

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

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 research 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 <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

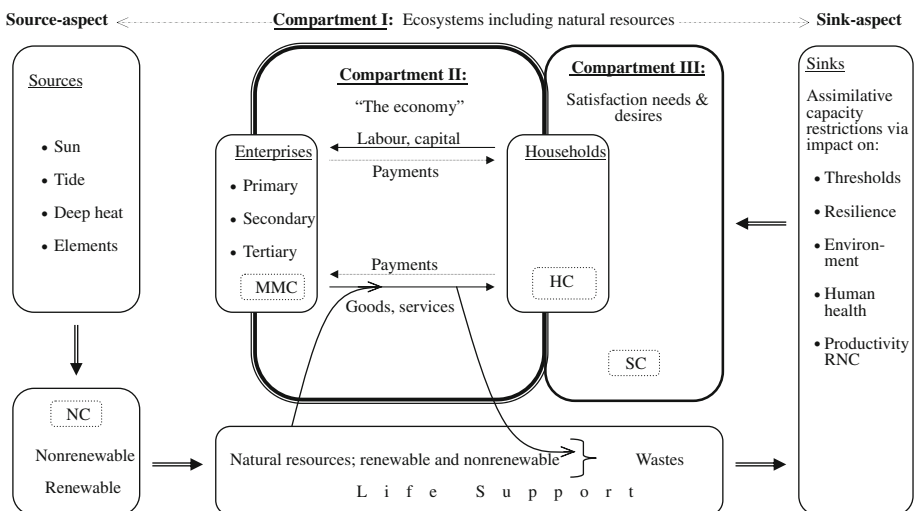


Fig. 1 A conceptual model of the economy in its ecological and social context (from Hellstrand et al. 2009)

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 sectors⁷ 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:

$$Q(t) = A(t)f(L(t), C(t)) \quad (1)$$

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)

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 GDP¹⁰ 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:

$$Q = nE \quad (2)$$

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:

$$\int_0^t \left(\frac{dQ}{dt} \right) dt = \int_0^t P dt \quad (3)$$

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) ($\frac{dQ_g}{dt}$) 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 imprecisive 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)

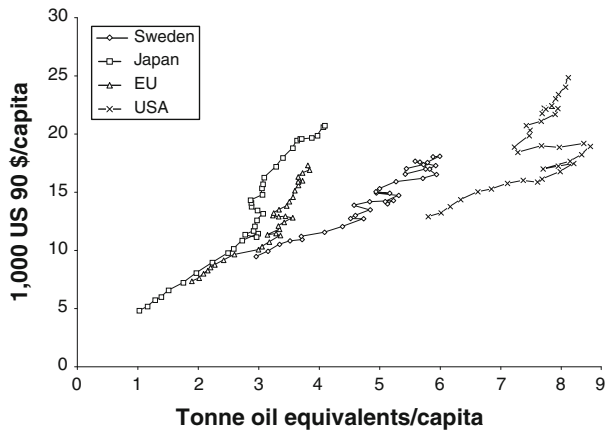


Table 1 Some results from regression analysis between total primary energy supply and GDP in purchasing power parities in the EU, Japan, Sweden and USA 1962–1997

	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. *** $p < 0.001$, ** $p < 0.01$

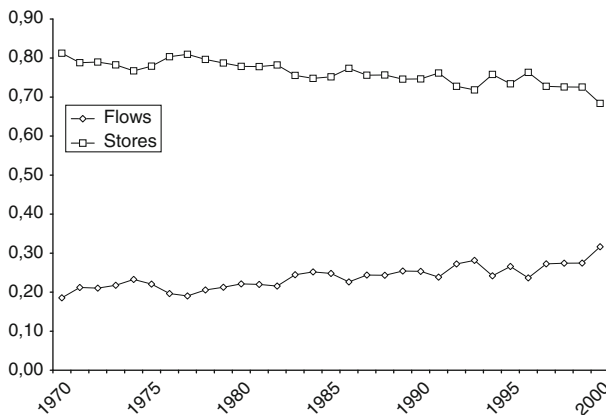


Fig. 3 Energy supply in Sweden from flows and stores 1970–2000 in fractions of total supply. Included in stores are crude oil and oil products, natural gas and gasworks gas, coal and coke and nuclear power (gross). Included in flows are biofuels and peat, heat pumps in district heating, hydropower (gross) 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, $\frac{dE_p}{dt}$ 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: CO₂, carbon dioxide; NO_x, nitrogen oxides; SO₂, 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:

$$\frac{dQ_s}{dt} = n_s(t) \left(\frac{dE_s}{dt} \right) \quad (8)$$

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:

$$\frac{dQ_s}{dt} = n_s c_s E_s(t) (E_{sm} - E_s(t)) \quad (9)$$

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 ($E_{sm} - E_s(t)$) at that time. In the early phases of exploitation exponential economic growth of type

$$\frac{dQ_s}{dt} = n_s \left(\frac{dE_s}{dt} \right) = n_s c_s E_s(t) \quad (10)$$

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 $(E_{sm} - E_s(t))$ 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

$$\frac{b_s E_s(t)}{(E_{sm} - E_s(t))(E_s(t) - E_{sr}(t))} \tag{15}$$

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:

$$\begin{aligned} \frac{dQ_f}{dt} &= n_f \left(\frac{dE_{fn}}{dt} \right) = n_f \frac{b_f E_f(t)}{(E_{fm} - E_f(t))(E_f(t) - E_{fr}(t))} E_f(t) (E_{fm} - E_f(t)) \\ &= n_f \frac{b_f E_f(t)^2}{(E_f(t) - E_{fr}(t))} \end{aligned} \tag{16}$$

where $E_f(t) - E_{fr}(t) > 0$ and $E_{fm} - E_f(t) > 0$.

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:

$$\frac{dL_{sus}}{dt} = \frac{dL_{sus}}{dt_{t=0}} - h \left(\frac{b_f E_f(t)^2}{(E_f(t) - E_{fr}(t))} \right) \tag{17}$$

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 $l \frac{dL_{sud}}{dt}$ in (5). This gives

$$\frac{dL_{sud}}{dt} = \frac{g \left(\left(\frac{dE_s}{dt} \right), \left(\frac{dE_f}{dt} \right) \right)}{l} \tag{18}$$

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:

$$\frac{dL_{sud}}{dt} = \frac{g \left(\left(\frac{dE_s}{dt} \right), \left(\frac{dE_f}{dt} \right) \right)}{l} = \frac{g \left(\frac{b_s E_s(t)^2}{(E_s(t) - E_{sr}(t))}, \frac{b_f E_f(t)^2}{(E_f(t) - E_{fr}(t))} \right)}{l} \tag{19}$$

$E_s(t) - E_{sr}(t) > 0$, $E_f(t) - E_{fr}(t) > 0$ 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:

$$R(t) = \frac{dL_{\text{sus}}}{dt_{t=0}} - h \left(\frac{b_f E_f(t)^2}{(E_f(t) - E_{fr}(t))} \right) - \left(g \left(\frac{b_s E_s(t)^2}{(E_s(t) - E_{sr}(t))}, \frac{b_f E_f(t)^2}{(E_f(t) - E_{fr}(t))} \right) \right) \quad (20)$$

$E_s(t) - E_{sr}(t) > 0$, $E_f(t) - E_{fr}(t) > 0$ 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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