress the importance of

- being efficient in all subsystems affected in the sustainability context in terms of the production of wanted goods and services per unit resource used no matter whether the resources emanate from natural capital, man-made capital or human capital on the donor side of the subsystem at hand; and "wanted" relates directly or indirectly to the use of the product in the receiving system,
- producing and consuming within the sustainability limits of systems affected; and
- applying a system perspective.

With a system perspective, it is obvious that one subsystem may well have a high environmental cost per se, but due to its capacity to enhance overall system performance; it may well be of vital importance for a high general system performance. A subsystem that has a high cost in natural resources may well be a prerequisite for a high and sustainable societal welfare level.

It is essential in the sustainability context to not use up available capital assets, but to live on the interest, i.e. the sustainable flux of goods and services from capital stocks. In the work preceding the bill for local communities in 1953 (1953 års kommunallags förarbeten) the principle was stated that the current generation do not have the right to use up what previous generations have brought together to the benefit of generations to come[49]. This is quite similar to common definitions of sustainable development and its prerequisites (OECD 2001). It relates to the importance of maintaining sufficient capital stocks taking into consideration their different features.

Figure 18 shows the trend from 1993 to 2012 of the equity in the local community Kils kommun.

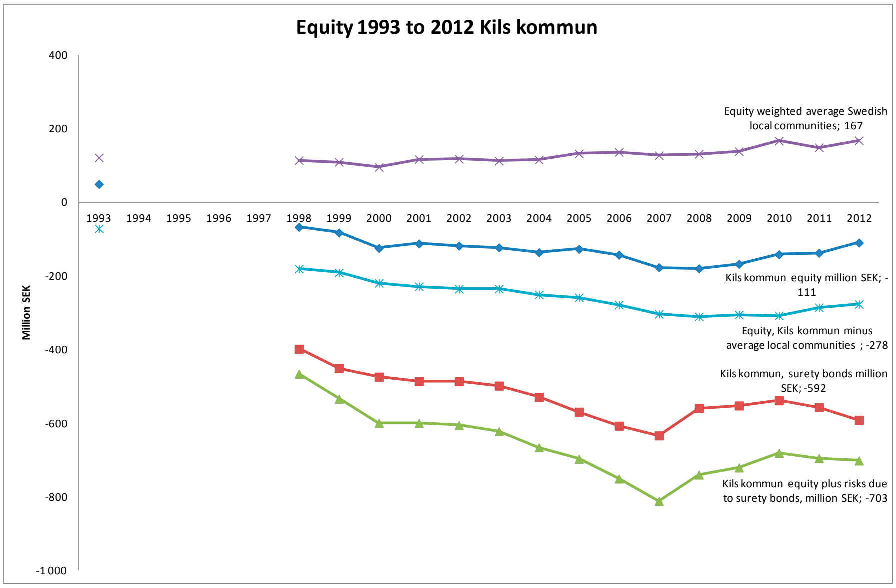


Figure 18. Contribution to GDP from acreage-dependent sectors in Sweden, Northern Europe, Western Europe, Europe, North America, Asia, Africa and the world 1970–2011, fixed price. Relative to a value 1.00 in 1970.
Data from www.kolada.se, accessed 2014-02-22, for the year 1993 from Jan Sturesson PWC, 2004.

From 1993 to 2008 the equity value fell from 49 million SEK to minus 181 million SEK. To 2012 this deficit had decreased from minus 181 to minus 111 million SEK, thus the equity had increased by 70 million SEK in this four year period. Kil has around 12 000 inhabitants.

As I have lived in Kils kommun since 1990; I have a strong societal interest; and I am trained from my professional occupations since 1982 to analyse system performance in production biological, energetic, system ecological, and economic terms for enterprises and as societal values, I have since the

49. Sturesson, J and A. Haglund. 2004. Pressmeddelande PricewaterhouseCoopers 2004-12-03. PricewaterhouseCoopers.

autumn 1991 to and through analysed economic trends and the consideration of economic aspects in the decision-process in Kils kommun. That had from the beginning two purposes. The first was to if possible contribute to a better development in the community where I live. The second was to learn to what degree the institutional context on local community level supported the development of agriculture and forestry towards their important role in a sustainable society, where “Land, including all natural resources, is the scarce factor of production in the long run” (Daly and Cobb 1989, p. 324). Hellstrand (1995a,b; 2003b; 2005a, 2009) treats the role of communities in a sustainable society including their impact on the possibilities for acreage dependent sectors to fully provide the ecological basis of a sustainable society through the production of ecosystem services.

With my professional training, it was quite easy to see in the beginning of the 1990s that Kils kommun were moving into economic problems if not economic aspects in the future would be valued higher (Hellstrand 1995b). In different roles such as a member of the board of an association for local, rural development; PhD-student; concerned citizen; local politician; one of the auditors appointed by the local parliament; and as consultant, I have repeatedly provided this information to Kils kommun. After about 15 years this contributed to a shift in the culture of the organisation where it become possible to take actions where a trend of 15 years with an annual loss of equity with 15 million SEK was reversed to a new trend were the deficit in equity was decreased with around 18 million SEK per year. The information I had provided contributed to this shift from a 15 years trend of loss of equity to a period of rebuilding it. Without this information the rate towards positive values of the equity would be lower.[50]

Basically, the same analytical approach and tools were applied, as when providing in depth analysis of the production biological and economic performance of around 100 dairy farms in Värmland from 1982 to 1986 (Hellstrand 1988).

A central theme in the thesis and accompanying papers is resource efficiency in the economic process. Paper II presents long-term trends for national economies such as the GDP produced per unit of natural resource used. Paper III shows such measures for the Swedish economy and the milk production sector.

In the public sector, the majority of the natural resources are indirectly appropriated, through the natural resources used in the economy paying the taxes that fund public activities, See Figure 1.

In 2006 the total GDP in Sweden was around 3 000 billion SEK, the use of energy was around 600 billion kWh, and the carbon dioxide emissions were around 60 billion kg. Thus in the Swedish economy, the cost of the

50. Personal communication from Georg Forsberg 2014-02-07, one of two “kommunalråd” in Kils kommun.

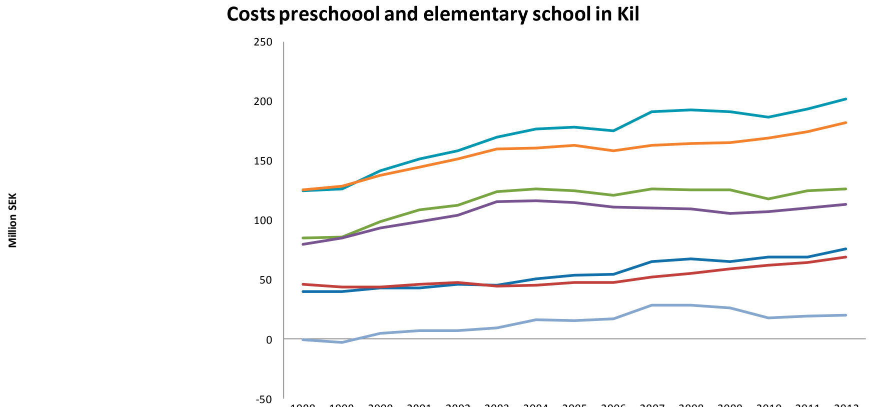
production of 1 SEK GDP in 2006 was 0.2 kWh of energy, and 0.02 kg carbon dioxide.

From the perspective of a sustainable society, it is equally important that primary sectors such as agriculture; secondary sectors such as industry; and tertiary sectors such as public services are efficient and operates within their resource limits. Deterioration of assets as seen in the trends in Figure 18 is not sustainable over time, either for households, enterprises or local communities. Similarly, when society deteriorates the stocks of natural capital that it depends on, the path is not ecologically sustainable.

For sustainable development, it is not sufficient for the system to be sustainable; the development criteria imply an increasing capacity to meet the needs of humans within the sustainability limits of affected systems.

A closer examination of the economic results in Kils kommun shows that 80% of the regain of own assets from 2008 to 2012 is due to increased incomes through fees. During decades the incomes through fees in Kils kommun has been substantially lower compared to average of local communities, while taxes and cost-levels have not compensated. From the years 2007 and 2008 to an average for the years 2009 to 2012 this gap was decreased from 40 million SEK less in incomes through fees to 26 million SEK annually less[51]. Data are from www.kolada.se

Figure 19 shows the cost level over time in preschool and elementary school in Kils kommun.



	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Preschool, real costs	40	40	43	43	46	45	51	54	54	65	67	65	69	69	76
Preschool, costs if national average	46	43	44	46	47	44	45	47	48	52	55	59	62	64	69
Elementary school, real costs	85	86	99	108	113	124	126	124	120	126	125	125	118	124	126
Elementary school, costs if national average	80	85	93	98	104	116	116	115	111	110	109	106	107	110	113
Preschool + elementary schoool, real costs	125	126	142	151	158	169	177	178	175	191	192	191	186	193	201
Preschool + elementary schoool, costs if national average	125	129	137	145	151	160	161	162	158	162	164	165	169	174	182
Real costs minus average cost level	0	-3	5	7	7	9	16	15	17	29	28	26	17	19	20

Figure 19. Costs in preschools and elementary schools in Kil, 1998-2012. Data from www.kolada.se, accessed 2014-01-14.

51. Data from www.kolada.se, accessed 2014-01-14.

Taken together, real costs for preschool and elementary school have increased above national averages[52], from a level that equalled national averages around the year 2000 to a level that as an average was 21 million SEK above that average the years 2004 to 2012, i.e. 12.5% higher. The pedagogic result in Kil from elementary school is not better, nor worse than the average among schools in Sweden (Hellstrand 2010). As a consequence, the efficiency in elementary school in Kils kommun was ranked 199 of a total of 290 local communities in 2012[53].

This suggests that there is a similar situation here as when discussing sustainability impacts of resources (purchased feeds) to dairy cows above the economically optimal level. Here we have around 20 million SEK (ca 12%) more in costs compared to national averages while the pedagogic result is at the average level.

This amount of money as a share of Swedish GDP corresponds to 4 million kWh of energy used, and the emission of 400 000 kg of carbon dioxide.

Four conclusions follow:

- The analytical tools developed can be applied to dairy production as well as to public services.
- The toolkit in the papers also contributes to an understanding of the ecological dependency of the public sector.
- The toolkit presented supports the understanding of the dependencies of subsystems for the overall system performance of society in its ecological context.
- It is equally important to increase the efficiency in primary, secondary and tertiary sectors of the economy and society.

4.9.6 Relevance on regional level

In the early 1990s, there was a process regarding the establishment of a new and bigger regional airport in the county of Värmland. As a member of the board of the regional association for the conservation of nature (Naturskyddsföreningen), I had the task to evaluate the analyses underpinning the decision. This was in the early phase in my development of the toolkit supporting sustainable development that is presented in this thesis. However, I was able to utilise my experience from agriculture, including how to perform investment analyses.

The regional authorities planned for a capacity of 400 000 to 500 000 passengers annually. In this task I applied basically the same approach as when

52. Taking into consideration the impact of structural factors the local community cannot control as expressed within the system of a national balancing of costs among local communities in Sweden (“kommunala kostnadsutjämningssystemet).
53. Data from www.kolada.se, accessed 2014-01-14.

analysing the investment space in systems for forage-harvesting and storage in milk production that was one of the major tasks as "Lantbrukskonsulent husdjur", i.e. the public official with the main responsibility for animal production in Värmland county in 1982–1984. The outcome showed that there were major problems in the investigations supporting the process for the new regional airport (Hellstrand 1995b) that influenced the decision process. For example, the positive contribution to the regional economy was based on an assumption that future trains to Stockholm would have the same low quality that they had in the 1980s, while the X2000 service with fast trains from the centre of Karlstad to the centre of Stockholm had already been launched. In reality, that system was more cost-efficient and too strong a competitor to the regional airport. This resulted in the trend for passengers from Karlstad airport that is shown in Figure 20.

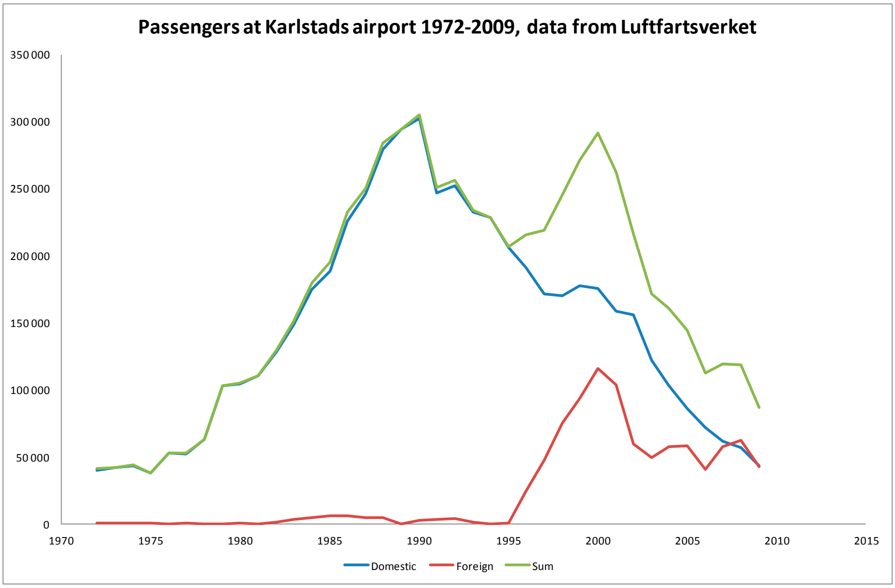


Figure 20. Passenger numbers at Karlstad airport, 1972–2009.

Instead of 400 000 to 500 000 passengers the level in 2009 was well below 100 000.

Karlstad airport is one of the airports with the worst negative results in Sweden since its establishment at the new location. Public resources have subsidised the airport, meaning that a transportation system with natural high resource and emission costs per person and km has been favoured while systems that are more efficient both from a narrow economic and a wider natural resource perspective have not.

From this five conclusions follow:

- The previous example at the local community level showed that the toolkit supporting sustainable development could be applied in analysis of fluxes of resources (monetary), providing new information that supported increasing assets and reduced pressure on the natural resource basis of society. This example shows that it is also applicable when going from an investment calculus focusing on investments increasing the stock of capital (man-made) where this affects future fluxes of resources in monetary terms and also in terms of natural resources.
- The three examples regarding dairy production, the economy of a local community and a regional airport show that there is often congruency between economic efficiency in a quite narrow and short-term perspective and ecological sustainability in a wider and longer perspective.
- Factors other than a good description of reality using established methods and knowledge within disciplines with competence of excellence regarding concerned systems and issues[54] often govern the decision process.
- This can cause substantial sustainability costs in the ecological, economic and social dimensions.
- This is indeed positive information. The potential for improved system performance within sustainability limits is significant, and different actors such as dairy farmers and local and regional authorities have the power to decide over factors that matter.

The two examples from local and regional levels show that when the system boundaries of the toolkit for sustainability are narrowed so far that the ecological dimension is excluded, the toolkit does a good job in traditional economic analyses. This is part of the relevance test of the toolkit. It is difficult to argue that LCA can make a similar contribution when evaluating the economy of local communities, or in connection with an investment calculus for a regional airport, taking into account its ambition to cover all impacts from cradle to grave.

Both examples illustrate that the toolkit is well suited for analyses where fluxes of resources are related to stocks of capital.

4.9.7 Relevance on national scale

Figure 21 shows the development of several economies, countries and some of the major global regions from 1970 to 2012.

54. The toolkit supporting sustainable development presented in this thesis was developed though an expansion of system boundaries of traditional and well proven methods. Individually powerful in their traditional core fields, they are often also powerful in a sustainability context.

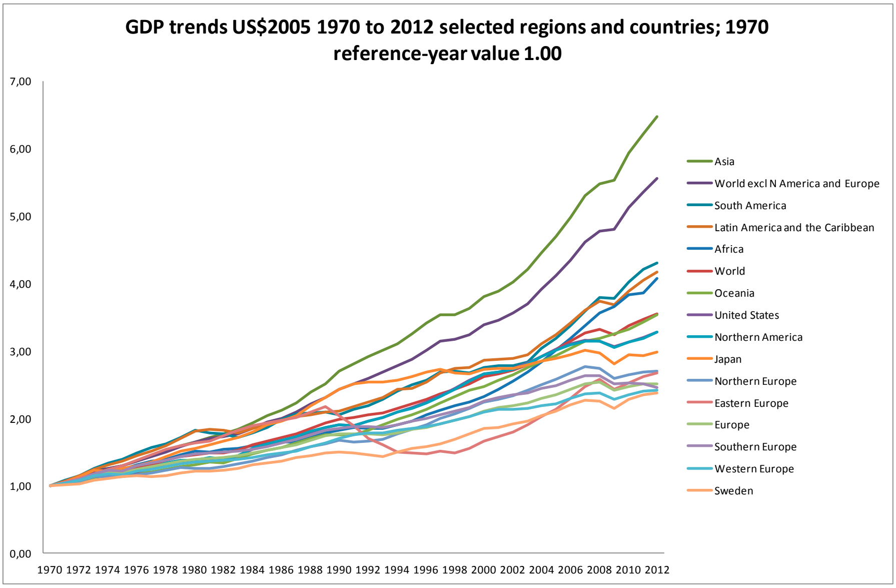


Figure 21. Development of national and some major regional economies, 1970–2012.
Data from UN stats. Relative to 1970, with value 1.00.

Sweden has had the lowest economic development measured in traditional GDP terms and fixed prices between 1970 and 2012 of the economies presented in Figure 21. All the regions of Europe have a lower growth than the other nations and regions presented.

Since the turn of the Millennium both Sweden and the EU have had a goal of becoming leaders of global economic development. An important means to this end was "green growth". A common opinion in Sweden is that Swedish industry and agriculture apply more "environmentally friendly" methods than in most competitor countries. The use of natural resources and emissions per unit of Swedish product would be smaller compared to products from other nations, in general. Sweden has a lower population density than most nations, thus the area of ecosystems and hence the production of ecosystem services per inhabitant and per unit GDP in Sweden is higher compared to most other developed nations. This suggests that when efficient measures supporting sustainable development are implemented in Sweden, the EU, and internationally, then the development of the Swedish economy should stand out in a positive way compared to other nations and regions. Figure 21 communicates the opposite situation. The trends for the regions of Europe that are part of the EU suggest that the ambition to become global leaders in growth through environmentally driven growth in the EU has not been successful over the past decade.

One possible reason for these trends in Sweden and the EU is that the policies implemented with the aim of supporting sustainable growth were not efficient. Another possible cause is that other factors in the economy and in society had a stronger influence. Even so, the perspectives in this thesis suggest that it is equally important that all parts of the economy and of society work well for sustainable development to be realised. If factors in the economy or society obstruct sustainable development, then they ought to be addressed with suitable tools.

4.9.8 The IPPC directive and the BAT principle

Papers II and VI and Hellstrand (1997; 1998; 2005b) treat weaknesses in the EU directive Integrated Pollution Prevention and Control. The purpose of the directive is to handle environmental damages due to human activities such as industry and large scale agriculture. In Sweden this directive is implemented through "Miljöbalken", the Environmental Bill. An important part of the bill is "Miljökvalitetsnormer" (MKN)[55], in English Environmental Quality Objective.

MKN are steering in a number of environmental policy contexts, and are related to EU decisions. Among other factors, they are important in decisions on production permit conditions for industry.

The Swedish Environmental Protection Agency has developed guidelines[56] for defining the quality of water systems in relation to set MKN. Länsstyrelsen i Dalarna (the County Administrative Board of Dalarna) has compared the outcomes of these guidelines with their actual knowledge about lakes in Dalarna (Länsstyrelsen i Dalarna 2010).

They found that for nearly 60% of investigated lakes, the classification based on these guidelines resulted in classes of ecological status that did not agree with the real status of the same lakes. This is a problem as MKN is powerful in the context of environmental law, which may ultimately result in permission permits that actually harm both the environment and the economy of industrial plants. If so, it can cause negative effects on employment rates and tax incomes at local community level in the long run.

One cause of this situation is that there is a low level of current knowledge about the conditions of water systems and their natural variation. Increasing this knowledge costs money. An alternative approach would be to construct standards in the form of guidelines when generating the MKN. A problem occurs when these standards deviate from actual conditions of real lakes to the degree that the map of the ecological status generated by the MKN deviates too far from reality. This was the case for the majority of lakes in the investigation by Länsstyrelsen in Dalarna.

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55. See http://www.naturvardsverket.se/Start/Lagar-och-styrning/Miljokvalitetsnormer/, acessed 2013-01-04 (Swedish).

56. See Naturvårdsverkets föreskrifter och allmänna råd om klassificering och miljökvalitetsnormer avseende ytvatten (NFS 2008:1); and Bilaga A till Naturvårdsverkets handbok 2007:4 Bedömningsgrunder för sjöar och vattendrag.

This study is another example of a policy context where the importance of the production factor land is substantially reduced by applying theoretical criteria with low connection to real conditions in real ecosystems, i.e. water systems in this case.

Hellstrand (2005c), using the version of the toolkit for sustainability presented in the thesis at that time, analysed the sustainability relevance of production permits in 9 cases where the IPPC directive was applied. Some cases were analysed briefly, and others were analysed in detail. One concerned a saw-mill, two concerned managed fish production in lakes, and six were pulp and paper production. Substantial potentials for improving the eco-efficiency of set production permits were identified. This confirms the findings in Hellstrand (1997; 1998; 2013) and Hellstrand et al. (2010). One of the conclusions was that the BAT principle (Best Available Technology) is product-oriented, and not oriented towards the environment. Criteria for natural resource use and emissions are set per unit product and not in terms of the impact on affected ecosystems. Of course it is still important to not waste resources in the production process and to not cause unnecessary emissions.

However, as shown by Figures 12 and 13, this is important but not enough to secure a sustainable production. The location of the production also matters. Identical production plants may cause substantially different human health and ecosystem impacts if located in EU regions with the highest economic activity and high environmental loads per ha compared to regions with low economic activity per ha and low environmental load per ha.

If too narrow an interpretation of the BAT principle is used, there may even be a reduction of one or more substances at the margin, causing such high energy costs that other emissions increase exponentially due to the same basic mechanisms as was analysed in detail in previous sections treating the issue of feeding intensity to dairy cows. The mechanisms behind Figure 3 are central here. Just as increasing amounts of nutrients in crop production and feeds in animal production are required per unit increase in production in biological production systems, increasing inputs of energy and other resources as well as monetary resources are needed per unit emission at the margins. Hellstrand (1997; 1998) discussed this in depth, and showed that situations can occur where little or no benefit may be achieved in the local ecosystems while production costs, energy costs, and environmental costs at higher system levels increase.

From a Swedish perspective this costs competitive power. Swedish production often combines fairly resource and emission-efficient production systems in agriculture and in industry with locations where the delivery of the ecosystem service waste assimilative capacity is substantially less appropriate compared to production systems in most competitor countries. With "environmental" standards that relate to the product and not to the impact on affected ecosystems, Swedish production cannot capitalise this environmental benefit. The disadvantage increases if set environmental standards do not reflect real conditions in real ecosystems. This is not good for the companies or the environment. Better information about the production options of the production factor land is needed, as well as better adaptation of production permits for industry to the production factor land.

4.9.9 Correlation between price of oil and food

Figure 22 shows the price of oil from 1861 to 2012.

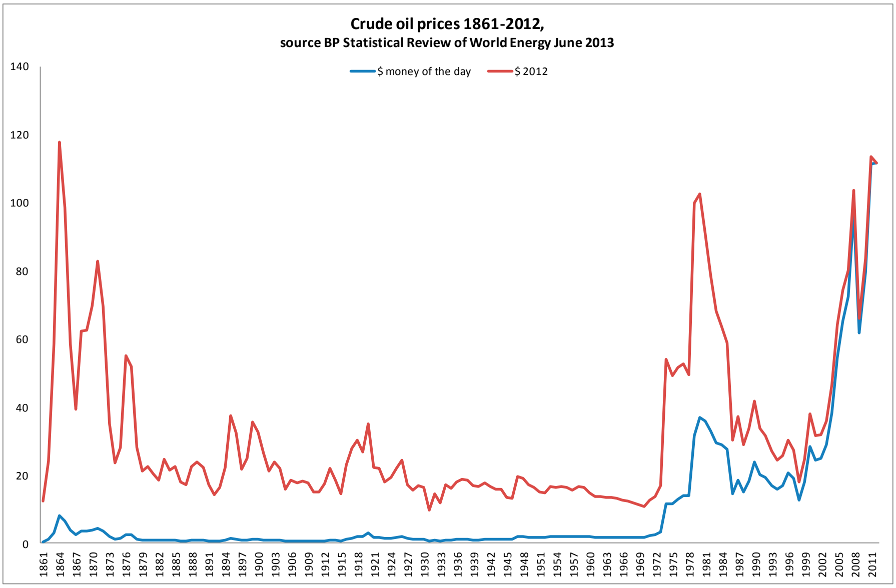

Figure 22. Price of crude oil, 1861–2012.
Based on data from BP (2012).

There was a strong increase in crude oil prices beginning in 1998. In 2012 US$ the price per barrel in 1998 was 18, and in 2012 it was 112, a 6.2-fold increase.

Figure 23 shows the relative change in crude oil price and food price from 2000 to 2010.

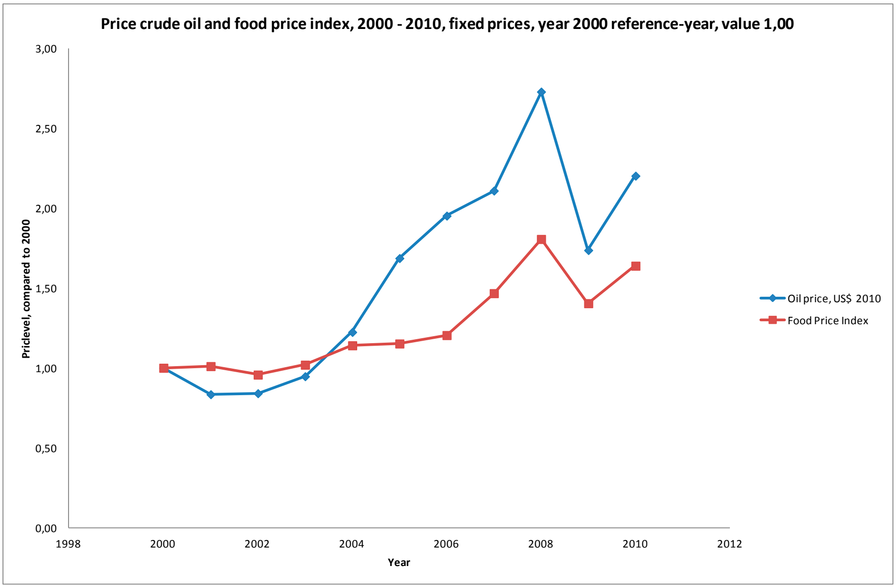

Figure 23. Relative change in crude oil and food prices, 2000–2010. Based on time series with fixed price.
Sources: Oil prices from BP, food prices from FAO .

The prices of food and oil are closely linked.

Figure 24 shows the statistical relation between the trends in oil and food prices.

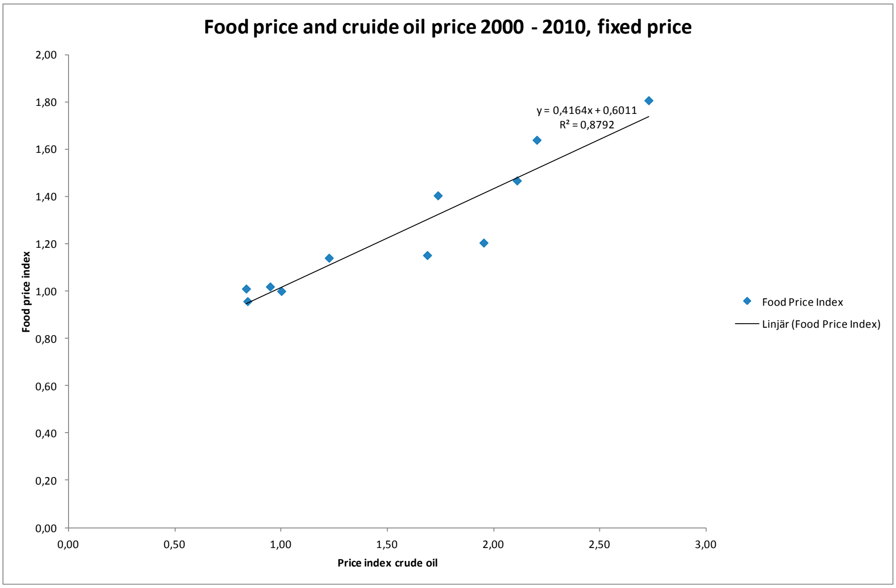

Figure 24. Statistical relation between food and crude oil prices, 2000–2010.

The result of the regression analysis presented in Figure 24 is that when crude oil price increases by one unit from the level in 2000, the food price as measured by FAO increases by 0.42 units. The R^2-value is 0.88.

This is not a scientific proof of a causal relation. However, the result of the statistical analysis supports the possibility that there may be a causal relationship. Given the dependency of modern agriculture on energy-demanding inputs, and the increasing competition of land for food and fuel purposes, there is a need to investigate further the strength of a possible causal relationship, and measures to decouple it.

The measure described in Papers V and VI regarding utilising otherwise marginal agro-ecosystems in the northern parts of Sweden and worldwide for production of food via ruminants is one such measure. Increasing the efficiency of feed-utilisation in milk production as discussed in Papers III, V and VI is another. A third measure is to improve the production level per dairy cow, as discussed in Papers V and VI.

Together, these three measures can substantially reduce the acreage of arable land appropriated for food production globally, making large areas available for increased production of food, bioenergy, and other renewable natural resources.

Two principles for sustainable development can be met through these three measures. One is improved efficiency in the utilisation of resources; the other is a contribution towards the substitution of non-renewable natural resources by renewable ones.

4.9.10 Conclusions related to recent trends

The important parts of the papers in the thesis and of the thesis itself are the proposals for methodological improvements that support the bridging of current implementations and knowledge gaps regarding sustainable development. With the proposed changes, substantial potentials for good economic and social development in rural and urban areas in Sweden and internationally can be realised, based on the insight of the interdependencies between urban and rural areas.

As a side effect, such a bridging may substantially improve the competitiveness of the Swedish economy as it allows the entire economy to reinforce its sustainability profile by balancing consumption of ecosystems services with the high level of production of ecosystem services in Swedish rural ecosystems.

If this occurs, the contribution to GDP will increase in those areas in Sweden that are now experiencing falling populations and lower economic development than other areas.

Another side effect is that the thesis provides a knowledge and methodological platform where integrated competence from different disciplines and actors in Sweden can make a contribution in Sweden, the EU and globally.

On the global level, the briefly presented 4P principle in combination with the methodological toolkit for sustainable development may simultaneously contribute to fulfilling the first UN Millennium Development goal of eradicating extreme poverty and hunger. This may provide a channel where actors emitting carbon dioxide can pay, e.g., 30 US$ per tonne carbon dioxide more in the topsoils in agriculture. FAO (2006) provide an example regarding pastoral dry lands in Africa. They suggest that modest improvements in management may gain 0.5 tonnes C per ha and year, i.e. 1.8 tonnes of carbon dioxide per ha and year. Typical population densities are one person per 10 ha. This could result in improved incomes corresponding to 18 tonnes times 30 US$ = 540 US$ per person and year. This is almost twice the current incomes of many herders in Africa. The same measure may improve soil productivity at the same time.

This indicates how systems for payment of ecosystem services (PES) can improve incomes in rural areas in developed nations such as Sweden and in marginal areas in Africa, while simultaneously enhancing production of ecosystem services.

Increasing incomes from acreage-dependent sectors in Africa, Sweden and other rural areas around the world imply that the rent per unit of land increases, and thereby the value of land as production factor will increase.

This indicates how methodologies presented in Papers I to VI and complementing sections in the thesis point towards a way to further develop theories regarding the rational localisation of production and consumption in the geography supporting physical planning for sustainable development. This can contribute to current theories regarding rational physical planning that have emerged from earlier contributions such as Andersson (1987), Christaller (1933), Lösch (1940), von Thünen (1826) and Weber (1909). Johansson (1991) treats the issue of infrastructure and productivity by applying a geographic perspective on the productivity issue. He used traditional economic production functions of the same type that formed the backbone of the work by the Swedish productivity delegation (SOU 1991). This implied that production value was assumed to be a function of inputs of labour and capital only, while the importance of the production factor land, and thereby the ecological dimension of the economy, was ignored. Although the infrastructural investments selected as rational by Johansson and the productivity delegation increased the volume, speed, and distance of physical fluxes in society, i.e. the ecological impact was substantial; they were based on analyses ignoring the production factor land, i.e. the ecological dimension of the economy.

Hellstrand (2009) used the toolkit presented in this paper to develop new methods to evaluate the value of agricultural land in a sustainability context and applied them, in a task from Göteborgs stad, to support long-term physical planning for sustainable attractiveness. The toolkit is now used in a similar job for Lerums kommun.

Currently in Sweden, major efforts are being made to develop and implement a policy for zero emissions of climate change gases by 2050. An important part of this work concerns long-term physical planning. I propose that an update of the approach of Johansson including a broadening of the analytical perspective, thereby including the importance of land, labour and capital in the context would be fruitful. Biophysically anchored production functions (Paper II) can make a contribution here.

With the current (January 2014) financial crisis ongoing in some EU nations the thesis, with the 4P principle, suggests that there are options available where a development of the market system as a tool supporting good economic and social development within affected ecosystems´ carrying capacity limits can link producers of environmental services to consumers. If so, incomes may increase in acreage-dependent sectors in the EU that provide good support for the demands of a society with sustainable growth. If this occurs, the market system increases its capacity to consider the production factor land, then the need for EU subsidies to agriculture and rural development will decrease. This will release pressure on the EU budget, making it possible to use some of the financial resources no longer appropriated in these systems to fulfil basic needs for those sections of the EU population that now bear the heaviest burdens in the present crisis. The financial resources released may also be used to secure financial systems in the EU and its member states.

Figure 2 in Paper I and Figure 1 in this thesis describe basically the same system from the perspectives of economic theory and systems ecology respectively. A key message is that most, if not all, systems are related to each other. This implies that, given the compartment conceptual model of the economy, where compartment 1 concerns the ecological system, compartment 2 concerns the GDP economy, and compartment 3 concerns the fulfilment of needs through the economic resources produced in the GDP economy, a doubling of the efficiency in

- the primary sectors making natural resources available,
- the GDP economy where through inputs of labour and capital natural resources are upgraded to goods and services of economic value, and
- the fulfilment of human needs and desires by the means produced in the GDP economy,

will result in an increase in eco-efficiency by a factor of 8, i.e. 2 * 2 * 2: From the same amount of ecological resources appropriated, the fulfilment of human needs will be 8 times higher.

This also suggests that the efficiency in e.g. local communities' use of tax money is related to the total pressure of the economy on the natural resource base. All things being equal, more efficient local communities can support a higher welfare level per unit of natural resource appropriated.

Another advantage of efficient local communities is that they can provide the same level of welfare as other communities at a lower tax rate. If so, citizens will have more money available to buy goods and services, i.e. the demand for locally and regionally produced goods and services will increase. In addition, with more efficient local communities, a lower tax rate can improve results among firms in the geographic area of the local community, increasing future investments.

The cases presented from local and regional levels show that the tools supporting a sustainable development presented in the thesis can be applied in traditional economic contexts, that they generate relevant results, and that this through the mechanisms indicated above, can support the overall objectives of sustainable development.

The example regarding "Miljökvalitetsnormer" from Länsstyrelsen in Dalarna supports the proposal in Papers II and VI that the Integrated Pollution Prevention and Control Directive can be improved, favouring both the environment and the economic results of industrial plants, and thus local and regional economies.

The trends presented in the thesis regarding GDP and the share of the contribution to GDP from acreage-dependent sectors suggests that there is still a substantial implementation gap regarding sustainable development. Despite a growing number of analyses that show substantial economic and social values in the production of ecosystem services, actual payments to managers of ecosystems have not changed in a way that affects national accounts. On the contrary, the relative economic values of acreage-dependent sectors on most economic levels analysed are in rapid decline. This may be understood as an intended consequence of global structural economic changes, where most people experience a growing material welfare level.

However the analyses in the thesis, including Papers I to VI, suggest that there is a problem in that many analytical approaches now used with the ambition of supporting sustainable development do not correctly present the ecological foundation for a good economic and social development, and that this may eventually harm vital sustainability assets, including the future global food supply. These analyses affect policy measures from regional to global level.

Another explanation for the shrinking share of the contribution from acreage-dependent sectors to GDP may be that on the operative level, actual measures still underestimate the importance of the production factor land. This may be valid from the regional and national level in Sweden and other nations to the global scale.

A concern is the close relationship between the prices of energy and food, in combination with the rapid increase in energy prices in recent decades. Given the dependency of modern agriculture on energy-demanding inputs, and the increasing competition for land for food and fuel purposes, there is a need to investigate further the strength of a possible causal relation, and measures to decouple it.

The measure in Papers V and VI regarding utilising otherwise marginal agro-ecosystems in the northern parts of Sweden and worldwide for production of food via ruminants is one such measure. Increasing the efficiency of feed utilisation in milk production, which is treated in Papers III, V and VI, is another such measure. A third measure is to improve the production level per dairy cow globally, as discussed in Papers V and VI.

Together, these three measures can substantially reduce the acreage of arable land appropriated for food production globally, making large areas available for increased production of bioenergy and other renewable natural resources. The reason this can be made is that ruminants can utilise 3.4 billion ha permanent pastures for food production thus releasing the pressure on the 1.4 billion ha of arable land. Together, permanent pastures and arable land contributes with the dominating part of in total 4.9 billion ha agricultural land.

Many analysts of agricultural systems and their efficiency are not aware of the quality differences between arable land and permanent pastures. This is reflected in their results.

The presented results show that there are significant win-win solutions that can be exploited. Sound analytical methods in combination with the next generation of incentives will support this.

The basic perspective and conclusions regarding the importance of agriculture in Sweden and globally that is presented in this thesis has previously been presented by Jansson (1970).

4.10 Policy implications

The thesis provides a toolkit that supports sustainable development which is consistent with the perspectives on sustainability in

- the UN Millennium Goals;
- Millennium Ecosystem Assessments; and
- OECD.

It supports analysis of unbroken causal chains from the rumen physiological level to the global sustainability level. The toolkit considers

- Thresholds;
- Irreversibilities;
- Resilience phenomena; and

- Mutual dependencies between systems and system levels of importance in the sustainability context.

The analysis of 25 applications that aim to support sustainable development based on engineering sciences showed major problems that basically reflected that engineering sciences do not provide the state of the art knowledge regarding analysis of sustainability impacts in ecological, economic and social systems. The analysis of mainstream economic theory (Papers I and II) showed a limited capacity, if any, to cope with ecological sustainability limits. A contribution regarding a safe operating space for humanity within systems ecology actually prioritised sustainability for ecosystems before humanity. To a large extent, this was a consequence of excluding agricultural systems from the analysis. Paper VI showed significant potentials to simultaneously improve the economic results of farmers, a number of important ecological sustainability objectives, and global food security in an analysis of measures within animal production systems.

The consequence of the findings in Papers I to VI and the previous sections of the thesis as briefly summarised above, is that through the methodological contribution, the thesis supports

- sustainable development on the macro ecological-economic level,
- the development of agricultural systems with increased capacity to support a sustainable societal development, and
- the development of animal production systems with increased capacity to support a sustainable societal development.

The methodological contribution is not in conflict with engineering approaches. The contributions from engineering sciences are crucially important for sustainable development. However, the thesis suggests paths to improve the relevance of engineering approaches through integration with contributions from other fields. This is achieved partly by applying the engineering approaches in contexts where they have comparative advantages, i.e. within their relevance boundaries.

The results may be of significant value in future development of energy and protein standards systems for dairy cows.

The methodological contributions suggest how environmental monitoring systems could be improved.

The thesis has shown that there are substantial potentials to improve farmers' economic results, reduce contributions to climate change and eutrophication, and increase global food security through measures in animal production systems.

5 Conclusions

Collectively, the six papers offer a toolbox that supports the operationalising of sustainable development. It consists of:

- A conceptual model of the economic system in its ecological and social contexts.
- Biophysically anchored production functions.
- A methodology for evaluation of sustainability impacts in the ecological, economic, and social dimensions, from low to high system levels, of production systems.
- A simulation model of animal production that integrates production-physiological relations and common agricultural economic management tools.
- Empirical results to support the interpretation of results obtained in future applications of the toolbox.

The toolbox is consistent with principles for sustainable development expressed by OECD and the UN, and known properties of ecological-economic production systems in economic theory, systems ecology, and agricultural sciences.

When the biophysically anchored production function is specified in time and space, a system of Ecological Economic Accounts (EEA) is generated. These may focus on changes of stocks of natural capital, man-made capital, human capital, and social capital. They can also focus on fluxes of economic and ecological goods and services in the landscape.

Compared to Life Cycle Assessment (LCA) and related approaches, this toolbox for sustainability with its individual but related tools has merits, since it is built on known properties of the concerned systems within relevant disciplines. Conversely, LCA and related concepts, in their conventional applications, are not based on fields with state of the art knowledge in those systems in which ecological, economic and social sustainability are defined. Thus, the tools presented in this thesis may help to overcome these limitations in LCA when dealing with the sustainability contribution of biological production systems.

As the thesis covers areas from the general conceptual level, to specific and detailed tools that can support everyday decisions, as well as system levels from the physiological conditions of rumen microbes up to allocation of agricultural land for different crops, the policy implications are many and substantial.

The thesis support the implementation of measures that

- strengthen economic and social development within ecological carrying capacity limits from individual product level to the global scale;
- increase the capacity of animal production systems to
    - support farmers' incomes,
    - reduce eutrophication,
    - reduce acidification,
    - reduce climate change effects,
    - increase global food security, and
    - increase bioenergy production capacities;
- integrate rural and urban landscapes and their activities, increasing total ecological economic sustainability;
- integrate industrial activities and activities in forestry and agriculture, increasing total ecological economic sustainability.

This outcome is the result of considering the significance of land. It is common in currently delivered proposals for actions to support sustainability to ignore the importance of vital aspects of land, causing the implementation gap in sustainable development that OECD stressed. The thesis contributes to the closing of this implementation gap and the associated knowledge gap.

Has the thesis treated the scientific gaps that were put forward in the introduction? It has contributed to an increased understanding of

- the value of land (including ecosystems),
- the relations between land and society on a conceptual level and in operative terms,
- the relations between system levels and the three sustainability dimensions, ecological, economic and social, and
- the importance of agriculture and animal production in a sustainable development.

The thesis has thus treated the scientific gaps put forward in the introduction.

Around 40% of the total product value in global agriculture is from animal products; permanent pasture covers around 70% of total agricultural land; and around 70% of the biomass appropriated in the food system from agricultural land supports animal production. Therefore it is obvious that animal production is hugely important in the global food system. This is emphasised further by the substantial positive and negative environmental impacts associated with animal production.

The importance of agriculture is reflected in the carrying capacity of global ecosystems expressed in terms of the human population before and after the introduction of agriculture. Estimates of global population at the time agriculture was introduced suggest that the carrying capacity is now between 100 and 1 000 times the carrying capacity when humans were solely dependent on gathering, hunting and fishing. Access to cheap fossil fuels has also contributed to this increase.

The results presented show that

- land is crucial for sustainable development,
- the understanding of the economic significance of land is a factor limiting a sustainable development,
- the thesis provides initial insights that contribute to the understanding of the importance of land.

Thus the ambition of the thesis is fulfilled.

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Papers

Paper I

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The relevance of ecological and economic policies for sustainable development

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Abstract A sustainable development can be understood as social and economic development within ecological sustainability limits. The operationalisation of a sustainable development presupposes integration of resource concepts covering relevant disciplines and systems levels. In this paper descriptive domains within physical resource theory (PRT), nutrition theory (NT), economic theory (ET) and emergy theory (EmT) are joined in what we call a "sustainability map." The sustainability map represents a conceptual model of the economic production system in its ecological and social contexts. It is a contribution within the field integrated assessment. The relevance domain of each resource concept is analysed by comparison with the sustainability map. It is concluded that resource concepts that well supports a sustainable development should recognise the process restrictions that defines ecological, economic and social sustainability limits; thus recognise and in a relevant way treat threshold—and resilience phenomena; and capture the use-value of resources for human well-being. We suggest that the integration of NT, ET and EmT may contribute, while we find the value of PRT limited, as physics, thus PRT, is indifferent to life as a system characteristic, while life of microbes, plants, animals and humans is central in the sustainability context. The paper contributes to a theoretical foundation supporting a bridging of the implementation gap of a sustainable development, e.g. through its proposal of how to develop more accurate natural resource concepts.

Readers should send their comments on this paper to: BhaskarNath@aol.com within 3 months of publication of this issue.

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Abbreviations

AHP	Animal and human physiology
ANT	Animal nutrition theory
EmT	Emergy theory
ET	Economic theory
HC	Human capital
HNT	Human nutrition theory
ILA	Impredicative Loop Analysis
MMC	Man-made capital
NC	Natural capital
NNC	Non-renewable natural capital
NNR	Non-renewable natural resources
NR	Natural resources
NT	Nutrition theory
PRT	Physical resource theory
RNC	Renewable natural capital
RNR	Renewable natural resources
SC	Social capital

1 Introduction

Currently, the drawbacks from Nature to Society due to the pressure that Society puts on Nature are clearer than ever before. Human actions affect Nature in a way that eventually affects global security. Socioeconomic trends such as population growth, urbanisation, increased material welfare per capita, increased world trade combine into biophysical trends where the volume, distance and speed of material fluxes increase. This will ultimately

1. deplete stocks of non-renewable natural capital (NNC)
2. first, turn stocks of renewable natural capital (RNC) into the class of NNC, as harvests exceeds sustainable yield levels, second, deplete these stocks as well
3. decrease the life-supporting capacity of ecosystems that provide the physiological necessities for human and other life, through
   - depletion of stocks of RNC
   - increased leaching of wastes and emissions through the global production chain beyond sustainable waste assimilative capacities
   - changed land-use regimes, that decrease ecosystem-services provided and habitats and share of solar energy fluxes available for ecosystems, while increasing nutrient leaching.

Thresholds and resiliens phenomena are typical for ecosystems. When thresholds are passed, the balance between organising and disorganising forces is impaired, causing fast and systematic changes, not easily reversed. Well functioning ecosystems have a sufficient resilience. Resilience presupposes biodiversity, and, thus, sufficient quality and quantity of habitats, including environments not disturbed by land-use change and discharges. Functioning ecosystems are a prerequisite for sustained human well-being (Odum 1989). The protection and sustainable management of biodiversity—including genetic resources, species and ecosystem services that support human development—is central to achieving the Millennium Development Goals, a set of measurable, time-bound goals and targets adopted by world leaders at the UN Millennium Summit in September 2000 (UNDP 2008). Important, early contributions regarding economic and ecological aspects of the complex living systems discussed above are Common and Perrings (1992), Costanza and Perrings (1990), Holling (1973, 1986), Jansson et al. (1994), Kay (1991), Odum (1985, 1989), Perrings (1994), Perrings et al. (1992).

Pimentel and Pimentel (2008), McNeill (2001), Scheffer et al. (2001), Steffen et al. (2004), and the number of reports launched through the Millennium Ecosystem Assessment are later examples exploring these relations. Former UN Secretary-General Kofi Amman initiated the Millennium Ecosystem Assessment. It assessed the consequences of ecosystem change for human well-being. It involved the work of more than 1,360 experts worldwide (Millennium Ecosystem Assessment 2008). Food production and food security is an ecosystem good of a special importance for human well-being (Pimentel and Pimentel 2008; Lundqvist 2007). Thus, the first of the eight Millennium Development Goals by UN is "Eradicate extreme poverty and hunger" (UN 2008). At the same time, agriculture is a major factor causing environmental disturbances. Thus, to achieve a sustainable development, resource concepts that can handle the issue of poverty and hunger, and trade-offs between human needs and greed, and between ecosystem services and goods is needed.

The principles and incentives for sustainable development OECD (2001) put forward, agree well with contributions within Ecological Economics ca 10 years earlier (e.g. Costanza 1994; Daly 1990; Daly and Cobb 1989; Jansson et al. 1994). At the World Summit on Sustainable Development, Johannesburg, 2002, sustainable development was recognised as superior principle for the work of the UN (UN 2002). It is also the superior objective of Sweden (Regeringen 2004), and a key priority for OECD and its member countries (OECD 2001).

Ten years after the Rio Conference on the Environment and Development, the concept of sustainable development is firmly rooted in standard economic analysis (OECD 2001). But for all the work at the conceptual level, its implementation in practice remains muted and uneven. OECD formulates the question: Given the urgency with which the case for sustainability is often made, why have concrete actions lagged behind? They conclude that the gap between the need of policies due to the urgency of the sustainability challenges and the policies in place reflects both knowledge and implementation problems.

This gap is the cause for this paper. Its objective is to increase the understanding of their relevance borders through an analysis of different resource concepts and their system boundaries. It presents

- a three-compartment model of the economy in its ecological and social context
- resource concepts within physical resource theory (PRT), animal and human physiology (AHP), economic theory (ET) and emergy theory (EmT).

Emergy theory is a special branch of systems ecology, a discipline of major influence on the development of ecological economics.

The three-compartment model provides a sustainability map. The map is used to identify measurement points of PRT, AHP, ET and EmT; their relevance domain; and synergetic effects to be realised by integration. From this ground, we suggest how resource concepts can be further developed, that simultaneously consider ecological source and sink restrictions to socioeconomic systems, especially the importance of resilience and thresholds within organisms and ecosystems.

2 Drawing a sustainability map

2.1 The challenge to handle key system characteristics of complex systems

The kind of systems that we are interested in is characterised by mutual dependencies between socioeconomic and biophysical systems and between high system levels (such as the global economy and the biosphere) and low system level (such as the sub cellular mechanisms for uptake of toxic substances in microbes, plants, animals and humans). Giampietro (2003) makes a major review of this field. Within integrated assessment, he develops the Impredicative Loop Analysis (ILA) as a means. The Royal Swedish Academy of Agriculture and Forestry (KSLA 2003) in a process involving 20 organisations in the green sectors including forestry industries, authorities, farmers and NGOs involved in the conservation of nature, strongly advocated the importance of integrative assessment in studies of the societal values produced in agricultural and forestry ecosystems. The purpose was to influence the national research priorities of the Swedish government. The Millennium Ecosystem Assessment applies the approach of integrated assessment (Millennium Ecosystem Assessment 2008).

Giampietro (2003) argues that the experiences of advanced consultancy have a contribution to make in this context, as complement to traditional science. There are a number of contributions at the interface between science and advanced consultancy (e.g. Drake and Hellstrand 1998; Hellstrand 1997, 2006; Hellstrand and Landner 1998, 2001; Landner 1990, 1994; Landner and Reuther 2004; Landner et al. 1996, 2000a, b).

The references in the preceding paragraph represent studies where methods and concepts in agricultural science (production biology and economy) and extension services, environmental economics on macro scale, and applied environmental research and consultancy have been integrated. The references include, literally, cases when causal chains from such low system levels as the root-uptake of cadmium in agricultural crops as a function of the form in which nitrogen fertilisers is applied up to the prevalence of cadmium induced renal disturbances in the Swedish population; as well as the impact of changed strategies to satisfy the physiological needs of the rumen microbes of Swedish dairy cows (considering actual price relations between feeds and milk products on the market) on farmers net income, national ammonia emissions, and global food security, respectively, successfully was examined. The coherence between the work in these studies and ILA is profound. The knowledge level regarding eco- and human-toxicological aspects down to cellular and sub cellular level was stronger, thus supporting a more precise localisation of thresholds and resilience domains in studied systems, compared to the more general methodological outline of Giampietro.

This supports the conclusion (Giampietro 2003) that lessons learned in a combined consultancy and research context have a contribution to make in the development of scientific methods supporting a sustainable development. This is accurate in the development of resource concepts supporting an efficient use of natural resources for human wellbeing.

The principle model in Fig. 1 summarises experiences from the contexts above.

The message in the figure is the following: Given the context of a sustainable development, where thresholds, resilience, irreversibilities, food security, trade-offs between economic and ecological objectives, trade-offs between different ecosystem services and goods are typical; life of micro organisms, plants, animals and humans is a critical system feature. It complicates the system. Relevant resource concepts must in a relevant way deal with this life-induced system complexity.

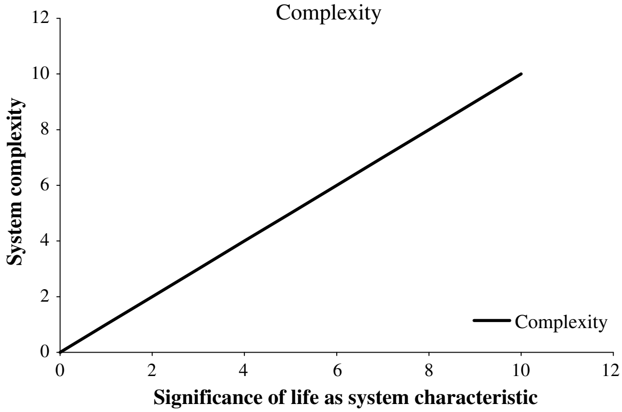

Fig. 1 Principle relation between the complexity of systems and the significance of life as system characteristic

2.2 The sustainability map

Mind map refer to predominating mental models of reality in a discipline, providing the backbone for the tools applied when segments of reality are explored. Descriptive domain is another name (Giampietro 2003).

PRT focuses on the physical aspects of resources. AHP treats physiological process constraints to a sustainable development, where one significant aspect is the capacity of agriculture to support global food security. Another contribution is the physiological context for biodiversity, considering ecotoxicological effects, and changed nutrient conditions. ET is powerful regarding analysis of transactions in the human economy and in analysis of the welfare and distributional outcomes of human efforts. Systems ecology is strong in its perspective where the human economy is embedded in the ecological system, providing ecological sink and source restrictions to society.

Figure 2 shows a sustainability map obtained by integrating the mind maps of the disciplines mentioned.

The model contains three compartments. Ecosystems including natural resources (NR) constitute Compartment I. Sun, tide and processes providing heat in the depth of the Earth are independent power sources driving processes in economic and ecological systems. According to the first thermodynamic law the amount of energy is constant while according to the second the quality of energy is degraded in real world processes (Pimentel and Pimentel 2008). The amounts of elements are assumed to be constant. Although this is not correct with regard to nuclear processes, it is an appropriate assumption for the purpose of this paper. In geobiophysical processes driven by the independent power sources elements are rearranged into stores of natural capital (NC). NC provides life-support, that is, the physiological necessities for life (Odum 1989). The economy consumes renewable and non-renewable natural resources (RNR and NNR, respectively), appropriated from the stock of NC. The availability of natural resources (NR) provides source restrictions to the economy. This is the source-aspect of ecological sustainability.

Ecological sustainability includes, also, a sink-aspect. The sink-aspect refers to the capacity of ecosystems to assimilate wastes from the economy without such negative environmental impact that the life-support capacity is threatened. Land-use may also affect the life-support capacity, and may, thus, be constrained by ecological sink-restrictions. The impact of the economy on thresholds, resilience, environment, human health and the

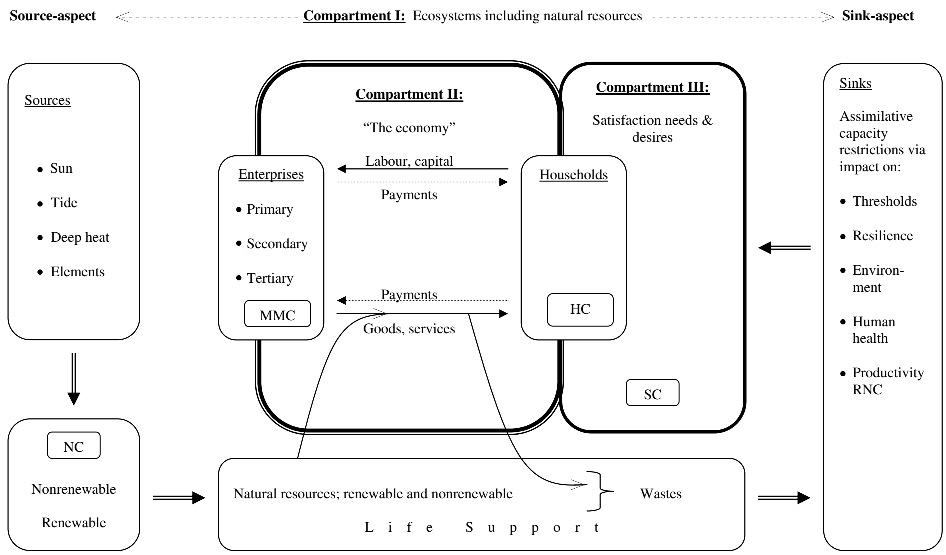

Fig. 2 A conceptual model of the economy in its ecological and social context

productivity of RNC is crucial in the understanding of how Nature trough ecological sink-restrictions trough the pressure Man puts on Nature, affects future human well-being.

In Compartment II, energy and other resources are transformed to goods and services measured in terms of GDP in processes steered by man-made and human capital (MMC and HC, respectively). HC refers to the capacity of the individual to contribute to production in Compartment II. It is a measure of the productivity of the individual. The primary sectors[1] act as a bridge between the first and second compartments, making NR available to the rest of the economy.

In Compartment III ecological goods and services produced in Compartment I as well as goods and services produced in Compartment II are consumed, satisfying human needs and desires. Social capital (SC) is related to the degree of social sustainability and is connected to aspects such as democracy, legitimacy of authorities and distribution of resources. At the interface between Compartments II and III, consumer prices and production values are established. Compartment II, including the interfaces to Compartments I and III, respectively, is the primary focus in economics. It can be called the GDP economy. Prices are important information carriers and basis for production and consumption decisions by market actors. Consumer surpluses describe the social value of the goods and services consumed and invested. GDP is an estimate of production, not welfare.

Compartment I defines ecological restrictions to society, Compartment II provide the means, while Compartment III contains the objective; human well-being.

The sustainability map in Fig. 2 is inspired by the way the ecological economic system was presented in ecological economics in the early 1990s (for references, see Sect. 1). It corresponds well with OECD (2001).

[1] Agriculture, forestry, fishery, mining and power production.

3 Resource concepts from different disciplines

3.1 Physical resource theory

Energy, materials and information are physical resources (Wall 1986, p. 3). PRT has been defined as the science dealing with physical resources (Kåberger 1999). Thus, the relevance domain of PRT is the physical aspect of solar energy, tidal energy, energy from deep earth, NNR, RNR and the conversion of these resources (Fig. 2).

For the purpose of this paper, we focus on the definition of exergy.

Exergy is the result of a combination of the first and second laws of thermodynamics. Theoretically, exergy is the amount of work obtainable when some matter is brought to equilibrium with the common component of the natural surroundings by means of a reversible process (Szargut et al. 1988). Kåberger and Månsson (2001, p. 171) express exergy as the maximum amount of useful energy that one can get out of a certain system, given specified conditions. Exergy is calculated under freedom of process constraints other than ideality; thus, it is essentially a generalisation of the common free energy concepts of physics and chemistry. Free energy is the energy that can be transformed to mechanical work provided that the processes are ideal (no entropy production) and a specification of the restriction that applies for the particular kind of system.

Before the name exergy was agreed upon, the concept was called useful energy, available energy and availability (Kåberger and Månsson 2001).

Ideal processes take place at equilibrium, thus no entropy is produced. Strictly speaking, ideal processes are impossible, as equilibrium processes are impossible. No thermodynamic changes can occur when all thermodynamic forces are balanced (Kåberger and Månsson 2001, p. 168).

Thus:

1. Exergy is defined in a model of the real world, where all process restrictions other than thermodynamic ideality are omitted: All process-restrictions that constitute ecological, economic and social carrying capacity limits are located outside the system borders of the conceptual model of reality, in which exergy is defined. Thus, phenomena such as thresholds and resilience are located outside the system borders of the conceptual model by which exergy is defined.
2. The condition that exergy is defined under the condition of thermodynamic ideality, i.e., equilibrium, makes the concept resource meaningless: At equilibrium, no processes take place. With no processes a situation with a flux of "resource" C from system A → system B is impossible. And, if still a flux of "resource" C were possible from system A → system B, still no processes could occur in B where the "resource" C contributed. And, if still C contributed in processes in system B, the existence of an observer D notifying the resource value of C is not possible.

Having said that, is not the same as to argue that "exergy"-analysis, the way it in real world situations is performed, is use-less. The point is that in a fundamental aspect the world "exergy" as used in these contexts, differ from the word "exergy" given its scientific definition. Such gaps in meaning may cause confusion. (This points towards Wittgenstein's analyses of possibilities and restrictions to communicate through the language, which, in fact, relates to an important area in integrated analysis.)

Other resource concepts in PRT as entropy and negentropy are strongly related to the definition of exergy (see Kåberger and Månsson 2001). We conclude that the conceptual models in which resource concepts in PRT are defined are abstracted so far away from the characteristics of systems where life is a key system characteristic, that their use for the purpose of this paper is limited.

Cleveland et al. (2000), in the context of analysing fuel qualities arrived at a similar conclusion. Exergy was of little value, as the measure ignored the use-value in the receiving system.

To avoid misunderstanding, this is not to suggest that the first and second thermodynamic laws should be rejected. Within the physical constraints of the thermodynamic laws, process restrictions defining ecological, economic and social sustainability operate, that are several magnitudes of order stronger. Therefore, the capacity of PRT to locate ecological, economic and social carrying capacity constraints is limited. Furthermore, by ignoring the mentioned process restrictions when constructing the mental map by which PRT understands reality, they risk the fallacy of misplaced concreteness (see Daly and Cobb 1989): For each extra real world process restriction ignored, the perceived degrees of freedom for human actions increases (metaphorically). However, this is not a measure of real options for actions, but a measure of a widening gap between the map and the terrain. This conclusion is general regarding real systems and models of real systems (see Giampietro 2003), and addresses a major cause behind the implementation gap of a sustainable development.

3.2 Animal and human physiology

There are a number of low-level system models of interest in the analysis of relevant resource concepts. We here analyse animal (ANT) and human nutrition theory (HNT), respectively.

A fair understanding of processes on physiological level within plants, animals and humans is a prerequisite for a sustainable development. This is required knowledge for understanding human-induced environmental and human health effects. Nutrition theory (NT) is a part of physiology. A central theme in NT is how to quantify/measure the nutritive value of feeds and foodstuffs in physiological processes such as maintenance, growth, motion, lactation, gestation, traction taking into consideration characteristics of the feed/food as well as the individual consuming the feed/foodstuff. Therefore, it is plausible that NT may have something to offer in a further development of resource-concepts.

The characteristics of the resource (the feed) are a function of the resource-producing system such as crop production. Here the environment, such as climate and soil fertility at the actual location, plays a significant role, in interaction with choices of the crop producer regarding crops used and cultivating practices applied. The nutritive value of feeds is at the same time a function of the characteristics of the "consumer". Typical relevant characteristics of the consumer are species, breed, sex, age, production level, to mention a few. Resource-measures in NT are a function of the system producing the resource, thus in that sense "donor"-based, and a function of the consuming system, thus "receiver-based" (McDonald et al. 1981; NRC 2001).

One challenge of sustainable development is how to manage the conflict between sufficient and sustainable production. ANT, has, like other areas of agricultural sciences, for decades and centuries struggled with this conflict. The system manager—dairy cow—rumen microbes constitutes a system in which one challenge is to make the dairy cow—rumen system perform in such a way that the objective of the owner of the cows is fulfilled. This implies

1. Acknowledging the relevance of thresholds and resilience within the dairy cow—rumen system, to be able to exploit those domains where continuous dose—response relations dominates, while at the same time

2. Take the actual position within the global ecological economic network into consideration.

The manager that fails condition (a) will experience a too high prevalence of catastrophic shifts of the ecosystem dairy cow—rumen expressed in terms of severe illnesses. NRC (2001) discusses a number of severe feeding related dairy cow diseases, which are a result of imbalances between the dairy cow and the rumen system. The manager that fails condition (b) will show too low profit, and thus, given her/his socio-economic context, become economically unsustainable. Crop production and agriculture in general has for thousands of years dealt with principally the same challenge between sufficient and sustainable (food) production. When the equation was not solved, civilisations were threatened.

The position of ANT in the system in Fig. 2 is among primary sector enterprises. ANT concerns important conversion/transformation processes in the animal production subsystem in the agro-ecosystem. In these processes, food such as milk, meat and eggs with high human nutritive value are produced from inputs such as crops and forages, which in turn are the outputs from the conversion/transformation processes in the crop production subsystem in the agro-ecosystem. Another output is manure, which in some contexts is a valuable product and in other contexts a burden in economic and ecological terms.

When agriculture was introduced, the carrying capacity of the Earth in terms of the number of people that could be fed increased by a factor of 100 to 1,000. Animal production was one important means in this technology shift. It can increase the capacity of ecosystems to fulfil basic human needs. McNeill (2001) estimated the global population 8,000 B.C. to 11 million people. Currently, we are ca 6 billion, and are estimated to reach ca 10 billion around 2050, i.e. 1,000 times the population around the time agriculture was introduced. Current productivity in agriculture is heavily dependent on industrial production forms with huge dependency on high energy inputs. Pimentel and Pimentel (2008) provide estimates where hunters and gatherers need 150-50,000 ha of land for food supply per person. As a comparison, the amount of arable land per capita in Sweden is ca 0.25 ha, and the total land area is ca 5 ha. The population density in Sweden is low. Of course, such huge interference with biological high productive land as agriculture is, causes environmental effects. The environmental impact per unit human well-being supplied through global animal production is currently increasing, where current socioeconomic trends implies a major shift from vegetables to animal products, not seldom to a population already suffering from obesity (Lundqvist 2007). This results in substantial and negative trade-offs between animal production, environmental effects and global food security. This is the cause for the FAO-report (Steinfeld et al. 2006), Livestock's long shadow, about environmental consequences of current trends.

WHO (1985, p. 12) defines human energy requirements:

> The energy requirement of an individual is the level of energy intake from food that will balance energy expenditure when the individual has a body size and composition, and level of physical activity, consistent with long-term good health; and that will allow for the maintenance of economically necessary and socially desirable physical activity. In children and pregnant or lactating women the energy requirements includes the energy needs associated with the deposition of tissues or the secretion of milk at rates consistent with good health.

Thus, the position of HNT in Fig. 2 is in Compartment III, with implications on Compartment II. The nutrition of humans concerns one of the basic physiological needs. If parts of a population are undernourished while other are over-fed, there are welfare costs because basic needs are not fulfilled for some while other suffer from obesity, and the distribution of resources fundamental for a decent life is uneven: The world for food in Sweden is “Livsmedel”, which in translation is “Means for life”.

Under-nourishment affects the economic sustainability, through decreased productivity of the labour force. Food habits are closely related to health standards and thus to health care costs. However, most important are the social costs if basic needs are not met or if the resources are too unjustly distributed. The consequences of this can be personal suffering and social conflict. Currently, the prevalence of hunger and obesity is significant (Lundqvist 2007).

ANT and HNT, thus, are at the centre of the issue of a sustainable development, with substantial importance for the understanding of its social, economic and environmental dimensions.

We propose that the way the conversion of energy and nutrients are treated in the metabolism of organisms in NT may be of general interest for the understanding of conversion of energy and materials in the metabolism of societal systems. Compared to PRT, this would add some valuable features. The importance of physiological process constraints for global food security is considered. Estimates are based on process constraints affecting conversion efficiencies in real situations. Estimates are context-dependent.

3.3 Economic theory

The actor is the economic man. The organising principle is the striving of the actor to maximise own “utility”. Value is determined on the market through selection by competition, and measured in monetary terms. The result is the evolution of economic systems. The producer who in competition manages to produce a product at a price that consumers are willing to pay will survive. The values that occur on the market are set at the intersection between the demand and the supply functions (curves) after selection through competition. At the market price no producer is willing to produce another unit and no consumer is willing to buy another unit.[2] Thus, the value in the market economy is a function of both production costs and the consumer’s willingness to pay; it is a function of the conditions of the situation with regard to the producer and the consumer. To be precise: In economic theory, consumer surpluses used in welfare economics are receiver-based, while exchange values are market-based, and thus both receiver- and donor-based.

Values are, thus, context-dependent. They are set in real systems while considering social, economic and ecological process constraints. However, the sustainability issue shows that current consideration of social, economic and ecological factors in the economy is not always sufficient. Only resources that are scarce from the point of view of final consumption are considered in ET. On the market only uses of resources for which an actor has the capacity to charge a price, due to ownership and institutional support, will be considered in the price.

Natural resource economics, agricultural economics and environmental economics focus mostly on the interface between Compartments I and II in Fig. 2. The first two concern mostly the resource flows from I to II, and the latter the flows (pollution) that goes the other way. Industrial organisation and growth theory focuses on the value-adding processes within Compartment II. GDP can be measured as the sum of all value added in

[2] The problems of estimating the values of consumer or producer surpluses are not considered here.

Compartment II or the flows of goods and services, or wages and capital returns, through the interface between Compartments II and III, where the exchange values (relative prices) are established. Micro- and macroeconomics focus mostly on market transactions taking place at that interface on the individual/firm and societal level respectively. In Compartment III, human needs and desires are satisfied, which is analysed in welfare economics. By, for example, using the consumer surplus, the total utility received by consuming a product, including the distributional aspects, and not only the market price, can be brought into the analyses. Welfare economics is not only concerned with the social aspects but also with ecological aspects such as environmental degradation, as humans value not only marketed goods and services but also goods and services provided directly by Nature, and the state of the Environment as such, as well.

3.4 Emergy theory

Howard Odum is, together with his brother Eugene Odum, one of the pioneers in systems ecology. The importance of H. Odum's work for ecological economics and a variety of other disciplines concerned with sustainable development is acknowledged by, e.g. Hall (1995) and Cleveland et al. (2000). In later years, he synthesised his knowledge in emergy analysis. In this paper, we mainly discuss concepts in the EmT behind emergy analysis.

The following, brief summary, is mainly based on Odum (1988), an article in Science, although he also published widely during the 1990s. The reason to focus on Odum (1988) is that this is when the EmT was probed on the highest level within the scientific community. Furthermore, most of available EmT-papers have been published within the frame of the descriptive domain evolved by Odum. Therefore, they have not been exposed to external, independent critique to the same extend.

In emergy analysis the studied system is linked to the surrounding economic and ecological system back to the basic flows and stores feeding the processes in the biosphere. Within the economic systems, the method is capable of analysing both monetary flows and material flows. Emergy analysis considers quality differences between different energy forms. This results in energy hierarchies, where one energy unit at a later stage in a chain of energy transformations has higher value compared to earlier stages. There is a loss of energy at each energy transformation step. Thus, there is a strong linear approach in the emergy analysis, where value is added in each step where energy is added. The analogy to the labour-value concept of Marx is strong, and explicitly acknowledged by Odum (1996).

Possible strengths of the emergy analysis is the linkage of the studied system to surrounding economic (Compartment II and III, Fig. 2) and ecological systems (Compartment I) back to the basic stores and fluxes feeding it; and the parallel analysis of monetary and material fluxes, respectively. However, whether these are real strengths, depend on the relevance of how these dependencies are expressed. Emergy analysis does not focus on the human actor and his utility in compartment II and III as ET does, but on the whole system, where compartment II and III are seen as subsystems of compartment I, i.e. it is eco-centric.

Odum (1995, p. 521) claims that his energy systems approach is a general systems formulation of which there are examples in each field, and that there are special cases of the general principles in electrical, mechanical, biological, geological and economic systems. If so, the position of EmT in Fig. 2 is the whole system presented. The conclusion about EmT as a general system formulation with special cases expressed within a wide range of fields is a claim that emergy analysis is a major tool supporting all aspects of a sustainable development. Such claims have been made, see, e.g. Odum (1988; 1996) and Brown and Ulgiati (1999). This calls for a thorough examination of its basic logics.

Odum in 1988 defines emergy (p. 1135):

> as the energy of one type required in transformations to generate a flow or storage.

We will look closer at three basic emergy concepts: (1) the transformity, (2) the maximum empower principle and (3) the proposal that the emergy cost calculated for a product or process measures the value of the product or process in the system, in case selection through competition has operated.

Odum (1988, p. 1135) defined transformity as:

> Extending food chain concepts to thermodynamics generally, we defined a new quantity, the *transformity*, which is the amount of energy of one type required to generate a unit of energy of another type (in real competitive conditions of optimum loading for maximum power).

In connection with the definition of transformity, Odum proposed that

> a transformation is useful only if it is to a higher quality that can amplify more with less energy. Work will not become part of a real world system unless it includes transformation to a product that can reinforce another flow. Thus, real work is redefined as a useful energy transformation.

Odum (1988) "transformed" the food chain concepts to evaluation of value in processes in ecosystems in general. Transformity, in emergy analysis, is the sum of emergy in inputs per unit energy in the product, the unit being solar emergy joules (emjoules) per Joule. The purpose of the transformity is to support an expression of resources on a common denominator, which considers the differences between qualities in real, not ideal, conditions. The transformity concerns processes in real systems exposed to selection through competition.

Odum (1988, p. 1135) formulated the maximum empower principle as the principle of self-organisation for maximum emergy use. He proposed a connection between emergy and value (pp. 1135–1136):

> self-organizing systems use stores and flows for purposes commensurate with what was required for their formation. To do otherwise is to waste resources, making products without as much effect as alternative designs. Thus, emergy appears to measure the value of a flow or storage to a system in the long run after self-organizing selection processes have been at work.

The proposal that emergy measures the value of a flow or process is linked to the definition of the transformity: it concerns processes in real competitive conditions of optimum loading for maximum power (Odum 1988). Thus, he suggested that emergy measures the value of a product or service to a system, if this product or service exists in a real system that has been exposed to selection through competition.

There are similarities between basic concepts in EmT and ET.

However, there is an internal conflict within EmT, where value is sometimes defined as both donor- and receiver based (see above), while at other times strictly defined as donor based (see Odum 1988, 1995, 1996, 1998; Brown and Ulgiati 1999). Thus, Cleveland et al. (2000), rejected emergy concept in their analysis of fuel qualities, by a similar argument as they rejected exergy: The information about the value in the receiving system was limited, given the context of that system in the specific situation.

4 Comparisons of resource concepts

Based on the results of the previous analysis, we locate the investigated theories in a Life–System Complexity dimension as in Fig. 3.

As in all analyses of complex systems, this exercise contains an element of subjectivity.

We locate PRT at the point (0; 3). The *x*-value is 0 because life is outside the system borders of physics, and thus PRT. Thus, the capacity to handle system complexity in a sustainability context, where life is a significant system-feature, is limited. Therefore, the *y*-value 3:

With the basic resource concept exergy defined under freedom from such process restrictions that defines ecological, economic and social sustainability limits, and presupposing thermodynamic ideality, implying that the mere word resource lacks meaning; and where the definitions of the other basic resource concepts entropy and negentropy is strongly related to the definition of exergy, the capacity of resource concepts in PRT to capsulate typical system features of life such as thresholds, resilience, irreversibilities, food security, trade-offs between economic and ecological objectives, trade-offs between different ecosystem services and goods; i.e., the features of life in micro organisms, plants, animals and humans is strongly limited. The map is abstracted too far away from the sustainability-terrain.

We give EmT *x*-value 5 and *y*-value 6. EmT deals with complex systems. The slightly lower value for the *x*-value is motivated by the focus on the donor-perspective in defining value, implying that actual impact in living systems ("the receiver") is of secondary interest. Furthermore, in the definition of the basic concept "emergy" in emergy analysis in Odum's later work, (see e.g. Odum 1996), the dependency of the exergy concept is stronger than before, implying that the weaknesses in the exergy concepts is influencing the emergy concepts at its core. This reduces the capacity of EmT to represent the true complexity of systems with interdependencies between systems and system levels. One reflection of this is the limited capacity to handle eco-toxicological effects, where impact on cellular and sub cellular physiological level, has a major influence on system performance on macro-scale. This is partly the reason why we give EmT substantially lower *x*- and *y*-values than NT and ET. Another reason is the combination of (a) very vast system borders, including the total system in Fig. 2, and even the Universe, and (b) the strive to deliver very aggregated results (in the emergy-dimension only). The EmT is abstracted so far away from real world systems, that vital parts providing meaning is lost. The "map", is

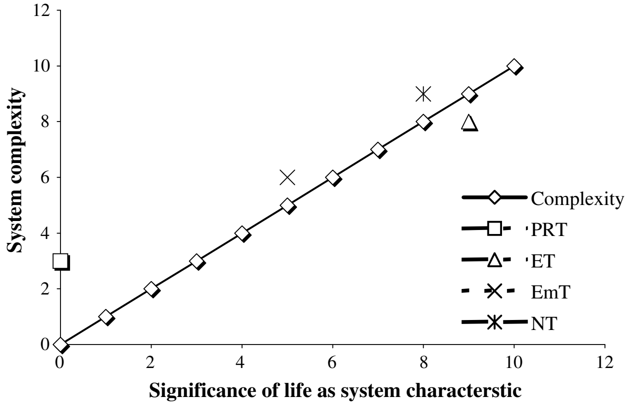

Fig. 3 The location of investigated theories in a Life–System Complexity dimension

abstracted to far from the terrain. The mere ambition of general relevance results in shallowness. Thus, the significance of achieved emergy values for operative decisions in real world situations is unclear. A further limitation for EmT as a basis for policies for human well-being is the indifference to human life, as it is eco-centric.

We give high *x*- and *y*-values for ET and NT, with a slightly higher *y*-value for ET, and *x*-value for NT, respectively. The reason is that ET has a stronger general system-perspective, while NT is stronger in its capacity to catch interdependencies from very low physiological level to high ones, from cellular and sub-cellular physiological level to the first UN Millenium Development Goal, eradicating extreme poverty and hunger.

Economic systems are highly complex, where life as system characteristic is important. The nutritive systems of humans and animals are highly complex, and, it is at the core of the issue of life as system characteristic. In ET and NT higher and lower system levels restricts each other's. ET and NT have high capacity to catch the network- or web-character of living systems where humans matter. From resource concepts in ET and NT, respectively, future resource concepts can be developed that better capsulate both ecological source- and sink-restrictions in the societal metabolism of natural resources, and in doing that, recognise interdependencies between systems and system levels. Interesting is that market values in the analysis by Cleveland et al. (2000) had high capacity to reflect natural resource qualities of fuels, while exergy and emergy had low. Thus, resource-measures of ET had a higher precision to measure actual physical resource-quality differences, than resource concepts of EmT and PRT. The reasons for this are something to further explore within this fields, in a further development of their concepts.

Emergy theory can make a contribution on conceptual level, in the process of identifying the system-structure at hand, when in general terms developing future resource concepts from an integration of ET and NT. Simultaneously, NT and ET can merge into EmT, increasing its practical relevance.

In this process, PRT has little to offer, as Kåberger and Månsson (2001) so rightly conclude: PRT is suitable to apply in technical and industrial contexts. In socio-economic and ecological contexts, its value is limited.

5 Discussion

The analysis in the paper is not only of an abstract, academic interest. Pending the way conceptual models are set up, the resource limits to the global economy differ by a factor 10,000.

Kåberger and Månsson (2001), based on resource concepts from PRT, conclude that the current influx of resources through sun light is a factor 10,000 higher than the current use in the global human economy. The Royal Swedish Academy of Agriculture and Forestry in a document that expresses the opinion regarding research needs in the green sectors of 21 organisations to the government, with the ambition to influence the national research policy (KSLA 2007), arrives at a similar estimate. Meadows et al. (1992) conclude that the solar energy influx is ca 16,000 times the current human use of fossil fuels.

In contrast to these measures, the estimate provided by Odum (1988) implies that the, human use of previously stored resources, was 1.5 times higher than the resource influx through solar light. That is, human interference with global ecological resource fluxes was profound.

A. Assume that the measures (excluding the one of Odum) are correct, i.e., that the methods by which the results were provided in a relevant way reflect such ecological source and sink restrictions that in the real world defines resources value in socio-economic systems, where the objective is to support human wellbeing without risking ecological sustainability, and paying due attention to thresholds and resilience, including functional biodiversity. If so, current discussions about resource restrictions to global society regarding land, food, bioenergy, fossil fuels, phosphorus, water, is an illusion. It is not a restriction in the supply of resources per se, it is a restriction in the human capacity to utilise an abandoned flux of renewable resources, solar energy. Actually, this is the argumentation in KSLA (2007), aiming at influencing the Swedish governments criteria for the size and allocating of future research fundings. If this is reality, research fundings in Sweden and other nations should be focused on technological progress colonizing this still mainly unused resource flux: The natural resource budget of the global society is just 0.0001 times the solar energy resource influx.
B. However, another interpretation is possible. Measured this way, human appropriation of global environmental space, is 0.0001 the available environmental resource space. That can be assumed equal to non-existing. Thus, continued exponential material growth of the global economy can be sustained to a volume that in physical terms are 10 and 100 times the current one. However, at the output side of the economy, i.e., when considering ecological sink restrictions, a slightly different picture evolves. Eutrophication, increased levels of ozone close to the ground, amount and effects of chemical hazards, human health effects due to environmental disturbances, global climate change and its possible socio-economic and security impacts, sign that the possible “illusion” of a resource restriction problem, can by itself be an illusion. If so, it can be a product of resource measures defined by models abstracted so far away from real world systems, that their capacity to catch real world limits to natural resource use is limited.

Assume that B is the case, while scientists, wrongly, argues that A is the case. Then the policy-sphere has a problem. Scientists offer an emergency exit to the policy-sphere, where they on the one hand, can cope with a sustainable development, based on fluxes of renewable resources, i.e., solar energy. On the other hand, they can benefit for another 300 years from a continued exponential material growth of the global economy by 2% per year, and still with margin remain within global carrying capacity limits, only 3.8% of it is appropriated. And, with such sustainable growth potentials, there is no need for the politicians to really address the tricky distribution issue within and between nations: The future promises luxury for all at least the coming 300 years, through “sustained”, even increased exponential material economic growth.

We suggest that this situation is a part of the cause for the implementation gap of a sustainable development, identified by OECD (2001). The scientific community has not yet, in a sufficient way, been able to capture the combined effect of ecological source and sink restrictions for a sustainable development. Natural resource measures are in this context crucial, because they define our current position in relation to ecological source- and sink-restrictions. As shown above, the estimate of the size of human use of natural resources in relation to the solar resource influx, differ a factor of 10,000 between EmT and PRT. Whether either (or none) of these measures are correct, has major influence on what future policies that are rational, in the context of future sustained human well-being.

This strategic reasoning shows why it is important to develop resource concepts that capsulate real world sink- and source restrictions, thus supports policies for increased sustainable human well-being. This is needed in a world where the drawbacks from Nature to Society due to the pressure that Society puts on Nature are clearer than maybe ever before.

6 Conclusions

In the context of a sustainable development, there is a need for natural resource concepts with an improved capacity to capsulate:

- Ecological sink- and source restrictions.
- Use-value in receiving systems.
- Interdependencies between systems and system levels.
- The significance of physiological effects in micro organisms, plants, animals, and humans for a sustainable development.
- The significance of thresholds, resilience and biodiversity.

We suggest that the sustainability map presented in this paper supports that purpose. The integration of vital features in ET, NT and EmT will contribute. However, PRT has little to contribute, basically due to the fact that life, as a system characteristic, lies outside the system borders of physics and therefore of PRT, and life is at the core in a sustainable development.

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Paper II

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A biophysically anchored production function

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Abstract The first part presents a conceptual model of the economic system in its ecological and social context. It is developed via an integration of basic concepts in physical resource theory, animal and human physiology, economic theory and systems ecology. The capacity of the model to support analysis of such complex systems where life is a key system characteristic is high. The conceptual model shows the dependency of the human economy on support by non-renewable and renewable resources from Nature (i.e. ecological source restrictions), as well as the capacity of ecosystems to assimilate wastes (ecological sink restrictions). The analysis focuses general principles; thus, the high level of abstraction results in an apparent simplicity. In the second part, we integrate traditional economic production functions and the conceptual model, which results in the formulation of a biophysically anchored production function (BAPF). The BAPF by itself, and through the system of ecological economic accounts that can be derived from it, represent a toolbox that supports the operationalisation of a sustainable development from micro to macro level. It is coherent with Impredicative Loop Analysis, existing management systems within agricultural sciences, OECD's principles for sustainable development and the approach of Millennium Ecosystem Assessment. Compared to analytical approaches used in the formulation of sustainability policies in the private and public sphere, based on conceptual models ignoring the complexity when life (bios) is a defining system characteristic, its relevance for the operationalisation of sustainable development approaches infinity. The third part presents results from statistical analysis of relations between gross

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domestic product and energy supply and some emissions, respectively, for different nations and time periods, delivering values on levels and trends for parameters in the BAPF as well as a first test of the relevance of the BAPF proposed. The paper is ended by a theoretical analysis of the costs of provoking an economic system working under ecological source and sink restrictions to follow exponential growth: The need to decouple economic growth from natural resource use and emissions is highlighted. Otherwise, the erosion of the ecological foundation of the economy with regard to source as well as sink aspects will be a function of exponential growth.

Keywords Biophysical productivity · Energy use · GDP · Emissions · Time trends

Abbreviations

BAPF	Biophysically anchored production function
EROIE	Energy return on invested energy
GDP	Gross domestic product
HC	Human capital
MMC	Man-made capital
NC	Natural capital
NDP	Net domestic product
NNC	Non-renewable natural capital
NNR	Non-renewable natural resources
NR	Natural resources
RNC	Renewable natural capital
RNR	Renewable natural resources
SC	Social capital

1 Introduction

1.1 Economic theory and land

In classical economic theory, land was used as a synonym for ecosystems including natural resources. In the following, “land” and “Nature” is used with that interpretation. During the eighteenth and nineteenth century, the interest focused on the capacity of land to produce natural resources, i.e. on its (re-) source function. In that period, the waste assimilative capacity of land, the sink capacity, was not a major economic restriction. During the twentieth century, the use of non-renewable resources such as fossil fuels and phosphorous fertilisers increased. The increasing use of non-renewable resources, which at the time seemed unlimited, made the land constraints to the economy appear to be less pressing. As a consequence, the interest in economic theory during the twentieth century focused on the productivity of labour and capital while taking the support from Nature for granted. Daly and Cobb (1989) give an overview of the development of economic theory over centuries. A late example from the policy sphere of the ignorance of the production factor land is the Swedish Productivity Commission, initiated by the government, with the task to perform an extensive analysis of the Swedish economy and its productivity issue and from that basis suggest a united strategy to secure future durable development of the

Swedish welfare (SOU 1991). Currently, reported interactions between ecological and economic systems are once again moving the focal point towards the economic significance of the source and sink capacities of land. This is the core message in the concern for a sustainable development regarding its ecological dimension. The concept a sustainable development was established by the so-called Brundtland Commission (see WCED 1987). There are a number of expressions of this concern around 1990 within the, at that time emerging discipline, ecological economics (e.g. Common and Perrings 1992; Costanza 1994; Daly 1990; Daly and Cobb 1989; Perrings et al. 1992). There are expressions of the same perspective within the policy sphere on a high authoritative level around 10 years later, from an OECD council meeting at ministerial level (OECD 2001), and at the intersection between science and the policy sphere through the Millennium Ecosystem Assessment (MEA 2009). Concern for the sustainability of the human progress was expressed also much earlier by important authors, see the comprehensive review by Martinez-Alier (1987) and the writings of Georgescu-Roegen.

However, economical models including labour and capital, but not land are still guiding economic policy in most industrial countries. Such models are indifferent to the ecological dimension of sustainability. The fact that a report about policies to enhance a sustainable development was produced at the OECD ministerial level (OECD 2001) is an expression of the lack of policies in work efficiently promoting a sustainable development. This report stressed the implementation gap regarding a sustainable development: It concludes that though we quite well know and agree upon what as is needed to achieve a sustainable development, policies at place are at a low and uneven level. The report also states that the understanding of a sustainable development is well within the borders of economic theory. We propose that one important reason for the implementation gap is that though the economic discipline now in abstract terms are "recycling" land as production factor as a function of the sustainability context due to overall general long-term policy objectives, the core of the operative tools yet applied in public and private sphere are derived from economic models ignoring the importance of land. This causes a gap between overall objectives and the consequences of the total impact of everyday choices.

1.2 "Environmental analysis" and land

Another reason we propose causing the implementation gap is the following. In the sequence of ecological succession, when new resources become available they are first utilised by organisms and systems, which have their competitive advantage in the rate by which they can colonise new resources. This is extensively treated in Odum (1989) and is one important foundation for the maximum empower principle proposed by Odum (1988) as a universal principle for self-organising systems. In metaphorical terms, the growing priority given to the concept of sustainable development in private and public sphere nationally and internationally triggered an increasing demand on management tools that in a cost-efficient way could communicate to citizens and consumers that the issue was taken care of.

- In the short term, that put a selection pressure in favour of approaches that combined
  - the criteria of minimising problems in the business-as-usual actions within authorities and in enterprises and
  - appropriated little financial resources, and made the citizens and consumers happy, that is minimised the short-term negative consequences.

- Assume that a sustainable development in reality
  - introduces something fundamentally new needed to consider in management systems such as the consequences of mutual dependencies between systems and system levels and the need of considering the values of different affected groups now and in the future, resulting in the complexity of the systems in focus in a sustainable development,[1]
  - implies that the natural resource use and emissions in developed nations must be reduced and
  - that the ethical base in the concept a sustainable development is strong, as it concerns some level of even distribution of resources within and between generations.

If so, the concept of a sustainable development will have substantial impact on the everyday work of authorities, enterprises and individuals. Common and Perrings (1992) found that a sustainable development is not per definition an objective that is expressed in consumers preferences. Thus, a probable outcome of the made assumptions is that in the first phase the demand on analytical tools and management systems to cope with the new concept a sustainable development is steered towards alternatives that support the illusion that nothing really is needed to be changed in the everyday actions of authorities, enterprises and individuals, more than some insignificant choices with high symbolic value. Odum (1989) discussed the urban-industrialised landscape and its activities as a parasite on the cultural and natural landscape from a system-ecological perspective. As the major part of the assets in developed nations are located in the urban-industrialised landscape and owned by the actors engaging in its activities, it is quite clear that the first phase of analytical tools will meet the demand of the actors of the urban-industrialised landscape of results that communicate their high sustainability performance profile. One way to meet that demand is to develop analytical approaches for analysis of the environmental impact of production

- based on existing analytical approaches regarding industrial production systems,
- focusing the technical, engineering aspects of production and
- ignoring vital parts of the ecological, economic and social dimensions, thus of the sustainability limits in these dimensions.

In the most extreme variant, the approach of environmental analysis would be based on such assumptions that locate the environment and ecosystems outside the system borders of the analysis, thus the so-called environmental analysis become harmless, as in the analysis the natural resources appropriated by and emissions from production cannot be linked to any carrying capacity limit in any ecosystem affected by the production. A theme elaborated in Daly and Cobb (1989) is economic models floating free from the biophysical world. An ambition of this paper is to suggest how to anchor such economic models in the biophysical world. The schematic discussion above points towards the conclusion that in the first phase in the work for a sustainable development, approaches for "environmental" impact analyses might dominate which are indifferent to real impacts in real ecosystems.

Hellstrand et al. (2009) found that a central natural resource concept in physical resource theory, exergy, is defined in a conceptual model of real world systems where all process restrictions that define ecological, economic and social systems are ignored. It is not possible within the frame of this paper to present an analysis of the guiding assumptions and characteristics of different more operative approaches for analysis of the

[1] See Giampietro (2003) for an extensive overview.

environmental impact of production. In the following, a number of applications are listed which have four factors in common,

1. the physiological and biological aspects of the carrying capacity limits of ecosystems are ignored,
2. ecosystems affected by production and consumption are located outside the system borders,
3. the variation in the conditions of ecosystems in space and time is ignored and
4. the capacity of ecosystems, managed and natural ones, to produce ecosystem goods and services is ignored.

The examples are the following:

- the system of environmental and economic accounts in Sweden (Statistics Sweden 2009),
- analysis of the environmental impacts, quantifiable and non-quantifiable, from Swedish agriculture, including upstream and downstream effects (Engström et al. 2007),
- sustainable pig production (Stern et al. 2005),
- sustainable milk production (Gunnarsson et al. 2005; Sonesson 2005),
- life-cycle assessment of milk production (Cederberg and Flysjö 2004; Cederberg et al. 2007),
- life-cycle assessment of seven different food items (LRF 2002),
- the Integrated Pollution Prevention and Control-directive and its BAT (Best Available Technology) principle,[2] supporting the development of sustainable industries in the EU,
- the Integrated Product Policy of EU (Wijkman 2004),
- the main streams approach in life-cycle assessment (Baumann and Tillman 2004), and
- the system conditions for sustainability of the Natural Step.[3]

The consequence is that none of these approaches comply with the principles for sustainable development regarding its ecological dimensions as expressed by Millennium Ecosystem Assessment (MEA 2009), OECD (2001) and the UN Millennium Goals (UN 2008). This follows from the factors (1) to (4) that they have in common.

The Swedish National Food Agency (see SNFA 2008, and Lagerberg Fogelberg 2008), in their mission given by the government to integrate environmental and human health aspects in recommendations for human food intake, rely heavily on the contributions of Cederberg and Flysjö (2004), Cederberg et al. (2007) and LRF (2002), so does the Swedish Board of Agriculture (SBA 2008) in their governmental mission to present a climate change strategy for Swedish agriculture. The Swedish hamburger company MAX in their environmental strategy focuses the climate change aspect based on results from life-cycle assessment studies of the same type as the ones mentioned earlier (MAX 2009). A major research programme in Sweden regarding sustainable food production is FOOD 21. Its overall long-term goal is to define optimal conditions for sustainable food production that generate high quality food products. The major part of the work was performed at the Swedish University of Agricultural Sciences.[4] The fundings summed to around 130 million

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[2] See http://eippcb.jrc.ec.europa.eu/index.html, and ftp://ftp.jrc.es/pub/eippcb/doc/ppm_bref_1201.pdf, accessed 2009-09-01.

[3] http://www.thenaturalstep.org/the-system-conditions, accessed 2009-06-14.

[4] From http://www-mat21.slu.se/eng/index.htm, accessed 2009-09-01.

SEK,[5] i.e. 13 million €, of which 120 million SEK emanated from MISTRA. The work was performed in close cooperation with the food industry and the Swedish farmers federation. MISTRA is a foundation. It shall promote the development of robust research environments of the highest international class that will have a positive impact on Sweden's future competitiveness.[6] Cederberg and Flysjö (2004), Gunnarsson et al. (2005), Sonesson (2005) and Stern et al. (2005) are all products of FOOD 21. Cederberg et al. (2007) is basically a reproduction of Cederberg and Flysjö (2004), in another Swedish region, in a cooperation between the Swedish food industries reserach institute SIK, the Swedish University of Agricultural Sciences, and the Swedish Dairy Association (ibid.).

The typical characteristics of complex systems constituted by small subsystem (holons) which system by system level are organised in an hierarchically integrated structure (a holarchy) with mutual dependencies between systems and system levels implies that the strength and weaknesses of individual analysis are reflected in studies operating on higher system levels (see Giampietro 2003, for a detailed presentation regarding this issue). To the same degree as typical features of ecological/environmental systems are ignored in individual studies; studies that aggregates the results from such studies on more general levels reflects the same ignorance. Here, we have a situation in the Swedish context where authorities in their policy-generating process aiming at a support of environmental sustainability rely on studies that ignore typical features of ecological/environmental systems. At the same time, the national agricultural university generating such studies, in their mission to increase the knowledge regarding the ecological base for sustainable food production, utilises an approach that mainly is indifferent to the impact on real ecosystems affected of the resource use and emissions from production.

In this paper, economic production functions are generated that reflect the significance of the ecological dimension. They reflect the value of the production factor land, with its broad meaning in economic theory. From such production functions, a system of ecological economic accounts can be generated, that maintains the advantages of the methods used in the earlier mentioned studies, while complementing them by integration with known properties of ecological economic systems from nutrition physiology, economy and systems ecology.

1.3 Approach

The analytical framework is constituted by a conceptual model of the economic system in its ecological and social context, constructed by integration of physical resource theory, animal and human physiology, economics and systems ecology. It is easy to visualise that physical resource theory, economic theory and systems ecology have important contributions to make within the frame of a sustainable development. This is not that clear concerning animal and human physiology.

On a more principal level, it can be argued that most if not all aspects of sustainability contend an element of physiology: If there is no physiological process within plants, humans or animals affected, it can be argued that no aspect of sustainability has been affected. Even the well-being of individuals are reflected in their physiological status. In a more operative sense, the focus of animal and human nutrition theory is the usefulness of feeds/foods for the fulfilment of physiological requirements, taking into account relevant

[5] From http://www.mistra.org/mistra/english/research/researchprogrammes/completedprogrammes/ ood21 sustainablefoodproduction.4.1eeb37210182cfc0d680007079.html, accessed 2009-09-01.

[6] See See http://www.mistra.org/mistra/english/aboutmistra.4.11126f6102410ddca180002203.html, accessed 2009-09-01.

economic, environmental and physiological process restrictions within the individual and its environmental and socio-economic context (Hellstrand et al. 2009).

The model visualises the limits of the relevance domains of traditional economic models and more specialised models used in resource accounting economics with respect to ecological sustainability. Biophysically anchored production functions (BAPFs) can be derived from the conceptual model, in which production value is a function of

1. the use of non-renewable resources,
2. the use of renewable resources and
3. the impact on the life-support systems.

A BAPF is a proposal for how to internalise the ecological dimension of the economy into standard economic models, resulting in tools supporting the operationalisation of an ecologically sustainable development. Trends and current size of some parameters in a BAPF are analysed. One version of the proposed BAPF is used in an analysis of economic effects over time of material exponential growth of an economic system operating under ecological source and sink restrictions.

2 Analysis

2.1 A model of the economy in its ecological and social context

Hellstrand et al. (2009) constructed a model of the economy in its ecological and social context (Fig. 1) by integrating basic concepts in physical resource theory, animal and human physiology, economic theory and systems ecology.

The model contains three compartments. Ecosystems including natural resources (NR) constitute *Compartment I*. Sun, tide and processes providing heat in the depth of the Earth are independent power sources driving processes in economic and ecological systems. According to the first Thermodynamic Law, the amount of energy is constant while the quality of energy is degraded in such processes. The amounts of elements are assumed to

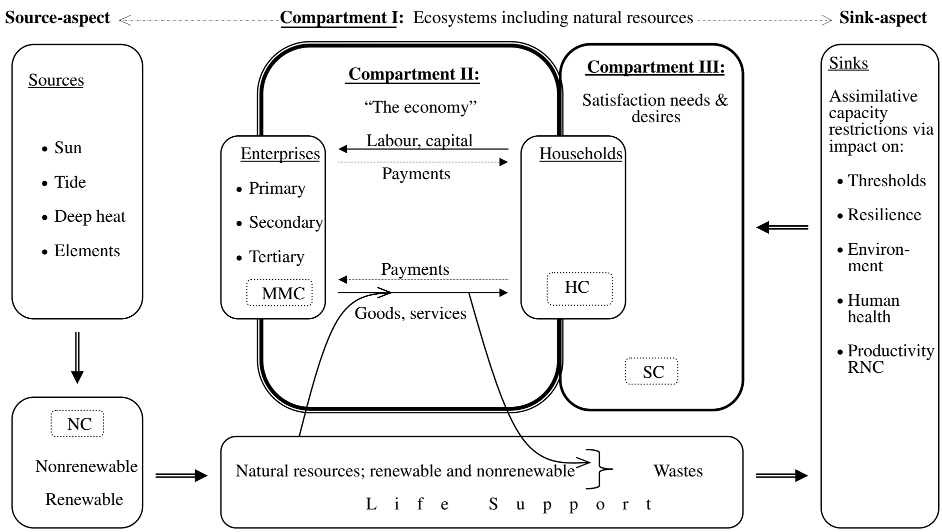

Fig. 1 A conceptual model of the economy in its ecological and social context (from Hellstrand et al. 2009)

be constant. Although this is not correct with regard to, e.g. nuclear processes, it is an appropriate assumption for the purpose of this paper. In geobiophysical processes driven by the independent power sources elements are rearranged into stores of natural capital (NC). NC provides life support, that is, the physiological necessities for life (Odum 1989). The economy consumes renewable and non-renewable natural resources (RNR and NNR, respectively), appropriated from the stock of renewable and non-renewable natural capital (RNC and NNC, respectively) that together provide the stock of natural capital (NC). The availability of NR provides source restrictions to the economy. This is the source aspect of ecological sustainability. Ecological sustainability includes, also, a sink aspect. The sink aspect refers to the capacity of ecosystems to assimilate wastes from the economy without such negative environmental impact that the life-support capacity is threatened. Land use may also affect the life-support capacity and may thus be constrained by ecological sink restrictions. Regarding sink restrictions, the impact of the economy on thresholds, resilience, environment, human health and the productivity of RNC should be considered. In *Compartment II*, energy and other resources are transformed to goods and services measured in terms of GDP (gross domestic product) in processes steered by man made and human capital (MMC and HC, respectively). HC refers to the capacity of the individual to contribute to production in Compartment II. It is a measure of the productivity of the individual. The primary sectors[7] act as a bridge between the first and second compartments, making NR available to the rest of the economy. In *Compartment III*, ecological goods and services produced in Compartment I as well as goods and services produced in Compartment II are consumed, satisfying human needs and desires. Social capital (SC) is related to the degree of social sustainability and is connected to aspects such as democracy, legitimacy of authorities and distribution of resources. At the interface between Compartments II and III, consumer prices and production values are established. Compartment II, including the interfaces to Compartments I and III, respectively, is the primary focus in economics. It can be called the GDP economy. Prices plus consumer surpluses describe the social value of the goods and services consumed and invested. GDP is an estimate of production, not of welfare.

Sustainable development is a development within ecological carrying capacity limits. When the economy is very small, biophysical growth can be part of a sustainable development. When the economy is (close to) trespassing ecological carrying capacity limits, sustainable development can still be achieved through increased efficiency in the use of limited natural resources such as land, water and energy from Compartment I for the satisfaction of human needs in Compartment III.

The limits and possibilities of basic concepts within physical resource theory, animal and human physiology, economic theory and systems ecology, respectively, to contribute to the understanding of a sustainable development can be discussed in more detail (see Hellstrand et al. 2009).

2.2 Economic production functions and the missing production factor

General economic models discussed in economic textbooks and used in the design of general economic policies, usually take this form:

$$Q(t) = A(t)f(L(t), C(t)) \tag{1}$$

[7] Agriculture, forestry, fishery, mining and power production.

where t = time, $Q(t)$ = production in GDP terms,[8] $A(t)$ = productivity as a function of time, $L(t)$ = input of labour and $C(t)$ = input of capital. Capital here refers to HC and MMC. The unit of production and inputs of labour and capital is money per time.

The relevance domain of (1) is the GDP economy per se in Fig. 1, i.e. Compartment II and its intersections to Compartment I and III. The possibility of ecological source and sink restrictions to the economy is not considered. Land, one of three production factors is no longer assumed to have unique characteristics that make it necessary to provide a three-dimensional model of the economy. It is assumed that the economic significance of land is sufficiently well described in the dimensions labour and capital. Historically, these simplifications may have been reasonable. The sustainability issue shows a need for analytical tools and databases explicitly considering the possibility of the existence of ecological restrictions to the human economy. In economic resource accounting literature, environmental and resource constraint questions are dealt with.

2.3 Resource accounting efforts within the academic discipline of economics

Theoretical economic models are explicitly or implicitly used in resource accounting, in order to properly account for qualitative and quantitative changes in the NC. What is sought is often a (partially) environmentally adjusted net domestic product in which one could take into account depletion and/or deterioration of NC in a similar way as depreciation of real capital is accounted for. The appropriation of assimilative capacity is rarely dealt with in economic resource accounting models.

Hicks (1939) can be said to be the modern founding father of the economic models used in resource accounting as he discussed income as net return on total capital stock. Weitzman (1976) developed the theoretical framework, showing how net domestic product (NDP) under certain conditions can be interpreted as a perpetual (sustainable) income. Hartwick (1977) showed that a sustainable income stream required that all returns from expropriating non-renewable resources was reinvested in (preferably renewable) capital, for the total capital stock not to decrease. In Hartwick (1990) and Mäler (1991), accounting rules for the use of renewable and non-renewable resources were established.

There was a growing recognition in the 1960s that economic growth could have detrimental effects on the environment and that many developing countries achieved their economic growth at the expense of depleting their NC. An interest emerged in adjusting the national accounts for externalities of economic activities (Daly and Cobb 1989; Nordhaus and Tobin 1973). A few empirical studies have been carried out, mostly in developing countries, primarily dealing with depletion issues (Repetto et al. 1989). The approach is generally very pragmatic and takes the data availability as a starting point, rather than the theoretically ideal environmentally adjusted net domestic product measure. In the first years of the 2000s, both the academic society of resource economics (see e.g. Heal and Kriström 2000) and the network of statistical offices named the London Group on Environmental Accounting were preparing handbooks in resource accounting.[9] The UN Committee of Experts on Environmental-Economic Accounting (UNCEEA) (UN 2009)

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[8] $Q(t)$ in (1) denotes a flow. From (3) flows will be expressed in the form $\frac{dQ}{dt}$, emphasising that the economy belongs to the class of dissipative systems together with, e.g. organisms and ecosystems, which structures are maintained as long as the system manages to metabolise a sufficient amount of resources. Two important contributions are Odum (1988) and Giampietro (2003), who elaborate on this aspect of the economy and its significance for scientific contributions to a sustainable development.

[9] See http://unstats.un.org/unsd/envaccounting/londongroup/, accessed 2009-09-01.

was established by the UN Statistical Commission at its 36th session in March 2005. Ecological Economics devoted a special issue volume to the system of environmental-economic accounting developed by the UN (Ecological Economics 2007).

Resource economics consider mainly the use of renewable and non-renewable resources, and the resulting emissions leading to environmental degradation, increased corrosion of real capital, decreased labour participation from human health effects and leisure welfare losses (ibid). Although the theoretical literature on the issue has grown extensively since 1990, and accounting rules for depletion of resources have been established, the full cost of eroding the ecological support system has not yet been resolved. The EU-initiative Beyond GDP[10] and the initiative by Sarkozy, gathering a number of Nobel Prize winners in economy around the question about what GDP measures and do not measure,[11] elaborate on this aspect among other's. Later, suggestions on how to resolve this question are made. The importance of solving this question is stressed by the fact that economic models guiding policy choices do not yet normally consider the implications of growth on ecosystems and resource depletion.

2.4 Biophysically anchored production functions

The focal point when generating a BAPF is the relationship between Compartment I ("Nature") and Compartment II ("the GDP economy") in Fig. 1. Values considered are production values, measured in monetary terms on the market.

2.4.1 Physically anchored production functions

Hall et al. (1986) related production to energy use:

$$Q = nE \tag{2}$$

where Q is monetary value of goods and services produced per year (GDP); E total amount of energy used per year; and n the efficiency of energy use in GDP per unit energy used. n is a measure of the eco-efficiency of the studied system with regard to its energy metabolism. (2) focuses on the flux of NR, here energy, from Compartment I to II, and the value of the production it supports.

Hubbert (1956) analysed the cycle of production of exhaustible resources, such as oil, and defined the cumulative production Q to time t by:

$$\int_0^t \left(\frac{\mathrm{d}Q}{\mathrm{d}t}\right)\mathrm{d}t = \int_0^t P\mathrm{d}t \tag{3}$$

where P is production rate. (3) differs from (1) and (2) in two ways. Q in (3) is production in physical terms. Furthermore, it is the integral of the production rate, i.e. an amount not a flux. Q in (1) and (2) actually concerns a flux: production per unit time. (3) is a physical description of the support from Nature to the economy. A physical description is necessary but not sufficient in an analysis of the ecological aspect of sustainable production. In our effort to formulate biophysically anchored production functions, we integrate Eqs. (1)–(3).

[10] See http://www.beyond-gdp.eu/, accessed 2009-09-02.

[11] See http://www.stiglitz-sen-fitoussi.fr/documents/draft_summary.pdf, accessed 2009-09-02.

2.4.2 Biophysically anchored production functions

General economic production functions (1) and the functions of Hall et al. (2) and Hubbert (3) are used as a point of departure, in an attempt to provide a biophysically anchored economic production function.

Equation 2 can be specified in continuous time and written:

$$\frac{dQ_g}{dt} = n(t)\frac{dE}{dt} \tag{4}$$

where Q_g represents the cumulative amount of production, measured in monetary terms. g stands for gross and shows that the production value is not corrected for environmental degradation. Production per year in (4) $\left(\frac{dQ_g}{dt}\right)$ equals GDP in national accounts. To stress the character of the economic system as a dissipative system, metabolising NR, annual production is in the following expressed in the form $\frac{dQ}{dt}$. (4) can be applied on other system levels than national. E is cumulative amount of work extracted from the environment, measured in biophysical terms. It is assumed that the smallest common denominator of NR is a capacity for work in thermodynamic terms (see Daly and Cobb 1989). Within physical resource theory, measures of resource quality such as (low) entropy (Kåberger and Månsson 2001) and exergy (Kåberger and Månsson 2001; Wall 1986) have been suggested. Within systems ecology, emergy is proposed as a measure of resource quality (Odum 1988). Within nutrition theory, energy available to feed physiological processes is at the core. The mentioned resource measures have different relevance borders that define their relevance in the implementation of a sustainable development (Hellstrand et al. 2009). Here, we simply assume that E is an appropriate measure of NR.

Rules of partial derivation suggest that (4) should contain the term $E(t)\frac{dn}{dt}$. However, if so, changed conversion efficiencies (n) would affect the production value obtained from resources already used up. This is not possible, thus the term $E(t)\frac{dn}{dt}$ is excluded from (4).

In Eq. (4), NNR are not distinguished from RNR. The value of production is not corrected for the impact on the environment. Considering these aspects gives:

$$\frac{dQ_n}{dt} = n_s(t)\left(\frac{dE_s}{dt}\right) + n_f(t)\left(\frac{dE_f}{dt}\right) + l\frac{dL_{su}}{dt} \tag{5}$$

where $\frac{dQ_n}{dt}$ is value of net production per time unit, considering the environmental impact. The indices s and f stand for stores and flows, respectively. $\frac{dE_s}{dt}$ denotes NNR metabolised by the economy, while $\frac{dE_f}{dt}$ refers to RNR metabolised. $\frac{dL_{su}}{dt}$ concerns the sum of current and future impact on the life support of the production that occurred at one time, discounted to the time of production. l is the value per unit life support. Welfare effects are not considered. Thus, l relates to the part of the environmental impact that affects future production of RNR and the productivity of MMC and HC.

An alternative and more general BAPF is:

$$\frac{dQ}{dt} = f(L, C, E_s, E_f, W, L_u, C_{so}, C_{si}) \tag{6}$$

Inputs of L, C, E_s, E_f have already been defined. Markets exist where these inputs can be valued in monetary terms. W, L_u, C_{so}, C_{si}, respectively, stand for wastes, land use, carrying capacity of ecosystems regarding supply of resources (source restriction) and carrying capacity regarding assimilative capacity (sink restriction). Carrying capacity limits that may restrict patterns of land use are also included in C_{si}. When the economic significance of W, L_u, C_{si}, respectively, is not accurately considered, the economy runs the risk of transgressing ecological sink restrictions. If C_{so} is not sufficiently well considered, the economy may inflict ecological source restrictions as well. Equation (6) indicates some of the complexity in the interactions between the human economy and ecosystems. In the following, a somewhat more simple approach is used.

2.4.3 Life support as a function of natural resources used

Use of NNR and RNR results in wastes. Wastes and land use patterns affect the environment. When the rent of RNC is used, the size of the stock itself is affected, and thus the production of life support from RNC. If the rent was not used, it would have increased the size of the stock. RNC such as forest- and agro-ecosystems produces RNR such as fibre, bioenergy and food in processes in which the photosynthesis is a key process. In parallel to the production of these for the economy significant RNR, the very same processes produces other forms of life support. Therefore, use of some types of RNR will affect the capacity to produce life support. Thus, $\frac{dL_{su}}{dt}$ in (5) is a function of the use of RNR and NNR. Hence, (5) can be reformulated:

$$\frac{dQ_n}{dt} = n_s(t)\left(\frac{dE_s}{dt}\right) + n_f(t)\left(\frac{dE_f}{dt}\right) + g\left(\left(\frac{dE_s}{dt}\right), \left(\frac{dE_f}{dt}\right)\right) \tag{7}$$

where $g\left(\left(\frac{dE_s}{dt}\right), \left(\frac{dE_f}{dt}\right)\right) = l\frac{dL_{su}}{dt}$. Equations (1) and (7) can be combined to:

$$\begin{aligned}\frac{dQ_n}{dt} &= A(t)f\left(\frac{dL}{dt}, \frac{dC}{dt}\right) + l\frac{dL_{su}}{dt} = A(t)f\left(\frac{dL}{dt}, \frac{dC}{dt}\right) + g\left(\left(\frac{dE_s}{dt}\right), \left(\frac{dE_f}{dt}\right)\right) \\ &= n_s(t)\left(\frac{dE_s}{dt}\right) + n_f(t)\left(\frac{dE_f}{dt}\right) + g\left(\left(\frac{dE_s}{dt}\right), \left(\frac{dE_f}{dt}\right)\right)\end{aligned}$$

In this expression, the production value is a function of labour, capital,[12] NNR, RNR and the impact of production on the life support. The expression can be rearranged in different ways to show, e.g. the productivity ($A(t)$) as a function of inputs of labour, MMC and NR, considering or not considering the value of the environmental impact of the production. In combination with empirical data and statistical analysis, this points towards a route to increase our knowledge of economic growth and growth accounting, and its biophysical dependencies. This type of general relations can be explored through impredicative loop analysis (Giampietro 2003) to increase

- the understanding of environmental prerequisites for economic and social development as well as
- the mutual dependencies within and between ecological and socio-economic systems and between system levels.

However, that is beyond the scope of this paper.

[12] Inputs of labour and capital are presented in the form $\frac{dL}{dt}$ and $\frac{dC}{dt}$, respectively, to stress the character of the economy as a dissipative system, which structures are a function of resources metabolised, such as, e.g. the products of past and current photosynthesis.

2.5 The size of some parameters in the BAPF

2.5.1 Conversion efficiencies

The different types of n in (5) and (7) are conversion efficiencies showing the value of goods and services produced divided by NR used. They can be estimated on an aggregated level or with a high level of resolution. A high aggregation is obtained if GDP is divided by national supply of primary energy. Different studies (Hall et al. 1986) showed strong relationships between energy use and value of production in monetary terms within nations over time, between nations and between sectors within nations. Figure 2 shows the result when GDP per capita (purchasing power parities) was plotted against supply of primary energy per capita for EU, Japan, Sweden and USA, respectively, during the period 1962–1997. Table 1 shows the results from regression statistics (GDP dependent variable, supply of primary energy independent variable) for the same economies and periods. Figure 2 suggests a quite close relationship between GDP per capita and primary energy supply per capita within nations.

The relationship is confirmed in the statistical analysis; within each nation, the R^2 values and significance levels are high (>0.85 and <0.001, respectively).

However, this is no proof of a causal relationship. An underlying temporal trend may affect GDP as well as energy supply. In order to avoid jumping to conclusions about causality between GDP and energy supply, regression analysis was performed on yearly change in primary energy supply (independent variable) and yearly change in GDP

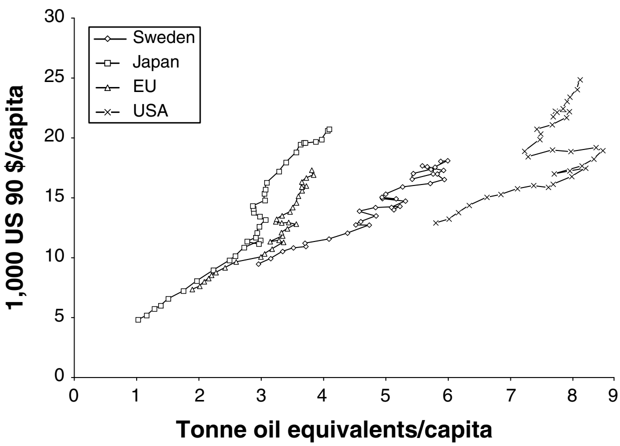

Fig. 2 GDP/capita plotted against total primary energy supply (TPES) in tonne oil equivalents/capita. Data concern the EU, Japan, Sweden and USA 1962–1997. *Source*: Own processing of data from IEA (1999)

Table 1 Some results from regression analysis between total primary energy supply and GDP in purchasing power parities in the EU, Japan, Sweden and USA 1962–1997

	Regression coefficient, US 90 $/kg TPES oil equivalent	Intercept	R^2-value
GDP and energy use			
EU	4.81	−938	0.90***
Japan	5.61	−286	0.95***
Sweden	2.96	−0.05	0.95***
USA	3.84	−2 269	0.86***

Source: Processing of data from IEA (1999). TPES, see Fig. 2. *** $p < 0.001$

Table 2 Some results from regression analysis between change in total primary energy supply and GDP in purchasing power parities, respectively, from 1 year to another, in the EU, Japan, Sweden and USA, respectively, 1963–1997

	Regression coefficient[a]	Intercept (Y when $X = 0$)	R^2-value
Change in GDP and change in energy use			
Japan	0.55	0.024	0.69***
USA	0.54	0.018	0.55***
EU	0.33	0.021	0.58***
Sweden	0.22	0.018	0.25**

[a] Change in GDP in US 90 $/change in TPES in kg oil equivalents. Sources and further explanations, see Fig. 2 and Table 1. *** $p < 0.001$, ** $p < 0.01$

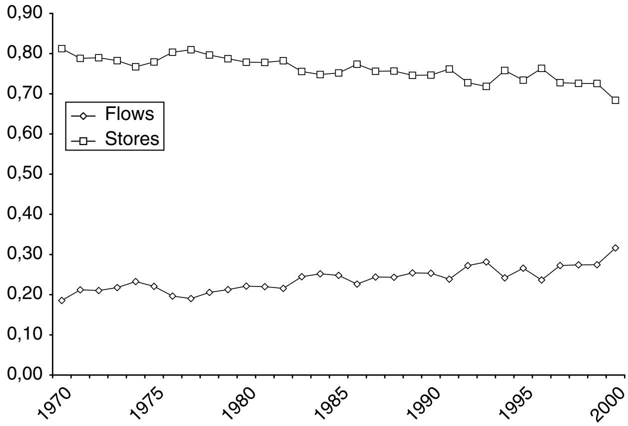

Fig. 3 Energy supply in Sweden from flows and stores 1970–2000 in fractions of total supply. Included in stores are crude oil and oil products, natural gas and gasworks gas, coal and coke and nuclear power (gross). Included in flows are biofuels and peat, heat pumps in district heating, hydropower (gross) and wind power. Imports and exports of electricity not considered. *Source*: Own processing of data in Swedish National Energy Administration (2001)

(dependent variable). The statistical relationship was still strong, though somewhat weaker (see Table 2).

The statistical analysis suggests that the general structure of the BAPF suggested (Eq. 5) with regard to use of NR and conversion efficiencies regarding GDP obtained through NR used is relevant. The NR primary energy is of primary interest.

Figure 3 shows that the Swedish economy 1970–2000, with respect to energy, was oriented towards the use of NNR, which provided 70–80% of the total primary energy supply. Thus, in terms of influx of primary energy, $\frac{dE_s}{dt}$ in this period dominated in the BAPF describing the Swedish economy.

It should be noted that the Swedish economy compared to most developed economies to a higher extent is fuelled by energy from renewable energy carriers.

2.5.2 The value of environmental impact

The impact of the economy on the ecological system and then back on the economy is a complicated issue, e.g. a simple dose–response function often does not exist. Holling

(1973, 1986) introduced the resilience concept. The concept of resilience has been used as a point of departure for later studies of the economic significance of changes of the environment (Common and Perrings 1992; Scheffer et al. 2001) and human well-being (MEA 2009). Resilience can be understood as the balance between organising and disorganising forces. When disorganising forces exceed organising ones, a system moves to a new state or stability region. Regarding ecological systems, this may have substantial economic effects (Scheffer et al. 2001). Two main points in Scheffer et al. are

1. Ecosystem state shifts may cause large losses of ecological and economic resources and restoring a desired state may require drastic and expensive intervention.
2. Efforts to reduce the risk of unwanted state shifts should address the gradual changes that affect resilience rather than merely control disturbances.

The challenge is to sustain large stability domains rather than to control fluctuations. Stability domains typically depend on slowly changing variables such as land use, nutrient stocks, soil properties and biomass of long-lived organisms. These factors are related to a physically growing economy. Following their line of argumentation, a physically growing economy increases the *risk* for what they call "catastrophic" changes in ecosystem states. Thus, one way to analyse the value of the environmental impact of a physically growing economy is via the *increase* in the risk cost due to economic growth.

Table 3 Some results from regression analysis between GDP (independent variable) and different emissions in Sweden 1900–1990

	GDP		Fission-energy free GDP	
	Slope, g/SEK	R^2	Slope, g/SEK	R^2
To air				
CO_2	58	0.81***	78	0.93***
NO_x	0.26	0.96***	0.33	0.97***
SO_2	0.16	0.32***	0.26	0.55***
CO	1.2	0.82***	1.5	0.94***
VOC	6.4E-2	0.14***	7.1 E-2	0.11**
CFC	1.1	0.87***	1.3	0.81***
Pb	1.7E-3	0.13***	2.5E-3	0.17***
HM	3.8E-3	0.25***	6.4E-3	0.47***
To water				
BOD7		NS	0.24	0.13***
Solid wastes				
Radioactive matter (dm^3)	1.7E-6	0.92***	−3.2E-6	0.79***

SEK, Swedish crowns, price-level 1991. Abbreviations: CO_2, carbon dioxide; NOx, nitrogen oxides; SO_2, sulphur oxide; CO, carbon monoxide; VOC, volatile organic compounds; CFC, chlorine fluorine carbonates; Pb, lead, HM, the heavy metals Cu, Zn, An, Ni, Cr, Kd; BOD7, organic matter discharged in water measured by a certain method. Statistical analysis based on GDP 1900–1949 from Johansson (1967), 1950–1990 from time series regarding Swedish National Accounts extracted in 1999 from the EMEC model at Swedish National Institute of Economic Research. Time series transferred to price-level 1991 by living cost indexes from Swedish National Institute of Economic Research (2002). Emissions 1900–1990 in Sweden on which the analyses in Lindmark (1998) are based, obtained as excel file from the author 2000. Energy supply from Swedish National Energy Administration (1998), radioactive wastes estimated via energy supply and the production of wastes from fission power estimated by the LCA-program LCA Inventory Tool 2.0

*** $p < 0.001$, ** $p < 0.01$, *NS* non-significant

Table 4 Some results from regression analysis between energy supply (independent variable) and different emissions in Sweden 1970–1990

	Energy supply		Fission-energy free energy supply	
	Slope, g/kWh	R^2	Slope, g/kWh	R^2
To air				
CO_2	−230	0.64***	450	0.93***
NO_x		NS		NS
SO_2	−2.3	0.73***	3.9	0.83***
CO	−4.4	0.72***	6.6	0.63***
VOC	−0.10	0.22*	0.21	0.36**
CFC		NS		NS
Pb	−1.2E-2	0.83***	1.6E-2	0.64***
HM	−5.4E-2	0.76***	8.3E-2	0.71***
To water				
BOD7	−2.7	0.72***	4.3	0.74***
Solid wastes				
Radioactive matter (dm^3)	4.4E-6	0.89***	−6.2E-6	0.74***

Data sources, see Table 3. *** $p < 0.001$, ** $p < 0.01$,* $p < 0.05$, *NS* non-significant

For the investigated time periods and economies, Tables 1, 2, 3 and 4 show strong statistical relationships between use of the NR primary energy and GDP; GDP and some emissions; and use of primary energy and some emissions.

This suggests that it is relevant to describe GDP as a function of the metabolism of NR, and the environmental impact of production as a function of the NR used, as is done in Eq. (7). The results in Tables 1, 2, 3 and 4 do not support a quantification of the value of the environmental impact of production. However, the results suggest that for investigated economies and time periods GDP growth has been achieved through means increasing the environmental pressure and decreasing stability domains of ecosystems. The risk for catastrophic shifts of ecosystems, of the type Scheffer et al. (ibid.) describe, has increased.

2.6 Effects of material exponential growth on future production

In this section, the effects on production value of exponential material growth of an economic system when transgressing ecological source and sink restrictions are analysed. The paths investigated are impacts on future availability of (1) NNR and (2) RNR, respectively, and on (3) resilience of ecosystems.

2.6.1 Use rate and non-renewable natural capital

Let $\frac{dQ_s}{dt}$ denote the value of the metabolic processes in society as measured by GDP driven by a flux of NNR. Index *s* shows that production is based on stored resources (i.e. NNR). Combined with (4) this gives:

$$\frac{dQ_s}{dt} = n_s(t)\left(\frac{dE_s}{dt}\right) \tag{8}$$

In the following analysis, the logistic curve is used in an effort to relate $\frac{dQ_s}{dt}$ to (1) the use rate of NNR; (2) the stock of NNC when exploitation starts; and (3) the stock of NNC that remains at a certain time. Reasons for this choice are

1. The logistic curve is built on a simple assumption: at the beginning of the use of a non-renewable resource, all is available, and at the end, all is used up (Hall et al. 1986; Hubbert 1956).
2. The logistic curve has provided good predictions of future use of oil and gas in the United States, as well as good predictions of the exhaustion of the stores of these resources in the United States (Hall et al. 1986; Hubbert 1956). The Hubbert prediction is the basis for more recent predictions of future global oil production by petrogeological consultants (see e.g. Campbell and Laherrère 1998; IEA 1998a, b). The Association for the Study of Peak Oil and Gas was formed in the first years of the Third Millennium. Its theoretical approach is based on Hubbert (ASPO 2009).
3. Without energy with quality, there will be no economic process. Different energy carriers provide energy with quality with the capacity to power the metabolism of society.
4. In an energy budget for the global economy, fossil fuels dominate. In 2010, it is expected that fossil fuels will account for almost 90% of total primary energy supply on the global level (IEA 1996). Thus, the pattern of exploitation of fossil fuels will have a globally dominating impact on the pattern of future energy supply.
5. A strong relationship between energy use and economic performance in monetary terms has been shown for a variety of situations (see Sect. 2.5.1).

To simplify the reasoning, $n_s(t)$ is assumed to be constant. Adapting the logistic function to the given assumptions gives:

$$\frac{\mathrm{d}Q_s}{\mathrm{d}t} = n_s c_s E_s(t)(E_{\mathrm{sm}} - E_s(t)) \tag{9}$$

where c_s = a rate constant, E_{sm} = the stock of NNC when exploitation starts, and n_s is a constant, showing the efficiency in the transformation of NNR to goods and services measured in monetary terms. Regeneration of NNC is not considered. Regeneration of NNC does not affect the principal argumentation.

According to (9), GDP at time t is a function of the cumulative use of NNR (= the use up of NNC as described by E_s) and the remaining stock of NNC $(E_{\mathrm{sm}} - E_s(t))$ at that time. In the early phases of exploitation exponential economic growth of type

$$\frac{\mathrm{d}Q_s}{\mathrm{d}t} = n_s\left(\frac{\mathrm{d}E_s}{\mathrm{d}t}\right) = n_s c_s E_s(t) \tag{10}$$

is possible. Source restrictions are not yet operating.

In (10), c_s equals ln $(1 + r)$, where r is the rate by which Q_s grows. The link between the rate constant c_s and the interest rate r in (10), combined with the economic ecological model in Fig. 1, provides a platform for analyses of positive and negative trade-offs between traditional strategies for economic growth and different aspects of sustainability. However, this is beyond the scope of this paper.

To force an economic subsystem, which otherwise would follow logistic growth, to follow exponential growth, measures must be taken to replace the rate constant c_s in (9), with a rate variable, which cancels out the restricting effect of $(E_{\mathrm{sm}} - E_s(t))$ in (9).

This results in:

$$\frac{dQ_s}{dt} = n_s\left(\frac{dE_s}{dt}\right) = n_s\frac{a_s}{(E_{sm} - E_s(t))}E_s(t)(E_{sm} - E_s(t)) = n_s a_s E_s(t) \tag{11}$$

$E_{sm} - E_s(t) > 0$.

The rate-increasing variable that replaces c_s is

$$\frac{a_s}{(E_{sm} - E_s(t))} \tag{12}$$

where a_s is a constant.

At $t = 0$, when exploitation starts, the value of expression (12) equals c_s in (9) and (10). When $t > 0$, the value of this rate-increasing variable changes in such a way that it precisely cancels out the growing restricting effect caused by the continuing depletion of NNC, described by ($E_{sm} - E_s(t)$). In the experiment of thought described by (11), the output of the economic subsystem follows the exponential curve, until all reserves of E_s (all NNC) are physically used up. This point is reached when the marginal costs in further exploitation (in quality corrected energy terms) equal the benefits. If exploitation continues after that point, it results in a net drainage of energy resources from the economy. This mechanism is explored by e.g. Hall et al. (1986). It is the basis for their EROIE analysis of resources (see later). In this hypothetical example, the exploitation goes from an all-time high to zero in one infinitely small time step.

If exploiters are rational, reserves that contribute most per unit effort invested are used first (Hall et al. 1986). The fraction of NR exploited needed to reinvest in the exploitation process increases as a function of the depletion of the stock of NNC. The EROIE value, i.e. energy return on invested energy, has been used in analysis of the change of resource qualities as a function of exploitation, applied on several types of natural resource exploitations, e.g. oil (Hall et al. 1986). Over time decreasing EROIE values in oil exploitation was found (ibid.). Assume that this is a general trend. Then, an increasing fraction of exploited NR must be reinvested in exploitation in order to keep up the capacity to deliver NR with constant quality, despite the decreasing quality of NR exploited by the primary sectors as a function of previous cumulative production. Thus, measures are taken that are mathematically described by the insertion of:

$$\frac{E_s(t)}{E_s(t) - E_{sr}(t)} \tag{13}$$

in (11) resulting in

$$\begin{aligned}\frac{dQ_s}{dt} &= n_s\left(\frac{dE_{sn}}{dt}\right) = n_s\frac{b_s E_s(t)}{(E_{sm} - E_s(t))(E_s(t) - E_{sr}(t))}E_s(t)(E_{sm} - E_s(t)) \\ &= n_s\frac{b_s E_s(t)^2}{(E_s(t) - E_{sr}(t))}\end{aligned} \tag{14}$$

where $E_s(t) - E_{sr}(t) > 0$, and $E_{sm} - E_s(t) > 0$. b_s is a constant. $E_{sr}(t)$ is the cumulative amount of NR from stores that at time t has been reinvested in the exploitation of NR.

$\left(\frac{dE_{sn}}{dt}\right)$ is the net amount of NR from stores delivered from the exploiting sector feeding the production in the rest of the GDP economy at time t, after the fraction of NR, $\frac{dE_{sr}}{dt}$, invested in the exploitation of NR due to decreasing resource quality has been accounted for. The rate variable (12) in (11) is in (14) replaced by

$$\frac{b_s E_s(t)}{(E_{\text{sm}} - E_s(t))(E_s(t) - E_{\text{sr}}(t))} \tag{15}$$

Eq. (11) compensates for the resource restriction which power increases with the depletion of a NNC. It is measured at the system border between Compartment I (Fig. 1) and the primary sector exploiting that NNR. Equation (14) also compensate for the increasing fraction of NNR exploited by the primary sector, which is needed to reinvest in the primary sector, in order to meet the demand from the rest of the economy on NNR of a certain quality delivered from the primary sector. It is measured at the border between the primary sector exploiting the NNR in question, and the rest of the economy. The difference between expression (11) and (14) expresses transformation losses in the exploiting sector.

According to (14), cumulative production value is not affected by the exploitation rate of NNC. Thus, decreasing efficiency in the use of NR as a function of increasing use rate is not considered. However, examples of such a relation has been found (Hall et al. 1986), and suggested (ibid.) as support to the maximum empower principle provided by Odum (1988, 1996). There is, however, in (14) a transfer (redistribution) of production values from the far future to the present and near future. The dynamics in this transfer (redistribution) in time are indicated by the difference between the rate constant c_s in (9), and the rate variable (15). That redistribution affects the social sustainability of society. That effect is located in Compartment III in Fig. 1.

2.6.2 *Use rate and renewable natural capital*

The earlier mentioned discussion on relations between use rate of NNR, NNC and the production rate can be applied to RNR as well. When harvests of RNR exceed regenerative capacity of RNC, the capital stock itself is used up. The RNR has become a NNR, thus (14) also describe the erosion of RNC. Change of indices gives:

$$\begin{aligned}\frac{\mathrm{d}Q_f}{\mathrm{d}t} &= n_f\left(\frac{\mathrm{d}E_{\text{fn}}}{\mathrm{d}t}\right) = n_f\frac{b_f E_f(t)}{\left(E_{\text{fm}} - E_f(t)\right)\left(E_f(t) - E_{\text{fr}}(t)\right)}E_f(t)\left(E_{\text{fm}} - E_f(t)\right)\\ &= n_f\frac{b_f E_f(t)^2}{\left(E_f(t) - E_{\text{fr}}(t)\right)}\end{aligned} \tag{16}$$

where$E_f(t) - E_{\text{fr}}(t) > 0$ and $E_{\text{fm}} - E_f(t) > 0$.

The index f shows that the relations concern the part of the economy using NR from flows that is commonly perceived as RNR. However, in the hypothetical example, they become NNR. The loss of production value when the use rate depletes the stock of RNC, summed over eternity, is infinitely high.

2.6.3 *Impact on the resilience*

We analyse the costs of the environmental impact of a materially growing economy through *increased risks* for catastrophic shifts of ecosystem states due to a loss of resilience. In Sect. 2.5.2, the reasons for that choice is delivered. We assume that the resilience can be described as a balance between organising and disorganising forces. The balance between organising and disorganising forces is affected by exponential growth in two ways: (1) RNC decreases through, e.g. cutting down of forests and transfer of wetlands to agricultural land, which reduces production of life support such as assimilative capacity. Thus, organising forces decrease as a function of a biophysically growing economy. (2) A biophysically growing economy increases the wastes produced and, hence, the environmental pressure. The disorganising forces grow.

Through (1) and (2), the stability domains of ecosystems decreases, increasing the risk that stochastic events will push systems over critical thresholds.

2.6.4 Organising forces

Let $\frac{dL_{sus}}{dt}$ be supply of life support at time t. The pattern of use of RNR (and use up of RNC) in an economic subsystem that in spite of ecological source restrictions is manipulated to follow exponential growth is described in Eq. (16). We assume that decreasing RNC decreases production of life support and thus the organising forces. The capacity of ecosystems to supply the economy with life support corrected for the erosion of the stock of NC providing this flux is thus:

$$\frac{dL_{sus}}{dt} = \frac{dL_{sus}}{dt_{t=0}} - h\left(\frac{b_f E_f(t)^2}{\left(E_f(t) - E_{fr}(t)\right)}\right) \tag{17}$$

where $E_f(t) - E_{fr}(t) > 0$. $\frac{dL_{sus}}{dt_{t=0}}$ is the production of life support at time $t = 0$. At that time, the use of RNR exactly matches ecological source restrictions. The function h shows how increasing use of RNR above sustainable harvest levels decreases production of life support. The expression in the parenthesis is the one in (16) showing the use rate of RNR.

2.6.5 Disorganising forces

Equation (7) contained the expression $g\left(\left(\frac{dE_s}{dt}\right), \left(\frac{dE_f}{dt}\right)\right)$, where that expression equals $l\frac{dL_{su}}{dt}$ in (5). This gives

$$\frac{dL_{sud}}{dt} = \frac{\left(g\left(\frac{dE_s}{dt}\right), \left(\frac{dE_f}{dt}\right)\right)}{l} \tag{18}$$

where $\frac{dL_{sud}}{dt}$ is the demand on life support, i.e. a measure of the disorganising forces that the economy produces.

Inserting (14) and (16) in (18) gives the following expression:

$$\frac{dL_{sud}}{dt} = \frac{g\left(\frac{dE_s}{dt}\right), \left(\frac{dE_f}{dt}\right)}{l} = \frac{g\left(\frac{b_s E_s(t)^2}{(E_s(t) - E_{sr}(t))}, \frac{b_f E_f(t)^2}{\left(E_f(t) - E_{fr}(t)\right)}\right)}{l} \tag{19}$$

$E_s(t) - E_{sr}(t) > 0$, $E_f(t) - E_{fr}(t) > 0$ and $l > 0$. Equation (19) shows the growth of disorganising forces, due to exponential growth of an economic system exposed to ecological restrictions.

2.6.6 The resilience

We assume that the balance between organising (Eq. 17) and disorganising forces (Eq. 19) gives the resilience:

$$R(t) = \frac{\mathrm{d}L_{\mathrm{sus}}}{\mathrm{d}t_{t=0}} - h\left(\frac{b_f E_f(t)^2}{\left(E_f(t) - E_{\mathrm{fr}}(t)\right)}\right) - \left(\frac{g\left(\frac{b_s E_s(t)^2}{(E_s(t) - E_{\mathrm{sr}}(t))}, \frac{b_f E_f(t)^2}{\left(E_f(t) - E_{\mathrm{fr}}(t)\right)}\right)}{l}\right) \tag{20}$$

$E_s(t) - E_{\mathrm{sr}}(t) > 0$, $E_f(t) - E_{\mathrm{fr}}(t) > 0$ and $l > 0$.

According to (20), a material exponential growth of the GDP economy results in a growth of disorganising forces and a decline of organising ones following exponential growth raised to the second power. The resilience is "eaten up" from two sides, via increasing demand on life support and decreasing supply, both as a function of a materially growing economy.

3 Concluding discussion

The model of the economy in its ecological and social context presented is the result of an integration of descriptive domains of physical resource theory, animal and human physiology, economic theory and systems ecology. It provides a conceptual model of the GDP economy in its social and ecological context. The three versions of BAPF proposed (see Eqs. 5, 6 and 7) provide a means to analyse relationship between production value and inputs of land, capital and labour. Capacity of ecosystems to support the human economy with resources, and other forms of life support is included in land. The BAPFs are means to evaluate the importance of land to the economy. The results obtained indicate that there might be a need to reflect on the hierarchy between general economic policies and land use policies. General economic policies is subordinated to a good management of land (land in a broad sense) when the socio-economic system is exposed to ecological source and sink restrictions.

From the BAPFs, systems of ecological economic accounts can be generated that comply with known properties of the type of complex systems (holarchies) that is the focus in a sustainable development and, as a consequence, comply with the conditions for a sustainable development as expressed by MEA, OECD and UN. That is a complement that substantially increases the relevance of the group of methods and approaches for analysis of the environmental impact and impact on ecological sustainability, which are based on such assumptions that the analysis ignores the impact on the carrying capacity in the environmental systems that actually are affected by the production.

The BAPF is a mean to evaluate under which economic and ecological conditions a sustained interest is possible: If the economic subsystem has trespassed ecological carrying capacity limits with regard to sink and/or source restrictions, Eqs. (16) and (20) suggest that the net value of production is negative, thus the interest is negative. Equation (10) introduces an explicit relation between the interest and the net value of production over time, which is further developed in the following stages. The analysis performed suggests a frame for further analyses of relations between traditional economic growth, sustained welfare and the resilience of ecological economic systems. That supports increased understanding of the conditions for sustainable interest levels and sustainable incomes. It also supports increased understanding of the preconditions for a management of different stocks of capital, supporting a sustainable development.

The analysis of temporal trends regarding conversion efficiencies from 1962 to 1997 in the EU, Japan, Sweden and USA showed that GDP was quite well predicted by supply of primary energy, assuming a linear relationship between energy supply and GDP.

Differences between nations in level and trends regarding conversion efficiencies were found, suggesting potentials for increased efficiency in the use of Nature. In Sweden, (the only economy investigated for this type of relations) statistically significant correlations were found between a number of emissions and GDP for the period 1900–1990. The variation in GDP explained the major part of the variation in some emissions, while for others the explanatory power was substantially lower, suggesting that for these emissions the relationship between growth and environmental disturbances was broken. The analysis of relations between GDP, energy use and emissions, respectively, represents an effort to improve the knowledge about the source and sink restrictions to the human economy as a contribution to the operationalisation of a sustainable development. It is a first effort to identify important parameters in a BAPF.

In a theoretical approach, it was found that a continued exponential material growth of an economic subsystem beyond the carrying capacity of the ecological economic system causes negative environmental effects, which with a profound dynamics inflict future production value.

The most profound dynamics were associated with the pattern in the loss of resilience in the ecological economic system, following the pattern of exponential growth raised to the second power. The dynamics in the loss of resilience describe the path of the ecological economic system towards threshold points where it may experience catastrophic shifts towards new state conditions, where the effects on future production value are unknown. Regarding the impact on resilience, the cost explored was the increase in the risk for ecological state shifts, due to material growth. However, it must be stressed that the results are a product of the given assumptions, which represent drastic simplifications of the complexity of real systems. Thus, there is a need to further probe the assumptions against empirical data, improving the knowledge about costs and benefits of material growth of real human economies.

OECD (2001) declare that a sustainable development has top priority among its member nations. Regarding criteria for a sustainable development OECD stresses the importance of

- maintaining sufficient amounts and qualities of natural, man made, human and social capital
- restricting the use of non-renewable natural resources within volumes possible to substitute by renewable natural resources or resources from other capital forms
- efficient use of renewable and non-renewable natural resources
- restricting emissions within the assimilative capacity of ecosystems while paying sufficient attention to phenomena such as thresholds and resilience within ecosystems.

Furthermore, OECD noted that the concrete implementation of policies for sustainable development is lacking.

The conceptual model, the BAPF, the system of ecological economic accounts that can be derived from the BAPF, the empirical analyses of different parameters in the BAPF and the theoretical analysis of different costs of provoking an economic subsystem exposed to ecological source and sink restrictions to follow the path of material exponential growth presented in the paper represent a tool kit supporting the operationalisation of a sustainable development. The tools are internally congruent and congruent with the criteria for a sustainable development put forward by OECD. They are thus well suited to meet the demand on tools needed for the concrete implementation of policies for a sustainable development, on the general policy level as well as regarding land use policies, asked for by OECD, increasing the biophysical productivity of the society, as a major means for a sustainable development.

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Paper III

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A MULTI-CRITERIA ANALYSIS OF SUSTAINABILITY EFFECTS OF INCREASING CONCENTRATE INTENSITY IN SWEDISH MILK PRODUCTION 1989–1999

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Abstract. The concept of sustainable development is forcing standard economic analysis to acknowledge and address the existence of dimensions of performance, which are not reducible to monetary accounting. In particular, the implementation of this concept in practice requires: (a) the simultaneous handling of indicators developed in different disciplinary fields; and (b) an approach more related to the procedures adopted by consultants (Participatory Integrated Analysis), rather than theoretical academic analysis looking for 'the' optimal solution. The case study considered in this paper is a multi-criteria analysis of changes, which occurred in the Swedish milk production sector for the period 1989–1999. Multi-criteria impact matrices and multi-criteria representations are used to provide a transparent method of integrated analysis. Changes are characterized and quantified in a way that makes it possible to relate the impact of existing trends in relation to different sub-objectives (variation in performance in relation to social, economic and ecological indicators). The results of this analysis confirm a few well known predicaments of sustainability associated with agriculture. The growth of Sweden economy is driving a major increase in material throughputs within its agricultural sector. The need of increasing agricultural throughput (especially labour productivity) has moved the Swedish dairy sector in a clear situation of decreasing marginal return (=large increases in inputs are not reflected in a proportional increase in output). Therefore, sound policies of development of this sector aimed at increasing the goal of sustainability have to be developed by considering several indicators of performance, and not only economic variables.

Key words: integrated assessment, milk production sector, multi-criteria analysis, sustainable animal production, Sweden.

Abbreviations: AAT: = Amino acids absorbed in the small intestine; DM: = Dry matter; ECM: = Energy corrected milk; GDP: = Gross domestic production; IA: = Integrated assessment; ME: = Metabolizable energy; MCIM: = Multi-criteria impact matrix; MCR: = Multi-criteria representation; RAM: = Result analysis milk-production; SEK: = Swedish crowns; TPES: = Total primary energy supply.

1. Introduction

1.1. The Methodological Issue

Sustainable development has been officially endorsed as a key priority objective for OECD countries (OECD, 2001). It entails considering simultaneously, as equally

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relevant, social, economic and ecological dimensions. After the general agreement reached at the Rio Conference on Environment and Development, the concept of sustainable development should have been included in standard economic analysis (OECD, 2001). Unfortunately, such an inclusion, so far, has been far from satisfactory. In particular innovative methods of analysis aimed at sustainable development should result useful:

- In the design of policies that, wherever possible, can enhance the sustainability of socio-economic development. This can be obtained only by considering social, economic and ecological dimensions simultaneously.
- In the selection and implementation of these policies. This can be obtained by providing an open and transparent process about how to decide criteria (subobjectives within the frame of a sustainable development) and how to weigh their relative importance in the case of trade-offs. This requires involving the stakeholder in such a process.

Sustainable development is based on multi-criteria decisions following the Paretoconcepts (Pareto, 1896).

This paper wants to explore the potential of multi-criteria analysis to the issue of integrated analysis of sustainability. The approach followed in the case study is based on my experience as consultant (integrated analysis of environment, economy, agriculture, milk production, forestry) during a period of 20 years (Hellstrand 1988, 1989, 1996, 1997, 1998; Drake and Hellstrand 1998; Hellstrand and Landner 1998, 2001; Landner et al. 2000). A consultant is required to follow causal chains between system levels and disciplines as far as the benefits (for the customer) are higher than the costs. This approach requires often combining useful information, which refers to different levels of analysis. For example, within agriculture, knowledge about processes at field and animal level are studied in biological, ecological and economic terms (i.e. technical coefficients studied and defined at the microlevel). This information, however, is crucial for the understanding characteristics manifested at the macro-level (economic, social and ecological viability). In the same way, changes at the macro level (prices of commodities, government regulations) are crucial for determining the feasibility or relevance of activities performed at the micro-level. Therefore, the concept of sustainable development requires the ability of establishing connections among processes occurring at the macro- and the micro-level as well as the ability of understanding how these links are relevant in relation to policy implementation.

One ambition of this paper is to investigate whether a consultancy approach may contribute to the implementation in practice of the policies for sustainable development according to the frame proposed by OECD (2001). Therefore, the analysis in this paper follows OECD's conceptualisation of sustainable development. A sustainable development, based on the simultaneous consideration of social, economic and ecological dimensions, implies the preservation of a sufficient stock of capital for each of the four types: human capital, social capital, human-made capital and natural capital. This is identified as a precondition for a sustainable development, since these different types of capital are crucial for the generation of each other. This also means that improving the coherence between environmental and economic policies would support economic development able to respect ecological carrying capacity limits. In particular OECD (2001) indicates as related goals: efficiency in use of renewable and non-renewable natural resources; restricting emissions within the assimilative capacity of affected ecosystems, and acknowledging the significance of thresholds and, associated to that, resilience in ecosystems. With regard to agriculture, this implies that a major aspect of sustainable development is a high and sustainable capacity to satisfy human needs of energy and protein *per ha of agricultural land.*

Transparency and accountability are also crucial factors in this task. This implies that the process through which decisions are reached should be open to the public, which should be informed about the full range of possible consequences of a given choice (OECD, 2001).

Thus, sustainable development, the way OECD presents it, is a quite a complicated issue. It implies a major challenge for the scientific community. It requires re-discussing traditional criteria of good science. Scientists have to provide an input relevant for the understanding of the behaviour of complex systems operating on different scales and relevant in relation to different dimensions of analysis. Even more challenging is the request to provide anticipatory models and mechanisms of control for steering the trajectory of development toward states considered benign for humans.

For such a challenging task an approach inspired by consultancy is required but is not enough. Good consultancy is not equal to good science. This is why in the field of integrated analysis of sustainability, it is becoming crucial to develop procedures of analysis, which combine the merits of good consulting (capability to dealing in a holistic way with several relevant issue and capability to tailor the analysis on the specific interest of the customer), with the merits of good science (capability to provide useful and verified knowledge in relation to typologies of processes and situations). For an overview of this issue see the book of Giampietro (2003). In particular, Giampietro in the first part of his book discusses the problems associated with Integrated Assessment (IA), Sustainability Impact Assessment, Strategic Environmental Assessment, Extended Cost Benefit Analysis, when dealing with the sustainability of agro-ecosystems. These analytical tools all deal with three huge systemic problems:

1. It is not possible to formalise once and for all a definition of 'the right set' of relevant criteria to be considered in a 'sound analysis' of sustainability. This task can only be performed after having set a specific context of reference and a set of stakeholders.
2. It is unavoidable to find legitimate contrasting views among different agents in relation to what should be considered as an improvement or the best alternative to select.

3. Uncertainty and ignorance cannot be excluded from scientific analyses, which are required for sustainability assessments. Not all data, indicators and models required to consider different dimensions of analysis (to reflect the views of different agents at different levels) have the same degree of reliability and accuracy.

These problems, according to Giampietro, motivate the use of participatory procedures of Integrated Analysis based on a multi-criteria characterization of the performance of agro-ecosystems in relation to sustainability.

In conclusion, when adopting a conceptualisation of sustainable development as suggested by OECD, it is necessary to develop analytical tools that combine the experiences typical of consultancy and the capacity of standardize information typical of science. An example of this approach is given in the rest of this paper. The case study is an integrated analyses of sustainability aimed at characterizing the changes, which occurred in the sector of Swedish milk production for the period of 1989–1999. In particular, this paper will quantify and discuss the effects that existing trends in the use of concentrate feeding generate in relation to different indicators of sustainability. The goal is to identify a set of indicators that can translate into practice what the abstract concept of sustainable development means in terms of milk production occurring within a developed country, like Sweden. The results of this analysis, therefore, should identify areas in which measures can be taken to improve sustainability in relation to social, economic and ecological dimension.

Before going into such an Integrated Analysis, I present in the following section a brief overview of the major changes and drivers of the Swedish milk and cattle production system.

1.2. Swedish Milk and Cattle Production

In Swedish cattle production, the use of crop protein feeds in purchased feeds increased 2.7 times for the period of 1991–1999 – this increase was mainly associated with the use of soya bean meal (Statistics Sweden, 1997, 2000). This represents a dramatic change in the meaning and role played by cattle within the Swedish socio-economic system.

In fact, cattle-production has been a major element in the Swedish food system for thousands of years. The quality of pasture in Sweden, in quantitative and qualitative terms, is similar to that of other regions of the world from the south to the northern parts, while only the southern parts of Sweden can compete in grain production.[1] The supply of chemical energy and crude protein of pastures is very low for humans and for other mono-gastric animals, such as pigs and poultry, while ruminants via the rumen microbes can transform the output of pasture into high quality food such as milk and meat. This is the physiological/historical reason why most Swedes belong to the global minority of populations, where most adults tolerate intake of lactose.[2] Animal products for Sweden were a way for using resources that otherwise could not be used by humans. Whereas, a massive increase in the use of crop protein feeds purchased to feed cattle (mainly imported soya bean meal from outside Europe) implies a major change in strategy. Resources that could be used directly by humans to satisfy physiological requirements of energy and protein are used to feed animals with the only goal to increase economic profit. Moreover, the feeding value of low quality feeds is higher for ruminants than for mono-gastric animals, whereas the feeding value of high quality feeds is lower for ruminants compared to mono-gastric animals due to fermentation losses in the rumen.[3] All these considerations seem to indicate that actual trends may provide conflicting assessment of performance when different objectives for sustainable development (different criteria of performance) are considered.

In particular technological changes in agriculture are a function of (Giampietro, 2003):

(i) changes in the socioeconomic system to which the farming system belongs;
(ii) the characteristics of the ecosystem managed for agricultural production; and
(iii) farmers feelings and aspirations.

Therefore, economic growth (on the macro-level) pushes for increases in the throughput per ‘hour of labour’ at the farm level (Giampietro, 2003). In developed countries, such as Sweden, in the long term, the growth of the economy, when assessed in GDP-terms – tends to be associated with the growth of energy consumption in the society. Hall et al. (1986) provided a detailed review of different studies available at that time showing strong connection between economic growth and the use of energy. Data from IEA (1999) show that this relation is valid when considering the performance of developed economies such as Japan, EU and USA. In conclusion, when looking at the changes occurring in the milk production system of Sweden, we can explain the increase in the use of concentrates (= crop protein feeds and grains) in dairy production as an increase in the material throughput of the production process, which is required to increase the economic productivity of labour in this economic sector in order to remain competitive with the rest of Swedish economy.

1.3. Goals of the Case Study

The goals of this case study are:

(i) To verify the usefulness of Integrated Analysis based on multi-criteria characterization of performance for a deeper understanding of the implications of “sustainable development” for animal production systems operating in developed countries; and
(ii) To provide useful information over the recent trends in one important animal production branch, milk production, in Sweden. The set of data organized in multi-criteria impact matrices and multi-criteria representations provide a transparent method of integrated analysis to study changes in relation to societal objectives of sustainable development.

2. Materials and methods

2.1. Data on Trends 1962–1995 in Swedish National Economy and Milk Sector

The physical throughput and economic output per labour hour in the Swedish economy 1962–1995 has been estimated using the following data: (a) total primary energy supply (TPES) and (b) purchasing power parities in fixed prices from IEA (1999); (c) labour data from the EMEC–model, Swedish National Institute of Economic Research.[4] Biological throughput and economic output, respectively, per labour hour in Swedish milk production sector 1960–1990, has been estimated using the following data: (a) supply of Metabolizable Energy (ME), (b) milk yield, (c) input of labour; from SHS (1991). Revenues from milk production, fixed price, were estimated in relation to milk prices (ibid.) and Swedish consumer price indexes from Statistics Sweden.[5] In SHS (1991) the size of cow herd is assumed constant over time. Thus, the impact of lower labour costs per cow due to advantages of scale is not considered. Incomes from dairy cows are estimated via revenues from the product milk. Other incomes are from calves and from meat sold out from the dairy farm. However, milk contributed with 80% of total incomes on the dairy farm in 1990 (ibid.), thus this simplification is a minor source of error.

2.2. Nitrogen Influxes Via Purchased Feeds to Cattle 1989–1999

Nitrogen influxes to Swedish agricultural sector via purchased feeds to cattle 1989–1999 has been estimated via amounts of different feed stuffs used in the production of purchased feeds (Swedish Board of Agriculture, 1992, 1995, 1997, 2001) and the content of crude protein in these feed stuffs (Spörndly, 1991). The influx of crude protein has been divided by 6.25 (ibid.) to obtain the influx of nitrogen. In 1991 we found the lowest record for nitrogen influx. In that year the officially recommended system to evaluate protein content in feeds and to estimate protein requirements was substantially changed. The official tables and feeding standards closest before and after this shift are in the report of Spörndly (1989, 1991). In 1995, the procedure to estimate energy and protein requirements to lactating cows was changed. The first official representation of energy and protein requirements to lactating cows after the changes in 1995 is reported by Spörndly (1995). Due to the changes in protein evaluation system in 1991 combined with the fact that the lowest nitrogen influx to Swedish cattle via purchased feeds was obtained in 1991, the rest of the analysis was focused on the period 1991–1999.

2.3. Multi-Criteria Analysis of Trends in Concentrates Feeding 1989–1999

According to the procedure proposed by Giampietro (2003) to evaluate simultaneously social, economic and ecological effects in an Integrated Analysis, several criteria of performance – and relative indicators – have been considered to characterise the effect of changes in the use of concentrate feeding to cattle in Sweden for the period of 1991–1999. In particular, the analysis focuses on crop protein feeds and grain products in purchased feeds. Common cereals dominate grain products. E.g., for 1999, contribution to "grain products" from different sources were: 70% oat, barley, wheat and rye; 12% other cereals, while remaining 18% are by-products from milling (Swedish Board of Agriculture, 2001). The results of such an integrated analysis are presented in the form of a multi-criteria impact matrix (MCIM), in which quantitative estimates are provided for the years 1991, 1995 and 1999 in relation to 14 indicators (Tables I and II). The same results are also presented in the form of a multi-criteria representation (MCR) – a spider-web graph (Figure 3). Both tables and figures will be discussed in detail in Section 3. For 1991 the value in the MCR for each variable in the MCIM, is set to 1.0. The values for the years 1995 and 1999, respectively, show the proportional change compared to the situation 1991.

In the rest of this section, I provide for each variable/indicator included in the MCIM the reason of its choice and the path through which its numeric value is estimated. Data sources covering the time period 1991–1999 are presented below. Some of the sources indicated in Section 2.1 for the time period 1962–1990, and 1995 may differ.

Indicators of throughput

Information on throughput in the national economy and in the milk-producing sector, are required to verify the hypothesis that throughput trends in the milk sector 1991–1999 are driven by throughput trends on the national scale, resulting in increased incomes.

- Material throughput in the Swedish economy is measured in terms of energy use (Swedish Energy Agency, 2001), in accordance with international standards regarding energy statistics.
- Gross Domestic Production – GDP – provides information about the economic output from the material throughput on the national scale. Trend for GDP, price-level 1995, is from Statistics Sweden.[6]

Indicators of inputs

- Material input to the Swedish milk sector is estimated using two variables: (a) *Energy use in milk production*. The energy input considered is used to feed physiological processes of dairy cows. (b) *Protein input to feed*. This second variable represents a key indicator for an integrated analysis of changes of this sector. Moreover, the performance of feeding requires a balanced supply of energy and protein. This requires considering both the energy and protein requirements of the animal.
- Data on the amount of grains and forages fed to dairy cows, which are produced on the own farm (or on neighbour farms and traded directly to the dairy farms) are not available on the national level in Sweden (Tomas Ericsson,

Swedish Board of Agriculture; personal communication 2003). Furthermore, records of milk production for cows outside the official milk record programme are not available. Thus, the supply and use of energy and protein to the milk production had to be estimated for these cows. For the rest, energy and protein need for maintenance (assumed live-weight 600 kg/cow) and milk production in 1991 was estimated using: (a) total number of dairy cows in Sweden (Statistics Sweden, 1997); (b) milk yield, expressed in ECM (Energy Corrected Milk) per cow, as resulting from the official milk record programme (ibid.); and (c) official feeding recommendations for maintenance and milk production (Spörndly, 1991). In any case, estimating national averages using average production values of the cows included in the official milk record program is a defendable choice. In fact, while not all dairy cows are within this program, the program covers a large fraction of them. In 1991, the fraction of dairy cows included in the milk record programme was 77% (Statistics Sweden, 1997). The fraction became 87% in 1999 (Statistics Sweden, 2000). Moreover, it is unlikely that differences between the cows included or outside the programme is so dramatic to invalidate such an estimate. The calculations of nutritive needs were based on 12 months calving intervals and 6 weeks dry period. The length of the dry period affects the length of the lactation period, and thus the estimated nutritive needs for maintenance during lactation. "Gestation needs" and "maintenance needs" during dry period were not considered. These requirements are to a minor part fulfilled via purchased feeds. Furthermore, of the total nutritive needs during one year, the needs during the dry period play a marginal role. Thus, all energy needs for gestation plus maintenance during dry period sum to only 6% of the total energy requirements of a cow producing 8000 kg ECM. Assumed forage ration was 8 kg dry matter (DM) per cow and day with the average energy and protein content of analysed forages in 1991 (Swedish Dairy Association, 2001).

- Benchmark level for needs of energy and protein to dairy cows. It was assumed that in 1991 the supply of energy and protein to the dairy cow stock was exactly 100% of the needs. Thus, the estimate of the nutritive needs of the Swedish dairy cow stock for this year is also an estimate of the supply of nutrients. This provides a fixed level of amount of energy and protein fed the dairy cow stock used as reference. The fixation of a benchmark level in a specific year facilitates the analysis of observed trends.
- Actual supply of energy and protein to dairy cows compared with requirement. The supply of energy and protein, given by SHS (1992), for 823 dairy herds within the program result analysis milk-production (RAM) is equal to 109% and 110%, respectively of requirements in 1991. The RAM-herds represent a positive selection from the total population of dairy herds. Hellstrand (1988) in a field investigation on 15 dairy farms representing high-, middle- and low- producing herds found that the allowances of energy and protein, respectively, was 12 and 17% above requirements. In the study, all feeds fed were weighted and analyses of nutritive content of feeds were performed.

- Supply of energy and protein to the milk sector in 1995 and 1999 was estimated via the changes in the allowances of energy and protein from 1991, added to the estimate of the level of supply in 1991. The change in the allowance was calculated by assuming 8 kg DM forages per dairy cow and year with the average nutritive content as of analysed forages that year (Swedish Dairy Association, 2001). Total amount of energy and protein to the dairy stock provided from grain and crop protein feeds that was not included in purchased feeds was assumed to be the same as in 1991. Change in energy and protein from purchased feeds was estimated via change in total amounts of grains products and crop protein feeds in purchased feeds (Swedish Board of Agriculture, 1992, 1995, 1997, 2001), respectively, multiplied by the nutritive content of grain products and crop protein feeds, respectively. In these calculations it was assumed that the nutritive content of grain products and crop protein feeds, respectively, equalled the one of barley (Spörndly, 1991) and soya bean meal (ibid.), respectively.

Indicators of the Level of Grain and Crop Protein in Purchased Feeds

Levels of grain and protein-crops, and trends regarding the use of purchased feeds are crucial for the integrated analysis of this paper. Changes in the level of grain and crop protein used in the feeds dominate trends for purchased feeds in the period 1991–1999. In 1991 the contribution from grain products and crop protein feeds together was 62% of purchased feeds and in 1999 it was 72%. In the period, 1991–1999 grain products and crop protein feeds contributed 88% of the total increase in use of purchased feeds to cattle in Sweden. Data on grain products and crop protein feeds are from Swedish Board of Agriculture (1992, 1995, 1997, 2001). The procedure for estimating nitrogen in purchased feeds has been described in Section 2.2.

The cost of purchased feeds to cattle indicates an investment of economic resources in the agricultural sector that otherwise could have been used for other purposes. Mainly, this cost has to be attributed to the milk sector, since the major fraction of purchased feeds to cattle is used for milk production. Thus, during the period 1991–1998, 87–89% of purchased feeds to cattle were categorised as feeds to dairy cattle, while in 1999 such a fraction was 86.3% (Swedish Board of Agriculture, 1992, 1995, 1997, 2001).

Ideally, the costs of purchased feeds (fixed price) should be estimated using the average price over the total amount of purchased feeds sold. However, official statistics do not provide this information. Statistics Sweden (2002a) provides the total cost of purchased feeds referring to poultry, pigs and cattle together. Swedish Board of Agriculture (1992, 1995, 1997, 2001) has data on total amount of purchased feeds. Division gives the average price per kg. Multiplication by consumer price indexes (Statistics Sweden[7]) gives average price on purchased feeds 1991, 1995 and 1999, price level 1991. In this study the price of purchased feeds to cattle is assumed to be equal to the average price on all purchased feeds to cattle, poultry and pigs. Thus, an estimate of the costs for purchased feeds to cattle has been obtained by multiplying the amount of purchased feeds to cattle (Swedish Board of Agriculture, 1992, 1995, 1997, 2001) by such a price.

Indicators of Outputs: Useful Products

Revenues in milk production show the economic output from the material throughput in milk production. The source is Statistics Sweden (2002a). Multiplication by consumer price indexes gives a fixed price-level.

Material output. The input of feeds is transformed in the production system into an output of valuable products such as meat and milk. The amount of milk produced is measured in kg ECM. The method for estimating the national production of milk has been presented before, in the section referring to the assessment of inputs. Data are estimated starting from the information available on the cows included in the official milk record programme (Statistics Sweden, 1997). Meat production is estimated from Statistics Sweden (1997, 2000). The total meat production from cattle is partitioned in one flux of meat from the stock of dairy cows and one from the stock of cows used for meat production only. The partitioning is based on the assumption that the fluxes are proportional to the fraction of total number of cows used for dairy production and for meat production only.

Indicators of Outputs: Losses of Nitrogen

Losses of nitrogen are an important indicator of negative ecological effects. In fact, emissions of ammonia contribute to acidification and eutrophication. The Oslo-Paris convention (OSPAR) has provided a method for estimation of nitrogen balances in the whole agricultural sector, so-called farm gate balances (Statistics Sweden, 2002b). The objective for participating countries are to reduce discharges of nitrogen to the North Sea by 50% compared to the level of 1985. Considered influxes to the agricultural sector are commercial fertilisers; feeds; sewage sludge; atmospheric deposition; and fixation through leguminouses. Considered effluxes are crops and animal products exported from farms; emissions of ammonia; leaching of nitrate to water systems; and denitrification (ibid.).

The nitrogen efficiency in the Swedish agricultural sector 1985, 1991, 1995, 1997, and 1999, respectively, was 32, 35, 32, 35, and 32%. The efficiency is the ratio of outputs in crop and animal products out from the agricultural system through total influxes. The difference between (i) sum of influxes and (ii) effluxes through crops and animal products, respectively, measures surplus influxes. In 1999, the surplus was 71 kg nitrogen per ha. Of this surplus, 46% leached as nitrate, 26% was emitted as ammonia in the animal production system, and 28% was accumulated in top soil. Farms with intensive animal production had higher surplus influxes than others, despite higher crop yields. This increases the risk for losses to the environment (ibid.).

In the situation described, with a nitrogen efficiency in the agricultural sector from 1985 to 1999 of 32–35% reported years, and where (for 1999) 46% leached to water systems as nitrate, and 26% was emitted as ammonia from the animal production system, one can clearly state the following:

Increased loads of nitrogen to the Swedish agricultural system through increased content of nitrogen in feeds to dairy cattle will in a situation with constant effluxes of nitrogen in meat and milk contribute to an increased load to top soil. This increased load will directly contribute to increased leaching of nitrate, and also indirectly result in increased leaching through mineralization of nitrogen in organic matter when ley is succeeded by grain in the crop rotation. It will also increase ammonia emissions.

The amount of milk and meat produced from the dairy stock is quite constant from 1991 to 1995 and 1999 (see Table I). This translates into the obvious fact that the nitrogen output associated with these products has been constant too. Therefore, the increased input of nitrogen associated with the increasing use of purchased feeds is associated with an increase in the emissions/discharges of ammonia and nitrate into the Swedish environment. Of the nitrogen effluxes in manure and urine, 30% is emitted as ammonia (Danell, 2001), while the rest contributed to increased discharges of nitrate to water systems. The relationship between the weight of nitrogen and the weight of ammonia with the same amount of nitrogen is 17/14 = 1.21.

Indicators Referring to the Ecological Opportunity Cost of Milk

As discussed in the introduction, a major aspect of sustainable development (Regeringen, 2001, and OECD, 2001, respectively, provide late expressions of the interpretation of a sustainable development on the national and international level, respectively) within agriculture is a high and sustainable capacity to satisfy human needs of energy and protein *per ha of agricultural land.*

To this respect using grain products and crop protein feeds in purchased feeds for dairy production implies reducing the possibility of using these products as food for humans. Therefore, in this paper, I propose the use of an indicator, which is represented by the number of people whose energy and protein requirements could have been supplied by the amount of grain products and crop protein feeds used in purchased feeds to cattle. Since the production of these grain products and crop protein requires the use of arable land, the higher is the use of these input as feeds (especially when not necessary), the lower is the capacity of satisfying human needs per ha of agricultural land. More discussions on this point are given later on.

The indicator is based on the following assessments. Nutritive needs in terms of energy and protein are the ones of moderate occupational work as average for men (70 kg) and women (60 kg) (WHO, 1985). The protein requirements were corrected for the lower content of essential amino acids in grain products and crop protein feeds compared to egg, milk and meat in accordance with the procedure recommended by WHO (ibid.). The chemical content of grain products is assumed to equal the chemical analysis of barley (Spörndly, 1991) and the chemical content of crop protein feeds is assumed to equal the one of soya bean meal (ibid.). In this way, the calculation of grain products and crop protein feeds in purchased feeds can be directly linked to an estimate of how many people could be fed if the same quantity of these products were used as food. Here, I only consider needs and supplies of energy and protein. The aspect of milk as an important source of calcium, e.g., is not considered. Spörndly (1991) provide direct values on crude protein content. Division by 6.25 gives the nitrogen content. Available energy, when used as food for humans' per kg barley and soya bean meal, respectively, was estimated by applying the Atwaters factors (WHO, 1985) to the chemical composition of the mentioned crop products in Spörndly (1991).

3. Results

Figure 1 shows changes over the value taken by biophysical throughputs and economic output in the Swedish economy and milk production sector per labour hour 1965–1990/95.

From 1962 (the reference year) to 1995 the growth on the national level of material throughput measured as TPES and GDP measured as purchasing power parities per labour hour followed each other's quite closely. These trends confirm that increased welfare in Sweden during that period (measured in GDP-terms) was associated to an increase in the material throughput in the milk production sector.

From 1962 to 1990 the growth of material throughput (MJ ME) and economic revenues in milk production in Sweden per labour hour increased in a similar way. Furthermore, they followed the same paths as material throughput and economic output on the national level (Figure 1). Thus, the results in Figure 1 confirm that during this time window, in a growing national economy, the sector of milk production had to increase material throughput per labour hour. This resulted in a corresponding increase in the value of the major output; milk.

Figure 2 shows trends regarding use of different kinds of feeds in purchased feeds to cattle in Sweden expressed in terms of nitrogen influxes 1989–1999.

In the period 1991–1999 the use of crop protein feeds in purchased feeds to cattle increased by a factor 2.7 in Sweden. The major part of this influx was purchased feeds to dairy cows.

Table I shows the results for the 14 variables included in the MCIM for Swedish milk production 1991, 1995 and 1999 in quantitative terms.

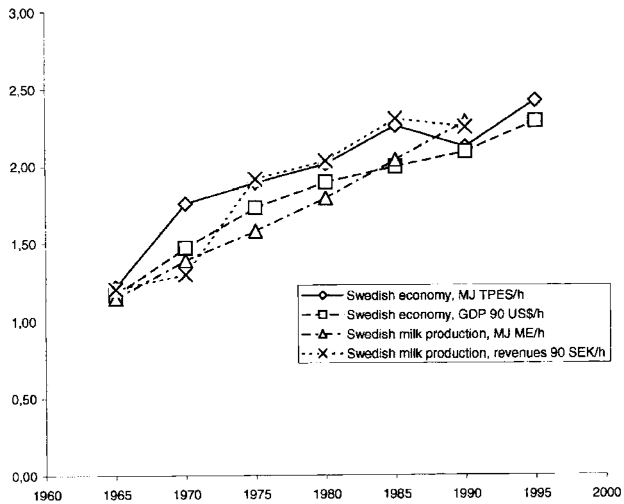
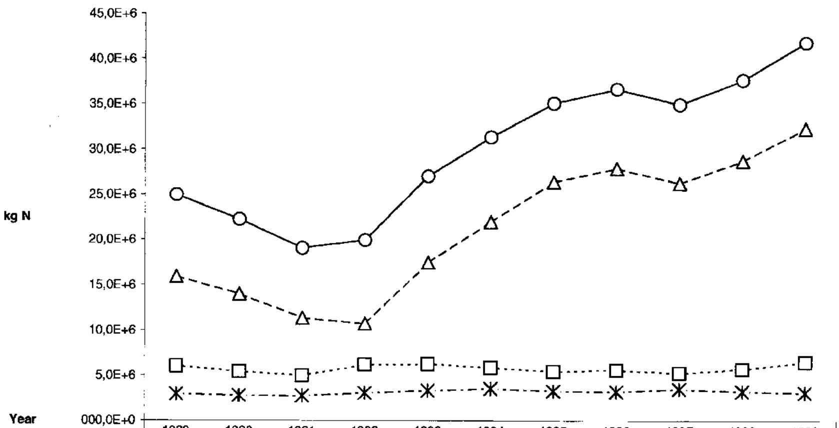


Figure 1. Biophysical throughput in the Swedish economy and milk production respectively, measured as MJ primary energy supply per labour hour (MJ TPES/h) and MJ metabolisable energy per labour hour (MJ ME/h), respectively. Economic output per labour hour in the Swedish economy and milk production respectively, measured as GDP fixed price (GDP 90 US$/h) and revenues milk production fixed price (revenues 90 SEK/h), respectively. For the reference year 1962, all numerical values are 1.0.



	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Grain	6,0E+6	5,4E+6	5,0E+6	6,2E+6	6,2E+6	5,8E+6	5,4E+6	5,6E+6	5,3E+6	5,7E+6	6,5E+6
Protein feeds, crops	15,9E+6	14,0E+6	11,3E+6	10,7E+6	17,5E+6	22,0E+6	26,4E+6	27,9E+6	26,2E+6	28,7E+6	32,3E+6
Sugar feeds	2,9E+6	2,7E+6	2,7E+6	3,0E+6	3,3E+6	3,5E+6	3,3E+6	3,2E+6	3,5E+6	3,2E+6	3,1E+6
Sum	25,0E+6	22,2E+6	19,0E+6	19,9E+6	27,0E+6	31,3E+6	35,1E+6	36,7E+6	34,9E+6	37,7E+6	41,8E+6

Figure 2. Annual nitrogen influxes (kg) to Swedish agriculture via purchased feeds to cattle. 1989–1999. Values are expressed in the form 10 Eta, which equals 1.0×10^{a}

Table II shows the results for the 14 variables included in the MCIM for Swedish milk production 1991, 1995 and 1999 in relative terms.

While the energy use in Sweden increased by 3% from 1991 to 1999, the GDP in fixed prices increased by 21%. This suggests a positive trend on the national level with a substantial increase in the amount of GDP achieved per unit energy used (+17%).

However, in the milk-producing sector, the development was in the opposite direction, with a decrease in the revenues per unit energy used with 25%. The energy use in milk production increased by 9% in the same period, while the revenues decreased by 18%. Looking at the information given in Tables I and II we can notice the peculiar effects of post-industrialisation in terms of economic growth and biophysical intensity of the economic process. An increase in the

TABLE I. Multi-criteria impact matrix of Swedish milk production 1991–1999, quantitative terms.

	1991	1995	1999
1. Energy use Sweden, E+9MJ	2.13	2.16	2.20
2. GDP, E+12 SEK (price–level 1995)	1.65	1.77	1.99
3. Energy use, Swedish milk production, E+10 MJ ME	3.13	3.36	3.40
4. Revenues milk, E+9 SEK (price–level 1991)	10.8	9.00	8.82
5. Grain in PF, E+8 kg DM	2.59	2.82	3.40
6. Crop protein feeds in PF, E+8 kg DM	1.77	3.95	4.71
7. Nitrogen, PF, E+7 kg	1.90	3.51	4.18
8. Costs PF, E+9 SEK (91)	1.99	2.27	2.37
9. Milk, E+9 kg.	3.90	3.90	3.76
10. Meat, E+8 kg	1.11	1.06	1.02
11. Ammonia, PF, E+6 kg	6.94	12.8	15.2
12. Nitrate-N, PF, E+7 kg	1.33	2.46	2.93
13. Food security, energy, E+6 No adults	1.72	2.65	3.18
14. Food security, protein, E+6 No adults	3.58	8.34	10.21

TABLE II. Multi-criteria impact matrix of Swedish milk production 1991–1999, relative terms.

	1991	1995	1999
1. Energy use Sweden, MJ	1.00	1.02	1.03
2. GDP, SEK	1.00	1.08	1.21
3. Energy use, Swedish milk production, MJ ME	1.00	1.07	1.09
4. Revenues milk, SEK	1.00	0.84	0.82
5. Grain in PF, kg DM	1.00	1.09	1.31
6. Crop protein feeds in PF, kg DM	1.00	2.23	2.66
7. Nitrogen, PF, kg	1.00	1.84	2.20
8. Costs purchased feeds, SEK	1.00	1.14	1.19
9. Milk, kg	1.00	1.00	0.96
10. Meat, kg	1.00	0.95	0.92
11. Ammonia, PF, kg	1.00	1.84	2.20
12. Nitrate-N, PF, kg	1.00	1.84	2.20
13. Food security, energy, No adults	1.00	1.54	1.84
14. Food security, protein, No adults	1.00	2.33	2.85

throughput of productive sectors (in this case the fast increase in use of purchased feeds to cattle between 1991 and 1999) is translated into an increased welfare (expressed in GDP-terms) for the whole country, which was not accompanied by a corresponding increase in energy use. This apparent paradox can be explained by the fact that the productive sectors experiencing a major increase in energy intensity per hour of labour (agriculture, manufacturing, energy and mining) are also the sectors that experienced the most dramatic reduction of labour input. Therefore, the ability of moving human activity to leisure, education and work in the service sector – where the energy intensity per hour of labour is much lower – was able to more than compensate such an intensification of the productive process (Giampietro, 2003).

In the milk-producing sector, the increase in energy use occurred at the same time as the revenues from milk decrease substantially. The amount of grain products in purchased feeds increased by 31% (Table II), while the input of crop protein feeds increase by 2.66 times from 1991 to 1999. In price-level 1991, the costs for purchased feeds to cattle increased by 380 million SEK. In physical terms, the amount of milk produced declined by 4% while the amount of meat declined by 8% from 1991 to 1999. Thus, also when measured in physical terms it appears that the increase in the use of grain products and crop protein feeds in Swedish milk production – i.e. the increase of this material influx to the milk-production system – has not resulted in an increased output of valuable products. This confirms the well known law of decreasing marginal return in biophysical processes, according to which we should expect that after passing a certain level of throughput, further intensification of the rate of production no longer pays. In this situation, an increase of material input, which is not associated with an increase in expected output, must result in an increase of unwanted effluxes. In fact, Table II indicates that the increase of nitrogen influxes associated with purchased feeds has not resulted in a corresponding increase of nitrogen associated with valuable products. Rather, it contributed to increased effluxes of ammonia to air and nitrate to water systems by 2.2 times.

The increase in ammonia emissions over the considered period is 8.3 million kg, and the increase in discharges of N in nitrate is estimated to 16 E + 6 kg (Table I).

Finally, the number of adult people whose energy need could have been supplied using the grain products and crop protein used to feed Swedish cattle was estimated to 1.72 million people in 1991 and 3.18 million people in 1999. Within systems ecology, the term ecological footprint has become popular to describe the area of ecosystem, which has the capacity to produce resources and assimilate wastes in relation to a certain economic activity. In a similar way, I suggest, that the number of people whose nutritive needs could have been supplied via the feeds now used for animal production, can be interpreted as a measure of a "social induced ecological footprint", which is associated to animal production. That is, the particular method of production requires appropriating a certain amount of biomass to be used as feed that could have had an alternative use as food. By introducing this indicator I do not want to imply that it is wrong to feed cattle with concentrates. On the contrary, the use of concentrate can improve the economic return of this activity. My goal is rather that of visualizing the existence of a "non-economic cost" that should be considered as relevant when assessing the pros and cons of using concentrates [e.g. soya bean meal] in high-intensive cattle production.

The number of people whose protein needs could have been supplied by grain products and crop protein used as feed to cattle increased by a factor of 2.85 from 1991 to 1999. Thus, the "social induced ecological footprint" of Swedish milk production increased from 3.6 million people to 10.2 million people during that period.

Figure 3 provides a graphic representation in the form of a MCR of the results given in Table II.

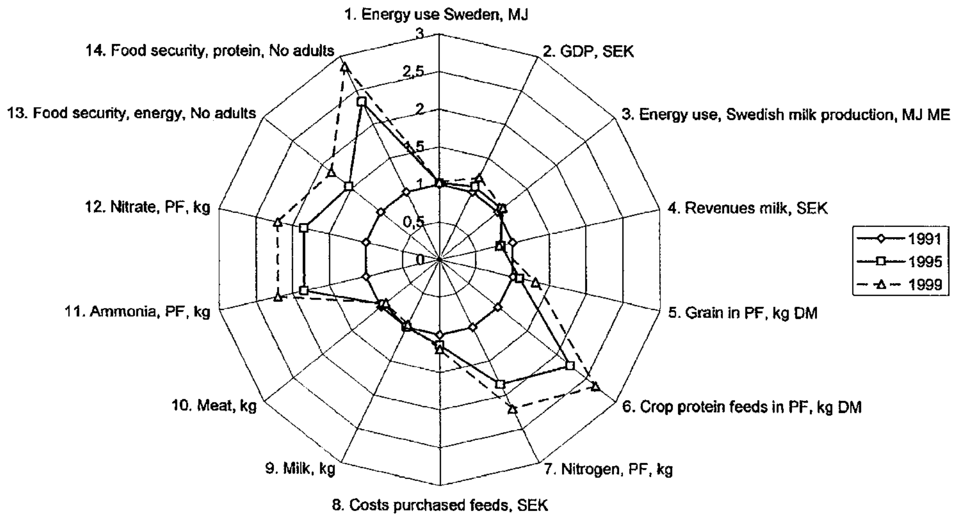


Figure 3. Multi-criteria Representation of impacts of Swedish milk production 1991–1999, relative terms. All variables have value 1.00 for 1991.

The advantage of the MCR in Figure 3 is that it provides a faster way to get an overview of data regarding a large number of parameters – in this case 14 – than when the same data set is presented in the form of a table.

The use of purchased feeds in some animal production branches in Sweden 1991, 1995 and 1999 is presented in Figure 4 together with the production in the same branches.

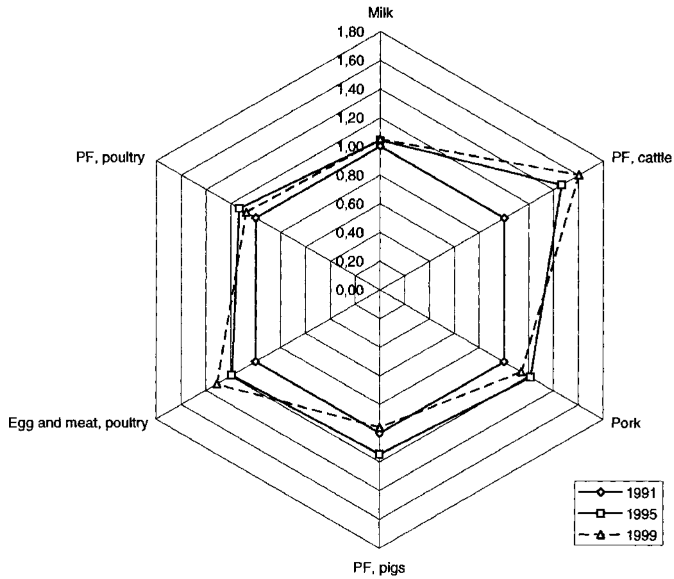


Figure 4. Use purchased feeds in pig, poultry and milk production in Sweden, 1991, 1995 and 1999, and production of valuable products, in physical terms, from the same production branches. Values for 1991 is 1. Own processing of data in Statistics Sweden (2002a).

According to Figure 4 poultry production increased more than 30% from 1991 to 1999, pig production increased about 20%. There was a slight increase in production of meat from cattle, while milk production was constant from 1991 to 1999. There was a minor increase in the use of purchased feeds to poultry, while the use of purchased feeds to pigs was the same in 1999 as in 1991, despite an increase in the production of about 20%. Thus, in both poultry and pig production, an increase in feeding efficiency has occurred. The physical amount of valuable products has in relative terms increased faster than the inputs of purchased feeds.

In cattle production, the trend is the opposite one. The amount of purchased feeds to cattle increased by 60% from 1991 to 1999, with the major increase occurring between 1991 and 1995. On the contrary, milk production remained constant during this period. As mentioned earlier, feeds to dairy cows dominate heavily among purchased feeds to cattle.

Variations in the price per kg milk and purchased feeds, respectively, in fixed prices over the period 1991–1999 are given in Figure 5.

The prices on milk and on purchased feeds have followed the same pattern from 1991 to 1999. Thus, there has been a substantial increase in the use of crop protein

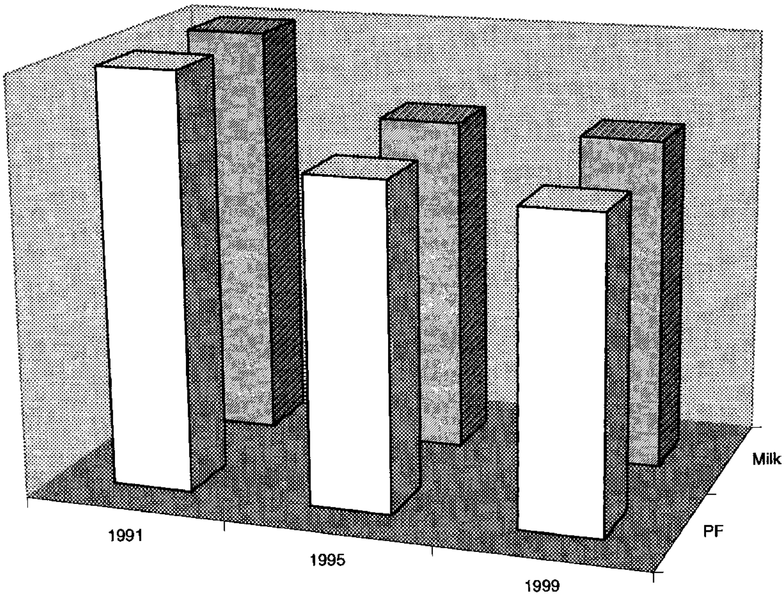


Figure 5. Price per kg milk and purchased feeds, respectively, in fixed prices 1991, 1995 and 1999, Own calculations based on data in Statistics Sweden (2002a) and consumer price indexes from Statistics Sweden, www.scb.se.

feeds in Sweden in purchased feeds to cattle from 1991 to 1999. This has caused a number of impacts detectable in different variables, which are important for sustainable development when considering its social, ecological and economic dimensions. The increase in the use of purchased feeds is exclusive for cattle production. Pig and poultry production has not experienced a similar trend. As the relative price of milk and purchased feeds has followed a quite similar path between 1991 and 1999, the increase in use of purchased feeds cannot be motivated by changed relative prices between purchased feeds and milk.

4. Discussion

The main purpose of this paper is to illustrate the potentiality of the approach of Integrated Analysis, which means (a) the simultaneous handling of indicators developed in different disciplinary fields to cover different and non-reducible dimensions of sustainability; and (b) an approach more related to the procedures adopted by consultants (selecting and tailoring the set of relevant indicators on the special issue dealt with), rather than theoretical academic analysis looking for "the" optimal solution based on the consideration of a standard set of sustainability indicators.

The analysis in this paper focuses on the effort to track vital relations between systems and system levels by applying methods of IA. Researchers at Wageningen University have investigated the capacity of life cycle assessment as a tool to assess the integrated environmental impact of conventional and organic animal production.

For example, in order to illustrate this aim, Boer (2003) provided a pilot study comparing conventional and organic milk production. This is an example of a more detailed analysis of different environmental impacts such as contribution to global warming, acidification, eutrophication, pesticide use, and land use. This approach complements the one presented in this paper.

The presentation of the results illustrated so far and quite clearly that when structuring the problem in this way – the discussion of the trends in the use of purchased feeds in the milk sector of Sweden is actually an excellent case study – it becomes evident that the issue of sustainability entails facing always incommensurable trade-offs. Rather than pretending to look for win–win–win solutions, it is better to acknowledge the need of discussing how to reach compromising solutions.

Coming to relevant information related to the trends in the sector of milk production, there are three relevant observations:

4.1. Nitrogen Losses

One of the major negative environmental impacts from Swedish milk production is the emission of ammonia, contributing to problems such as eutrophication and acidification. Out of the total emissions of ammonia in Sweden in 1999, cattle production contributed 31,900 metric tonnes, i.e. 58% of the estimate of total emissions (Statistics Sweden, 2001). The increase of nitrogen influxes via purchased feeds to cattle 1991–1999 of 22.8 E + 6 kg (Table I) is estimated to result in an increase of ammonia by 8.3 million kg. This corresponds to 15% of total ammonia emissions in Swedish society in 1999 (ibid.).

4.2. Use of Natural Resources

One of the major fractions of renewable resources used in milk production is feeds. In the section of Materials and methods, I presented an approach to estimate the amount of energy and protein supply which is above the requirement of 1999, which was adopted as a benchmark.

The value of 1999 energy requirement for dairy cows in Sweden was 2.88E + 10 MJ Metabolizable Energy (ME), whereas the protein requirement was 2.15E + 8 kg Amino Acids Absorbed in the small intestine (AAT). AAT is the dimension in which the protein requirement of dairy cattle is expressed in Sweden since 1991 (Spörndly, 1991). The system is also used in the other Nordic countries. If the dairy cows in 1991 were fed exactly according to their needs, the above-requirements content of the rations in 1999 was 5.2E + 9 MJ ME and 5.6E + 7 kg AAT. The estimates of energy and protein correspond to 18% and 26% energy and protein, respectively, fed above requirements in 1999.

This paper focuses fluxes of energy (and protein) in feeds to dairy cows in Sweden. However, the amount of e.g. auxiliary energy required is another aspect that must be considered in an analysis of the sustainability of animal production systems. Pimentel (2004) found for another industrialised nation, USA, the following relations. The average fossil energy input per unit energy in protein produced in animal production was 25:1. This was about ten times the corresponding ratio in grain production. The ratio for chicken–broiler production was 4:1, for turkey production 10:1 and for milk production 14:1. As food to humans, animal protein had about 1.4 times higher biological value compared to grain proteins. Nearly all feed protein consumed by broilers was grain, whereas it for milk production was about two-thirds. However, milk production can be based entirely on, forages (ibid.).

4.3. Economic Effects

Costs for purchased feeds to cattle increased by 380 million SEK from 1991 to 1999 (Table I). In terms of the price-level 1999, this equals 440 million SEK. Table I, Figures 2 and 3, provide information implying a substantial increase in influxes of purchased feeds to cattle. As already noted, this increase was not associated with a corresponding physical increase in valuable products (useful output) from the dairy stock herd, or an increase in economic value per physical unit of useful output. Thus, it is possible to calculate the reduction in the economic cost for purchased feeds to dairy cows in 1999, if in that year, the milk sector of Sweden had used the same amount of purchased feeds of 1991. According to the Materials and methods section and using the data about total amounts of purchased feeds to cattle in 1991 and 1999, the difference between the estimates of the costs for purchased feeds in 1999 and in 1991 (= the increase in the amounts used multiplied by the price 1999) is a measure of the potential reduction of the economic costs in milk production in 1999. Such a reduction can be estimated around 1000 Million SEK. In fact, considering that 88.5% and 86.3% of purchased feeds to cattle in 1991 and 1999 (Swedish Board of Agriculture, 1992, 2001), respectively, was classified as feeds to dairy cows, the estimate of the potential for reduced costs for purchased feeds in Swedish milk production 1999 of 840 Million SEK price-level 1999. This corresponds to 1880 SEK. per dairy cow, which corresponds to 23% of the total payments for inputs of own labour and capital in the agricultural sector in Sweden in 1999 (see Statistics Sweden, 2000). Payment for milk constituted 32% of the total income of Swedish farmers in 1999 (ibid.).

This estimate of the potential for reduced feeding costs is slightly higher than the 720 million SEK obtained by Hellstrand (2002). It should be noted that based on the assumptions provided in Material and methods, the requirements of energy and protein through purchased feeds to the Swedish dairy stock herd in 1999 was 1.4% higher and 0.7% lower, respectively, than 1991. Thus, it is quite fair to use the use of purchased feeds in 1991 as reference value in an estimate of the potential to reduce costs for purchased feeds in milk production in 1999.

5. General conclusions

The results obtained in this paper support the conclusions that:

– Tools and approaches developed from the field of consultancy may support transparent analyses of complicated issues such as sustainable development.
– In a scientific context, adoption of the consultancy experience to the procedure of Integrated Assessment and Multi-criteria analysis improves the quality of the analysis. Multi-criteria impact matrix and multi–criteria representation provide a form to present results from analysis of complex issues that helps the communication with stakeholders.
– The classification of capital in the forms social, human, natural and human-made helps a characterization of the issue based on multiple indicators. This structured analysis can show how a particular trend may affect the different objectives associated with sustainable development at different system levels and in relation to the social, economic and ecological dimension, A procedure for integrated assessment based on classification of capital forms, the consultancy approach (tailoring the selection of indicators on the specific situation) and the scientific characterization of the various trade-offs seem to be appropriate for supporting a two-way integration of abstract models and practice.
– The results of this case study regarding the use of purchased feeds in Swedish milk production 1989–1999, especially 1991–1999 suggest that the existing trend has implied an increased appropriation of:
– Natural capital (in terms of land supporting a constant amount of milk production and in terms of waste assimilative capacity);
– Human-made capital (in terms of technology needed to produce more purchased feeds resulting in a constant milk production, and in terms of an increased appropriation of rents from own capital in milk production due to increased costs in production that have not resulted in increased incomes); and Social capital due to the alternative cost of grain products and crop protein feeds used in milk production that otherwise could have supplied human needs.
– Thus, the ecological, economic and social footprint of Swedish milk production 1991–1999 increased while the production remained constant.
– The results of this case study imply a trend towards a transformation of the traditional role of ruminants in Sweden. From transformer of energy and protein in feeds of low or no nutritive value for humans and other mono-gastric animals into valuable products, to transformer of nutrients in feeds that already have a high nutritive value for humans and other mono-gastric. The advantage of this change of role is doubtful, especially when considering the integrated set of goals associated with the concept of sustainable development. This would imply the possibility that restrictions in availability of non-renewable resources as well as renewable resources could imply the need of imposing restrictions on the goal of optimizing the economic criteria. This possibility should be seriously considered when acknowledging the obvious fact that land (in a broad sense) is

a form of renewable natural capital of major importance, as the surface area on Earth, where most ecological and economic processes occur, is fixed.

– The trends considered in this case study in relation to the use of purchased feeds to cattle in Sweden 1991-1999 are in conflict with a number of important sub-objectives associated with the concept of sustainable development. This implies that action should be taken to adjust them.

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Notes

[1] Regarding grain, see e.g. mean barley yields 2000–2004 for Africa, France and Sweden, http://apps.fao.org/faostat/servlet/XteServlet3?Areas = 359&Areas = 361 &Areas = 210Items& = 44&Elements = 41&Years = 2004&year = 2003&Years = 2002 &years = 2001&years = 2000&Format = Table&Xaxis = Years &Yaxis = Countries& Aggregate = &Calculate = mean&Domain = SUA&ItemsTypes = Production.Crops. Primary&language = EN, last accessed March 2005. There is a lack of international statistics regarding ley yields. In the northern agricultural production areas in Sweden (latitude 66°) the annual yield per ha of spring barley and ley is 2800 kg and 6200 kg dry matter (DM), respectively, In the southern production area (latitude 56°), the corresponding values are 5900 kg and 8200 kg DM, respectively (Swedish University of Agricultural Sciences, 1995a, 1995b).

[2] http://www.livsmedelssverige.org/halsa/all-lakto.htm, last accessed April 2005 (in Swedish). The Swedish National Food Administration provides the information at this link: In Sweden 2–3% of the adult population suffers from lactose intolerance, while the figure for our neighbouring country Finland is 15–20%, in the Mediterranean countries is ca. 50% and in areas in Asia up to 100%.

[3] See e.g. the nutritive contents for the same feeds when fed cows and pigs, respectively, in Eriksson et al. (1976); during :1976–1989 this was the official Swedish feeding table.

[4] Presentation of the EME-Cmodel; http://www.konj.se/4.2f48d2f18732142c7fff 5393.html.

[5] See www.scb.se.

[6] See http://www.scb.se/statistik/nr0102bnp1950dial.asp.

[7] See attp.//www.scb.se/statistik/pr0101/pr0101dia7.asp.

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Paper IV

An animal production simulation model and its results in production biological and economic terms when applied on an ecological and a conventional system

by
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Abstract

A simulation model for evaluation of production biological and economic performance of different management strategies in animal production is generated by integrating knowledge and tools in animal production biology and agricultural economics developed and extensively applied during the 20th century in Sweden. The model is a contribution within agroecology and integrative assessment. With modifications to national characteristics the simulation models has general international applicability.

The model is used to estimate inputs needed (all variable costs) for one ecological and one conventional system in physical and monetary terms producing the amount of milk and meat from cattle and pigs consumed in Sweden.

The model supports choices among alternatives with regard to their capacity to fulfil objectives of farmers and society. It is one link in a chain of tools supporting the identification of (i) the role of animal production in sustainable development and (ii) obstacles for the development of this role.

Key words: Animal production, production biology, production economics, simulation model, sustainable agriculture, agroecology.

1 Introduction

In this paper a simulation model of animal production is developed and its results presented. Its focus is traditional production biological and economic effects studied by methods that have been developed and successfully applied within agriculture, especially animal production and agricultural economic sciences and practice, during many decades in Sweden. Early roots to the simulation model within agricultural economics are the contributions by Nanneson et al. (1945), Renborg (1957), and Johnsson et al. (1959). The basic frame of their work is in later time expressed in the production branch calculus and systems for optimising the production on farm level based on these calculus from the Swedish University of Agricultural Sciences (for version 1989 see SLUa,b; for current version see www.agriwise.org). Important roots in animal science are Nanneson et al. (1945), and Wiktorsson (1971, 1979). Methods and results provided by these sources were the core in the huge transformation of the Swedish agricultural, animal production, and dairy production sectors after the Second World War, given the overall objective of economic growth. Thus, the relevance of their concepts has been successfully and extensively empirically and scientifically tested over decades, given the societal context of the time. The paper expresses an effort to further develop and integrate the mentioned contributions within agricultural production biology and economics into a tool that is adapted to the current societal context expressed by sustainable development. The rationale is that the huge empirical application has resulted in analytical structures with the capacity to manage the complexity of farming systems. These methods now need to be updated to the societal context given by a need for sustainable development. The updating process contains two elements: A deepened understanding of the societies demand on agriculture in the sustainability context (Hellstrand et al. 2009[a,b]); and a deepened understanding of the consequences of this demand within the agricultural system (Hellstrand 2006). This paper focuses an internal agricultural perspective, increasing the capacity of agriculture to support a societal traditional growth strategy, as well as a sustainable development strategy. The arguments for such methods in perspective of a sustainable development are further presented below.

Ecological and socioeconomic process constraints affect choices of farming systems (Giampietro 1997). Choices on farm level are dependent on constraints provided by the local ecosystem as well as by the socioeconomic context of the farm (ibid.). In analyses of farming systems there is a need for using biophysical and socioeconomic analyses in parallel to identify the performance of the system in relation to both ecological and socioeconomic constraints. Furthermore, agricultural systems operate on several hierarchical levels, with parallel processes definable only on different spatiotemporal scales. Agricultural effects on different spatiotemporal scales and the complexity inherited in the sustainability concept imply high probability for conflicts between objectives. Sustainability in agriculture has to do with conflict management and with providing adequate support for decision making in the context of complexity. Methods that link actions at one scale to consequences at other scales are a prerequisite for achieving this (ibid.).

Animal production is an important part of the global food system. In 2007, total meat production was 43 kg per capita, meat from pigs and cattle contributed by 62%, total milk production was 102 kg per capita, of which cow milk provided 83%. The production of egg, milk and meat corresponded to 28 g protein per capita and day the same year. Of that, 88% came from milk and meat. As just shown, milk from cows and meat from pigs and cattle dominate in these fractions. The estimates are based on production levels from FAOSTAT (2009); population from GeoHive (2009); and assuming that the protein levels are as follows; in milk 3.4 % (Swedish Dairy Association 2009), meat 13% (Gunnar Malmfors 2009; personal communication) and egg 12.6% (Livsmedelsverket 2009). Animal production has vital direct and indirect economic and environmental effects (FAO 2006). Its influence on global food security is strong. Thus, the understanding of animal production is one piece of information contributing to the understanding of the social, economic and ecological aspects of a sustainable development.

Many studies have been performed during the recent decade, analysing the sustainability of animal production systems in Sweden and internationally.
The purposes of the paper are to

- analyse the level of the production biological and economic basis in some studies of the sustainability of animal production systems in Sweden, Brazil and globally,
- develop a simulation model of animal production based on pigs and cattle through an integration of knowledge and tools in animal production and agricultural economics developed and extensively applied in agricultural sciences and practice in Sweden during the 20th century, and
- use the simulation model for analysis of the outcome in production biological and economic terms when producing the same amount of milk and meat from cattle and pigs that was consumed in Sweden in 1989 from one conventional and one ecological production system.

There are three reasons to locate the analysis to 1989. (i) The major work in constructing the model was done in spring 1991. When taking up the model in 1999 a major question was the accurateness of the model, given that the system of feeding standards in Sweden had undergone three major changes from 1991 to 1999. In order to evaluate whether this was a minor or major problem for the relevance of the model, major trends in Swedish milk production was analysed. The results were presented in Hellstrand (2006). (ii) Those trends showed a substantial decline in nitrogen efficiency in Swedish milk production from 1991 to 1999 causing major sustainability costs in economic, ecological and social dimensions from individual cow to global food supply level, i.e. during the time of three major changes of feeding standard and feed evaluation systems. Hellstrand (2008) reports the results from an investigation of the causes behind these increasing sustainability costs on the behalf of the Swedish Environmental Protection Agency. (iii) That showed that the changed system of feeding standards in combination with the way they were applied at farm level, explained substantial parts of the increasing sustainability costs of Swedish milk production during the 1990s. Substantial internal logic conflicts were detected, as well as it was found that the level of scientific probing was low. Thus, the changed energy standard in 1995 was based on a student work, while the changed protein standard the same year was based on an internal PM at a department at the Swedish University of Agricultural Sciences, which no longer can be found (ibid.). Thus, updating the simulation model to the feeding standards of current time would not improve its quality rather decrease it.

The following sections present the sustainability context of animal production in Sweden and globally; results from an analysis of the gap between the knowledge level expressed in some studies of the sustainability of animal production with regard to agricultural and animal production sciences compared to established knowledge within these fields; material and method, and results for the animal production simulation model; discussion; and conclusions.

2 Sustainability significance of animal production

The importance of a fair understanding of animal production systems in the context of a sustainable development is elaborated below.

I. Of the total area of arable and pasture land used in Sweden in 2007, 58% produced forages and pasture and 20% barley and oats (Statistics Sweden 2008), hence, crops including forages and pasture mainly used as feeds were produced on 78% of agricultural land. One of the major negative environmental impacts from Swedish milk production emanates from the emission of ammonia, contributing to eutrophication and acidification. Of the estimated total emissions of ammonia in Sweden in 2005, cattle production contributed 30 000 metric tonnes (Statistics Sweden 2007a), i.e., 57%. Of total incomes to the Swedish agricultural sector in 2006 from agricultural products, milk provided 27%, meat from pigs 10% and meat from cattle 11% (Statistics Sweden 2008). Hence, cattle and pigs in Sweden in 2006 provided 48% of total incomes from agricultural products in Swedish agriculture.

II. From I follows that animal production provides a substantial part of the total demand on crop production, which affects the economic and environmental profile of crop production.

III. Hellstrand (2006, 2008) analysed temporal trends in Swedish cattle production 1989-1999. From 1991 to 1999 he found a substantial increase in the use of purchased feeds to cattle where the increase in use of crop protein feeds dominated. That had major negative impacts on sustainability objectives in the social, economic and ecological dimensions, such as global food supply, farmer incomes and emissions of ammonia

(Hellstrand 2006 provide the estimates). Regarding nitrogen leaching the results in Hellstrand (2008) imply increased nitrogen leaching from agricultural soils by around 8 million kg, after considering the retention of around 6 million kg which will add to the eutrophication of the seas. This is 14% of total annual discharges from agricultural land. The estimated increased in pressure on tropical forests was 160 000 ha (ibid.). Following the route of calculations in FAO (2006) this on the margin results in an increase in contribution to climate change by 112 million ton carbon dioxide, which are twice the Swedish annual emissions (see SEPA 2009). The welfare costs of this contribution to climate change is 168 billion SEK (Swedish Crowns, around 17 million €), if applying the price on carbon dioxide emissions used by Swedish authorities when estimating external costs of emissions (SIKA 2002).

No economic reasons for these trends could be found (Hellstrand, 2006). They were to a major part explained by changed feeding standards and the way they were applied (Hellstrand, 2008). A concern is that a common new feeding standard system, the NorFor-system, is now being launched in the Nordic Countries except Finland, where available data suggest that the feeding efficiency may decrease, that way increasing the sustainability costs from farm economic to global food security level presented above (ibid.). Different findings suggest that the situation and trends in Sweden are not unique, rather they reflect a common international situation (ibid.).

IV. A special aspect achieving wide attention is the methane-emissions of ruminants. FAO (2006) estimated that livestock are responsible for 18 percent of total greenhouse gas emissions, a bigger share than that of transports. One significant contribution is through the methane emissions from ruminants. Although important, that is not the major concern for FAO. Due to trends regarding feeding, production, level of industrialised rearing systems, FAO expressed a deeper concern regarding global pig and poultry production. About one third of the estimated total climate change impact of animal production is related to deforestation linked to increased production of feeds like soya. FAO concluded that pig and poultry production are more important driving forces.

Aspects I – IV express a demand on a tool that from a solid base in agricultural sciences, support analysis of measures increasing the contribution to a sustainable development from animal production.

3 Studies of sustainability in animal production

Here, the knowledge gaps between common knowledge in agriculture regarding production biology and economy in milk production and the way it is presented in studies that have their methodological foundations mainly within the engineering sciences are evaluated.

3.1 The FPD-ALBIO-model

The purpose of the Food Phytomass Demand-model (the FPD-model) (Wirsenius 2000; 2003a,b), later called the ALBIO-model, is to identify where in the global food supply system efficiency-gains can be made. A (i) crucial element is the conversion efficiency measure introduced, which measures the gross energy (GE) in food consumed through GE in the plant biomass appropriated. It is assumed that high such efficiency-ratios denote efficient food production pathways, while low such ratios show the opposite. Another crucial element (ii) is that the topsoil layer in agricultural land is located outside the system borders. (i) and (ii) decreases the relevance of the developed measures:

- GE is not a relevant dimension of the numerator in an efficiency-ratio between fulfilment of human nutrition-physiological requirements through appropriation of the renewable natural capital agricultural land (see, e.g., WHO 1985). The nutritive value of poisonous mushrooms, wheat, or oil is not expressed by their GE-content; therefore this is not a suitable dimension of the numerator in a conversion efficiency measure of food system.
- GE is not a relevant dimension of the denominator in such an efficiency-ratio, as different types of agricultural land and crops can produce quite similar amounts of gross energy in phytomass, while their nutritive value may differ widely between crops, and between different paths through, e.g., animals, in the transformation to high quality human food (Hellstrand et al. 2009[a]; McDonald et al. 1981; NRC 2001; WHO 1985).
- Around 50% of the biomass appropriated in the production of food is recycled to the fields in the form of manure and crop residues (Wirsenius, 2000). This enhances the productivity of the topsoil layer through positive effects on organic content and nutritive status. The condition of the topsoil layer in global crop and pasture land is crucial for global food security. As the top soil layer is not included in the FPD-ALBIO-model, the significance of these refluxes for long term soil fertility and food security cannot be detected. Therefore, provided estimates of inefficiencies in the global food supply system due to these refluxes (ibid.) is substantially biased due to the set assumptions.

In conclusion, the FPD-model is abstracted far away from human nutritional and agroecological context. The relevance for the development of agricultural systems that fulfils the objectives of a sustainable society as expressed by, e.g., UN Millennium Development Goals (UN 2008), the Millennium Ecosystem Assessment (2005), and OECD (2001) is limited.

3.2 Life-cycle assessment

FOOD 21 was a major research program in Sweden regarding sustainable food production in 1997-2008 (FOOD 21 2009). LCA was a major tool in their analysis of environmental sustainability (see, e.g, Cederberg and Flysjö 2004; Gunnarsson et al. 2005).

The way FOOD 21 treated the production biological and economic aspects in their analysis of milk production, reflects to a substantial part how the research program treated these aspects in relation to the total Swedish agricultural sector. A synthesis report (Gunnarsson et al. 2005) presented the sustainability profile of two future scenarios for milk production, obtained by the application of LCA. One is similar to current conventional production system, and the other to ecological milk production, called conventional and ecological in the following.

A detailed analysis of assumed production levels and feed consumption levels shows disturbing facts. The conventional cows are fed energy approx. 10% below the official feeding requirements while the ecological ones are fed 35% above. The amount of feeds used per kg milk is 48% higher in the ecological system. As the environmental impact and the economic result is a function of the feeding efficiency, this severely distorts the environmental and economic analyses.

Cederberg provided two studies of the environmental performance of milk production. One was a contribution within FOOD 21 (Cederberg and Flysjö 2004). In this study 23 farms in the south-western parts of Sweden were investigated, of which 6 had ecological production. Cederberg et al. (2007) followed the same analytical approach in a study of milk production in the northern parts of Sweden. Here 23 farms were studied, of which 7 had ecological production. The consumption of feeds produced on the farm (forages, pasture and grain) was estimated by the amount of diesel consumed as noted in the accounts of the farms. Typically 50-75% of the feeds are produced on the own farm. This measurement point is too distant from the parameter in the real system estimated, the consumption of feeds produced on the farm considering their nutritional content, to be relevant. For example, due to taxation rules, diesel that is declared to be used in agriculture, can in reality be used for the cars of the farm family, if so, this would increase the estimate of the consumption of feeds. Data regarding purchased feeds were based on the accounts of the farm. Thus data regarding the animal production system were obtained by indirect measurements, and not on data on the animal production system, which quite easily could have been obtained through the management tools in milk production most farmers uses.

In both studies the influxes of nitrogen through purchased feeds were substantially lower on the ecological farms than on the conventional ones. This gives lower nitrogen content in manure. Lower values give lower emissions of ammonia, contributing to acidification and eutrophication; N_2O, a powerful climate change gas; and nitrate leaching, contributing to the eutrophication of seas. These impacts are significant. This information was not used: Cederberg and Flysjö (2004) and Cederberg et al. (2007) estimated the nitrogen content in manure for both conventional and ecological systems through the STANK-program from the Swedish Board of Agriculture. That program provides estimates of nitrogen in manure from dairy cows, based on standardised feeding rations for conventional cows from1996, assuming a significantly higher protein feeding than the official standards. Thus, the emissions of ammonia and of N_2O from ecological farms in these studies from 2004 and 2007 are based on feeding rations for conventional farms produced about ten years earlier, with a substantial over-feeding of protein (Hellstrand 2008). As ecological farms uses much less protein feeds, this results in substantially too high estimates of their contribution to climate change, acidification, and eutrophication. Not surprisingly both studies found no differences in contribution to climate change and acidification between ecological and conventional farms, and higher contribution to eutrophication at the ecological farms, where this reflects the anomaly introduced by the chosen method as discussed.

In conclusion, in the analysed applications of LCA the analyses have been abstracted so far away from the animal production system that the relevance for a sustainable development is restricted. The way the animal production system has been treated in production biological terms compared to common knowledge within animal production shows such gaps, that the relevance of these studies for the development of agricultural systems that fulfils the objectives of a sustainable society as expressed by UN Millennium Development Goals (UN 2008), the Millennium Ecosystem Assessment (2005), and OECD (2001) is limited.

3.3 Potential to integrate milk and sugarcane production in Brazil

Sparovek et al. (2007) analysed the possibility to expand sugarcane ethanol production in Brazil through a model in which sugarcane and milk production was integrated. The objective was to see if that simultaneously could provide local socio-economic and global environmental advantages, where the environmental aspect focused was climate change.

They concluded that the expansion model was feasible at current market conditions and should have good prospects for complying with sustainability criteria within various certification schemes presently under development. A case study in Pontal do Paranapanema region (state of São Paulo, Brazil) illustrated the model in agrarian reform settlements (ibid.). Egeskog and Gustafsson (2007) provide extensive information about the case-study.

The information (ibid.) is that

- Positive socio-economic effects are achieved assuming that
    - the ethanol plant produces a full ration feed from by-products from the ethanol production, and sell it to the farmers that combine sugarcane and milk production for half the market value the coming 25 years,
    - the farmers increases the milk production with a factor 7 up to 105 cubic meter of milk per year to be milked by hand, with no payment for the extra work, and
- positive climate change effects will occur assuming that
    - an increase in feed consumption by a factor 3 for an increase in milk production by a factor 7 does not affect land use,
    - the increase in methane emissions by a factor 3 due to the increase in feed consumption for 7 times more milk produced results in a decreased climate change effect (sic!).

The analyses has been abstracted so far away from the animal production system studied, that the relevance of its results for the development of agricultural systems that fulfils the objectives of a sustainable society as expressed by UN Millennium Development Goals (UN 2008), the Millennium Ecosystem Assessment (2005), and OECD (2001) is limited.

4 Material and method

4.1 The simulation model

The core of the simulation model is the dairy cow subsystem. Thus, the following presentation is focused on this subsystem.

The simulation model is the product of an integration of

- agricultural economics regarding production branch calculus and the system to integrate such calculus in the analysis of the performance on the individual farm from the Swedish University of Agricultural Sciences (SLU 1989a,b; 2009) and
- animal nutrition theory and practise (Hellstrand 1988, 1989; Spörndly 1989; Wiktorsson 1971, 1979).

Production branch calculus are tabulated point estimates of production functions. Simulation of effects in production biological and economic terms of, e.g., feeding rations, is not possible. Hence, for some production branches in the simulation model, sub-models called feeding-plans are constructed. They express the production functions that produced the production branch calculus. In the feeding plans the amount of feeds needed and the biological production achieved are estimated as a function of nutritive values of feeds and of feeding rations, as well as of animal dependent factors such as breed, size, sex and lactation phase. Via the feeding plans the impact on dependent production biological and economic parameters of changes in independent production biological variables is simulated.

The simulation model is applied on one conventional and one ecological animal production system producing the same amount of meat and milk from cattle and pigs as was consumed in Sweden in 1989. The conventional and the ecological production system are both products of the structure of the simulation model, in interaction with the guiding principle in the production strategy chosen in each system. In both systems, the first choice is to produce the assumed amount of meat and milk. In the conventional system, the second choice is to maximise profit given market-based prices of capital and labour. In the ecological system, the second priority is to produce the assumed amount of meat and milk (almost) exclusively using forages as feed. In both systems, an equal and high technological level is applied. Table 1 presents the production branches in the two systems and the production branches for which feed-plans have been developed. If nothing else is noted, values of production biological and economic parameters are the ones as in SLU (1989a).

Table 1. Production branches in one conventional and one ecological animal production system; the products of the production branches; and the production branches with feeding plans embedded

Production branch	*Products out from the farm* Milk production	Meat production	*Products used on the farm*:	Feeding plan included
Ecological				
Dairy cows[1]	XX	X	Calves: heifers and steers	X
Dairy breed heifers		X	Cows	X
Dairy breed steers		XX		X
<u>Remaining meat need</u>				
Beef breed cows[2]		X	Calves: heifers and steers	
Beef breed heifers		X	Cows	X
Beef breed steers		XX		X
Conventional				
Dairy cows[1]	XX	X	Calves: heifers and steers	X
Dairy breed heifers		X	Cows	X
Dairy breed steers		XX		
<u>Remaining meat need</u>				
Sows		X	Piglets: fattening pigs and recruitment gilts	
Fattening pigs		XX		
Recruitment gilts		X	Sows	
Sires				

[1]Swedish Read and White, [2]Charolais

In the production branches with feeding plans, the amount of feedstuffs and the production (milk or meat) are calculated as a function of the nutritive value of the feeds used, and of appropriate animal factors such as sex, breed, size and lactation phase. The other inputs are from the Swedish University of Agricultural Sciences (SLU, 1989a). For the others, no modifications were made to the production branch calculus from Swedish University of Agricultural Sciences (ibid.). XX denotes main product, X co-product.

5 Results

5.1 The structure of the simulation model

Fixed amounts of meat and milk are produced. The average milk yield per cow is estimated as a function of the nutritive values of feeds and feeding strategy chosen. From this yield, the number of cows needed to produce the required amount of milk is calculated. The recruitment-rate in milk production determines the number of recruitment heifers to produce. A co-product from the cows are calves, another is meat from slaughtered cows. Female calves not needed for recruitment and steer calves are used for meat production. This route of calculation estimates the number of the different animals in each production branch within the dairy cow subsystem. From the average carcass weight at slaughter and the number of animals slaughtered, the amount of meat from heifers, steers from the dairy cow stock and slaughtered cows is estimated. This is the meat-production which directly or indirectly emanates from the dairy cow herd. By multiplying the number of animals by the inputs needed per animal, the inputs behind the meat and milk production in the dairy cow subsystem are obtained. This is the structure of the dairy cow subsystem in both the ecological and the conventional system.

In the conventional system, the remaining demand for meat is supplied via pigs. Here, sows produce piglets, which are used either in the production of fattening pigs or recruitment gilts. The numbers of sires and fattening pigs are a function of the number of sows, as is the number of recruitment gilts. Thus, the amount of meat, which is produced directly and indirectly per sow and year, can be estimated via information of the number of animals in each category per sow and the meat production per animal and year within each category. By this path, the amount of meat produced from fattening pigs, sows, gilts and sires expressed in kg per sow and year is estimated. The value obtained is used to estimate the number of sows needed to fill up the remaining meat demand in the model. With the number of sows fixed, the number of sires, gilts and fattening pigs, respectively, is determined. By multiplying the number of each type of animal by the inputs needed per animal in the production branch calculus, the inputs supporting the pig production system are obtained. This is the meat-supplementing subsystem.

In the ecological system, Charolais cows are used instead of pigs in the meat-supplementing subsystem, assuming that this will maximise the use of forages in the production system, thus, maximising the use of feeds from crops that, given Swedish conditions, has high production levels without inputs of pesticides and mineral fertilisers. Here artificial insemination is used, thus no bull production branch calculus is included. The number of Charolais animals in each production branch is estimated in the same way as the number of pigs in the pig subsystem. Here the production branches are cows, steers and heifers. The Charolais heifers are either used for recruitment or for meat production. These are "brought up" in the same way, thus one production branch calculus is used, as delivers the products recruitment heifers and meat. The same is the case for the dairy heifer in the ecological system and the recruitment gilt in the conventional system.

5.2 In- and outputs

Tables 2-5 summarise the results of the simulation model when applied to the conventional and the ecological production systems. Table 2 shows some production biological characteristics of the two systems. Table 3 presents the number of animals, production per animal and price of animal products in the ecological and the conventional animal system. Table 4 provides the amounts of different feeds used in the two production systems. Table 5 presents inputs in the two systems in monetary terms and outputs in physical and monetary terms.

Table 2. Some production biological characteristics in the different animal production branches in an ecological and a conventional farming system

	MJ/kg DM[1]	Decrease kg FCM[2]/ month	Growth kg/day	MJ/kg growth of carcass weight	Repr. no of offspring/ dam and year	Births per year and dam	Kg feeds per kg live-weight growth
Ecological							
Dairy cow	10.8[3]	0.37[4]					
Dairy heifer	10.3		0.79	179			
Dairy steer	10.9		1.13	133			
Beef breed cow	10.0				0.95		
Beef breed heifer	10.0		0.6[5]	229			
Beef breed steer	11.0		1.28[5]	134			
Conventional							
Dairy cow	12.1[5]	2.2					
Dairy heifer	10.3		0.79	179			
Dairy steer			0.91	88			
Sow					21		
Gilt							
Sire							
Fattening pigs						2.8	2.8

[1]MJ = MegaJoule metabolisable energy, DM = Dry matter.

[2]FCM = Fat corrected milk.

[3]At peak lactation, first three months after calving.

[4]After peak lactation, i.e. after the three first months after calving. During peak lactation, no decrease in daily milk yield is assumed to occur.

[5]After weaning at approx. 6 months.

Table 3. Number of animals, production per animal and price of animal products in an ecological (Eco) and a conventional (Con) farming system

	No of animals, E+6		*Production per animal, kg*		*Price, SEK[1] per kg*	
Production; product	Eco	Con	Eco	Con	Eco	Con
Dairy cows; milk	0.63	0.36	5 277	9 185	2.82	2.82
Dairy cows; meat	0.63	0.36	91	94	26.32	26.64
Dairy heifers; meat	0.30	0.13	72	0	30.08	
Dairy steers; meat	0.30	0.17	300	120	30.08	31.86
Beef cows; meat	0.78		54		26.32	
Beef heifers; meat	0.36		154		30.78	
Beef steers; meat	0.36		360		30.78	
Sows; meat		0.20		67.5		7.12
Gilts; meat		0.15		26		14.85
Sires; meat		0.01		84		8.68
Fattening pigs; meat		4.19		78		14.85

[1]Price-level 1989. At that time, the value of 1 US$ was approx. 6.5 SEK (Swedish crowns).

Comment: It is assumed that the prices for meat and milk produced in the two systems are the same. In reality, consumers are often willing to pay more for ecological products.

Table 4. Feeds used in the animal production in one ecological and one conventional farming system in dry matter

	Ecological		*Conventional*		*E-K*
Type of feeds	E+6 kg	%	E+6 kg	%	E+6 kg
Forage	9 739	86.6	1734	40.1	8 005
Straw[1]	1 344	12.0	277	6.4	1 067
Grain	35	0.3	1646	38.0	-1 611
Purchased feeds[2]	125	1.1	672	15.5	-547
Total	11 243	100.0	4329	100.0	

[1]Including straw for bedding.

[2]Mineral feeds and some concentrates (mix of protein feeds, mineral feeds, fat and by-products from sugar industry).

Table 5. Inputs and outputs in animal production in one ecological (Eco) and one conventional (Con) farming system in kg (E+6) and in SEK (E+6)[1] and the difference in economic performance between the systems

	Kg		*SEK*		
	Eco	**Con**	**Eco**	**Con**	**Eco - Con**
Outputs					
Milk	3 314	3 314	9 346	9 346	0
Meat from cattle	400	55	11 818	1 577	10 241
Meat from pigs	0	345	0	5 164	-5 164
Sum outputs			***21 163***	***16 086***	***5 077***
Inputs					
Recruitment			53	211	-158
Delivering fee			0	0	0
Breed-premium			0	0	0
Feed preparation			1	14	-13
Purchased feeds			579	2 366	-1 787
Farm produced feeds			9 251	4 364	4 887
Health/production control			131	122	9
Artificial insemination			528	209	319
Electricity/oil			0	147	-147
Risk/ insurance			29	36	-8
Death			87	84	2
Diverse inputs			792	383	409
Interest; animal capital			1 060	305	755
Interest; circulating capital			599	171	428
Buildings, maintenance			1 791	1 194	598
Buildings; depreciation and interest on building capital			7 787	5 041	2 746
Labour			6 635	3 220	3 415
Sum inputs			***29 322***	***17 867***	***11 455***
Contribution to common costs on firm-level			***-8 159***	***-1 781***	***-6 378***

[1]Price-level 1989. At that time, the value of 1 US$ was approx. 6.5 SEK (Swedish Crowns).

6 Discussion

6.1 Production biological and economic results

The net contribution from milk production to the economic result on farm level was in the conventional system 377 SEK per cow and year, and in the ecological system –5 727 SEK. Here, costs for labour and buildings are considered. The same milk price is assumed. The average production was 9 185 and 5 277 kg FCM, respectively (Table 3). In 2006, 0.50 SEK was paid extra per kg ecological milk, and 1 600 SEK was paid extra per ecological cow (SLU 2006). Considering this premium for ecological production, the net contribution on farm level from the ecological cow is – 1 488 SEK.

In SLU (1989a), the highest production level was 7 100 kg FCM/cow, resulting in a net contribution on farm level of – 3 151 SEK/cow and year, after correction to the same forage-price as in the simulation model. Thus, the economic result in the simulation model was 3 528 SEK higher per cow than the best alternative in SLU (ibid.). The results imply that the manager in the conventional system was quite successful. Her/his first priority was to produce milk, the second to maximise the profit.

The answer whether the ecological manager has been successful in relation to her/his objectives cannot yet be delivered. In terms of the fraction of forages in the feeding rations she/he has been successful, the feeding rations consisted of close to 100% forages (Table 4). Whether this contributed to a production system that more efficiently delivers the goods and services demanded in a sustainable development, cannot be answered before an extended analysis has been applied. The results delivered are needed inputs in such an analysis.

6.2 Contributions towards operationalising a sustainable agriculture

The simulation model quantifies inputs and outputs needed to produce a fixed amount of meat and milk from cattle and pigs in production biological and monetary terms. It can follow causal chains from low physiological levels to impacts on national level in terms of the demand on crop products from animal production, and the economic result in animal production. It also provides the opportunity to analyse economic impacts on single farm-levels of choices on the national scale, affecting prices on products or subsidies to different production branches. Thus, it supports analysis of possible adoption strategies on the micro-level of measures taken on the macro-level.

The analysis of alternative studies of sustainability in animal production systems in Sweden, Brazil, and on global scale, clearly shows that their relevance were severely distorted due to too low quality in their design of the animal production systems. Their results are to substantial degree artefacts, due to the gap between the knowledge level regarding animal production they expressed, and common knowledge within the field.

Since 1996 a model called Totfor has dominated the construction of the production biological basis in national analyses of the ecological and economic performance of milk production in Sweden. It provided the basis for

- a major study of the sustainability in Swedish agriculture performed by the Swedish Environmental Protection Agency (Naturvårdsverket 1997),
- the dairy cow subsystem in the STANK program (Janne Linder, personal communication, January 2007), a program with the ambition to support measures

decreasing nutrient leaching from individual farms provided by The Swedish Board of Agriculture, and for

- a study regarding the possibilities to increase the amounts of feeds to Swedish milk sector produced in Sweden and/or in Europe performed by the Swedish Dairy Association (Emanuelson et al. 2006).

Totfor through the STANK-program has a substantial impact on official statistics regarding national nitrogen balances and ammonia emissions (Statistics Sweden 2007b, 2009), as well as on measures taken on individual farm level to increase nitrogen efficiency in the program Focus on Nutrients (Swedish Board of Agricultural 2009). Focus on Nutrients is the largest single undertaking in Sweden to reduce losses of nutrients to air and water from livestock and crop production (ibid.). Therefore, Totfor has a substantial influence on measures to increase the sustainability of Swedish agriculture, as expressed by the system of national environmental quality objectives regarding acidification and eutrophication. It is important that it provides relevant results.

Figure 1-4 are based on the results that Totfor provided in the most recent of the applications mentioned. Figure 1 shows a substantial difference in milk production during lactation months 1-4 between the two alternatives “Europe” and Sweden”, which is totally eliminated in lactation months 5-10. That is not in agreement with common knowledge within dairy production science and practice. Higher production levels during early lactation result in higher production during the rest of the lactation.

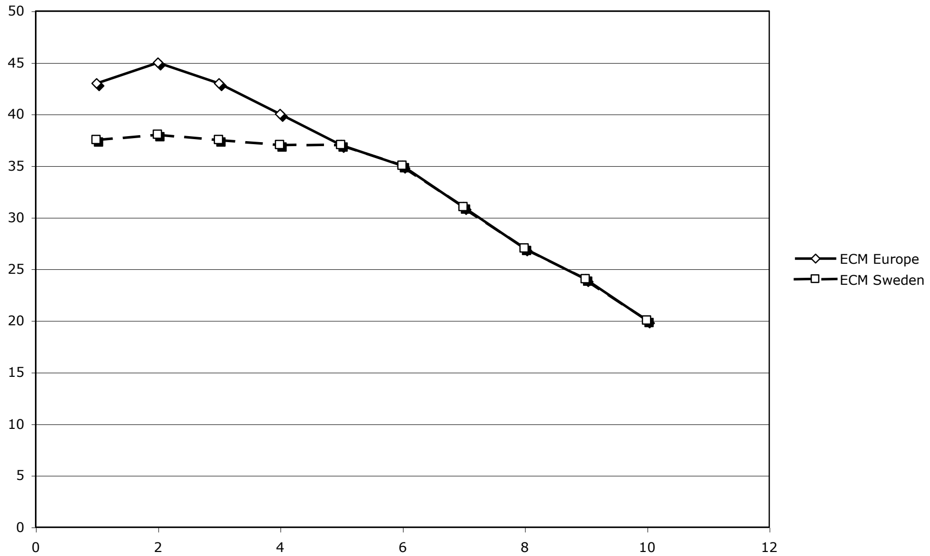
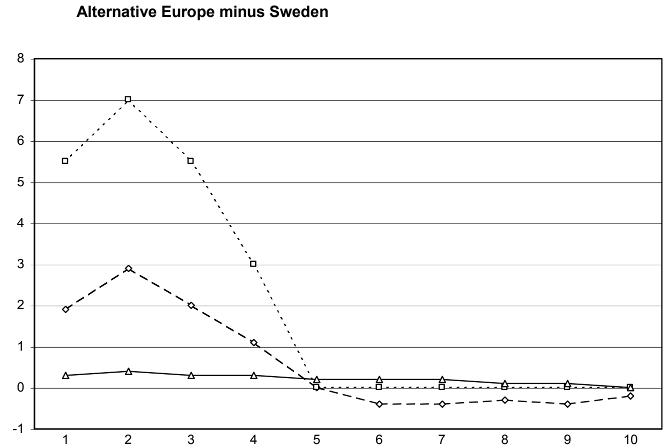


Figure 1. Lactation curves lactation months 1-10 produced by Totfor in two alternatives in Emanuelson et al. (2006).

Figure 2 shows the difference between alternatives “Europe” and “Sweden” in total consumption per cow and day; production of milk (ECM) per cow and day; and energy concentration of the daily feeding rations during lactation. Here, a higher milk production for "Europe" during lactation months 1-4 is accompanied by a higher energy concentration of the feeding ratio and higher feed intake. In lactation months 5-10 higher energy concentration for "Europe" results in lower feed intake, where the combined effect is identical milk production. For the total lactation, alternative "Europe" is assumed to produce 641 kg ECM more, with 7 kg milk per day more as most. This implies that 1 kg milk more per day during top lactation in total provide around 90 kg milk more during the whole lactation. A rule of thumbs in extension services says that one kg milk more in top yield per day results in around 200 kg more in total production during lactation. Burstedt (2001, pers. communication) investigated the impact on peak lactation and total production of different levels of energy supply in MJ metabolizable energy (ME)/kg FCM during lactation weeks 4-12. In lactation weeks 13-40 they were fed 5 MJ ME/kg FCM. He found a response of around 260 kg ECM more for the whole period of one kg more in top production per day, where 77% of the variation in total production was explained by peak yield. The lactation curves produced by Totfor (Figure 1 and 2) disagree with these findings.



	1	2	3	4	5	6	7	8	9	10
Consumption, kg dry matter per cow and day	1,9	2,9	2	1,1	0	-0,4	-0,4	-0,3	-0,4	-0,2
Production, kg ECM per cow and day	5,5	7	5,5	3	0	0	0	0	0	0
Energy concentration, MJ/kg dry matter	0,3	0,4	0,3	0,3	0,2	0,2	0,2	0,1	0,1	0

Lactation month

Figure 2. The difference in lactation months 1-10 between alternative "Europe" and "Sweden" in total consumption per cow and day, production of milk (ECM) per cow and day, and energy concentration of the daily feeding rations as estimated by Totfor in Emanuelson et al. (2006).

The results in Figure 2 regarding impact on milk yield conflict the ones of Bertilsson (2005). In a feeding trial comparing feeding rations based entirely on Swedish feedstuffs and a traditional one including soya meal, average milk yield were 34.6 kg ECM in both groups. Thus, no difference in production was shown.

Figure 3 shows the difference in milk yield; total consumption; energy concentration of the feeding rations; and consumption related to live-weight for two other alternatives produced by Totfor in the same study (Emanuelson et al. 2006). When comparing Figure 3 with Figure 2, something interesting emerges. Figure 2 shows a positive relation between energy concentration, feed intake and milk production during lactation month 1-4. For the alternatives compared in Figure 3, differences in feed intake and in energy concentration result in identical milk production. Instead a negative relation between energy concentration and feed intake is expressed. The reason why Totfor in the same study in some comparisons shows that a higher energy concentration result in a higher feed intake and milk production, while for others it results in a lower fed intake with no impact on milk production is not provided.

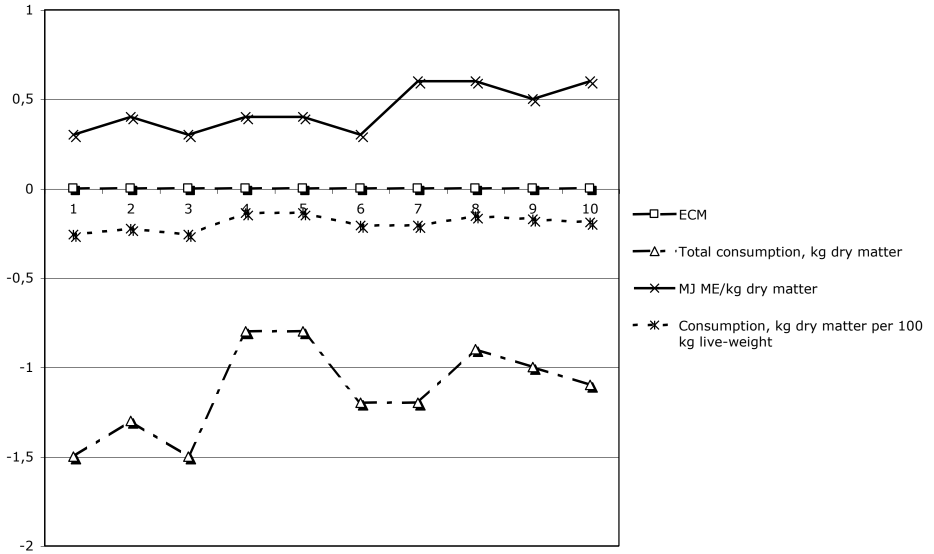


Figure 3. The difference in lactation months 1-10 between alternative "Skåne" with maize-silage, grain and protein concentrate; and "Västergötland" with grass silage, and complete concentrate mix regarding milk production (ECM) in kg per cow and day), dry matter intake (Total consumption, kg dry matter) per cow and day, energy concentration of daily feed rations (MJ ME/kg dry matter), and consumption as kg dry matter per 100 kg live-weight as estimated by Totfor (Emanuelson et al. 2006).

Figure 4 shows the total consumption of feeds for four alternatives, with the assumed limit in consumption capacity of 3.8 kg dry matter per 100 kg live-weight for the alternatives "Europe" and "Sweden" that the study set (Emanuelson et al. 2006, p. 19). In lactation month 2, the consumption in alternative "Europe" is 4.5 kg, i.e., 0.7 kg more than the set limit. The argument why the study introduces a limit, and then not follows it, is not provided.

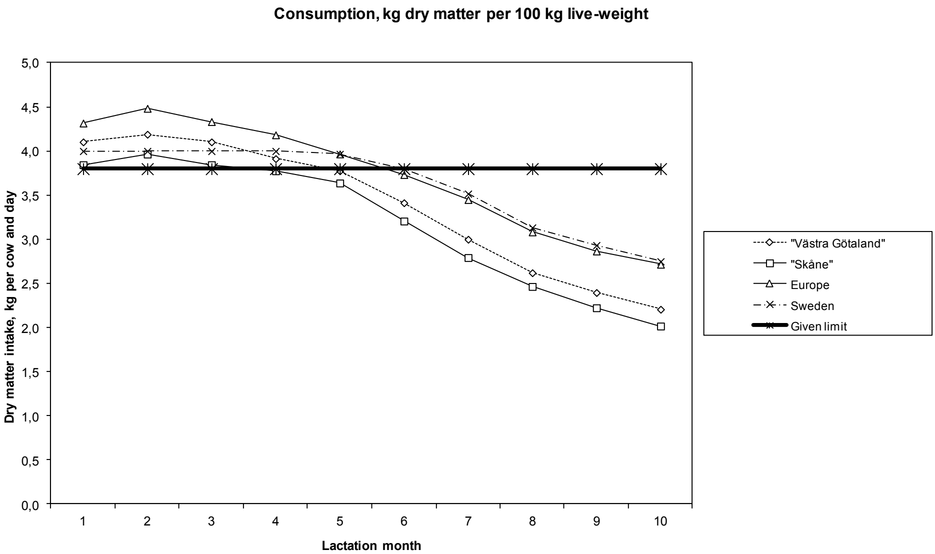


Figure 4. Consumption in alternatives "Västra Götaland", "Skåne", "Europe" and "Sweden" in lactation months 1-10 in kg dry matter per 100 kg live-weight according to Totfor (Emanuelson et al. 2006). The maximal consumption of 3.8 kg dry matter ("Given limit") set in the study is also shown.

The results of Totfor express major internal logical conflicts, and conflicts with common knowledge within dairy production sciences. The influence of Totfor on national level (see above) is a concern. The quality of the results on aggregated national level in the three applications mentioned above is a function of the quality in the basic production biological relations that constitutes Totfor. The analysis above shows that there are major problems in Totfor in this area. Hellstrand (2006) showed an increase of nitrogen influxes in Swedish cattle production from 1991 to 1999 with 22.8 million kg nitrogen due to increased use of purchased feeds, where the dominating part was due to increased use of crop protein feeds. In 1991 201 million kg was used, in 1999 536 million kg (Hellstrand (2008). Section 3 presents the sustainability drawbacks from this trend. Despite all the measures by authorities and the milk-producing sector (see also Gustafsson 2001) to increase nitrogen efficiency in milk production, the use of crop protein feeds to cattle in 2006 had increased to 644 million kg (Swedish Board of Agriculture 2007). Partly, this is a function of major production biological weaknesses in tools used on national scale as well as on single farm level to increase nitrogen efficiency, such as Totfor and the way it is applied in STANK. STANK cannot detect the impact of an increasing protein intensity in milk production, therefore national systems for the evaluation of trends regarding ammonia emissions from agriculture and nitrogen surpluses in agriculture, are blind for this aspect. This severely distorts the results in this national reporting. Hellstrand (2008) analysed this in detail. There are production biological problems of a similar and severe magnitude as well in the third national context mentioned where Totfor formed the production biological basis for evaluation of economic and/or environmental aspects of Swedish milk production.

Another important cause for the decreasing nitrogen efficiency in Swedish milk production 1991-1999 is the changed feeding standards the same period. The studies which provided the arguments for the changes contain important internal inconsistencies (ibid.) and expresses conflicts with basic production physiological, biological and economic principals. The level of the scientific probing for two of three major changes is low. The change of a fundamental principle behind the energy standard in 1995 was based on a work by a student, a change of a fundamental principle behind the protein standard the same year was based on an stencil at the department of Animal Nutrition and Management, Swedish University of Agricultural Sciences, which no longer can be found (Hellstrand 2008).

The Totfor-example, together with the results from the analysis of the FPD-model, the cattle-sugarcane example, and LCA-studies of milk production underlines the importance of analytical tools with a good anchoring in animal production biology and economics that can provide a sound production biological and economic platform for sustainability analysis of meat and milk production. That will benefit work for improved economic result in milk production and for a better environment.

The situation in Sweden and the Nordic countries is not unique, but may well reflect a global potential for improved feeding efficiency in milk production (ibid.).

The simulation model is an important tool in order to identify measures that through increased feeding efficiency in animal production simultaneously increase farmers incomes, support global food security, decrease ammonia emissions and nitrate leaching; and decrease the appropriation of land for animal production. This is of international interest. It is suitable in evaluation of economic and ecological effects of alternative feeding standard systems.

7 Conclusions

In the animal production simulation model production is described in production biological and economic terms as a function of the composition of the daily feeding plan, the nutritive values of used feeds, and of animal dependent factors such as breed, sex, size and lactation phase. The simulation model supports analyses on single farm as well as on national animal production sector level. The outputs of the model can be used in extended analyses in combination with other concepts and models, thus supporting the operationalising of animal production supporting a sustainable development.

When applied on a conventional animal production system, a substantial potential for improved economic result in Swedish milk production was identified, by a more skilful utilisation of the production potential of the animals and of high quality feeds.

The simulation model is a tool suitable for evaluation of economic and ecological consequences of alternative feeding standards in milk production.

Although the version of the simulation model here presented is applied to Swedish conditions, it can quite easily be adopted to the conditions of other nations by applying national variants of formulations of feeding requirements and feeding strategies.

Compared to other approaches used when analysing sustainability of animal production systems such as the FPD/ALBIO model of the global food production system; an integrated model for cattle and sugarcane/ethanol production in Brazil; and LCA of Swedish milk production the simulation model has strong advantages since it is based in science and experiences that have been developed during decades and centuries of application within animal and agricultural production. The mentioned alternatives were found to be weak in their

representation of basic production biological and economic conditions, where this severely distorted their analyses.
The animal simulation model expresses an effort to once again increase the integration of production biology and economy in animal production sciences. It is a contribution in bridging traditional agricultural management tools and methods and concepts within Integrative Assessment. This is crucial in order to develop methods that better than current ones, can improve the contribution of, e.g., animal production systems worldwide towards a sustainable development, considering the site-specific biophysical and socio-economic contexts at hand.

8 Acknowledgements

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Paper V

THE POTENTIAL TO INCREASE SUSTAINABLE GLOBAL GREEN ENERGY PRODUCTION THROUGH INCREASED EFFICIENCY IN MILK AND CATTLE PRODUCTION: - A SWEDISH CASE

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ABSTRACT:

This paper addresses the potential of sustainability improvement by increased efficiency in milk and cattle production. The experience of Swedish improvement over the last half century reveals the global potential for the sustainable management of land use, nutrition balance and bioenergy supply.

Ruminants are an important part of the global food production system. Ruminant production has the potential to substantially increase land area available for bioenergy production. They can use energy in foodstuffs with none human nutritive value and simple nitrogen compounds in the production of high quality feeds. They can convert renewable natural resources from ecosystems, that otherwise have low capacity to transform solar energy fluxes to food, to high quality food.

Globally, the area of pasture is 2.5 times larger than the area of cropland. Ruminants are an important part of the global food system, supplying human energy metabolism. Due to the competition for land, the skilfulness in rumen production affects potentials for green energy production supplying the energy metabolism in the technical systems of society.

This paper discusses two aspects of ruminant production affecting the potential for green energy production:

(i) The impact of increased nutritional physiological efficiency, i.e., better feeding strategies, and

(ii) The importance of utilising ruminants as ruminants, where they transform solar energy fluxes to high quality foodstuffs from ecosystems with low capacity to produce food through other paths.

The focal point is the impact on the land remaining for green energy production supplying the technical systems of society, after food supply needs are met. Estimates are provided on the impact on other sustainability aspects at different system levels as well as in the three sustainability-dimensions. The results are provided through the application of a methodology within the frame of integrated assessment for analysis of sustainability effects in systems with mutual dependencies between systems and system levels. This is of general interest as a methodology, supporting the development of sustainable green energy production and meeting the needs of society. It contributes with concrete results, supporting an increased sustainable production of green energy due to increased efficiency within a sector that competes for land

KEYWORDS: Bioenergy potentials; Ruminant production; Agroecology; Food security: Integrative Assessment

1. INTRODUCTION

1.1. The issue

The impact of animal production on global environmental problems has been highlighted on a high policy level. Thus, the contribution to anthropogenic global climate effect is estimated at 18%, while other huge environmental impacts such as eutrophication and loss of biodiversity are also stressed [1]. This has inspired work in Sweden aiming at reduction of the environmental impact of agriculture, especially climate change effects. Three exponents for this ambition are

- the cooperation between the certification systems for the Swedish Farmers Association Swedish Seal, and the one for the organic farmers KRAV, respectively, in the development of certification rules considering climate impact of food products [2],
- the work of the Swedish National Food Administration (SNFA) aiming at a system of advices to consumers supporting choices that reduces the environmental impact of food consumption, especially climate change effect [3] and
- the process within the Swedish Board of Agriculture (SBA), aiming at incentives reducing the contribution to global climate change from Swedish agriculture [4].

The main greenhouse gases (GHG) emissions in agriculture sector are carbon dioxide from combustion of fuels and fertilizer production, methane from enteric fermentation in livestock and nitrous oxide from agricultural land and production of nitrogen fertilizers.

The authorities, SNFA and SBA, stress in their public communication the contribution of ruminants to climate change through emissions of methane: "Meat from cattle generates one hundred times more greenhouse gases than the corresponding amount of beans" according to SNFA [3]. "The origin to emission of methane which contributes to climate change is largely due to the digestion of animals". For example, meat from cattle generates 14 kg CO2-equivalents per kg meat, while meat from pork and chickens generate 5 and 2 kg, respectively [4]. This discussion concerns the sink aspect of the sustainability limits to agriculture. The key question is: are the emissions/discharges within the assimilative capacity of affected ecosystems?

The resource aspect is another important sustainability aspect of agriculture, thus also of animal production and ruminant production. Emissions from livestock and agricultural soils represent a loss of valuable carbon and nitrogen resources. Thus, these emissions show the strong link between resource issues and environmental disturbances. The resource aspect relates to the capacity of agriculture to supply the metabolism of humans with food, and the metabolism of the society with energy. Of course, resources needed in the agricultural production such as fossil oil and phosphorus fertilisers are also crucial. Reductions in agricultural emissions will therefore also lead to productivity benefits for agricultural industries, and provide a win-win for agricultural production and environmental sustainability.

Figure 1 shows the price development of oil 1998-2008.

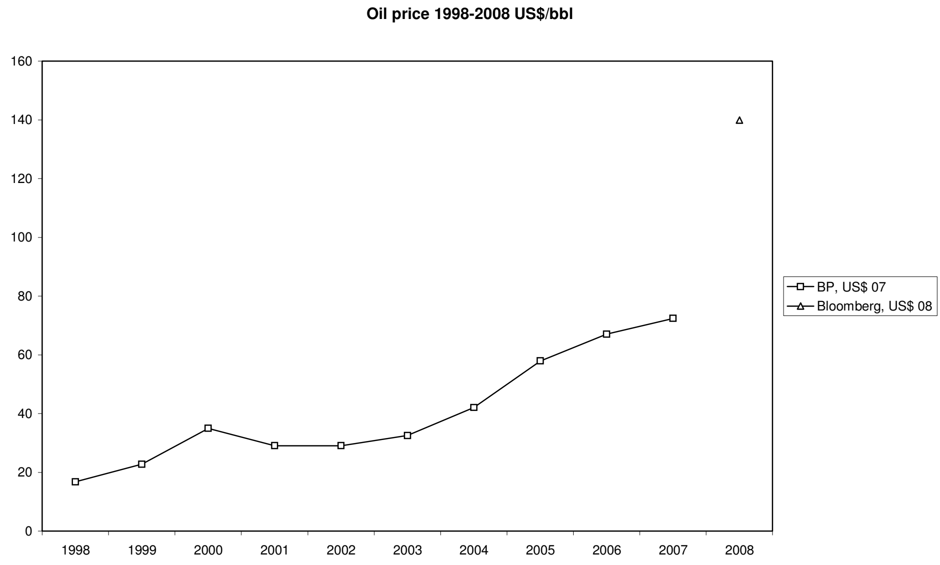

Figure 1. Price-trend oil 1998-2008 US$ per bbl. Source, own processing of data from BP covering the period 1998-2007 [5], the value for 2008 concern 1 of July 2008 [6].

Increased oil price (Figure 1) and the responses to climate change increased the demand from society on bioenergy produced in the agricultural sector. The price of oil in 2008 was 8 times higher than the price in 1998. The doubling time for the price was 5, 3, and 2 years, respectively.

Figure 2 shows the amounts of commercial energy used, and the gross energy in biomass appropriated in the global food system. That refers to the amount of phytomass that is used to feed the global food supply system, to that part that it is based on agriculture, measured in gross energy terms.

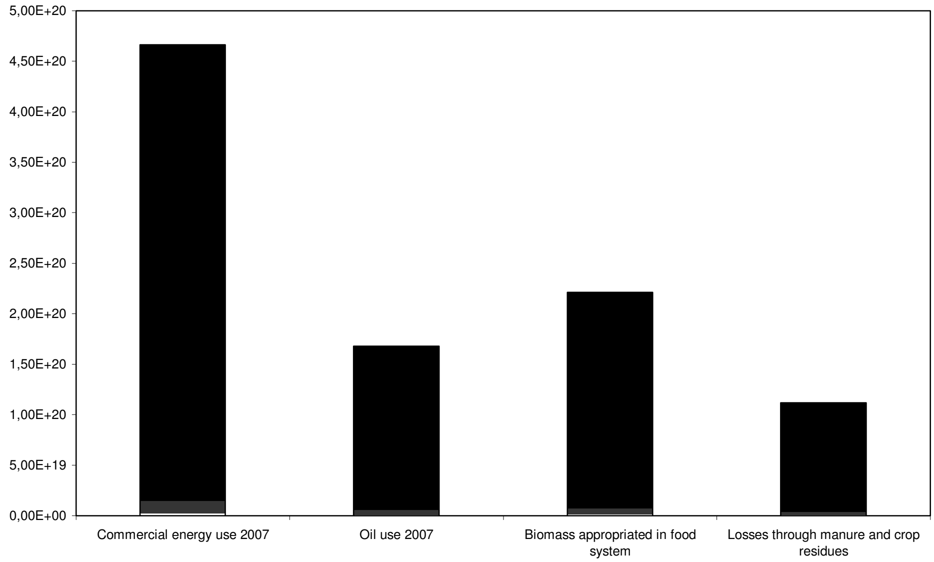

Figure 2. Total use of commercial energy and of oil in 2007 [5]; and amount of gross energy in biomass appropriated in global agricultural production of food and in losses through manure and crop residues [7]. The measure 1.00E+20 equals 1.00 $*10^{20}$ J equals 100 EJ.

Figure 2 provides information about the size of the use of oil, e.g., in relation to losses in the food system. Figures 1 and 2 explain the growing interest in production of bioenergy from agriculture: With a fast increase in the price of oil, and a global production of biomass in agriculture that in gross energy terms (GE) is greater than the current use of oil, the interest in agriculture for production of bioenergy is quite natural. This offers a new opportunity to integrate energy production through biomass with food production to address issues in not only energy supply but also climate change. If the fluxes of biomass in agriculture not used are substantial, the commercial interest is further increased. When bioenergy from agriculture substitutes fossil fuels, emissions of climate change gases are reduced at the same time as the dependency of fossil fuels.

Wirsenius [7] estimated the conversion efficiency in the global agricultural system to 8.7% as the ratio between amount of gross energy (GE) in food consumed and GE in the plant biomass appropriated for the production of food. The purpose of this measure is to provide an overall measure of the efficiency in the food supply system, where gross energy in food consumed by all humans is divided by the gross energy in the total amount of plant phytomass supporting the food system. Low conversion efficiencies suggest huge potentials to redirect fluxes of biomass to, e.g., bioenergy purposes. Later, Wirsenius has slightly modified the estimates [8] [9]. The found conversion efficiency in the animal production system was profoundly low, since the system accounted for roughly two-thirds of the total appropriation of phytomass, but only contributed about one tenth to the human diet [7] Thus, the estimated conversion efficiency in animal production was only 5.6% of that of crop and vegetable production for human consumption.

The feed conversion efficiencies of cattle meat systems were estimated at about 2 percent in industrial regions, and only 0.5 percent in most non-industrial regions (on gross energy basis). The conversion efficiencies for pig and poultry production were about a factor ten higher (ibid.). The estimated losses due to manure and crop residues were 51%, i.e. appr. 110 EJ. In a report to the Swedish government, it was concluded that on global level 50 EJ of bioenergy could be produced from crop residues and dung in agriculture [10]. The challenges to in real world systems realize the suggested potential include issues regarding impact on:

- soil fertility, as in the used model refluxes of manure and crop residues could not provide positive feedback on future harvests, as the soil compartment was not included in the model,
- the relevance of the used measure of conversion efficiency gross energy in food through gross energy in plant biomass appropriated, as it does not reflect the positive feedback of manure and crop residues on future harvests, neither the different physiological values of one unit gross energy in food consumed in the form of, e.g., grain or meat and
- to what degree used model and measures recognize the importance of the different types of feeds that different types of animals utilizes.

Studies about contribution to climate change in terms of GHGs emission per kg product, as well as of feed conversion efficiencies in different systems for producing meat, found that pig and poultry production are substantially more efficient with regard to the sink aspect (climate change) and the resource-aspect (efficiency in use of feeds) than ruminant production. Emissions of GHG are substantially higher per kg meat produced for cattle than for meat from pigs and poultry [4]. One reason is that cattle need more feeds per kg meat produced.

The information provided this far suggests that major measures for increasing the sustainability in the global agricultural system would be to

- substitute animal products with crop products,
- substitute ruminant products with pig and poultry products and
- increase the efficiency in remaining ruminant production systems for production of milk and meat.

1.2. The wider perspective: including food security and an agroecological perspective

However, the picture presented needs to be balanced. This far, results from studies where the sustainability in food production systems have been estimated in terms of

- emissions of GHG per kg product,
- conversion efficiencies measured as gross energy in food consumed divided by gross energy in food biomass appropriated and
- amount of feeds consumed per kg meat produced

have been discussed. The sustainability of food systems are something more.

The relationship between population and lactose is of interests to address the energy and climate change issues in connection to the food supply. The Swedish population is genetically extremely adopted to ruminant production, thus of the total population only 3-5 % is lactose-intolerant, in Finland 15-20, in the Mediterranean 50%, and in parts of Asia up to 100% [11]. Lactose is milk sugar. This illustrates the fact that within Sweden (and the other Scandinavian nations) milk and meat from the stock of dairy cows and other ruminants, since at least the time of the Vikings, has played a major rule in the supply of the nutritional physiological needs of the population. Ruminants have been a prerequisite for the Scandinavian civilisation. The power of this dependency is now expressed in the Scandinavian genome. The reason is that in Scandinavia, the climatic conditions are such that compared to other regions, forages and pasture provide comparative advantages, while crop production provide comparative disadvantages. Pigs and hens like other monogastric animals (to which humans belong) have low capacity to transform energy and protein in forages to high quality food, while ruminants have high such capacity. This is the beneficial side of the rumen fermentation capacity, where the methane emissions are an energy-cost for this capacity. The biomass of ruminants, and other animals like horses that have other solutions for achieving the same capacity through collaboration with microbes, of total biomass of farm and wild animals signs the value of this capacity to utilise this trophic level in ecosystems and agroecosystems, which without this cooperation with microbes, would not have been available.

This situation is not restricted to Sweden. On global level, of total land area of 13 billion ha 27% is pasture, and 11% is cropland [12], i.e. pasture covers 2.5 times more land. The production of biomass per ha pasture is estimated at 3.4 tonnes dry matter (DM), while on cropland the corresponding estimate is 5.1 tonnes. Pasture not eaten/crop residues are estimated at 52% on pasture, and 14% on cropland [7]. This gives a net yield after residues per ha of 1,6 tonnes for pasture and 4,4 tonnes DM on cropland; i.e. 2.8 times higher. This clearly shows the higher biological productivity on cropland, reflecting the lower quality of land used for pasture. Grazing ruminants have in these areas an important role transforming low quality pasture, which pigs and poultry cannot use, to high quality food. That way, they increase the total global capacity to produce food. By doing that, they decrease the pressure on cropland to produce food, i.e. they increase land area available for production of bioenergy, everything else equal.

1.3. Climate change and food security policies

On high-policy level a trade-off between production of bioenergy and food has been identified. The first of the Millennium Development Goals of the UN is to eradicate extreme poverty and hunger [13]. Climate effect is one aspect under one target under the seventh Millennium Development Goal. Thus, UN values food security substantially higher than the climate effect on a general societal level. If so, within the agricultural sector the priority rank would be even more favourable for food production compared to climate objectives. This rank of priorities correspond well with the one of Millennium Ecosystem Assessment (MEA), a major study of state and trends of major ecosystems globally and their capacity to produce ecosystems services, thus providing the ecological base for sustained welfare. MEA was initiated by former Secretary General of the UN, Kofi Annan, and involved more than 1 360 experts: The list of ecosystem services presented at the homepage is: clean water, food, forest products, flood control, and natural resources [14].

A discussion has evolved whether policies to substitute fossil fuels with biofuels might have resulted in increasing food-prices, increasing the number of people in poverty, experiencing hunger. Thus, a high level conference on world food security and the challenges of climate change and bioenergy was held in Rome, 3 -5 June 2008 [15]. From this information the following conclusions are important for the scope of the paper. Some national authorities now put a high priority on reducing climate impact of agriculture. This will work in favour of increasing production of biofuels. UN-related bodies prioritise food supply and the fulfilment of other basic physiological needs. Another important aspect of climate change and food security is how the utilization of the carbon sink capacity in agriculture can provide a buffer that have an importance for economic and for ecological systems increasing the time span for adoptions, and at the same time increasing soil fertility, thus, improving food security. Climate change also affect food security through increasing levels of carbon dioxide, temperatures, sea levels, and the impact of the pattern of rains [1].

Within the borders of this paper, we have no intention to solve the issue about the possible tension between objectives regarding production of biofuels and of food respectively. However, we conclude that all activities that can decrease this tension are welcome. To identify some such options within the field of ruminant production is the overall ambition of the paper.

More specific questions studied in this paper are:

1. What are the sustainability effects of substituting food produced from ruminants in more marginal agricultural areas, with food produced from pigs, studied through the Swedish example? In more specific terms, what is the implication for land available for bioenergy purposes?

2. What are the potentials to improve the efficiency in ruminant production, and how will that affect land available for bioenergy production?

The answer to the first question relies on the results from an analysis of impacts on different system levels in the ecological, economic and social dimension of sustainability of a system with mutual dependencies between systems and system levels. This indicates a way to provide analysis, supporting decisions for sustainability.

2. MATERIAL AND METHODS

The conceptual framework for the analysis is Hellstrand et al. [16]. They present a conceptual model of the economic system in its ecological and social context. Stocks of natural capital, man-made capital, human capital and social capital are included. The importance of thresholds, resilience, irreversibilities, life-support systems, assimilative capacities, interdependencies between systems and system levels are acknowledged. The contribution is based on 1) principles for sustainable development in ecological economics, 2) integrative assessment, a methodology that provided the analytical backbone of Millennium Ecosystem Assessment [14], and 3) traditional farm management tools in agriculture and agricultural sciences.

The methodology agrees with the principle for sustainable development presented by OECD [17]. The analysis of the sustainability impacts of changes in animal production follows the methodology developed by Hellstrand [18], which was then further developed by Hellstrand [19]. This implies an approach where material fluxes from fields to animals to humans are analysed, taking into consideration real world variation in production levels among production regions. Resources (feeds) not used, results in emissions or discharges. Knowledge within animal and human nutrition physiology is applied, enabling an analysis of when animal production competes with human nutritional objectives, and when it enhances food supply.

The feeding standards and tables for ruminants in Sweden as of 1989 [20] [21] provide the core in the calculations of the contribution to food supply from ruminant production. The material and data used is from agricultural production data for 2006. The production region focused is the northern part of Sweden including the forest sub-regions in the region Svealand and the whole of Norrland [22], which is here called Northern Sweden. This geographic area has the same altitude as the northern half of Hudson Bay. Due to the Gulf Stream, the climate is somewhat milder. Still the production alternatives are limited. The production alternatives compared are

A. Total production of milk that is supplied in Northern Sweden by current production of grain, forages and pasture

B. The same production of protein through pigs instead of through milk.

Regarding B, this production will occur in traditional agricultural regions, i.e. in other production areas than Northern Sweden: That region is not suitable for production of feeds to pigs, which is clearly shown in the official agricultural statistics [22] regarding regional distribution of farm animals, as well as production of crops, suitable as feeds to pigs. Thus, an realistic outcome of the alternative to produce the same amount of protein through pigs implies that this production occur in districts in southern Sweden or EU, suitable for grain and pig production, while current agricultural land in the northern part of Sweden become forests. That way, indirectly, this example informs about the general importance of using pasture for ruminant production globally. The alternative use of the agricultural land in Northern Sweden, somewhat simplified, is as forest or pasture for reindeers (also a ruminant), not other forms of agriculture.

The results are based on advanced analysis in animal production sciences. In the context of a presentation in the field of applied energy we have made the choice to focus on the general principles and results. If more detailed information is wanted about the animal production systems, contact the corresponding author.

3. RESULTS

Main results on sustainability effects of

- increasing or ceasing dairy production in Northern Sweden,
- increasing feed efficiency in Swedish milk production based on real world values,
- an example of the importance of increasing feed efficiency in milk production on global level and
- improving productivity in milk production globally

are presented.

The results are strongly related to the bioenergy uses, food supply and climate change issues.

3.1 Sustainability effects of ceased dairy production in marginal agricultural areas

Table 1 shows some sustainability effects of substituting milk produced in Northern Sweden, with pork produced somewhere else. Two scenarios are included:

A. Increased milk production in Northern Sweden.

B. Same amount of protein produced by pigs in major agricultural districts in EU.

A represents an ambition to in regions with high capacity for forage production utilise ruminants to convert the energy in feeds with low value for monogastric animals and humans to high quality food.

B represents an ambition to decrease the contribution to climate change from Swedish consumers by consuming meat from pigs instead of protein from ruminants.

Table 1. Some sustainability effects of substituting milk produced in Northern Sweden, with pork produced somewhere else. Data from Statistics Sweden [22], production year 2006.

	Alternative	
	A. Dairy cows in Northern Sweden	B. Same amount of protein produced by pigs in good agricultural districts in Sweden or in the EU
Acreage, ha, northern Sweden	400 000	
No of dairy cows,	261 980	
Milk production, ECM (energy corrected milk), tonnes	2 163 083	
Energy need, no of humans	1 600 000	
Protein need, no of humans	3 720 000	
Meat from slaughtered dairy cows, carcass weight, tonnes	31 400	
Contribution to climate change, through methane, ton CO2-equivalents	718 000	
Slaughter pigs, no		8 172 000
Meat, tonnes		368 000
Barley, used as feed, tonnes		1 462 807
Area for barley production in good agricultural districts, ha		293 000
Soya bean meal, tonnes		258 100
Area for soya production Brazil, ha		131 000
The number of people whose protein-need would have been supplied with these amounts of barley and soya		14 145 000

Table 1 shows that in alternative A, Northern Sweden can produce 2.16 million tonnes of milk, fulfilling the total protein needs of 3.7 million people. The emissions of methane have a climate change effect of 718 000 kg CO_2. 400 000 ha of land that otherwise have a low value for agricultural production is used.

In alternative B, the same amount of protein is produced through pigs. That demands 293 000 ha land in good agricultural districts in southern Sweden or other parts of EU, and 131 000 ha land in Brazil for production of soya bean meal. As pigs and humans (when humans consumes vegetables) from an ecosystem-perspective compete on the same trophic level, it is relevant to analyse the number of people whose nutritive requirements could have been supplied if the feeds to the pigs had been directly used as food to humans. In this example 14.1 million people´s protein requirements could be met with the grain and soya bean meal used by the pigs. Thus, marginal land used for ruminant production can on the margin increase global food supply and/or land available for bioenergy production. In this case, 400 000 ha land in the northern parts of Sweden used for milk production could on the margin provide 5.2 millions peoples need of protein, and make 147 000 ha good agricultural land in the EU and 65 000 ha in Brazil, available for bioenergy purposes, if the land area made available are split in equal parts for the fulfilment of the human metabolism and the societal metabolism.

In comparison between A and B, main observations can be drawn:

- Land use: Utilizing 400 000 ha (A) in a region that is normally defined as marginal agricultural land for a production form that is suitable, releases 424 000 ha good agricultural land in EU and in Brazil for production of, e.g., biofuels and food. If used for food, 14.1 million people more could be supplied with their total protein needs.
- Climate change: The climate change benefit of producing meat from pork (B) through the decrease in methane emissions sums to 718 000 tonnes.
- Bioenergy supply/production: The maximal marginal contribution to increased bioenergy production potentials through alternative A, is defined by the production levels of 293 000 good agricultural land in EU, and 113 000 ha land in Brazil

3.2. Potentials to improve the efficiency in milk production

3.2.1. Increasing feeding efficiency in Swedish milk production

Hellstrand [18] found that the increased use of purchased feeds, and especially crop protein feeds such as soya bean meal in the fraction purchase feeds to dairy cows between 1991 and 1999, increased production costs for farmers with 840 million Swedish Crowns (SEK) (140 million US$). The influx of nitrogen in purchased feeds to the stock of cattle increased with 22.8 million kg. Appr. 85% of purchased feeds to cattle are diverted to dairy cows. As the production of milk and meat were constant that period, the amount of nitrogen effluxes through manure increased with the same amount. The amount of ammonia emissions that the increase in nitrogen effluxes caused corresponded to 15% of reported total ammonia emissions in Sweden in 1999. The increase in the amount of energy above the feeding requirements was estimated at 18%. The increase in protein feedings was estimated at 26% above the nutritional requirements. Relative changes of prices and of purchased feeds and milk was equal, thus, economic reasons did not motivate this trend. The increased use of crop protein feeds had, if used to humans, instead meeting the total protein requirements of 6.6 million people. These measures express increasing ecological, economic and social footprints of Swedish milk production the investigated period.

Hellstrand [19] expanded the analysis to 2003. Regarding the period 1989-1999 the estimate of the costs for the farmers increased with 370 million SEK to 1.21 billion SEK, after also considering the impact of the change in the composition of the purchased feeds. In 2003, 70% of the increase in nitrogen influxes remained, thus the situation was better compared to 1999 but still not good.

The 26% protein fed above feeding requirements in 1999 corresponded to an extra area of land in Brazil for soya meal production of 160 000 ha (ibid.) As different protein sources substitute each others, and soya meal is the most important one globally, it is reasonable to express all in terms of soya meal; at the margin, more or less protein affects volumes of soya meal traded on the world market, everything else equal.

In a comparison of the feeding standards in the Swedish system, with those in Denmark, France, The Netherlands, and USA, a significant and interesting result evolved. All of these feeding standards except the Swedish would have further increased the feeding intensity, that is the amount of feeds used per kg milk produced, for the high yielding dairy cows (ca 35-40 kg ECM per cow and day). This would increase land area needed to support dairy production in proportion, i.e., decrease areas available for, e.g., bioenergy purposes.

This suggests that the potentials for improvement found in Swedish milk production could be also very relevant on global level. Thus, 15% decrease in land area supporting global milk production could be obtained as a one-time effect (1.0 divided by 1.18), with a higher share for land area producing protein feeds.

3.2.2. Global implications and possibilities

Total global production of milk in 2007 was 635 billion kg. Cow milk provided 83% of that amount. Buffalo, sheep, goats, and camels contributed the rest. Annual yield per cow was 2 249 kg [23]. Thus, global production of milk is about 200 times the Swedish production [19]. This implies that if the global feeding efficiency is similar to the Swedish one, there is a global potential to

- increase the revenues from milk production by appr. 40 billion US$ per year,
- decrease nitrogen emissions to air and water by appr. 4 000 million kg per year and
- decrease the pressure on forests in Brazil to produce soya bean meal by appr. 32 million ha in total or increase global food security through an increased capacity to fulfill human needs of protein for 1.3 billion people.

Assume that Swedish feeding standards are relevant across the world, that cows produce all milk, and that the average live-weight of cows was 500 kg (Holstein Frisian have a weight of 600-700 kg). The amount of energy needed for this production is, then, 8.70 E+12 MJ ME (Metabolizable Energy). Assuming 10 MJ ME per kg DM biomass, this correspond to 870 million tonnes of biomass DM. Given the production levels of biomass (in DM per ha) and the acreages of cropland and pasture [7], this amount correspond to 6.9% of total biomass production supporting global food production, i.e. 340 million ha.

The energy content per kg DM in gross energy (GE) terms is appr. 17 MJ (ibid.). The difference between the content of ME and GE, indicate the size of energy not used up in dairy production, which is still available in the effluxes of e.g. manure. Thus, (17-10)/17, i.e. 40% of the 6.9% appropriation of total agricultural biomass used in milk production are still available in manure to support some part of the total system, that can be as fertilising refluxes to agricultural land as well as energy resources to be used for society. Thus, the amount of energy appropriated for current global milk production is here estimated at 6,9 * 0,60 ≈ 4% of the total amount of gross energy in the biomass supporting global food production.

The estimation has not considered the energy needed to produce recruitment heifers, and energy needed for gestation. However, the amount of energy for gestation is quite marginal [20]. Energy for production of recruitment heifer is treated as an energy cost for production of the meat from the slaughtered cow that the heifer replaces, thus is not dealt with here.

Figure 3 shows the trends of milk production per cow on global level and in Sweden. Year 1 is 1900 for the Swedish trend, and 1961 for the global.

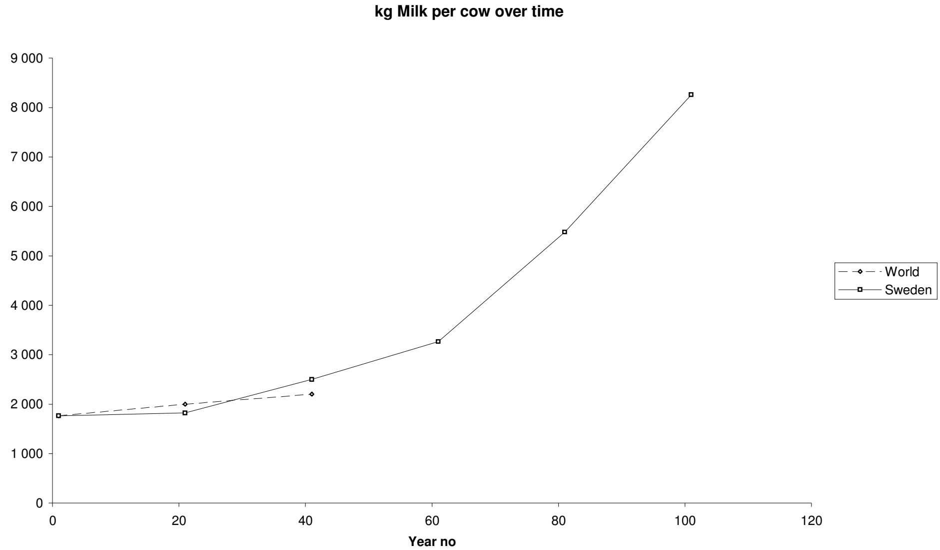

Figure 3. Milk per cow over time. Year 1 is 1900 for the Swedish trend, and 1961 for the global trend. Sources, own calculations based on Swedish Dairy Association [24] and FAO [23], respectively.

The production level per cow in Sweden in 1900 was the same as on the global level in 1961. After 40 years the two trends have quite similar positions. The increase in production in Sweden after the first 40 years was quite dramatic. Assume that a similar trend is possible to achieve on global level. What would that imply in terms of biomass needed to support a constant production of milk? Expressed in other words, how much energy in biomass would then be released that could be used for bioenergy purposes?

Figure 4 indicates the answers to the above questions. It shows the amount of energy needed to fulfil the physiological needs of the cow for maintenance and milk production, expressed in MJ (ME) per kg milk for three production levels: current global level, twice the current global level, and the Swedish production level of 2000.

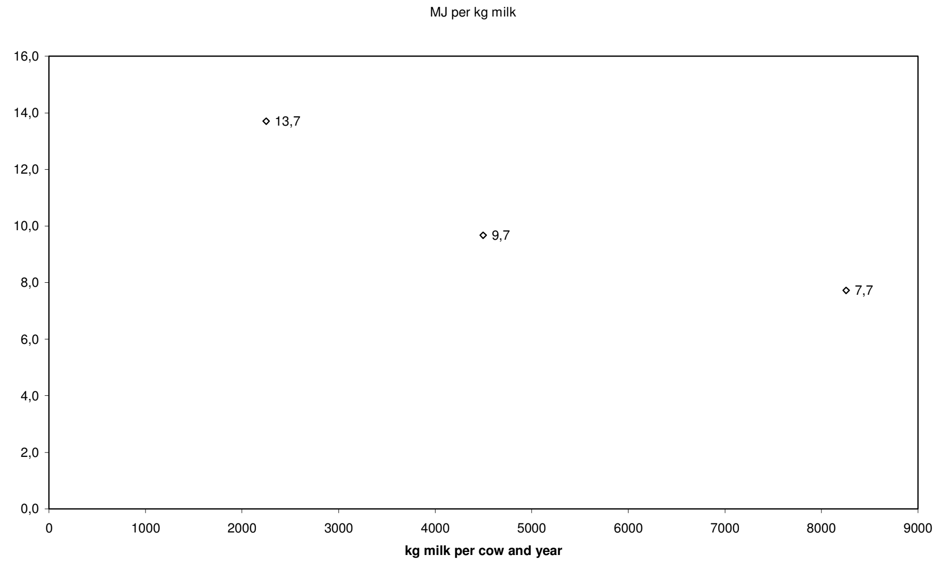

Figure 4. The amount of energy needed to fulfil the physiological needs of the cow for maintenance and milk production [20], expressed as MJ (ME) per kg milk.

At current (2007) global level, every kg milk costs 13.7 MJ (ME) to produce. If the production level is doubled, the amount of energy needed is decreased to 9.7 MJ. At the Swedish production level (2000) one kg milk on average costs 7.7 MJ to produce. The mechanism behind Figure 4 is the following. When production levels increases, the amount of energy needed for basal metabolism (60 MJ per cows and day if the weight is 600 kg) is allocated to more milk. Then, the total energy need per kg milk produced decreases. At the same time the impact on climate change through emissions of methane decreases in the same pattern, as the emissions of methane is proportional to the amount of feeds consumed. The energy need per kg milk is reduced with 44% when going from the current global level in production per cow, to the level in Sweden in 2000. This is an exact estimate of the reduced land requirements, given a constant production of milk, "just" through increasing yields per cow, everything else equal. Thus, 44% of current land area for milk production on global level would be made available for other purposes, e.g. bioenergy purposes, by such an increase in production per cow. That is 150 million ha, assuming that the reduction of pasture and crop land used, respectively, is proportional. Expressed in GE terms this corresponds to 6.7 EJ.

In the calculations of Figure 4, it is assumed that the cows also gain weight, from 500 kg over 550 to 600 kg live-weight, when going from lower to higher production levels. Thus, increasing needs for maintenance are considered.

4. DISCUSSION

Table 1 shows a spectrum of sustainability effects of closing down ruminant production in the more marginal agricultural areas in Sweden, compared to the option of using current production of forages, pasture and grains for milk production. 400 000 ha land in the northern part of Sweden can produce milk that supplies 3.7 million people with their total protein need.

If that amount of protein instead would be produced by pigs, it demands a further 293 000 ha good agricultural land in southern Sweden or the EU to produce grain, and 131 000 ha of land to produce soya bean meal, e.g., in Brazil. This is an increase of the demand on land that already is in short supply, due to the assumed ceasing of production on marginal agricultural land. This illustrates trade-offs between agricultural land in marginal production areas, and good agricultural land in the EU and in Brazil. Thus, in this example, 1 ha land in Northern Sweden less supporting milk production increases the use of high quality crop land in the EU with 0.73 ha, and land in Brazil for soya production with 0.33 ha. Thus 1 ha land feeding milk production in northern Sweden substitutes 1.1 ha highly productive land in the EU and Brazil producing the same amount of protein through pigs. The reason for this is the combined effect of

- comparably high production levels for forages in the northern parts in Sweden,
- higher nutritive value (the short summer nights result in higher levels of ME per kg DM, which supports higher production levels in milk production) and
- the high capacity of dairy cows to utilise these feed resources, that have so low nutritive value for monogastric animals.

These comparative advantages in ruminant production in Northern Sweden, where the capacity to produce food otherwise is quite limited, is not acknowledged by the studies of SNFA and SBA [3, 4]. Referring to the earlier quotation from SNFA, beans are not an option in Tornedalen at the border between Sweden and Finland, at the same latitude as Angmagssalik on Greenland.

This stresses the importance of not making the analysis to narrow, when processing proposals for policies in agriculture aiming at a reduction of climate effects. Impact on global food supply might still be of interest to include. The priorities of the UN suggest that this is the case. Furthermore, increased pressure on land in other areas might well, through deforestation or less land available for bioenergy production, result in indirect emissions of CO_2, which counterbalance the reduced emissions of methane from dairy cows.

The amount of extra grain and soya meal that in this case must be diverted to pig production, to fully compensate for the closing down of milk production in the northern part of Sweden, would by itself support 14,1 million people with protein. The environmental gain is a reduction of the emissions of methane corresponding to 718 million kg CO_2. That provides a trade-off, where a measure that decreases climate change, also decreases global food security.

The key-figure is 718 million kg CO_2 less divided by 14,1 million peoples protein supply, which equals 50 kg CO_2 per person-equivalent less regarding global food supply capacity of protein.

Globally, the production level of biomass per ha pasture is 30% (DM-terms) of that of cropland [7]. Of that yield, 52% of biomass produced on pasture is not eaten, and 14% of biomass produced on cropland is not harvested. That gives a net yield per ha for pasture that is 17% of that of cropland. Globally, the production of biomass on pasture is 40% (GE-terms) of the total biomass production on agricultural land, after reduction for crop residues and pasture not eaten [7]. This reflects the marginal character of pasture. For such marginal production areas pasture often are, the high level (52%) of biomass not eaten plus the dung from the animals grazing, is significant for their resilience, thus their long term production capacity, as well as their function as habitats providing biodiversity.

The results from the Swedish example combined with the production data on global level suggest that the major use of pasture in the global agricultural system should be as producer of feeds to ruminants. That way, the fragility of these areas can be coped with (if overgrazing is avoided), and they can support production of animal products. This production adds to production of other animal products such as egg, chicken and pork, it does not compete. The latter compete directly with production of crops and vegetables for human consumption, and with the use of agricultural land for biofuels. Thus, by maintaining and improving ruminant production in these marginal areas, they may substantially decrease the pressure on more productive land, thus increasing the capacity to simultaneously supply food security and societal needs of bioenergy. The Swedish example shows that the impact can be quite substantial, see Table 1.

The efficiency measures provided by Wirsenius [7] are based on fluxes of GE. However, GE is a poor estimate of the physiological value of biomass. It implies that the physiological complexity of animals and humans is reduced to the same level as a combustion engine, or even further. In animal and human nutrition, measures such as digestible energy, metabolizable energy, and net energy is used. By using GE as a measure of conversion efficiency, an impression is created that oil is as good a feed or food as straw, wheat, and meat, as the content of GE per kg is quite high. The efficiency measures provided by Wirsenius ignores the different physiological functions of energy in the form of sugar in beets and sugar cane; starch in grain and potatoes; pectin in fruits; fat in butter and vegetable oils; protein in meat, egg and cheese; not to mention the importance of minerals and vitamins; essential fatty acids; and essential amino acids. Furthermore, the topsoil layer is not within the system borders of Wirsenius model. Thus, re-fluxes of crop residues and manure to agricultural soils are by the model treated as losses, as there is no soil that could benefit from refluxes of organic matter and plant nutrients. A third limitation is that biomass production on permanent pasture is assumed to have the same quality as crop production.

These three circumstances;

(i) use of energy measures suitable for physical analysis of energy fluxes while ignoring the physiological context

(ii) the location of top soils outside the system borders

(iii) the ignorance of the fundamental differences between poor permanent pasture and productive cropland

limit the usefulness of the model. Due to these circumstances, the model will

- underestimate the value of animal products for human nutrition
- overestimate losses in the food system, especially regarding pasture land, as the importance of refluxes of organic matter for future production is not considered
- overestimate the potential to redirect fluxes of crop residues and manure for bioenergy production.

The model is valuable. However, it must be used with recognition of important characteristics of crop producing systems, animal producing systems, and the nutritive needs of humans, taking into consideration short and long term effects.

The results in Table 1 also imply that policies to reduce the climate change contribution from agriculture, should consider other sustainability objectives as well.

Figure 1 and 2 explain the interest in agricultural land for production of bioenergy. It is important that use of agricultural land for bioenergy purposes does not deteriorate future production capacity through production methods decreasing soil carbon content. The 50 EJ possible to use for bioenergy purposes from crop residues and manure earlier reported, correspond to a decrease in refluxes of biomass to agricultural land of 0.6 tonnes of an average yield globally of 2.6 tonnes per ha cropland and pasture, where the production level on pasture is 1.3 tonnes. This would affect the topsoil content of organic matter, thus future yields, as well as a reallocation of carbon in soils to carbon as CO_2 in the atmosphere. It is important that the impact of such a use is evaluated by models that include the topsoil layer in a relevant way.

The results provided in the paper are related to dairy production. The major fraction of meat from cattle production in Sweden is from the stock of dairy cows. Therefore, when analysing the efficiency in this system it is vital to recognise that meat and milk are products from the same production system.

5. CONCLUSIONS

The major conclusions are:

- Ruminant production has an important role in future food production systems.
- A conscious use of ruminants in marginal areas decreases the pressure on more productive land and supports global food security and other sustainability objectives, that way substantially decreasing the pressure on traditional cropland. Thus, use of 400 000 ha land in northern Sweden for milk production was estimated to
    - support the total protein needs of 7,1 million people more, and at the same time,
    - make 146 000 ha good agricultural land in the EU and 65 000 ha in Brazil available for bioenergy purposes,

  compared to the alternative that the same amount of high quality protein should be produced by pigs.

  As the area of pasture globally is 2.5 times the one of cropland, ruminant production is a general important means supporting food supply and bioenergy production.
- Increasing feeding efficiency at current production levels may substantially increase feeding efficiency, that way decreasing the demand on land, releasing areas for bioenergy production. In a numeric example, it was calculated that this could decrease the pressure on land in Brazil with 32 million ha.
- If global production of milk per cow 2007 reached the Swedish production level of 2000, the decrease in need of energy given a constant total milk production corresponded to 150 million ha that could be used for other purposes e.g. production of bioenergy.
- It is important that policies within agricultural sphere are based on a sufficient understanding of agricultural systems.
- Integration of agricultural and technological skills is valuable in the development of sustainable green energy systems.

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Paper VI

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Animal production in a sustainable agriculture

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Abstract This paper discusses the role of animal production systems in a sustainable society; sustainability problems within animal production systems; and four measures for the improvement of the contribution to societal sustainability from animal production. Substantial potentials for improvements are identified that were not previously known. The methodological basis is multi-criteria multi-level analysis within integrated assessment where elements in Impredicative Loop Analysis are integrated with management tools in Swedish agriculture and forestry developed during thousands of years, during which the well-being of the Swedish society and its economic and military power were functions of the land-use skill. The issue—the sustainability footprint of global animal production—is complex and available data are limited. The Swedish case is used as a starting point for an analysis of international relevance. Data from FAO and OECD support the relevance of extrapolating results from the Swedish case to level. The four measures are (i)decrease the consumption of chicken meat in developed nations with 2.6 kg per capita and year; (ii) develop the capacity of ruminants to produce high-quality food from otherwise marginal agroecosystems; (iii) improve milk production per cow with a factor four on global level; and (iv) increase feeding efficiency in milk production globally would substantially improve the societal contribution in terms of increased food supply and decreased pressure on land. The impact of measures (i), (iii) and (iv) on increased global food security was estimated to in total 1.8 billion people in terms of protein supply and a decreased pressure on agricultural land of 217 million ha, of which 41 relate to tropical forests. The 41 million ha of tropical land are due to a decreased demand on soymeal, where this represents more than a halving of total area now used for the production of soymeal. These impacts are of the character either or. The quality of the measures is as first-time estimates, supporting choices of where to direct further efforts in analysis. Two areas were identified as critical for achieving this potential: Feeding strategies to dairy cows as well as methods commonly used to evaluate the sustainability contribution of animal production needs adjustment, so that they comply with the “laws” of diminishing returns, Liebig’s “law” of the minimum

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and Shelford's "law" of tolerance, that is, in agreement with well-known principles for efficient natural resource management and the priorities of UN Millennium Development Goals. If not, global food security is at risk.

Keywords Agroecosystems · Integrative assessment · Animal production · Sustainable animal production · Food security · Climate change

1 Introduction

There is a growing concern regarding the capacity of global terrestrial ecosystems to support humanity given

1. socio-economic trends regarding urbanisation, population, material welfare, change of diets towards more animal products;
2. biophysical trends regarding
   a. depletion of non-renewable natural resources, such as fossil fuels and phosphorus;
   b. increased demand of renewable resources such as water, food, fibre and fuels produced from forest and agricultural land; and
   c. increased environmental impacts such as climate change, eutrophication, loss of biodiversity due to emissions and land-use changes.

Aspects 2.a and b relate to ecological source restrictions due to different sets of availability limits for non-renewable and renewable natural resources; 2.c relates to ecological sink restrictions. Hellstrand et al. (2009, 2010) treat this in detail with references to original work in this area.

In that context, animal production systems and ruminant production systems are of special interest. Of total global agricultural land of around 4.9 billion ha, 3.4 billion ha ($\approx$70 %) are classed as permanent pasture (FAOstat 2009). Furthermore, quite huge shares of arable land, for example, in Scandinavia and Northern Europe are best used for the production of feeds to ruminants. The reason is that ley and pasture produce well where ruminants have the capacity to convert the energy and nitrogen compounds in forages to high-quality food. For substantial parts of arable land, the alternative in this region is forestry. Increased cereal production is no option due to climatic conditions. The importance is reflected in the low prevalence of adult native people that lack tolerance to lactose (Hellstrand 2006). Lactating ruminants has for so many 1,000 years improved the capacity of land to support people with food so much, that it has caused a thorough genetic adaptation.

The reason why ruminants substantially expand global food production capacity is a trick that the enzymes of the rumen microbes allow ruminants to perform, which monogastric animals such as pigs, poultry and people cannot perform. Due to optical isomerism, the enzymes of rumen microbes can split the long chains of the polysaccharide cellulose built by units of glucose. The symbiosis between rumen microbes and the host animal allows ruminants to support their own physiological demands of energy and protein from fibre and simple nitrogen compounds such as urea. That explains why ruminants offer a path by which the products of the photosynthesis can be upgraded to high-quality food in regions where the biophysical conditions are such that the capacity to carry humans otherwise is poor or lacking. The domestication of ruminants has in these types of agroecosystems substantially improved the carrying capacity regarding sustainable human food supply. A price that ruminants pay for this unique ecological niche is emissions of methane from the processes in the rumen. Another is that high-quality protein is broken down in the rumen. Thus, one aspect to handle in the current discussion about climate change and ruminants is the trade-off between benefits to global sustainability through increased food supply and costs in terms of increased emissions of methane which contributes to global warming. One guideline from the international community is the first Millennium Development Goal, to end poverty and hunger. Climate change is in that structure found as one of fifteen aspects at the level below four sub-goals to the seventh of eight Millennium Development Goals (UN 2012). Another aspect relates to the issue of the reference value. What is the natural rate of emissions of methane from ruminants before humans become a major ecological player? Smith et al. (2010) found that within 1,000 years after the arrivals of humans to North- and South America by 11,500 years ago, 80 % of large-bodied herbivores such as mammoths, camelids and giant ground sloths were extinct. They estimated that this reduced annual enteric emission of methane by 2.3–25.5 Tg. Johnson (2009) suggests that this was a general pattern, showing that at different continents, the arrival of humans coincided with a substantial loss of megafauna, often its extinction. He concludes: "Living large herbivores are a small remnant of the assemblages of giants that existed in most terrestrial ecosystems 50,000 years ago. …. In several parts of the world, palaeoecological studies suggest that extinct megafauna once maintained vegetation openness, and in wooded landscapes created mosaics of different structural types of vegetation with high habitat and species diversity. Following megafaunal extinction, these habitats reverted to more dense and uniform formations." FAO (2006) estimated global enteric emissions of methane from dairy cattle to 15.7 Tg and suggested that animal production in total contributed to the emission of 7.1 Gt CO_2 equivalents annually of a total anthropogenic contribution of 40 Gt. Of that, 1.8 Gt is estimated to originate from enteric fermentation, due to the emissions of 85.6 Tg methane.

The findings of Smith et al. (2010) and Johnson (2009) suggest that before humans in a substantial way affected populations of larger wild animals, (i) the natural level of emissions of methane from wild animals globally might have been at the same level as current emissions from wild and domesticated animals together; (ii) global storage of carbon in plant biomass in forests and grasslands increased after the extinction of megafauna, that is, the level of carbon dioxide in the atmosphere decreased. Thus, systems of grazing cattle might have a higher potential to mimic natural ecosystems than other land-use alternatives in agriculture.

FAO (2006) identifies mitigations options within animal production systems regarding climate change through carbon sinks where grasslands dominate of the same size as the estimate of total contribution to emissions.

Together, this indicates that in optimal solutions satisfying societal demands regarding food security, biodiversity and climate change, cattle production systems may play a positive and vital role. As illustrated in Hellstrand (2006), cattle production may also harm sustainability goals. The point here is that cattle production has a contribution to make, if well designed.

In this paper, I investigate the capacity to through four measures increase the sustainability performance of global animal production systems: (i) decrease the consumption of chicken meat in developed nations; (ii) utilise the full potential of ruminants to produce valuable food from otherwise marginal agricultural land that way improving global food security and releasing good agricultural land for biofuel production (when food supply needs have been met); (iii) improved milk yield per cow as global average that way decreasing feed (i.e. land) appropriation per kg milk produced; (iv) increase feed efficiency in milk production in developed nations while maintaining high production levels per cow.

Section 2 provides context, approach and points of departure. The role of animal production in a sustainability context is defined in Sect. 3. Section 4 gives an overview of animal production in a broader societal and environmental perspective. It is based on FAO (2006). Section 5 presents four examples of how to enhance the contribution from global animal production systems to the sustainability base of society. Section 6 treats methodological aspects regarding feeding standards and methods to measure the sustainability performance of animal production systems where corrections substantially can improve the sustainability delivery. Section 7 provides final conclusions.

2 Contexts, approach and points of departure

The paper follows the perspective of a sustainable development as expressed in the contributions from the policy sphere through,

- On global scale: UN Millennium Development Goals (UN 2010), OECD's perspective of a sustainable development (2001) and Millennium Ecosystem Assessment (MEA 2009);
- On regional scale: the Baltic Sea Action Plan regarding a sustainable Baltic Sea (HELCOM 2009); and
- On national scale: the Swedish environmental objectives with the ambition to secure the ecological foundation for a sustainable Sweden (SEPA[1] 2009a).

Scientific contributions of importance are the ones within systems ecology and ecological economics from Odum (1988, 1989, 1991), Daly (1990), Daly and Cobb (1989) and Costanza (1994); in agricultural production biology and economy from Nanneson from the first half of the twentieth century (e.g. Nanneson et al. 1945), Renborg from 1950 to 1985 (Renborg 1957; Johnsson et al. 1959), Ebbersten (1972), and Wiktorsson (1971, 1979) from around 1970–2005; and in agroecology from Pimentel and Pimentel (2008) and Giampietro (2003).

Contributions from these sources have been integrated in a process generating a toolkit for the analyses and management of any production system, not the least animal production systems, supporting a sustainable development (Hellstrand 1998, 2006; Hellstrand and Yan 2009; Hellstrand et al. 2009, 2010).The tools within this toolkit have generated the results presented in the following.

3 Role of animal production

The major role of animal production systems is to act as a means that enhance the food support capacity of global ecosystems, mainly from arable land and permanent pasture. Other functions are as sources of traction power, wool, skin and assets. This indicates that the evaluation of the contribution from animal production to global sustainability presupposes a sufficiently developed combined eco-agricultural and agricultural-social perspective ending up in an eco-agro-social perspective. Without that, the capacity to improve human needs per unit ecological resource at hand, given factual ecological source and sink

[1] Swedish Environmental Protection Agency.

restrictions at hand, cannot be accurately estimated. As an example, Rockström et al. (2009) estimated nine biophysical limits that humanity had to obey in order to maintain a safe operating space. They end their paper with the conclusion that if doing so, the possibilities for a sustainable economic and social development were good. That conclusion has a weakness. The restriction regarding nitrogen implied that an annual application rate of 87 kg nitrogen per ha arable land as the sum from fertilisers and N-fixating crops should be reduced to 20 kg per ha. That would severely decrease yields globally, increasing starvation and social tension. In their analyses, agriculture was not included. They lacked the link agriculture in the eco-agro-social perspective required in this type of analysis.

Of total terrestrial land of 13 billion ha, 1.4 billion ha is arable land and 3.4 billion ha is permanent meadows and pasture (FAOstat 2009).[2] In total, agricultural land covers 4.9 billion ha (ibid.). Through feeds, animal production systems appropriate 70 % of the total amount of biomass produced on agricultural land (permanent pasture plus arable land) that supports the global food production system (Wirsenius 2000). Of these 70 %, two-thirds actually are recycled to agricultural land as manure and crop residues, supporting future production. The huge appropriation of agricultural biomass by animal production systems is reflected in the appropriation of land: 30 % of the land surface of the planet supports animal production systems (FAO 2006).

4 The FAO perspective

Livestock's Long Shadow (FAO 2006) has synthesised a substantial amount of knowledge about animal production systems globally and on regional level, considering aspects such as environmental impacts, geographical areas, animal production systems and level of industrialised animal production systems.

On global scale, animal production has a major influence on emissions/discharges contributing to climate change, eutrophication and acidification, while it through land-use changes is an important factor behind loss of tropical forests and biodiversity, and a major contributor to climate change. Pollution of antibiotics and hormones contribute, for example, to the emergence of antibiotic resistance and may cause feminisation or masculinisation of fish (ibid.).

During recent decades, the poultry production has shown the highest growth, while pig production also has grown substantially. Milk and meat from ruminants have increased at a slower pace. FAO concludes that as pig and poultry production compared to ruminants has a substantially higher dependency on high-quality feeds which can be used as food directly such as wheat and soya, and due to their higher growth-rate in human consumption, they are more important factors behind animal production driven deforestation in tropical areas. This conclusion needs modification. FAO (2006) does not analyse actual feeding rations to dairy cows. It is not unusual in dairy production in developed nations that the amount of concentrates to dairy cows is 50 % or more on a dry matter basis and that soymeal is a substantial part of the concentrates. Thus, dairy cows do not demand feeds that can be used as food as well. However, it is not uncommon that they are feed such high-quality feeds.

The physiological aspect is stressed, where ruminants through the rumen microbes have the capacity to utilise feeds and thus ecosystems that for monogastrics such as poultry, pigs

[2] FAOSTAT (2009), http://faostat.fao.org/site/377/DesktopDefault.aspx?PageID=377#ancor, accessed 2009-07-17.

and people are useless or of low nutritive quality. They can convert biomass from more marginal and often fragile production systems such as permanent pastures to food. In poorer regions, this is not a question of maximal economic output per hour of labour, but a question of survival. Of course, the grazing system if not managed well may cause overgrazing. Regarding other environmental problems such as eutrophication and acidification, FAO stresses the contribution from pig and poultry systems as they are mainly industrialised, and they quite commonly have higher level of geographical concentration.

The substantial carbon sink capacity in pastures supporting ruminant production is identified.

Although economically not a major global player, the livestock sector is socially and politically very significant. It accounts for 40 % of agricultural gross domestic product. It employs 1.3 billion people and creates livelihoods for one billion of the world's poor people. Growing populations and incomes, along with changing food preferences, are rapidly increasing demand for livestock products, while globalization is boosting trade in livestock inputs and products. Global production of all meat is projected to more than double from 229 million tonnes in 1999/2001 to 465 million tonnes in 2050, and that of milk to grow from 580 to 1,043 million (FAO 2006).

The global supply of whole milk per capita and day was in 2006 132 and 109 g meat (FAOstat 2009). Animal protein per person per year makes up 37 % of a person's protein diet. To provide the animal protein for the world human population, humans in 2006 raised 58 billion poultry, 1.3 billion pigs and around 540 million cattle worldwide (FAOstat 2009).

5 Enhanced sustainability contribution from animal production

Four measures enhancing the contribution from animal production to global sustainability are presented below. They represent substantial potentials for win^3 solutions (i.e. ecological, economic and social sustainability) not earlier known, where the same measure substantially improves

- *Economic* sustainability through farmers net incomes, thus the viability of rural societies,
- *Ecological* sustainability through decreased ecological footprints for the same production regarding natural resource use as well as emissions, and
- *Social* sustainability through improved food security.

The measures are as follows: (1) decreased amounts of chicken meat consumed in developed countries; (2) utilise the full potential of ruminants to produce valuable food from otherwise marginal agricultural land that way improving global food security and releasing good agricultural land for biofuel production (when food supply needs have been met); (3) improved milk yield per cow as global average that way decreasing feed (i.e. land) appropriation per kg milk produced; (4) increase feed efficiency in milk production in developed nations while maintaining high production levels per cow.

(1) The first measure was chosen, due to two reasons. In the debate regarding climate change and animal production, it is often claimed that if animal products are to be consumed, chose pork or chicken meat due to the higher feeding efficiency compared to ruminant products. Often, it is then ignored that monogastrics such as pigs and poultry, compete with humans about food/feed. Furthermore, as monogastric animals demand quite high shares of soymeal (or soymeal substitutes) in their feeding rations, they on the margin

may cause tropical deforestation. (2) Of agricultural land, 3.4 billion ha are classed as permanent pastures of a total of 4.9 billion ha. Of arable land of 1.4 billion ha, a substantial fraction, which often is poorer in quality, is used to produce ley and coarse grains as feeds, e.g., to ruminants. The case of agriculture in the northern parts of Sweden is used to illustrate how otherwise marginal agroecosystems through ruminant production may contribute to a spectrum of sustainability assets, where this type of production systems are important on global scale, not the least for the close to 1 billion of the poorest people, dependent on cattle production in marginal socio-ecological systems. Northern Sweden, of course, does not belong to this class. However, the general significance for global food security of this kind of marginal agroecosystems can be illustrated by this example. (3) In the debate, a common proposal is that through decreased ruminant production, land earlier used to produce feeds can be released to produce crops for human consumption or bio-energy purposes. In developed nations, the increase in milk yield per cow during the twentieth century is quite amazing. This has substantially improved the natural resource efficiency in production. A corresponding development of milk yields per cow can be anticipated globally. This illustrates how improved ruminant production may at the same time produce the same amount of products and decrease land appropriated. (4) Hellstrand (2006) shoved a fast increase in the use of crop protein feeds in Swedish cattle and milk production 1991–1999, with associated substantial negative sustainability impacts. In an effort to probe whether this was a change towards a lower feeding efficiency level common globally; data from international official sources were combined, suggesting that the Swedish trend was towards a situation that is common in milk production in OECD nations. Of total cow milk produced globally, 48 % come from OECD nations (analysis of data from FAOstat[3]). This suggests that it is alright to utilise the results from Sweden (Hellstrand 2006) to get a first-time measure on global level of sustainability improvements to obtain by increased feeding efficiency at constant milk yield. As the presentation above shoves these choices partly are a function of the own pre-understanding of global animal production systems, thus has an element of arbitrary choices.

Cattle and milk production are focused. The first reason is the significance of cattle production globally. On global scale, milk alone provides 36 % of total consumption of energy from animal products, milk and meat from ruminants 47 % while products from pig meat, poultry meat and eggs together represent 42 %. For protein, the corresponding values are 28 % for milk, products from ruminants 38 %, and pig meat, poultry meat and eggs together 35 %. Among the 20 most valuable agricultural products in 2007, animal products contributed with 50 %, and among the contribution from animal products, ruminant products represent 58 % (milk alone contributed with 34 % of the whole) while meat from poultry and pigs together with egg represented the remaining 42 %. The significance of ruminant production in terms of food supply and in economic values is reflected in the area of agricultural land appropriated. Permanent pasture corresponds to 69 % of all agricultural land where ruminants are the dominating "harvesting equipment."[4] The second reason is that a common interpretation is that the high share of agricultural land supporting ruminant production systems reflects genuinely inefficient choices among the native population as kg of food produced per ha is low compared to other agroecosystems (see Azar 2011; Chum et al. 2011; Wirsenius et al. 2010, 2011). I suggest that it is the other way around: The high share of global agricultural land supporting ruminant production systems illustrates that thousands of years of selection of farming systems supporting human societies has proven

[3] http://faostat.fao.org/site/569/DesktopDefault.aspx?PageID=569#ancor, accessed 2012-10-18.

[4] Based on own processing of data from FAOstat (2009).

that this is efficient land use. Other land-use options have not been competitive in these eco-agro-social contexts.

A third reason to focus cattle and milk production is to provide some data regarding the resource efficiency of ruminant production systems in a broader sustainability context than otherwise common. As just shown, it can be argued that ruminant production is resource-efficient both in developing and developed nations where the production options in available agroecosystems otherwise are limited. Lindberg and Wiktorsson (1995) who analysed the efficiency by which protein in feeds were converted to food (see Table 1), showed that this was the case in the Swedish context.

Conversion efficiencies in milk, and integrated milk and cattle meat production, are high compared with any other production system. This is despite the lower quality of the feeds they consume compared to other animal systems. Ruminants can maintain high conversion efficiencies for protein while using protein of lower quality than monogastric animals. The authors provide similar results with high energy conversion efficiencies for milk production compared to pig and poultry.

Table 2 summarises impacts on land appropriated, global food security and climate change of the four measures analysed.

Based on Swedish production technology, measure 1 estimates the impact of reducing chicken consumption by 7 g per capita and day in developed nations. The climate change effect through decreased pressure on tropical forests was estimated using methodology and data from FAO (2006). FAO estimates the amount of carbon in soils and in living biomass for forests, pastures and arable land. At deforestation, a huge amount of carbon in the biomass of forests are oxidised to carbon dioxide. That process may take decades. Eventually, all carbon has been oxidised. FAO allocates the cumulative amount of carbon dioxide emitted through this path to the year of clearing the land. This approach can be criticised as it implies that in the same accounts, figures regarding stocks are added to figures regarding fluxes. Furthermore, this measure is essential for the overall results in FAO (2006). Of total emissions of greenhouse gases, 34 % relates to deforestation. In Table 2, the expression "one-time event" is used to distinguish estimates related to the oxidisation of a stock of carbon from estimates of annual fluxes.

Impacts are estimated on global scale. Measure 2 investigates the importance of utilising ruminants as ruminants, that is, forages dominate the feeding rations. In the northern

Table 1 Efficiencies in the conversion of proteins in feeds to protein in food in some animal production branches, given Swedish conditions around 1990 (based on Lindberg and Wiktorsson 1995)

	Protein in animal products through protein in feeds
Milk	0.37
Cattle meat[a]	0.18
Meat and milk from the dairy cow stock	0.33[b]
Cattle meat, cows only for meat production	0.07
Egg	0.34
Chicken meat[a]	0.36
Pig meat[a]	0.18

[a] The terms "cattle meat," "pig meat" and "chicken meat," respectively, are used, as these are the terms used in FAOstat

[b] This is the average value estimated for the protein from the mix of meat and milk delivered from the stock of dairy cows

Table 2 Sustainability impacts of four measures in animal production

Measure	Agricultural land released, million ha	Food security, million people, protein supply	Climate change, gigaton CO_2 equivalents	Comment
1. Decreased consumption chicken meat, 7 g per capita and day developed nations	16.0 (9.1 soybeans; 7.0 wheat production)	470	−5.2 as a onetime event	Land estimated through global average yields for concerned crops
2. Ruminants used as ruminants on otherwise marginal agroecosystems (400,000 ha)	0.42, of which 0.29 is in Europe and 0.13 in Brazil	14.1	−0.09 as a onetime event +0.0007	Swedish level; decreased climate change impact through decrease land pressure and increased through more methane emissions; on global level, there are 3.4 billion ha marginal land as pastureland
3. Increased milk production per animal globally with constant total production	150			44 % of current appropriation for milk production released, divided on pasture land and arable land proportionally
4. Increased feeding efficiency	51 of which 32 are tropical forests	1,300	−22.4 as a onetime event	Increased economic result with around 40 billion US$
Summed effects measure 1, 3 and 4	217 of which 41 are tropical forests, 67 are arable land specified	1,770	−27.6	67 million ha specified as arable land, 150 not specified

For details of alternative 2–4, see Hellstrand and Yan (2009); for alternative 1 contact the author parts of Sweden, 400,000 ha arable land produce forages and coarse grain. If the total production was used for milk production, the milk production could increase with a factor 3.5. The measure was originally developed in order to illustrate the importance of a combined eco-agro-social perspective of animal production. The northern part of Sweden is located at the same latitude as the northern half of Hudson Bay. Although the Gulf Stream makes the climate milder, the agroecosystems of this area are marginal. They are best suited for the production of forages (pasture, hay, silage) and to some extent coarse grains (oats and barley). Through ruminants, these areas can make substantial contributions to a sustainable development, not the least to global food security (Hellstrand and Yan 2009). Measure 3 examines the importance of increasing the production capacity per cow assuming constant total production of milk globally. At the global production level of 2007, every kg milk produced cost 13.7 MJ (ME) (Metabolizable Energy). The production is slightly less than 2,000 kg per cow. If the production level per cow is doubled, the amount of energy needed per kg milk produced is decreased to 9.7 MJ ME. At the Swedish production level in 2000 (8,000 kg milk), one kg milk on average costs 7.7 MJ ME to produce. This level can be achieved on feeding rations with a high share of forages with an energy content of >10 MJ ME per kg dry matter (DM), and coarse grains supplemented with some crop protein feeds. The measure shows the sustainability gains of increasing the average global production level with a factor four to the Swedish level around 2000 (Hellstrand and Yan 2009).

Measure 4 presents the results of increased feeding efficiency in global milk production at constant production level per cow. The basis is the spectrum of sustainability costs associated with the increase in concentrate feeding, especially crop protein feeds, in Sweden to cattle from 1991 to 1999 identified by Hellstrand (2006, 2008a). Although cattle have the capacity to utilise protein in forages in the production of food, the reality is that high amounts of high-quality feeds such as soymeal, rape meal and other crop protein feeds often are used in cattle production. From 1991 to 1999, the amount of crop protein feeds in purchased feeds to cattle (85 % of purchased feeds to cattle go to dairy cows) in Sweden increased from 201 million kg to 536 million kg (Hellstrand 2006). In 2006, the amount was 644 million kg, following the same route of estimation. This results in an application of 320 kg of crop protein feeds per dairy cow in 1991, increasing to 1,020 in 1999 and 1,410 in 2006. This did not increase yields and thus depressed the economic result (ibid.). Official statistics suggest that the nitrogen efficiency in Swedish milk production from 1991 to 2006 moved towards a lower level common in developed nations.

Thus, of total influxes of nitrogen on farm level in Sweden in 2006 of 72.6 million kg through purchased feeds, 66 % was through feeds to cattle. Protein feeds to cattle such as soymeal alone contributed with 52 % of the total of this nitrogen influx (Fig. 1).

Figure 2 shows that the high influx of nitrogen on farm level through purchased feeds to cattle in 2006 is in line with a fast increase from 1991 and onwards. As milk production over this period was constant, this reflects a decreased feeding efficiency in terms of amount of milk produced per kg protein feed. An important question is why this occurred. My proposal is that the overall effect of three major changes of official feeding standards in Sweden during the 1990s in combination with how organisations dominating extension services in this area to commercial farms applied the same standards caused this decrease in feeding efficiency. This is further treated in Sect. 6. It can be noted that the dominating firm producing purchased feeds, Lantmännen, in the second half of the 1990s introduced their own feeding standards and feed evaluation system in Sweden called the LFU system. Quite surprisingly, their ambition was to press down the amount of crop protein feeds, that is, their own products, in the feeding rations (see Lantmännen 2003). The LFU system

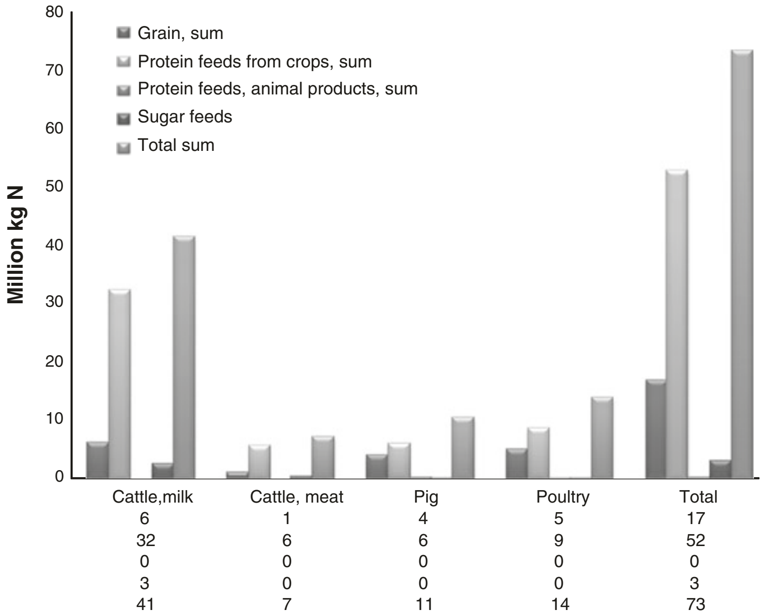


Fig. 1 Influxes of nitrogen on farm level through purchased feeds in Swedish animal production systems in 2006. Material and method Hellstrand (2006), analysis updated by data for 2006

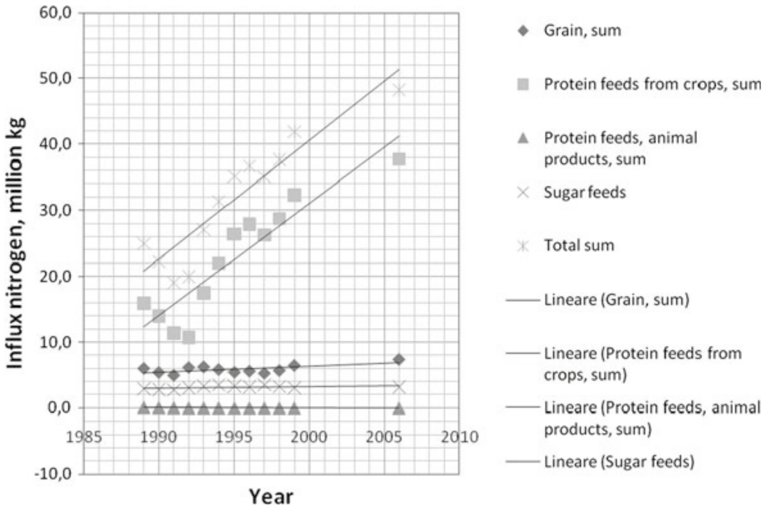


Fig. 2 Nitrogen influxes through purchased feeds to cattle production in Sweden 1989–1999 and 2006. *Source*: See Fig. 1. Of purchased feeds to cattle, 85 % are feeds to dairy cows

steers towards a higher feeding efficiency. This follows from the comparison of feeding standard systems in Norfor (2004).

A few of the leading national researchers in rumen physiology in Sweden had around 1995 left SUAS and started to work at Lantmännen, E. Lindgren and M. Murphy. They constructed the LFU system. Thus, by their actions, they showed such a low confidence in the official feeding standard system in Sweden, after three major changes 1991–1995, that they rejected the whole system and constructed another one from other points of departure. This suggests another possible cause behind discussed trends in feeding of purchased feeds, especially protein feeds. Two substantially different systems regarding feeding standards and feed evaluation for dairy cows are in charge in Sweden since around 1997, one is used by the organisation that dominates the production of purchased feeds when they design what they believe will be optimal for the farmers, another and very different system are used when the organisation dominating extension services actually from their believe try to optimise the feeding rations to farmers. National trends regarding the use of crop protein feeds, the increase in milk yield per cow and total production of milk show that this has not worked out well. Thus, the word "believe" is relevant. For the Swedish farmers, it should be a concern that they through two of their own organisations pay twice for the maintenance of two conflicting feeding standard systems that in combination results in suboptimal feeding strategies.

As shown in some more detail later, the trend in Swedish milk production is towards a lower nitrogen efficiency earlier established in other OECD nations. Milk production per kg feed (dry matter) consumed, and the nitrogen efficiency is higher in diets in Northern Europe than in North America (Huhtanen and Hristov 2009).

The impact of an increased production level per cow, releasing 150 million ha of agricultural land, would substantially improve the capacity to support global food security and/or the carbon sink capacity. This measure has been obtained by assuming that milk yield on global level was increased a factor four per cow and year. That would decrease the energy demand per kg milk produced, thus also the total feed requirements for a constant global production that is transferred to an area of land supporting the feeds required. For details, see Hellstrand and Yan (2009).

As the 150 million ha is not divided in pastureland and arable land, estimates partitioned on these different qualities of agricultural land cannot be provided.

FAO (2006) estimated the contribution from the livestock sector to climate change emissions to 7.1 gigaton of a total anthropogenic contribution of 40 gigaton. Compared to those estimates, the potentials to decrease the contribution to climate change through measures 1–4 in Table 2 are significant. It shall be noted that here the mitigation option that FAO (2006) identified through the carbon sink capacity in grassland and rangeland of 6.2 gigaton carbon dioxide (87 % of the FAO estimate of total contribution from livestock sector to emissions of climate change gases) is not considered. Nor the discussion earlier presented in this paper about the accurate reference value to use, before humans become major ecological actors (Sect. 1).

The release of 217 million ha agricultural land, of which 67 are specified as arable land (Table 2), are of global importance, given that total area of arable land is 1.4 billion ha. The reduced need of 41 million ha of soybean production as estimated is compared to the use of soymeal as feeds that in 2003 corresponded to 70 million ha soybean production (see below).

The increased feeding efficiency would increase farmer's incomes by 1.2 billion SEK[5] (Hellstrand 2008a). On a principal level, the route for achieving this is discussed in Sect. 6. SEPA (2009b) has presented a proposal for how Sweden should reduce its nitrogen and phosphorus discharges to the Baltic Sea with 21 million kg. In their proposal, 5.5 million kg nitrogen reduction is lacking. The marginal cost for reduced discharges is around 1,000

[5] Currently (October 2012), 6.5 SEK correspond to around 1 US$ and 8.5 SEK correspond to around 1 €.

SEK per kg nitrogen. Reclamation of the same efficiency in the use of purchased feeds in Swedish milk production from the lower level in 1999 to the higher level as of 1991 would result in annual societal benefits from reduced contribution to global climate change, acidification, and eutrophication from emissions of N_2O and ammonia of 2.7 billion SEK.[6] If allocating the cost of yearly using of the natural capital tropical forests over a period of 50 years, and valued through the emissions of carbon dioxide the deforestation causes, and assuming Swedish preferences for avoiding such emissions used by authorities, the annual cost is 3.4 billion SEK (assuming zero interest rate). Thus, the societal value of increasing the feeding efficiency sums to 6.1 billion SEK to be added to the estimated value of its contribution (2.5 million kg N) in the reduction of nitrogen discharges to the sea in that part of the Baltic Sea where the proposals from SEPA do not meet the set objectives, with a marginal price of 1,000 SEK per kg/N that is estimated at 2.5 billion SEK. This gives in total 8.6 billion SEK.[7] To that, the reduced production costs for the farmers of 1.2 billion SEK shall be added to get an estimate of the welfare-economic impacts, through mentioned factors and given preferences, expressed in the Swedish socio-economic system. Thus, in total, this measure—reclaiming the higher nitrogen efficiency in Swedish milk production in 1991 from the lower level in 1999—is estimated to increase the welfare-economic value of Swedish milk production by 9.8 billion SEK (slightly more than 1 billion €), allocated on approximately 400,000 dairy cows. This corresponds to the value of the total milk production in Sweden. In this calculation, the value of a reduction of nitrogen discharges with 3.5 million kg in other parts of the Baltic Sea is not considered.

Of course, this is a theoretical approach. One can ask if anyone really cares about, for example, deforestation. Swedish authorities use this kind of estimates in connection to agricultural policies, environmental policies and when ranking infrastructural investment alternatives. It is one way to evaluate the size of external effects. It shall be remembered that this relates to preferences in the Swedish society. Preferences are context-dependent in time and space. They can hardly be used as a basis for the evaluation of global impacts. Their relevance is to show whether the welfare impacts are substantial or not.

Other estimates provided in this paper, where production economic effects of improvements in milk production are estimated, are substantially stronger related to the production biological as well as the natural resource base. Such measures have a stronger relevance on global scale, also due to the balancing effect of the world market. The majority of sustainability impacts analysed relate to the analysis of causal chains in terms of natural and agricultural sciences. They have the highest general relevance of the mentioned level of measures. In general, the analysed systems are complex. Therefore, all estimates provided should be interpreted with an appropriate level of common sense.

Similar substantial potentials for reduced discharges of phosphorus are obtained when the same route of calculations is performed, keeping track of fluxes of phosphorus.

The eutrophication issue is interesting. Increased feeding efficiency in Swedish milk production in terms of a higher milk output per kg crop protein feed in combination with a reallocation of milk production to areas with low contributions of nitrogen discharges to the Baltic Sea per kg milk produced (due to a combination of agricultural practices and environmental conditions) is estimated to decrease nitrogen discharges to the sea with 6 + 6.4 million kg (Hellstrand 2008a, b). The importance of these measures is not commonly known; neither to reclaim a higher feeding efficiency; nor the regional ecological structural rationalisation indicated. Other sustainability gains such as conservation of

[6] For details in the calculations, contact the author.

[7] This is based on prices expressed in the Swedish society and economy.

Table 3 Sustainability gains by reclaimed feeding nitrogen efficiency in Swedish cattle production as of 1991 from the level 2006, regarding nitrogen from crop protein crops in purchased feeds (based on Hellstrand 2006, 2008a, b, 2010)

	Dairy production	Cattle meat	Sum cattle production
Ecological gains			
Decreased nitrogen influx, million kg	21.9	4.4	26.4
Decreased appropriation of crop protein feeds, million kg soymeal equivalents	269	55	323
Decreased eutrophication of the Baltic Sea, million kg N	6.5	1.2	7.7
Deceased contribution climate change, onetime event, million ton CO_2	108	22	129
Tropical reforestation, potential in ha	154,000	31,000	185,000
Economic gains			
Increased farmers economic result, billion SEK[a]	1.5	0.30	1.8
Social gains			
Increased food supply capacity, protein supply million people	6.3	1.3	7.6

[a] SEK is Swedish Crowns, 1 US$ corresponds to around 6.5 SEK; 1 € to 8.5 SEK

Not all effects are additive

tropical forests, preservation of the cultural landscape in marginal areas in Sweden, the conservation of biodiversity and a more efficient use of the non-renewable resource phosphorus are favoured.

In 2007, global production of soybeans appropriated 90 million ha,[8] of which 70 million ha were used to produce feed. Table 2 identifies a potential to reduce this appropriation by 9 million ha if reducing the consumption of chicken meat consumed in developed nations, and by 32 million ha with an increased feeding efficiency in milk production. The estimates are rough but they indicate the magnitude of potentials, since they are based on solid knowledge within agricultural sciences especially animal husbandry. Still, this is new knowledge to most people in the field of agriculture and environment.

On the other hand, the results presented are basically a product of applying the same methods and knowledge that I successfully used when being the main responsible for extension services regarding animal production in the county of Värmland in Sweden 1982–1986. At that time, that represented the main stream in animal husbandry in Sweden and dairy production science and had been doing so during most of the twentieth century. At individual farms, improvements in production biological and economic terms up to twice the size per animal were achieved (see Hellstrand 1988), as the ones that give the potentials for improvements presented in Tables 2 and 3. The core of the model for the analysis of production biological and economic performance in milk production generating the results presented in this paper was first presented in two publications from the Swedish University of Agricultural Sciences more than 20 years ago (Hellstrand 1988, 1989). This proven empirical relevance shows that the philosophy underpinning the analyses presented in this paper is relevant on real-world farms. The proposals regarding feeding standards as well as methods for the analysis of environmental impacts criticised below either have

[8] From FAOstat, http://faostat.fao.org/site/567/DesktopDefault.aspx?PageID=567#ancor, accessed 2009-08-16.

records from real-world systems that sign problems, or have not been probed against reality.

6 Methodological issues

There are two methodological issues needed to review further:

- Do feeding standards to dairy cows in developed nations result in feeding strategies that are suboptimal in terms of farmer's economic result and the sustainability performance?
- What are the sustainability risks of extrapolating methods developed within engineering sciences in the evaluation of the sustainability performance of production systems in general and ruminant production systems in particular?

Feeding standards are the rules used to estimate the feeding rations that meet the physiological nutritive requirements of the individual animal. Feeding standards are relevant when cows are fed in cowshed as well as during pasture.

6.1 Feeding standards to dairy cows

The use of crop protein feeds in Swedish cattle production increased dramatically from 1991 to 2006, from 201 million kg to 644 million kg. Sustainability aspects of these trends are analysed in the following. Furthermore, the international relevance of the Swedish trends is examined. Then, the issue whether this is caused by the design of feeding standards to dairy cows is treated.

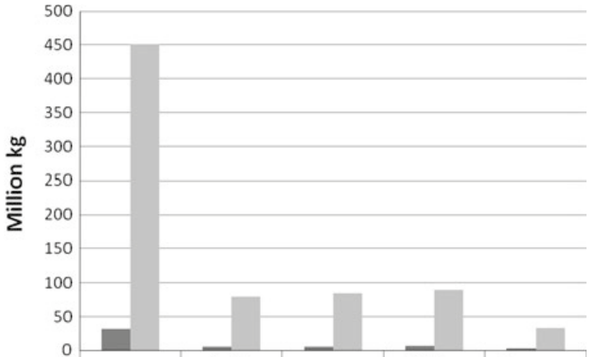
6.1.1 Feeding trends and sustainability impacts

Figure 1 shows the influxes of nitrogen through purchased feeds to different animal production systems in Sweden in 2006. Fluxes of nitrogen and of protein are similar measures. Crude protein in feeds to dairy cows is defined as amount of nitrogen multiplied with 6.25.

In the Swedish system, 66 % of these influxes relates to cattle production.

Figure 2 shows the trends regarding nitrogen influxes through purchased feeds within cattle production in Sweden 1989–1999 and 2006. A phase of fast decrease in nitrogen influxes via purchased feeds to cattle 1989–1991 was abruptly changed to a period of a fast increase from 1991 to 1999 with a prolongation to 2006. Of the total amount of purchased feeds to cattle, approximately 85 % are classed as feeds to dairy cows. The dominating part of the increase was due to the increased use of crop protein feeds (Fig. 2).

In Fig. 3, the results in Fig. 1 are expressed in terms of soymeal equivalents in million kg, allocated on the major animal production branches in Sweden. The reason is that soymeal has a similar role as oil on the global energy market. In 2002, the feed demand for soymeal was 130 million tonnes, while it was 20.4 million tonnes for rape and mustard seed meal, the second largest oilcake (FAO 2006). Thus, based on the crude protein content of different crop protein feeds, standardization can be made to soymeal equivalents. Here, two allocation problems have been treated. It is assumed that feeds for milk production relates to the dairy cow, that is, feeds for milk and maintenance. Feeds for the production of the recruitment heifer are treated as a cost for meat production, which is eventually delivered when the dairy cow is slaughtered. Feeds for gestation, growth and maintenance during the growth period are included. Gestation requirements are requirements for the



	Cow milk	Cattle meat	Pig meat	Chicken meat	Hen eggs, in shell
■ Nitrogen influxes, crop protein feeds	32	6	6	6	2
■ Crop protein feeds, soymeal-equivalents	451	80	84	89	33

Fig. 3 Use of crop protein feeds in purchased feeds in soymeal equivalents in million kg in Swedish animal production in 2006. *Source*: Hellstrand (2010)

growth of the foetus, that is, for meat production. This implies that of the total nitrogen influx to cattle via crop protein feeds in purchased feeds, 15 % is allocated to meat production and 85 % to milk production.

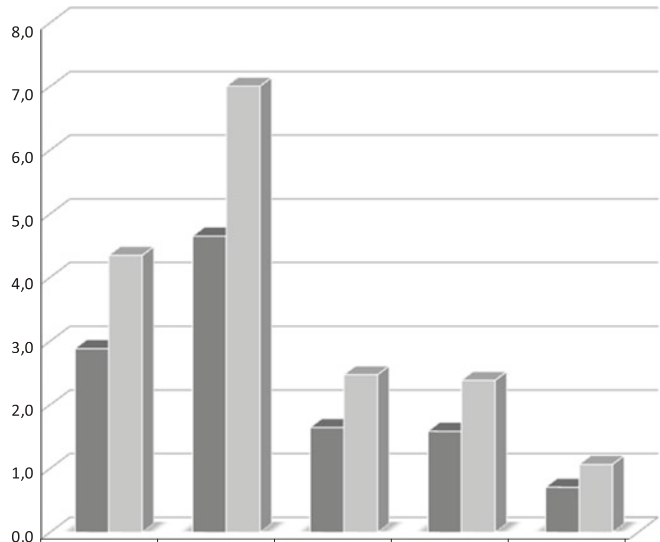
Regarding poultry production, in the official feed statistics in Sweden, 44 % is classed as feeds to laying hens, 40 is for chicken meat production and 2 % go to turkey production. It is assumed that all purchased feeds are evenly allocated to egg and poultry meat production. Feeding standards suggest that for per kg feed, the amount of crop protein feeds is 2.73 times higher in feeds to chicken meat production than for laying hens (30 % compared to 11). This is assumed to be the case also in purchased feeds to poultry production. This gives the results in Fig. 3.

By expressing the use of crop protein feeds in soymeal equivalents, and relating it to the production levels, it is possible to estimate different sustainability impacts per kg animal product. These measures support farmers to improve their sustainability efficiency, facilitate for authorities to establish relevant sustainability standards for farmers to meet and can form a basis for payment systems, for example, within the European Agricultural Policy, providing incentives that make it rational for farmers to contribute to a sustainable development. Of course, they can be used in direct communication between producers and consumers when reliable data regarding sustainability performance make a difference.

The basis for the analysis is Hellstrand (2006) with the methodology developed and the results it generated in the analysis of sustainability impacts due to the increased use of concentrates in Swedish milk production 1991–1999, combined with the information in FAO (2006) regarding the impact on carbon dioxide emission when tropical forest are converted to arable land. By considering yields of soybeans per ha and the fraction of total yield that becomes soymeal, the results in Fig. 4 are obtained.

Figure 4 provides results regarding impact on deforestation and food security through the impact on supply of protein for humans when protein feeds are fed to animals that can be used by humans.

Figure 5 shows the impact on global climate change.



	Cattle meat	Chicken meat	Hen eggs, in shell	Pig meat	Cow milk
Deforestation, m2	2,9	4,7	1,6	1,6	0,7
Food security, no of human daily prot requirements	4,3	7,0	2,5	2,4	1,1

Fig. 4 Sustainability impacts per kg animal product due to the use of crop protein feeds in Swedish animal production in 2006. *Source*: Hellstrand (2010). Deforestation concerns tropical deforestation because of the use of crop protein feeds used in the production measured in soymeal equivalents. The amount of soymeal equivalents represents an area of tropical deforestation on the margin, for producing more soymeal to the world market that is eventually used in the concerned production. This relates to the concept of ecological footprints. In a corresponding way, the use of crop protein feeds in animal production if directly used by humans as feed can support global food security, in terms of human protein requirements fulfilled. These two effects are of the kind either or. Daily production per capita and day in Sweden was in 2006 41 g cattle meat, 30 g chicken meat, 80 g pig meat, 30 g eggs and 954 g milk. Production from http://faostat.fao.org/site/569/DesktopDefault.aspx?PageID=569#ancor, Swedish population from http://www.ssd.scb.se/databaser/makro/SaveShow.asp, both accessed 2010-06-04

Table 3 gives sustainability gains, if the higher nitrogen efficiency in the use of crop protein feeds in purchased feeds to cattle in Sweden of 1991 was once again obtained from the lower efficiency level as of 2006. Here, the results are specified for milk and meat production, respectively.

The information above implies that

- important sustainability aspects are closely related to the use of crop protein feeds,
- they are closely related to the nitrogen efficiency in animal production branches, and
- in the Swedish context, milk production plays a major role.

Figures 1, 2, 3, 4, 5 illustrate how the management of animals on the individual herd level can be linked to global sustainability through impacts on climate change, food security and tropical deforestation per kg product, that is, a contribution when considering global impacts in the everyday operations in animal production on commercial herd level. In the prolongation, it indicates how future payment systems, for example, in the European Common Agricultural Policy, can be based on evaluating systems informing about the contribution at individual farm level to societal objectives from local to global community level.

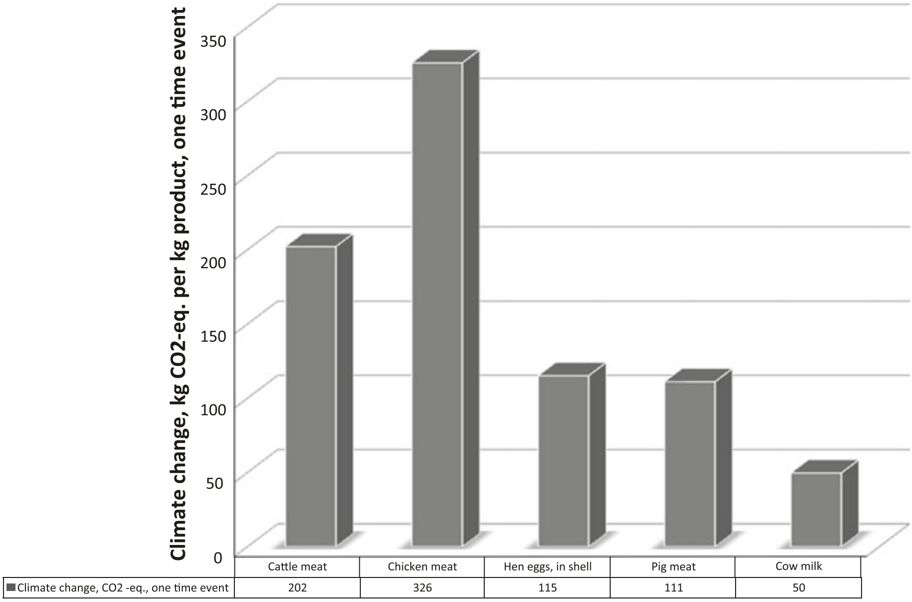


Fig. 5 Impact on global climate change through deforestation due to the use of crop protein feeds in Swedish animal production in 2006. *Source*: Hellstrand (2010). For the production per capita and day in 2006, see Fig. 4

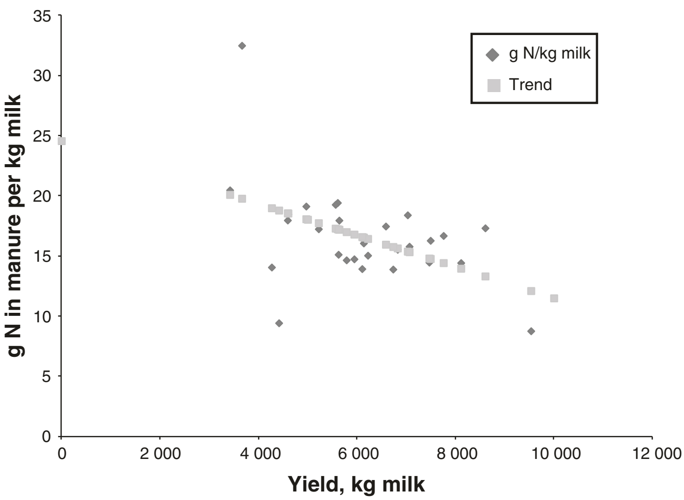


Fig. 6 The amount of nitrogen in manure from dairy cows in g per kg milk produced at different production levels among OECD nations. *Source*: Hellstrand (2010)

Figure 6 indicates the international relevance of the information in Figure Figs. 1, 2, 3, 4, 5. It presents the amount of nitrogen in manure from dairy cows in g per kg milk produced in OECD nations. The estimates are the ration between nitrogen effluxes in manure per dairy cow[9] and milk production per cow from FAOstat in OECD nations.[10]

The nitrogen balances reflect the nitrogen/protein content in the feeding ration and the total amounts of feeds consumed.

The figure shows that the nitrogen efficiency tends to increase with increasing yields, at the same time as the relationship is not strong: other factors explain 78 % of the variation in Fig. 6. Korea combines a high production level, around 9,500 kg per cow, with a high nitrogen efficiency. The amount of nitrogen in manure ("manure" here is manure + urine) is 8.8 g per kg milk, which is 3.3 g less than the expected value at this high production level. USA has a somewhat lower production, 8,600 kg per cow and year, with 17.3 g nitrogen in manure per kg milk, which is 4.0 g more than expected due to the milk yield level. Among nations with high production levels (>7,000 kg per cow and year), the Netherlands and Denmark have low nitrogen efficiencies; 3 and 2.3 g nitrogen more in manure per kg milk than expected at their respective production levels. Finland is the only nation in the group with high production levels with a lower value than the level predicted from yield, 0.3 g below the trend. The Swedish value in Fig. 6 is close to the expected based on the regression curve. Thus, Fig. 6 indicates that the decreasing nitrogen efficiency in Swedish milk production from 1991 to 2006 is towards a lower efficiency level common among OECD nations. That suggests that the decreasing efficiency in Sweden in that period is an estimate of a potential for improvement, which can be used as a departure for a first rough estimate of global potentials. Hellstrand (2006) investigated whether there were good economic reasons for this decreasing efficiency in the use of crop protein feeds. He found none. Hellstrand (2008a), in a study on behalf of SEPA, investigated the causes behind this trend. The major reason (ibid.) was the abandon of basic principles ruling feeding strategies in Swedish milk production during most of the twentieth century up to the beginning of the 1990s, concerning how to utilise the "law" of diminishing returns and Liebig's "law" of the minimum (see Wiktorsson 1979; Liebig 1840) when searching the economic optimal feeding intensity. Since 1995, the economic result at commercial herd level no longer influences the design of feeding standards in Sweden. For a late example of how to adjust feeding standards due to the variation in prices on feed inputs and milk output in the Swedish system in order to support the economic result on farm level, see Hellstrand (1989).

With a global production of 578 million tonnes cow milk in 2008[11] (FAOstat 2009; Hellstrand 2010), the estimate for Korea suggests a possibility for a nitrogen efflux in manure of 5,000 million kg, while with the lower efficiency of the USA, the nitrogen efflux in manure would be 9,800 million kg, that is, 4,800 million kg nitrogen more. 4,800 million kg nitrogen related to nitrogen in soymeal, correspond to around 34 million ha soybeans production. From that measure, the possible impact in climate change, on global food security, and on farmers' net income can be estimated through same route as earlier used.

To some extent, the differences in values for Korea and USA can be caused by differences in measuring methods and data accurateness. The objective of increasing the sustainability contribution from animal production globally implies a need to further

[9] From environmental performance of agriculture in OECD countries since 1990, http://stats.oecd.org/Index.aspx?datasetcode=ENVPERFINDIC_TAD_2008, accessed in August 2009.

[10] From http://faostat.fao.org/site/569/DesktopDefault.aspx?PageID=569, accessed 2009-08-08.

[11] FAOstat. http://faostat.fao.org/site/569/DesktopDefault.aspx?PageID=569#ancor, accessed at 2010-01-04.

analyse these values, their differences and causes. That supports methodological standardisation and improvement in international statistics, and the possibility to learn between nations.

The Swedish trend (Fig. 2) and the significant variation in nitrogen efficiency among nations (Fig. 6) are two arguments suggesting that the options for increased nitrogen efficiency in milk production globally are substantial, where this can significantly improve a spectrum of important sustainability aspects through paths discussed above.

6.1.2 Feeding standards feeding feeding trends

The sharp change of the Swedish trend, where a decreasing influx of nitrogen via crop protein feeds to cattle in 1991 was changed to a fast increase, appeared at the same time as a major change in protein evaluation and feeding standard system to dairy cows was implemented. In 1995, the energy feeding standard system to dairy cows was fundamentally changed, while at the same time, major changes of the new protein feeding standard system were made. These changes in feeding standards, I suggest, were driving forces behind the increasing influxes of nitrogen trough crop protein feeds (see also Hellstrand 2008a).

In 1991, the protein evaluation system was changed from digestible crude protein (dcp) to the AAT/PBV system. Gustafsson (1990) probed the outcome of the new system before its implementation in a field study covering 29 cow herds. Regression analysis resulted in statistical significance for the relationship between milk yield (ECM; energy-corrected milk) and consumption of dcp and PBV, respectively, but not between milk yield and AAT. This was quite surprising, as AAT was supposed to provide better estimates of the protein quality than dcp and PBV function as a waste fraction, not supporting milk production. The results suggested that the old system was better than the new system, and that the assumed waste fraction contained protein with a higher capacity to support milk production than the assumed quality fraction. Furthermore, the study showed that energy allowances were on average 14 % above assumed requirements (according to official feeding standards) while the protein allowances were 13 % above measured in terms of dcp. Measured in terms of AAT and using the standards that some year later came into practise, the protein allowance was only 4 % above the feeding standards. Thus, having the same cows, feeds and production levels, and only changing the protein measure used to estimate the feeding rations that exactly would balance assumed requirements of energy and protein, would result in a substantial reallocation of concentrates from coarse grains to crop protein feeds such as soymeal. Assuming that the cows in total consumed 135 kg nitrogen with the dcp system per lactation, and with the number of dairy cows in Sweden, the year of the field study (1987/1988) of 564,550, the total influx of nitrogen with feeds to dairy cows would be 76 million kg. If, with the new system we arrive at the same apparent balance between energy and protein, the shift from the dcp system to the AAT system would instantly increase the protein allowance with 1.13/1.04, i.e., 8.65 %. That would increase the influx of nitrogen to the stock of dairy cows with 6.6 million kg through concentrates. Hellstrand (2006) estimated an increase of nitrogen influxes via purchased feeds to cattle of 22.8 million kg from 1991 to 1999. Of that, 85 % can be allocated to dairy cows, that is, 19.4 million kg. The results of Gustafsson suggest that 34 % of the increased influxes of nitrogen through purchased feeds to dairy cows were caused by the introduction of the AAT/PBV system during the production year 1991.

Hellstrand (2006) estimated the impact of increasing use of purchased feeds 1991–1999 on feeding efficiency to dairy cows considering changes in production levels and the nutritive quality of forages. Hellstrand (2008a) investigated how changes in protein feeding standards 1991 and 1995, and the change of ruling principles in energy standards in 1995 affected nitrogen influxes to dairy cows. He also evaluated the impact of recommendations to further increase the protein allowances per kg milk above the official standards. The source for the later was a study of future and efficient Swedish agriculture performed by the Swedish Environmental Protection Agency (SEPA 1997).

Different paths through which these changes in feeding standards (with supporting feed evaluation system) would affect feeding efficiency are:

- The substantial reduction of assumed available protein in forages ("available" in terms having feeding value) with the introduction of the AAT/PBV system,
- The increase in assumed protein requirements for maintenance in 1991 further increased in 1995 with the AAT/PBV system,
- The change of ruling principle in 1995 for the energy standards from supporting economically optimal feeding intensity to predict milk yield from feed intake,
- The choice to formulate a new energy standard to dairy cows based on the regression analysis of results from feeding trials where in most trials, the cows consumed above economic optimal levels,
- The change of protein standards to a principle where the amount of protein per energy unit was assumed to be constant independent of production level while physiological common knowledge states that low-lactating cows have a lower protein requirement per unit energy due to the higher part of total requirements that are related to maintenance needs, and
- A fashion established in extension services that high-yielding dairy cows demand more protein than the official feeding standards suggest per kg milk produced.

Added to these paths were weaknesses in the probing of the changes made before full-scale implementation. Thus, there was a combination of weaknesses in the theoretical and empirical foundations of made changes, where the control system that should filter against such weaknesses had a corresponding flaw:

The new energy standards introduced in 1995 were based on a work by a student in agronomy (Andresen 1994[12]); the change of the protein standards in 1995 was based on an unpublished memo that the author himself around 10 years later could not find (see Hellstrand 2008a; Spörndly 1995). It is impossible to probe the quality of the analysis resulting in the proposed change in protein standards in a process that follows standard criteria of good scientific praxis simply as the analysis itself no longer exists.

The rationale for the change of the energy standards in 1995 was that high-yielding cows demand more feeds per kg milk than low-lactation cows. The physiological mechanisms behind this assumption are clearly laid out in NRC (2001).[13] That would result in a curvilinear relationship between feed intake and milk production. The intention, therefore, was to replace a linear relationship between energy intake and milk yield with a curvilinear

[12] This is not a critique against this student work; it is a critique regarding the choice to base such a fundamental change of such a fundamental relation in the most important production branch in Swedish agriculture on a work with such a low formal quality. This has an element of playing hazard with farmers' economy through decreased natural resource efficiency (feed efficiency) as well as with the environment through the spectrum of environmental costs that may cause.

[13] The relevance of this assumption when designing feeding strategies on commercial herd level can be questioned. However, it is outside the scope of this article to treat that issue.

one (Andresen 1994; Gustafsson 2000; Norfor 2004). When analysing the mathematical expression used to transform the earlier linear relation to a curvilinear one (Hellstrand 2008a), it shows that the outcome is a new linear relation. In one sense, this is not surprising, as the earlier linear expression was modified by multiplying it with a constant, then reducing the new value with a term. What as is a concern is that this indicates a lack in the capacity among the group of scientists and other professionals that at that time were responsible for the feeding standards to transform assumed physiological relations in milk production to mathematical expressions. As these expressions steer the programmes by which the feeding rations are calculated for most of the dairy cows in Sweden, this is not of marginal importance. Furthermore, if in such a principally simple task, there are such problems that by itself deflate the credibility regarding other and principally more complex aspects to handle in feeding standards and supporting feed evaluation systems. Such circumstances might contribute to an understanding why Lantmännen around 1997 launched an entirely different feeding standard and feed evaluation system (see Sect. 5).

The mode by which the feeding standards were applied in practice might further have decreased the feeding efficiency. In an evaluation of the international relevance, it was found that the Swedish feeding standards moved towards systems that already were implemented in Denmark, the Netherlands and USA (Hellstrand 2008a). The data behind Fig. 6 show that these nations are the ones with the lowest nitrogen efficiency among nations with high production levels per cow in 2004, while the Swedish efficiency is at an intermediate level.

Reasons why the changed feeding standards caused these effects are (ibid.):

- The protein evaluation and feeding standard system introduced in 1991 was in conflict with basic principles regarding typical features of such complex systems that the protein metabolism of ruminants have. Strict linear causal relations were presupposed in the applied model of this complex system with mutual dependencies between systems and system levels. Long chains of calculations were provided where each step in the calculations decreased the accurateness of obtained estimates. Values of parameters in each step were taken from different trials in different nations with their own specific context, within which the values are relevant, while the relevance is deteriorated when the same numeric values are used outside the contexts defining them.
- The energy feeding standard system was until 1994 based on the principle of diminishing returns. That was expressed in the objective to find that energy feeding intensity, which at the margin caused an increase in yield that had precisely the same value as the costs for the feeds causing that increase in yield. From 1995, the objective of the feeding standard was instead to predict the yield from the feed intake. This may be of interest for a researcher but it is not the prioritised objective for owners of commercial herds. Here, the objective is to arrive at the feeding intensity, that is, the energy allowance per kg of milk, which maximise the economic result. This principle ruled during most of the twentieth century in Sweden, until 1995, in the formulation of energy standards to dairy cows, and still rules the yearly upgrading of the official recommendations regarding fertiliser application rates considering changed prices of fertilisers and crop products.

The same situation as in Sweden is at hand regarding the ruling principles of protein and energy feeding standards and feed evaluation systems in other important milk-producing nations (ibid.). This is an indication that the results from Sweden are of international relevance.

6.2 Engineering science and sustainable ruminant production

Hellstrand et al. (2009) found that a central natural resource concept in physical resource theory, exergy, is defined in a conceptual model of real-world systems where all process restrictions that define ecological, economic and social systems are ignored. As a matter of fact, the mere concept resource becomes meaningless given the condition for its definition of thermodynamic ideality (ibid.) To discuss natural resource management strategies on global scale based on concepts that lack relevance in real-world systems may cause problems (ibid.).

Hellstrand et al. (2010) investigated a number of applications aiming at supporting a sustainable development at operative level. They all have emerged from the basis of engineering sciences. They had four factors in common,

(i) the physiological and biological aspects of the carrying capacity limits of ecosystems are ignored,
(ii) ecosystems affected by production and consumption are located outside the system borders,
(iii) the variation in the conditions of ecosystems in space and time is ignored, and
(iv) the capacity of ecosystems, managed and natural ones, to produce ecosystem goods and services is ignored.

The examples were the following:

- The system of environmental and economic accounts in Sweden (Statistics Sweden 2009),[14]
- Analysis of the environmental impacts, quantifiable and non-quantifiable, from Swedish agriculture, including upstream and downstream effects (Engström et al. 2007),
- Sustainable pig production (Stern et al. 2005),
- Sustainable milk production (Gunnarsson et al. 2005; Sonesson 2005),
- Life cycle assessment of milk production (Cederberg and Flysjö 2004; Cederberg et al. 2007),
- Life cycle assessment of seven different food items (LRF 2002),
- The Integrated Pollution Prevention and Control-directive and its BAT (Best Available Technology) principle,[15] supporting the development of sustainable industries in the European Union,
- The Integrated Product Policy of European Union (Wijkman 2004),
- The main streams approach in life cycle assessment (Baumann and Tillman 2004), and
- The system conditions for sustainability of the natural step.[16]

The consequence is that none of these approaches comply with the principles for sustainable development regarding its ecological dimensions as expressed by Millennium Ecosystem Assessment (MEA 2009), OECD (2001) and the UN Millennium Goals (UN 2010). This is the logical consequence for these approaches common factors (i)–(iv) above.

[14] The "environmental" aspects concern natural resources entering the economic system and emissions leaving it. The environment itself is located outside the system borders of the system of environmental economic accounts.

[15] http://eippcb.jrc.ec.europa.eu/reference/BREF/ppm_bref_1201.pdf, accessed 2012-10-19.

[16] http://www.thenaturalstep.org/the-system-conditions, accessed 2009-06-14.

A number of the examples above concern animal production system. Hellstrand et al. (2010) found that their impact on agricultural sciences and policies from national authorities as well as in the private sphere were substantial. If that conclusion is valid, as well as that the conclusion that these examples are in conflict with the principles for sustainable development regarding its ecological dimensions as expressed by Millennium Ecosystem Assessment (MEA 2009), OECD (2001) and the UN Millennium Goals (UN 2010), then there is a problem. The possibility and significance of this problem is somewhat elaborated on below.

There are two reasons for why the evaluation of the sustainability performance of ruminant production systems based on engineering sciences in Sweden has failed. Typically, the handling of (i) the metabolism of the cow in interaction with the feeds and (ii) the environmental impacts of the production systems could be better. The short reason is that they are products of engineering sciences, and engineering sciences do not have the competence of excellence regarding the physiology of dairy cows or the ecological, economic and social dimensions of a sustainable development.

As is shown in the following, this may cause substantial impacts on policies from local to global level which ultimately can inflict global food security. This conclusion is so serious that the analysis performed in this study needs to be presented in some detail, thereby facilitating the reader to evaluate the accurateness of the conclusion.

The following will treat both weaknesses in engineering-based approaches, as well as weaknesses in the feeding standard systems in Sweden, and the way they have been applied the latest 20 years. The reason to treat them together is that

- If having accurate methods for the analysis of environmental performance, the increasing environmental load associated with an increase in the use of crop protein feeds to cattle with a factor 3.2 from 1991 to 2006 for a constant or decreasing production had been detected;
- The huge differences in nitrogen efficiency and feeding strategies between conventional and organic milk production cannot be understood, without understanding the problems in the changes in the feedings standard systems from 1991 and onwards, forcing organic producers to manipulate the feeding standard systems in order to be able to feed the cows the amount of forages as the rules of organic milk production state;
- The understanding of the previous two points is needed to see why an evaluation of the sustainability profile of milk production should be based on the animal production and supporting plant production that actually is at hand.

Results and policy suggestions based on the results in Cederberg and Flysjö (2004), Cederberg et al. (2007), Wirsenius (2000, 2003a, b), Wirsenius et al. (2010, 2011) and Azar (2011) are a concern. By the same reasons as the sustainability relevance of a number of engineer-based measures and methods are rejected by Hellstrand et al. (2010); these examples are. Their results are in strong conflict with the perspectives and priorities of a sustainable development expressed in UN Millennium Development Goals, OECD principles for a sustainable development and Millennium Ecosystem Assessment. They focus ruminant production as a major sustainability obstacle by arguments in conflict with the perspectives of FAO (2006). Mainly, this expresses that these contributions are not based on an expertise competence regarding the ruminant, ecological, economic and social systems in which the sustainability contribution from grass ruminant systems are defined.

Some examples illustrate the problems:

Cederberg and Flysjö (2004) and Cederberg et al. (2007) estimate the quantity and nutritive quality of feeds grown on the dairy farm, which typically constitute 40–90 % of the feed intake on dry matter basis, by the amount of diesel used on the farm according to the accounting books. In the analysis of fluxes of compounds through the dairy cows, the law of mass constancy is violated. Cederberg and Flysjö (2004) and Cederberg et al. (2007) use values from a theoretical calculation about 10 years earlier regarding the protein efficiency in conventional milk production, as a starting point for the evaluation of emissions of N_2O and ammonia from manure from the organic milk production system. As the feeding strategies differ substantially between these systems, this is not relevant. The dominating system for certification in organic farming in Sweden is KRAV.[17] They provide a detailed list of rules to comply with, presented on 156 pages.[18]

The rules state that for milk-producing animals, concentrates may be at most 40 % of the daily dry matter intake. The official feeding standards to dairy cows in Sweden from 1995 (Spörndly 1995) is that lactating cows need 7.6 g protein per MJ ME (protein measured as AAT). Swedish Dairy Association provides "Kvalitetssäkrad mjölkproduktion:—Kvalitetssäkrad utfodring mjölkkor" (Svensk Mjölk 2003). That brochure delivers rules of thumb to advisers regarding the feeding of cows during different lactation phases. For cows in early lactation (the first 100 days), the recommendation is that the AAT allowance ought to be 8.0–8.5 g AAT/MJ. The reference provided is "Mjölkkor" (Dairy cattle in translation).

"Mjölkkor" is a Swedish textbook about milk production. Gustafsson (2000), in a contribution in this book, treats the issue of economically rational feeding. He argues that by economic reasons, it can be rational to increase the protein allowance above the official standard of 7.6 g AAT per MJ. He mentions that levels up to 8.5 g AAT/MJ are commonly used. In 1991 when the AAT system was introduced, the protein requirement was set to 40 g AAT per kg milk ECM. Gustafsson states (p. 136) that the level 40 g AAT per kg milk was supported by trials showing lower yields if lower allowances, while there were no or small increase in milk production in trials if cows were fed more than 40 g AAT per kg milk. The previous standard of 40 g AAT per kg ECM now is captured in the formulation that the requirements for lactating cows are 7.6 g AAT per MJ ME as the cows need to meet the energy requirements of lactation and maintenance together (ibid.).

Here, there is a contradiction: Empirical evidences showed no or small increase in milk yield for protein allowances above 40 g AAT per kg ECM. A standard conclusion regarding production functions based on dose–response functions in biological systems are that the biological optimum is at a higher input of, for example, feed or fertiliser than the economic optimum. If the biological optimum is at a protein allowance of 40 g AAT per kg ECM or slightly higher, then the economic optimum will be at a lower allowance. And, if the formulation of the protein requirement of 7.6 g AAT per MJ ME equals the one of 40 g AAT per kg ECM, then there can be no economic reason for increasing this protein allowance when generating feeding rations at commercial herd level. Thus, the conclusion by Gustafsson must be rejected: There are no empirical evidences that support the conclusions that by economic reasons, it can be rational to increase the protein allowance above the official standard of 7.6 g AAT per MJ.

[17] For information, see http://www.krav.se/System/Spraklankar/In-English/KRAV-/, accessed 2009-08-04.

[18] http://www.krav.se/Documents/Regler/englishEditions/Standards_for_krav-certified_produktion_january_2009.pdf accessed 2009-08-04.

Gustafsson presents the changed formulation of the energy requirement in 1995, where one linear expression was replaced by another one (see above), as if the new liner relationship was a curvilinear one (ibid.: p. 134–135).

From this, three conclusions follow.

(i) It is in conventional milk production recommended to increase the protein allowance with 5–12 % above official standards. This is supported by a textbook used in agricultural education.
(ii) The understanding of the definition of the optimal level in production functions in production biological and production economic terms is weak.
(iii) The understanding of how to represent a curvilinear relationship between energy intake and milk yield in a mathematical expression is weak.

The latest example where the principle of the relation in (iii) is clearly demonstrated in production biological and economic terms in the Swedish context is Hellstrand (1989). Nanneson et al. (1945) and Wiktorsson (1979) thoroughly treat this subject. This points towards the conclusion that the increasing protein allowances to dairy cows in Sweden 1991–1999, remaining at a high, possibly higher level in 2006 (see Figs. 1, 2) is a function of a decreasing capacity to handle issues regarding optimal intensities in biological and economic terms among the national expertise in Swedish dairy science.

The example here discussed regarding a believed rationality in overfeeding dairy cows with protein in the organisation dominating extension services to farmers is similar with the example in 6.1.2 regarding the feeding rations in milk production delivered by Spörndly in 1996 to SEPA to a study of future, rational Swedish agriculture. The future study was published in 1997(SEPA 1997). The task of the study was to outline what a sustainable and environmentally well-adapted agriculture was, and how it could be conserved, and further developed to the year 2021. The future study worked with two visions. In both set, sustainability objectives were assumed to be possible to achieve. In the one building on a development of conventional agricultural systems, the path towards sustainability and a good environment was described in terms of precise use of commercial fertilisers, pesticides and concentrates. Yields were high and animal production was characterised by high-yielding cows and pigs and poultry with low feed consumption per kg product.

A concern is the design of the feeding rations delivered regarding milk production. In 1995, the official protein standard in AAT terms was changed. The author for the publication where this is established is Spörndly (1995). In 1996, he had a task to provide SEPA with feeding rations supporting an economically efficient and ecologically sustainable Swedish milk production. The feeding rations provided[19] cover the months 1–12 in the lactation. For lactation month 9, the amount of energy and protein exactly matches the requirements according to Spörndly (1995). Then, the production is on average 25 kg ECM per cow. In lactation months 1 and 2, that is, one to 2 months after calving, the production level is 45 kg ECM per day. At that high production level, the allowance of AAT is 2,674 g per cow and day, at the production level 25 kg ECM, it is 1,467. Thus, an increase in production with 20 kg ECM increased the allowance of AAT with 1,207 g AAT, that is, 60.3 g AAT per kg ECM more. The feeding standard as of 1995, to be precise, implies an allowance of 42.2 g AAT per kg milk. Here, the same author as in 1995 published a new official feeding standard in Sweden regarding energy and protein, in a task for the SEPA 1 year later aiming at environmentally sound and economic efficient production for the

[19] I got them from one of the authors some time after the report from SEPA was published in 1997.

future, increases the protein allowance with 60.3/40.2 per kg ECM, that is, with precisely 50 %. The energy allowance by Spörndly in this task follows close to the official one as of Spörndly (1995). This implies that the amount of protein as AAT per MJ ME that Spörndly in 1996 assumes that is needed at increasing milk yields are 10.6 and not the 7.6 as from 1995 is the official Swedish feeding standard (Spörndly 1995). Such an increase in the assumed amount of protein required per MJ ME needed for milk production will heavily change the solution in the system of linear equations used when determining the amount of energy concentrates and protein concentrates, respectively, required to exactly match the remaining requirements of energy and protein given the weight and production level for the animal, and the allowances of energy and protein through fixed rations of forages.[20] This will cause a substantial substitution of grains typically produced on the farm or at near farms, with purchased protein concentrates, that to a substantial part contain intercontinentally produced soymeal.

Gustafsson is one of the leading experts in the feeding of dairy cows at Swedish Dairy Association the latest two decades, and Spörndly has had a corresponding position at Swedish University of Agricultural Sciences (SUAS) for a similar period. Bertilsson is another of the experts at SUAS. He is the source for the change of the formulation of the protein standards in 1995 (Bertilsson 1994), where the source (se Spörndly 1995) is an internal memo that no longer can be found (Hellstrand 2008a). Bertilsson and Spörndly were supervisors to Andresen (1994) in his student work leading to a new energy standard to dairy cows in 1995 (Spörndly 1995).

The paragraphs above suggest that the decreasing protein efficiency in Swedish milk production since 1991 partly is a function of a decreasing quality in the contributions in dairy science the same period.

The findings in Hellstrand (2008a) suggest that this reflects a movement

- From a good understanding of general principles for a resource-efficient and economically competitive milk production in Sweden, that had a tradition of the major part of the twentieth century, as expressed e.g. in Nanneson et al. (1945) and Wiktorsson (1979),
- Towards a lower level common internationally.

One historical reason why Sweden evolved a higher competence in this field than most nations is the socio-economic and biophysical contexts of the Swedish society over time. Ruminants were a major path to convert sunlight to food. The capacity to nourish the Swedish population was for a long period of time not sufficient. During the nineteenth and the first half of the twentieth century, the development of ruminant production systems in combination with crop rotations with leguminouses and grasses improved soil fertility and food security.

The historically strong dependency of ruminants of the Swedish population for the fulfillment of basic physiological requirements may well have put a higher selection pressure in favour of the development of efficient management strategies regarding milk production.

The changes in the way feeding strategies were constructed in Sweden during the 1990s implied a movement towards approaches common internationally, for example, in Denmark, the Netherlands and USA. Some references for this are Andresen (1994), Berg and Thuen (1991), NRC (2001). Other references are given in Hellstrand (2008a).

[20] In reality, they are not fixed. When constructing a feeding plan, the steps taken normally imply an assumption of fixed rations of forages. This is a way to come around the problems of milk production and feeding as a typical complex system with mutual dependencies between systems and system levels.

Compared with the previous dcp system, the AAT system implied that the value of protein in forages in relative terms was decreased substantially more than for grains and crop protein feeds. That follows from a comparison of the official feeding table for ruminants in 1989 and 1995, e.g., (Spörndly 1989; 1995). At the same time, the assumed requirements for maintenance per cow and day increased in g when going from the dcp to the AAT/PBV system (ibid.). The typical way of constructing a feeding ration (see Hellstrand 1988) implies in a mathematical way that forages are used to supply the demands for maintenance purposes, and hopefully, the first kg of milk produced. Then, remaining demands for remaining production are met by rations of energy (grains) and protein concentrates (with high fractions of soymeal, respectively).

With the new system, two effects come into place at the same time. Every kg of forages was assumed to have a substantially lower capacity to fulfil the protein requirements for maintenance and the first kg of milk produced. And, the assumed protein requirements for maintenance increased. This resulted in a situation where in the new solution of the system of linear equations needed to theoretically exactly meet the remaining requirements of energy and protein, substantial quantities of grains were substituted with protein feeds.

The rules for organic milk production state that concentrates may be at most 40 % of the total daily dry matter intake. Thus, the fraction of total feed intake that is forages is 60 % or more. (i) The assumed drastic reduction in feeding value of protein in forages in combination with (ii) the higher maintenance requirements in terms of AAT compared to dcp, and (iii) the rule in organic agriculture stating that >60 % of the daily feeding ration should be forages created a situation where the official feeding standards become obsolete. If following the official feeding standards, a well-functioning feeding ration could not be constructed. That resulted in a quite odd situation:

While extension service organisations as well as the expertise at SUAS assumed that conventional and high-yielding dairy cows needed substantially more protein per kg milk than the official feeding standard stated, extension services directed towards organic milk production assumed the opposite. In a similar text as the one advising extension officers to increase the assumed requirements of protein for milk production in conventional milk production, the advice when generating feeding rations in organic milk production was to reduce it (Andresen). Andresen suggest 7–7.5 g AAT per MJ ME during the early phase of lactation compared to the 7.6 that is the official standards; and the 8.0–8.5 recommended in conventional milk production. Gustafsson (1990) in a field study got results, implying that by going from the dcp system to the AAT/PBV system, the theoretically estimated protein requirement would increase with about 10 %.The discussion above suggests some paths that might have contributed to this effect. Here, Andresen proposes a reduction of protein allowances with up to close to 10 %. Thus, the organic system in that sense can represent the situation before the AAT/PBV system was introduced in 1991.

By Andresen's recommendations regarding how to manipulate the official feeding standards,[21] reasonable relations can be maintained between grains and protein feeds also

[21] A few years ago, I participated when a friend with organic milk production was visited by the extension officer. The feeding plan was constructed by these steps. First, the farmer told the extension officer how he would like the feeding plan to look. Then, the extension officer reported needed data regarding animals and feeds. In the last step in a trial-and-error mode, the extension officer probed different assumed protein allowance levels as the protein standard. When a feeding plan as the farmer believed in was obtained, the officer used the protein allowance behind as the protein feeding standard. This is quite a creative way of using feeding standards that have moved a long distance away from its original purpose, to condense experiences from feeding trials as a guide for farmers to achieve feeding plans fulfilling the physiological demands of the animals and the economy of the farmer.

in organic milk production while feeding the cows high forage rations. One reason why this can work is that in reality, ruminants through the selection advantage that rumination provides over millions of years have developed the capacity to utilise energy and protein from forages. Gustafsson (1990) (see Sect. 6.1.2) probed the outcome on commercial herds of the new protein evaluation system AAT/PBV. The outcome was surprising. The "waste fraction" PBV got statistical significance between level of PBV and milk yield, while allowance of the assumed quality fraction of protein AAT did not. That result indicates that the manipulation of the feeding standards recommended by Andresen can imply a correction of a flaw within the AAT system.

The following suggests one reason that might have caused the result in Gustafsson. A simple statistical analysis of all forages in the official Swedish feeding table for ruminants[22] shows the following R^2 values:

- MJ ME and crude protein 17 %,
- MJ ME and AAT 75 %,
- MJ ME and PBV 8 %,
- MJ and dcp 17 %,
- AAT and crude protein 8 %,
- AAT and dcp 8 %,
- PBV and crude protein 97 % and
- PBV and dcp 97 %.

So, with the new system AAT/PBV and talking in mathematical terms, a measure of the protein dimension of the nutritive content of forages (here "forages" is ley and pasture) was introduced, which mainly was a function of the energy, not the protein content of forages. In mathematical terms, this implies that when in the system of linear equations needed to balance the energy and protein requirements of the animal and when it comes to forages, the protein requirement of the animal is balanced by values that actually reflects the energy content of the feed, not the protein content. Then, the result of Gustafsson (1990) is no longer surprising but expected. A protein fraction with a believed higher quality, that to a substantial part actually is an energy measure not a protein measure, will have limited capacity to fulfil the protein requirements of the cows.

The manipulation of feeding standards proposed by Andresen just described results in a higher dependency of protein in the believed waste-fraction PBV in forages. That fraction has a high correlation with the protein contents of forages as determined by chemical analysis in combination with digestibility trials as reflected in the R^2 values above between PBV and dcp and crude protein, respectively (97 % both cases). The corresponding R^2 values for AAT are low, 8 % for both. Therefore, the chances that this will work on real farms are good.

Thus, by reducing the assumed requirement of protein as Andresen suggests, organic farmers might have corrected the aim of the rifle, so that the shot has a better direction.

The way of expressing the AAT value of forages as mainly a function of the energy content implies that the precision of the "shot" has decreased compared to the previous dcp system. The increase in protein allowances recommended in conventional milk production by the organisation dominating in extension services, Svensk Mjölk and associated organisations can be understood in terms of an insurance against the backlashes a decreased precision might cause. Then, it reflects mistrust in the organisation of the quality of the feeding standard system with associated feed evaluation system.

[22] Fodertabeller för idisslare 2003, http://www.slu.se/sv/fakulteter/vh/institutioner/institutionen-for-husdjurens-utfodring-och-vard/verktyg/fodertabeller/fodertabell-for-idisslare-vallfoder/, accessed 2012-07-17.

The discussion above concerns the AAT/PBV system the way at it has been applied in Sweden. The problems penetrated can be due to causes on lower system levels, as well as to a principally invalid approach that is outside the scope of this study to evaluate.

The discussion above is needed to understand how it can be that organic and conventional milk production in Sweden commonly uses so different protein allowances in milk production, while the cows themselves most probably are not affected of whether the nitrogen supply to the crops is from commercial fertilisers or from nitrogen-fixating microbes. This knowledge also needs to evaluate whether there is a problem in using values regarding the content of nitrogen in manure for conventional milk production as estimates for organic one as, e.g. Cederberg and Flysjö (2004) and Cederberg et al. (2007) do. The following evaluates the significance of the two opposing ways of manipulating the official protein feeding standards. It also informs about the major differences in the feeding strategies in organic and conventional milk production.

Table 4 presents data for producing the same amount of milk per cow in one organic and one conventional system. The difference in energy concentration of feeding ration at top lactation of 0.70 MJ per kg DM may theoretically support a higher milk yield per cow and year of around 1,200 kg ECM in the conventional system.

The amount of milk produced per cow is constructed from the lactation curve for one organic farm as reported in the official milk recording programme 1998, Höglunda gård in Kil in Värmland. The basis for the biological and economic profile is given by the production branch calculi from SUAS, production year 2009,[23] for the production area Plain districts Svealand. The protein allowances per kg milk follows the feeding ration behind the conventional milk production system in the future study of SEPA (1997) delivered by Spörndly in 1996,[24] where the dairy feeding expertise at SUAS at that time designed a feeding strategy for the future, with the ambition to support a good economic result and high environmental standards through "precise" use of concentrates. Thus, that feeding plan expresses the perception at that time of leading national expertise regarding how to design a good feeding plan in conventional milk production. Here, the protein allowances per kg milk are substantially increased compared with the official feeding standards of that time (see Spörndly 1995), as discussed above. In the organic system, the protein allowances are decreased compared to the official feeding standards as proposed by Andresen. The results in Tables 4 and 5 shall be interpreted as examples of conventional and organic milk production.

Table 4 shows a substantial difference between the two systems in the feeding rations when the amounts of forages, grain and purchased feeds are compared. The influx of nitrogen through purchased feeds is 56 kg higher per cow and year in the conventional system. Due to internal loops of nitrogen on the farm between cows—manure—forages, the difference in the efflux of nitrogen out from the farm is around 20 kg per cow. Still, this is a substantial difference, which will affect emission of ammonia and nitrous oxide to the air, and discharges of nitrate to water systems. Thus, it is not appropriate to use about 10-year-old feeding ratios for conventional milk production as the source for data input regarding the amount of nitrogen in manure among organic farms.

The production biological and economic profiles of the two systems are different. "Value of environmental services" relate to the level of payment for such services the way it is defined within the Common Agriculture Policy of European Union.

[23] www.agriwise.se, accessed 2012-10-15.

[24] Obtained from one of the authors of the future study.

Table 4 Production biological and economic profile of organic and conventional milk production, explanations see the text

	Organic	Conventional	Organic minus conventional
Energy concentration (MJ per kg DM, at top lactation)	12.05	12.75	−0.70
Production (kg ECM[a] per cow and year)	9,272	9,272	0
Milk delivered (kg ECM per cow and year)	8,577	8,577	0
Forages (kg DM)	4,722	3,040	1,682
Grain (kg)	1,092	1,100	−8
Purchased feeds (kg)	593	2,027	−1,434
Economic result, milk production (SEK)	9,034	−2,723	11,757
Nitrogen in manure (kg)	97	117	−20
Nitrogen influx, purchased feeds (kg)	27	83	−56
Forages (ha)	1.5	0.8	1
Grain (ha)	0.5	0.2	0
"Soya beans" (ha)	0.2	0.6	0
Sum (ha)	2.2	1.6	1
Diesel, field work + silage packing (dm^3)	91	55	36
Mineral fertilisers (kg N)	0	22	−22
Mineral fertilisers (kg P)	0	3	−3
Herbicide, no tablet Express 50 T		0.4	−0.4
Biocide (dm^3 Pirimor)		0.07	−0.07
Fungicide (dm^3 Tilt Top 500 EC)		0.2	−0.2
Value of environmental services	1,074	234	841
Result in crop production	2,394	−240	2,634
Sum result per cow, including supporting crop production, SEK	11,428	−2,963	14,390
Increase in results, SEK per hour (188 SEK per hour in calculus)			379

Value of SEK, see Table 3

[a] Energy corrected milk

If producing all milk in Sweden as organic (see Table 5), it will compared to conventional production

- increase land use in Sweden for the production of grain and forages with around 373,000 ha,
- decrease land use in, for example, Brazil with 151,000 ha,
- increase total land appropriated for the same production of milk with 222,000 ha,
- increase economic result with 5.5 billion SEK, that is, 380 SEK per hour labour,
- increase the use of diesel with 13,800 m^3,
- decrease the use of mineral nitrogen fertilisers with 8,500 tonnes,
- decrease the use of mineral phosphorus fertilisers with 1,250 tonnes,
- decrease the amount of nitrogen in manure with 8 million kg,
- decrease the nitrogen influx via purchased feeds with 21 million kg,
- decrease the use of insecticides and fungicides with 101 m^3 in Swedish agriculture and
- decrease the number of herbicide tablets with 144,000.

Table 5 Production biological and economic profile when producing 3.3 billion milk ECM, in an organic and a conventional system, respectively, assuming production profile per cow as in Table 4, further explanations see Table 4

	Organic	Conventional	Organic minus conventional
Delivered (billion kg ECM)	3.3	3.3	0
Forages (million kg DM)	1,817	1,170	647
Grain (million kg)	420	423	−3
Purchased feeds (million kg)	228	780	−552
Economic result, milk production (million SEK)	3,476	−1,048	4,524
Nitrogen in manure (million kg)	37	45	−8
Nitrogen influx, purchased feeds (million kg)	10	32	−21
Forages (ha)	586,072	299,931	286,141
Grain (ha)	182,750	96,190	86,560
"Soya beans" (ha)	72,964	223,670	−150,706
Sum (ha)	841,786	619,791	221,995
Diesel, field work + silage packing (m^3)	34,826	21,048	13,778
Mineral fertilisers (tonnes of N)	0	8,465	−8,465
Mineral fertilisers (tonnes of P)	0	1,250	−1,250
Herbicide, no tablet Express 50 T	0	144,286	−144,286
Biocide (m3 Pirimor)	0	29	−29
Fungicide (m3 Tilt Top 500 EC)	0	72	−72
Value of environmental services (million SEK)	413	90	323
Result in crop production (million SEK)	921	−92	1,013
Result in milk production, including supporting crop production (million SEK)	4,397	−1,140	5,537

Note, the difference in nitrogen influx of 21 million kg nitrogen is similar as the reported increase via purchased feeds to cattle from 1991 to 1999 of 22.8 million kg (Hellstrand 2006). The modification of the protein standards in this example implies a correction towards the situation just before the introduction of the AAT/PBV system. The conventional system in the example is based on the feeding strategy that leading national expertise chose at that time in a future study by SEPA, aiming at precise feeding supporting economic and environmental sustainability objectives: The results, thus, support the conclusion that changed feeding standards and the way they were used is a major explanation for the decreased nitrogen efficiency in Swedish milk production 1991–1999.

The evaluation of the sustainability of the two production systems in Tables 4 and 5 is not straightforward, as there is a conflict between productivity per ha and other sustainability aspects. The issue is further complicated as the conventional system to a higher degree utilises non-renewable natural resources. How the production levels would be in the conventional system compared to the organic if assuming that only renewable natural resources was used, is an open question.

This strongly inflicts the results in their comparisons between the two production systems given the situation 8 and 11 years later, respectively. In the analysis of the fertilising effect of plant nutrients in biological systems, strict additive effects are assumed between nutrients and between ecosystems globally irrespective of the situation in the concerned ecosystems. The analysis floats free from the context of the system and issue focused. The complexity and variation of conditions in ecosystems in time and space is reduced to zero. This is in strong conflict with the knowledge frontier regarding the same issue in agricultural and crop production science since the contributions by Liebig (1840) and Shelford (1913).

The model of the global system for food production developed by Wirsenius (2000) named the FPD/ALBIO model uses an efficiency measure expressed as ratio between gross energy in food consumed through gross energy in biomass appropriated. That way the physiological complexity of humans is reduced to the same as wood stoves. In the model, the top soil layer of agricultural land is not included. That implies that the 50 % of total biomass produced annually that is recycled in crop residues and manure to agricultural land in the model is classed as losses. That reflux is around 7 billion tonnes dry matter or 1.4 tonnes dry matter per ha. In reality, these refluxes are preconditions for maintained content of organic matter and plant nutrients securing maintained productivity of agricultural soils, that is, maintained quality of one of the most essential stocks of natural capital providing the physiological necessities for the life of 7 billion people. Azar concludes that meat production is responsible for about 18 % of global greenhouse gas emissions with reference to FAO (2007, should be 2006). The estimate of 18 % provided by FAO is for all animal production not only meat, including emissions in the transportation and processing from mines to food industry. That measure provided by FAO is before considering the annual carbon sink capacity in grassland and rangeland of 6.2 gigaton carbon dioxide (87 % of the FAO estimate of emissions) mainly supporting ruminant production that FAO also identified. Furthermore, Azar concludes with reference to Wirsenius et al. (2010) that a substitution of pork and/or poultry for 20 % of ruminant meat would “drop” pressure on tropical forests. Given the construction of the FPD/ALBIO model (see below), the analytical tool that Azar and Wirsenius et al. rely on, this conclusion cannot be drawn. It is also in conflict with the findings in FAO (2006): pork and poultry production depends on substantial fractions of soymeal, ruminant meat production do not have to utilize high rations of soymeal as their comparative advantage is the capacity to utilize forages (although there are feeding regimes to ruminants dominated by concentrates). FAO (2006) is clear about this and that the reason is that people, pigs and poultry are monogastric creatures, ruminants are not. Given typical feeding rations for pork and poultry in Sweden, one kg of pork or poultry meat replacing one kg of ruminant meat increases the consumption of soymeal with 0.8 kg. That results in an extra pressure on tropical deforestation of 3.6 m^2, which increases the emissions of carbon dioxide with 250 kg according to the route of calculations in FAO (2006).

Still though, a fact that can be confusing: In reality, cattle can use significant amounts of crop protein feeds (Figs. 1, 2, 3), while this is not a physiological requirement. Thus, in some production systems, cattle are reared as if they were pigs, and this is not efficient from a sustainability perspective. The conclusion from that is not to decrease cattle production but to improve its socio-ecological efficiency.

One reason why Azar has not realised this relation is that his argument is based on Wirsenius et al. (2010), which is based on Wirsenius et al. (2011[25]). The later is based on results from different LCA studies regarding animal production systems, e.g., Cederberg and Flysjö (2004). These LCA studies have not considered the impact of changed land use. Thus, when Azar draws conclusions regarding the positive impact on climate change mitigation and conservation of tropical forests of replacing ruminant products with products from pork and poultry, he provides an example of the risks of extrapolating results

[25] The version available on line in 2010.

from a part of reality investigated, to other parts not investigated. The conclusion is based on results from analyses that ignore the possibility of these impacts, while in reality, the causal relations are strong. That is one reason why that conclusion is in conflict with FAO (2006).

Wirsenius et al. (2011) have utilised the mentioned FPD/ALBIO model of global food production. The most detailed description is Wirsenius (2000). One limitation in its usefulness is that it does not consider the protein requirements of animals. Another is that it wrongly presupposes that dairy cattle do not use crop protein feeds. Therefore, when Azar refers to work that is based on the results in Wirsenius et al. (2011), in claiming that a substitution of pork and/or poultry for 20 % of ruminant meat would "drop" pressure on tropical forests, this cannot be supported by the provided reference, as the used analytical tool lack the capacity to on the margin link how changes between and within different animal production systems will affect demand on protein feeds. Without considering the physiological protein requirements of different animals used for different purposes, the used analytical tool lack capacity to relate such changes to, for example, changed pressure on tropical deforestation for soya production.

The work of Azar (2011) and Wirsenius et al. (2010, 2011) now influence or have the ambition to influence policy work from local community level, over regional level to Swedish Environmental Protection Agency to the EU level to the scientific committee of IPCC regarding climate change, renewable energy, and the perception of how to meet societal demands on food and biofuels (see also Chum et al. 2011 e.g. p. 230; SEPA 2011; Länsstyrelsen i Värmland 2012). With its weak foundation in agricultural sciences, where some of the weaknesses have been pointed out above, the issue at hand is whether the capacity of agricultural soils to provide enough food will be harmed, if suggested policy measures are enforced.

An epistemological issue is by what scientific criteria the professionals within one discipline can claim the right to extrapolate their methods and concepts to pressing issues in such fields of reality where they have no professional training.

More important, which this paper shows, development of ruminant production systems may at the same time make a substantial contribution in improving global food security, increasing land area available for bioenergy purposes, and supporting conservation of biodiversity and forests. This is not to deny that there are sustainability problems in current animal production systems. This stresses the need to handle them with accurate professional skills.

7 Conclusions

The paper shows that animal production is of great importance for global food production and for environmental issues related to agriculture. Around 40 % of total production value in agriculture relates to animals products. Of total land area of 13 billion ha, 1.4 billion are arable land and 3.4 are permanent pastureland, in total 4.9 billion ha agricultural land. Around 70 % of total biomass appropriated in food production from agriculture support animal production systems. Two-thirds of these 70 % are re-circulated in system-reinforcing feedback loops through manure and crop residues.

Substantial potentials for sustainability improvements in animal production systems have been identified through moderately decreased consumption of chicken meat in developed nations; develop the capacity of ruminants to produce high-quality food from otherwise marginal agroecosystems; increased milk production level per cow; and increased feeding efficiency in milk production.

For example, better feeding of dairy cows on global level in terms of improved nitrogen efficiency decreasing the assumed requirement of protein feeds would in rough terms, half the total area of the current acreage now devoted for soymeal production for feed purposes. The potential positive impacts on farmers result, conservation of tropical forest and of biodiversity, climate change, eutrophication and acidification, deterioration of the stratospheric ozone layer, global food and bioenergy supply are substantial.

The development of sustainable animal production systems requires methods that can measure ecological, economic and social impacts of production systems within a sustainability context, and identify potentials for improvements. The paper provide examples of such methods, basically through the upgrading of traditional management and analytic methods in agriculture that over centuries have been used and through a process of trial and error in the real world improved their capacity to successfully manage the complex ecological economic production systems that agriculture and animal production are. This upgrading has been achieved by integrating common tools for farm management with contributions within post-normal science as Impredicative Loop Analysis, and the analytical approach in Millennium Ecosystem Assessment. Contributions from systems ecology, economic theory and complex systems theories are integrated as well.

Furthermore, incentives on societal level are needed that support choices among households and enterprises that support a sustainable development.

Within animal production sciences, two critical areas are (i) ruling principles behind common systems for the formulation of energy and protein standards in milk production and (ii) methods now commonly used with the ambition to measure the sustainability performance in animal production systems. Interestingly, in general terms, the paper suggests the same measures in (i) and (ii). In order to improve feeding regimes in dairy production as well as general management strategies for sustainable natural resource management, there is a need to consider the "laws" of diminishing returns, the minimum and of tolerance in biological systems in such a way that economically feasible and ecological sustainable production is achieved.

The paper stresses the importance of strengthening the role of agricultural sciences in the sustainability context. That implies to go back to central findings in agricultural sciences regarding production systems that meet demands on sufficient productive and sustainable production systems; considering thresholds, irreversibilities and resilience phenomenon that agriculture during thousands of years of practice has learnt to deal with; and re-utilise this knowledge about the production factor land on societal level in the general sustainability context. It is suggested that in that process, methods and concepts in agricultural science are integrated with the latest contributions within the field of agroecology such as Impredicative Loop Analysis, for improving management of complex agroecosystems.

This is a prerequisite for the development of agricultural systems with increased capacity to support a sustainable society. In this context, animal production is of a significant importance. If not, global food security is at risk.

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