WORKING PAPER

Ecological-economic viability as a criterion of strong sustainability under uncertainty

by

Stefan Baumgärtner and
Martin F. Quaas

University of Lüneburg
Working Paper Series in Economics

No. 67

November 2007

www.leuphana.de/vwl/papers

ISSN 1860 - 5508

Ecological-economic viability as a criterion of strong sustainability under uncertainty

Stefan Baumgärtner[a,§] and Martin F. Quaas[b,]

[a] Centre for Sustainability Management, Leuphana University of Lüneburg, Germany

[b] Department of Economics, University of Kiel, Germany

November 2007

Abstract: Strong sustainability, according to the common definition, requires that different natural and economic capital stocks have to be maintained as physical quantities separately. Yet, in a world of uncertainty this cannot be guaranteed. To therefore define strong sustainability under uncertainty in an operational manner, we propose to use the concept of viability. *Viability* means that the different components and functions of a dynamic, stochastic system at any time remain in a domain where the future existence of these components and functions is guaranteed with sufficiently high probability. We develop a unifying and general ecological-economic concept of viability that encompasses the traditional ecological and economic notions of viability as special cases. It provides an operational criterion of strong sustainability under conditions of uncertainty. We illustrate this concept and demonstrate its usefulness by applying it to livestock grazing management in semi-arid rangelands.

JEL-Classification: D81, Q01, Q57

Keywords: capital (natural and economic), ecological-economic systems, ecosystem services, funds, stocks, sustainability, uncertainty, viability

[§]Corresponding author: Centre for Sustainability Management, Leuphana University of Lüneburg, P.O. Box 2440, D-21314 Lüneburg, Germany. Phone: +49.4131.677-2600, fax: +49.4131.677-1381, email: baumgaertner@uni-lueneburg.de.

1 Introduction

The imperative of sustainability requires sustaining nature's functioning and services for humans over the long run. There is a broad and diverse discussion about how exactly to define, operationalize and measure sustainability (surveyed e.g. by Heal 1998, Klauer 1999, Neumayer 2003, Pezzey 1992), reflecting the breadth and diversity of ideas about (i) what exactly is the normative content of sustainability and (ii) how exactly can the structure and functioning of ecological-economic systems be described.

In this discussion, a distinction has been made between so-called 'weak' and 'strong' sustainability (Neumayer 2003). Both positions presume that human well-being derives from services that are provided by different kinds of natural, manufactured and human capital, and that intergenerational fairness requires that this capital basis – which makes the opportunity set for present and future generations – is not to be diminished over time. Against this background, *weak* sustainability holds that the *aggregate* capital stock is not to be diminished, while *strong* sustainability holds that the various stocks of (critical) natural and economic (i.e. manufactured and human) capital are to be conserved *separately*. Strong sustainability, thus, does not allow that, say, a decrease in natural capital is made up by an increase in economic capital.

Strong sustainability is motivated by a belief that natural and economic capital are only to a limited extent substitutable against each other. Furthermore, as there is huge uncertainty about the preferences of future generations as well as about the exact functional relationships that govern ecological-economic interactions and the provision of services from different types of capital, precautionary responsibility and intergenerational fairness towards future generations require, according to this position, that the various stocks of natural and economic capital should be conserved separately (Daly and Cobb 1989, Ekins et al. 2003, Ott and Döring 2004, Pearce at al. 1989).

As uncertainty is one of the essential challenges of the long run, and sustainability is – by any definition – about the long run, the question arises of how to define and operationalize sustainability under uncertainty. Weak sustainability has been conceptualized as non-declining welfare over time, which can be operationalized with reference to the net change in the total value of various stocks of natural and economic capital (e.g. Arrow et al. 2003, Asheim 1994, Hamilton 1994, Pearce and Atkinson 1993, Pezzey and Withagen 1995). This approach has been extended to conditions of uncertainty, where sustainability is typically conceptualized as non-declining expected welfare (Asheim and Brekke 2002, Beltratti et al. 1998, Howarth 1995, Tucci 1998a,b, Woodward 2000). Strong sustainability, in contrast, has so far not been operationalized under conditions of uncertainty. While the whole concept can be seen as an approach to dealing with fundamental uncertainty about the future, where neither future preferences nor even the potential 'states of the world' are known, it has not been formulated in a more concrete manner under weaker forms of uncertainty, i.e. where probability distributions over known states of the world are known.[1]

In this paper, we propose to use the ecological-economic concept of viability as a criterion of strong sustainability under uncertainty. *Viability*, loosely speaking, means that the different components and functions of a dynamic, stochastic system at any time remain in a domain where the future existence of these components and functions is guaranteed with sufficiently high probability. The idea of viability is known in different academic disciplines. For example, in ecology a species' population is called viable if its probability of survival over a given time horizon is higher than a predefined threshold value (Soulé 1987, Beissinger and McCullough 2002, Frank 2005). This understanding of viability pertains to the continued existence of certain natural capital stocks. As another example, in economics and finance an enterprise or management action is called viable if it continually generates a cash flow higher than a certain predefined level. This understanding of viability pertains to the continued existence of certain services flowing from capital stocks. Also, a mathematical theory of viability been developed for conditions of certainty (Aubin 1991) and applied to ecological, environmental and resource economic problems (Béné and Doyen 2000, Béné et al. 2001, Doyen and Béné 2003, Pereau submitted, Martinet and Doyen 2007, Eisenack et al. 2006). While all these disciplinary conceptualizations capture some aspects of the basic idea of viability,

[1]For a detailed discussion of different forms of uncertainty, that is inspired by Knight (1921), see Faber et al. (1992).

they differ to various degrees in exactly what aspects of this idea they capture, and how, and, therefore, in their substantive content.

In this paper, we develop a general formalization of ecological-economic systems as stochastic dynamic networks of funds and services. On this basis, we conceptualize strong sustainability under uncertainty as ecological-economic viability. In particular, we develop a general and unifying ecological-economic concept of viability that encompasses the traditional ecological and economic notions of viability – continued existence of stocks and of services, respectively – as special cases. In so doing, we identify and discuss the various normative judgments that necessarily enter the concept. The ecological-economic concept of viability thus obtained provides an operational criterion of strong sustainability under conditions of uncertainty. It should thus help to better understand and devise sustainability policy, such as e.g. the so-called 'tolerable windows approach' that has been proposed as an approach to climate policy (Bruckner et al. 1999, 2003, Tóth et al. 2002).

The paper is organized as follows. In Section 2, we explicate in a general, abstract, and formal manner the structure and functioning of ecological-economic systems in terms of funds (i.e. capital stocks) and services. On this basis, we formally define ecological-economic viability and discuss the properties of this definition in Section 3. In Section 4, we illustrate this concept and demonstrate its usefulness by applying it to the example of livestock grazing management in semi-arid rangelands. Finally, Section 5 concludes.

2 Formal description of ecological-economic systems as dynamic networks of funds and services

The interrelationship between human economies and natural ecosystems comprises interactions on a wide range of different spatial and temporal scales. As a result, changes in one system may generate impacts in the other system and, in general, the subsequent changes have repercussions back on the system where the changes originated (Dasgupta et al. 2000, Norgaard 1981, Perrings 1998, Settle et al. 2002). In order to gain a comprehensive understanding of how human economic activity over time depends on and interferes with natural ecosystems, it is therefore necessary to employ models that capture the relevant internal structure and dynamics of both economies and ecosystems as well as their interaction in a unifying way (Costanza et al. 1993, Faber et al. 1996).

A particularly well suited starting point for a unifying representation of ecological and economic systems, as well as their interaction, is the observation that, in some sense, both systems consist of entities that render services for others. While this idea is quite obvious for economic systems, it may be applied to ecosystems and to economy-environment interactions as well. For example, one may think of an ecological food chain as a flow of service from resource to consumer, of 'ecosystem services' which are used and valued by economic agents (Daily 1997, Millennium Ecosystem Assessment 2005), or of economic agents 'investing in natural capital' (Jansson 1994).

This idea has been captured in a *Theory of Funds* by Faber et al. (1995) and (Faber and Manstetten 1998, 2003: Chapters 8, 9), which aims to provide a unifying conceptual framework for the description and analysis of ecological-economic systems and which is rooted in natural philosophy. A *fund*, in this framework, is an entity that gives something, but at the same time it is maintained or maintains itself. A fund is characterized by the following two characteristic properties:[2]

(i) A fund renders services to one or more other funds.[3]

(ii) A fund persists, as it maintains and reproduces itself, or it is maintained. Hence, it exists over a time scale that is not a priori limited.

A typical example of a fund is the population of some biological species. Also, the stock of some capital good or human societies may be seen as funds.

Formally and quantitatively, a fund can be described as the *stock* of something, e.g. the population of some biological species (measured in number of individuals or in total biomass) or the stock of some capital good (measured in physical or monetary units).

[2]The concept of funds, giving rise to flows of services, has been developed and applied to an ecological-economic analysis of economic production by Georgescu-Roegen (1971: Chap. IX).

[3]Rendering services does not need to be an intention of the fund.

The stock concept captures the permanency and the inertia in the dynamics of limited homogeneous entities (Faber et al. 2005, Faber and Manstetten 2003: Chap. 9). A stock can be quantified at any point in time by so-called stock-variables. It exhibits a certain dynamics over time which is determined by internal dynamics, external relationships and chance influences. Such dynamics can be formally expressed by dynamic relationships for the stock variables, e.g. difference or differential equations, or algorithmic rules.

A fund that can formally and quantitatively be represented by a (set of) stock variable(s) is what economists traditionally call *capital*, or, more exactly, a *capital good* (Baumgärtner et al. 2006: Chap. 4). While the traditional perspective of economics is that a capital good is intentionally produced by human activity so as to render productive services, the notion of capital has already been generalized to include so-called capital bads – which render disservices, e.g. pollutant stocks – and natural capital – which is not intentionally produced by human activity, yet renders productive and consumptive services to humans.

With this terminology, we can conceptualize an ecological-economic system as a network of funds; each fund is described by a set of stock variables; and the funds are connected by the services they render to each other.

This notion of an ecological-economic system is similar to the ecosystem network theory that has been used in ecology (e.g. Ulanowizc 1986, 1997, Wulff et al. 1989) and to ideas underlying the integrated modeling of ecological-economic systems (e.g. Eichner and Pethig 2005, 2006, 2007, Finnoff and Tschirhart 2003, Tschirhart 2000, 2003). In ecology the network is usually taken to be one of flows of energy or matter. It can conveniently be interpreted as a network of feeding relations, i.e. as a *food web*. The nodes are the populations of species or abiotic stocks of nutrients, and the links are the nutrient flows. Our conceptualization may be regarded as a generalization of the idea of a *food web* in two respects: (i) We allow to also include economic funds. (ii) We allow for a variety of qualitatively different services. These services can, but do not need to be, flows of energy or matter. For example, they can include the productive services of capital or knowledge.

In the following, we formalize the funds-services description of an ecological-economic system as a dynamic network of multi-functional funds and services.

An ecological-economic system, in this formalization, consists of $n \geq 2$ different funds and $m \geq 1$ different types of services. Graphically, the funds of the systems may

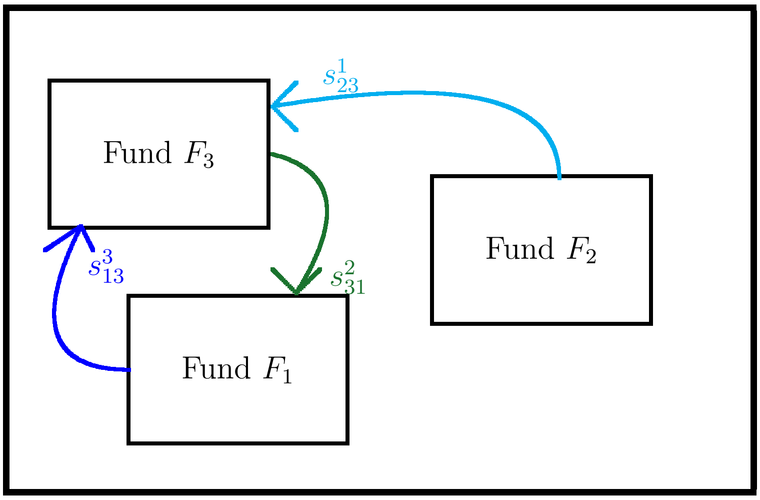

Figure 1: Graphical illustration of the ecological-economic system as a network of funds and services.

be represented as boxes (i.e. to symbolize the stock-like character of the funds) and the services may be represented as arrows between the boxes. In Figure 1, different types of services are denoted by different colors.[4]

The dynamic development of the system is considered in continuous time, $t \in [0, \infty)$, from the present, $t = 0$, into the infinite future, $t \to \infty$. The characteristics of each of the n funds F_i $(i = 1, ..., n)$ of the system are described by $l \geq 1$ different stock variables, denoted by $f^h_i(t) \in \mathbb{R}$ $(h = 1, ..., l)$. That is, each fund can have one, several or all of the l characteristics. When analyzing a particular system, the l different stocks characterizing the funds F_i have to be chosen so as to fully represent all important features of the funds under consideration. In total, we thus consider $n \times l$ stock variables in the system. At each point in time, the *state of the system* can thus be described by the $n \times l$-dimensional matrix $f(t) \equiv \{f^h_i(t)\}^{h=1,...,l}_{i=1,...,n} \in \mathbb{R}^{nl}$. Some of these quantities may be equal to zero for

[4]The notation used in the figure is explained in the following.

some time.

There are $m \geq 1$ types of services S^k ($k = 1, ..., m$). Each type of service can, in principle, be provided by every fund to every other fund. The flow of service type k between funds F_i and F_j is denoted by $s_{ij}^k(t) \in \mathrm{I\!R}$.[5] Note that the different types of services do not need to coincide with the different characteristics of the funds, i.e. m does not need to be equal to l.[6] In this setting, an *ecosystem service* is a service relation between a fund, which is part of the ecological subsystem, and another fund, which is part of the economic subsystem. When analyzing a particular system, it is important to identify the services that are important for defining the system functionally. In particular, the analyst's decision as to where to draw the system boundary determines which service relationships are endogenous in the ecological-economic system and what is an exogenous influence on the system. At each point in time, all endogenous service relationships between all funds are thus described by $n \times n \times m$ real numbers. In other words, the services are given by an $n \times n \times m$-dimensional *services tensor*,[7] $s(t) \equiv \{s_{ij}^k(t)\}_{i,j=1,\dots,n}^{k=1,\dots,m} \in \mathrm{I\!R}^{nnm}$. Some of these quantities may be equal to zero for some time.

At each point in time t, the ecological-economic system is completely described by the state of the system $f(t)$ and the services tensor $s(t)$. We denote the *dynamic trajectory* of the system over the whole time horizon by $\xi \equiv \{f(t), s(t)\}_{t=0}^{\infty}$ and the set of all possible dynamic trajectories by Ξ. Dynamic trajectories need not be continuous. In fact, the viability analysis that we are developing in this paper in no way hinges upon continuity assumptions.

Under conditions of uncertainty, the actual dynamic trajectory of the system is not known in advance. Adopting the particular notion of uncertainty that has been termed 'risk' by Knight (1921) or Faber et al. (1992), we assume that the set of all

[5] Rather than considering only net service flows, we explicitly distinguish between in and out flows, because the in and out flows of one particular service for one particular fund may take place on different time scales. Thus, the in and out flows may have different influences on the dynamics of the fund.

[6] In this respect, our framework is more general than the notion of Georgescu-Roegen (1971: 223) that 'a flow [service] is a stock [fund] spread out over time'.

[7] More exactly, s is a tensor of third order.

possible dynamic trajectories Ξ is known and that for each possible dynamic trajectory $\xi \in \Xi$ the probability density is known with which it will actually occur, that is, the probability distribution of all possible dynamic trajectories is known. We denote the set of all probability distributions on Ξ by $\Pi(\Xi)$.

The central aim of the formalization is to provide a conceptual framework which allows a sound sustainability assessment. But what is the subject of such a sustainability assessment? In order to derive results that are relevant for policy and the management of ecological-economic systems, we shall focus on human actions. Given a human action that affects the ecological-economic system, we want to assess whether the system's dynamic development can be deemed sustainable or not. In order to assess how a human action affects sustainability, we have to consider changes in the action under consideration. Hence, the action cannot be an endogenous part of the ecological-economic system. In order to distinguish the particular human action that is subject to the sustainability assessment from all other human actions that are endogenous parts of the system under study, we shall refer to this particular human action as a *project* and denote it by $x = \{x(t)\}_{t=0}^{\infty}$. This is a very general description of feasible projects. Of course, a project may start at some future point in time, or it may end within finite time. It may also be a one-time action. In such cases, $x(t) = 0$ for all times t except for those periods during which the project actually occurs. The set of all feasible projects is X.

Generalizing the framework of Arrow et al. (2003), who do not consider uncertainty, we define a *dynamic allocation mechanism* α as the mapping that assigns to each initial state $f(0) \in \mathbb{R}^{nl}$ of the ecological-economic system a probability distribution over all possible dynamic trajectories. As a project will alter the dynamics of the system, the dynamic allocation mechanism depends on the project:

$$\alpha(x) : \mathbb{R}^{nl} \to \Pi(\Xi) \ . \tag{1}$$

This is a very general description of the system's dynamics. The only underlying assumption is that the probability distribution of the system's future development may be completely derived from the present state of the system. This means in particular, we assume that there is no explicit direct dependency on the state of funds and services at times $t' \leq -1$. That is, we consider dynamics of the Markovian type. Also, we neglect the occurrence of evolution and novelty in our framework.

The dynamic allocation mechanism includes all endogenous ecological and economic dynamic mechanisms, the dynamic interactions and feedbacks between ecological and economic mechanisms in the system, as well as exogenous influences on the funds and services under study. Of course, for the sake of any concrete analysis, the dynamic allocation mechanism has to be specified. In many ecological models, for example, the probability distribution of dynamic trajectories is determined by a set of stochastic differential equations, individual-based models or cellular automata with some stochastic elements. In many models of environmental and resource economics, as another example, it is frequently assumed that resources are allocated in an optimal way. Other economic models assume that resources are allocated through the decisions of boundedly rational agents, or that perfectly rational agents' decisions are distorted through various forms of market imperfections. Again, the description (1) of the system's dynamics is so general that it can accommodate for any of those particular dynamic mechanisms.

Summing up, in our formalization an ecological-economic system is defined as follows.

Definition 1 (ecological-economic system)
An *ecological-economic system* E is given by (i) n funds F_i and m services S^k, (ii) an initial state $f(0)$ and (iii) a dynamic allocation mechanism $\alpha(x) : \mathrm{I\!R}^{nl} \rightarrow \Pi(\Xi)$.

3 Definition of ecological-economic viability

Based on the description of an ecological-economic system as developed in the previous section, we can now define ecological-economic viability. Again, we shall focus on the consequences of a particular human action ('project') and define the viability of a project for a given ecological-economic system.

Definition 2 (viability)
Given an ecological-economic system E, thresholds $\bar{f} \equiv \left\{\bar{f}_g^h\right\}_{g\in G}^{h\in H}$ with corresponding probability thresholds $p \equiv \left\{p_g^h\right\}_{g\in G}^{h\in H}$, thresholds $\bar{s} \equiv \left\{\bar{s}_{ij}^k\right\}_{i\in I, j\in J}^{k\in K}$ with corresponding

probability thresholds $q \equiv \{q_{ij}^k\}_{i\in I, j\in J}^{k\in K}$, where $G, I, J \subseteq \{1,\ldots,n\}$, $H \subseteq \{1,\ldots,l\}$, $K \subseteq \{1,\ldots,m\}$, and a time horizon T, a project $x \in X$ is *viable* in system E if and only if

$$\text{Prob}\left[f_g^h(t) \geq \bar{f}_g^h\right] \geq p_g^h \text{ and } \text{Prob}\left[s_{ij}^k(t) \geq \bar{s}_{ij}^k\right] \geq q_{ij}^k$$
$$\text{for all } (g,h,i,j,k) \in G \times H \times I \times J \times K \text{ and all } t \in [0,T], \quad (2)$$

In short: 'x is $(\bar{f}, p, \bar{s}, q, T)-$viable' in system E.

We would like to highlight some properties of this notion of ecological-economic viability.

- The essential element in our formalization of viability through Definition 2 are the various thresholds and corresponding probability thresholds. In the most general understanding of viability, a project must lead to dynamic trajectories that respect thresholds with respect to *all* funds and services of the system. As a special case, some of these thresholds may be set equal to zero, so that they are trivially fulfilled.

- The requirement that certain funds and services are sustained at levels *greater than* given threshold values reflects the underlying normative judgement that these funds and services are in some sense valuable and desired. In contrast, one may also think about nuisance funds and the dis-services they render, such as the stock of some pollutant and the environmental and health damages that it generates. One would want to keep such undesired funds and services at levels *smaller than* given threshold values. This can easily be brought under the formalism introduced here by the convention that undesired funds and services are represented by negative values of the corresponding stock or flow variables.

- Another essential element in the definition is the time horizon that has to be specified for an operational criterion of viability. As a result, it is possible that a project is found to be viable for some time horizon but not for another time horizon, or vice versa.

  In principle, the time horizon could be set to infinity. Yet, in this case, the probability that the funds and services under consideration are sustained at levels greater than the required threshold values over the entire time horizon may decrease to zero. That is, over an infinite time horizon most, if not all, feasible project may turn out to be not viable irrespective of the concrete threshold values.

- Definition 2 constitutes a *formal* notion of viability, not a *substantive* one, in that it remains completely open at what levels the thresholds, probability thresholds and time horizon should be actually set. A substantive idea of viability will specify these levels, and the formal notion developed here can then be used to operationalize such a substantive idea of viability.

- In Definition 2 we do not distinguish between threshold values (for stocks, services or probabilities) that are justified by some objective threshold-like behavior of the system's dynamics and such thresholds that are purely set due to some normative decision of society. Ultimately, every threshold that is employed in this ecological-economic viability criterion involves normative judgments. Thus, ecological-economic viability analysis always involves normative aspects.

- The notion of viability specified by Definition 2 is a unified and general ecological-economic notion. As it includes both funds and services, it comprises as special cases the notions of viability that are traditionally used in ecology (based on funds) and in economics (based on services). If we consider only ecological funds, i.e. populations of some species in an ecosystem, and thresholds for these funds, viability according to Definition 2 is exactly equivalent to ecological population viability analysis (Soulé 1987, Beissinger and McCullough 2002, Frank 2005), which is concerned with the preservation of one or several funds. If we consider only the service of cash flow of an enterprise, and a corresponding threshold value, Definition 2 is exactly equivalent to the notion of economic/financial viability, which is based solely on this particular service.

- Generalizing existing concepts of viability to the one given in Definition 2, one could go one step further and allow for time-dependent threshold values of $\bar{f}$, p, $\bar{s}$ and q. For example, decreasing probability thresholds over time could represent some form of discounting of future risks. While this generalization would be straightforward in formal terms, we believe that constant threshold values better correspond to the idea of strong sustainability according to which funds and services should be sustained above critical levels that are given irrespective of, say, short-term subjective valuations.

- Under conditions of certainty, viability as specified by Definition 2 reduces to the established notion of strong sustainability: Let G and H be the list of various stocks of (critical) natural and economic (i.e. manufactured and human) capital and let $\bar{f} \equiv \left\{\bar{f}_g^h\right\}_{g\in G}^{h\in H}$ be the current stocks. Criterion 2 of ecological-economic viability requires that these stocks have to be conserved separately – which is exactly what strong sustainability requires. Definition 2 goes beyond the established idea of strong sustainability, though, in that it may also require to preserve some of the services above some minimal level.

- Note that under uncertainty, viability is an ex-ante criterion: the probability in Condition (2) is a probability given all current knowledge, i.e. at time $t = 0$. It may well be that the dynamic trajectory under a viable project (sensu Definition 2) actually fails to exceed the thresholds $\bar{f}$ and $\bar{s}$; and also the other way round, a project that is not viable ex ante according to Definition 2 may, due to good luck, actually turn out to render a dynamic trajectory that exceeds the thresholds $\bar{f}$ and $\bar{s}$ over the whole time horizon.

  While one may criticize Definition 2 for its property that it may classify projects ex ante as viable that ex post turn out to be actually not viable, one should bear in mind that it is a fundamental property of all systems under uncertainty that one simply cannot guarantee that certain outcomes will be realized. In this sense, the criterion of strong sustainability under conditions of certainty – that some entities are sustained at levels greater than some threshold value – can simply not be met at 100 % certainty under conditions of uncertainty.

- Obviously, the criterion of ecological-economic viability depends on a number of normative decisions. It has to be decided upon what shall be sustained in four respects: (i) Which are the relevant funds and their characteristics, and which are the relevant types of services and between which funds; (ii) which are the threshold levels for the selected funds and services; (iii) which are the threshold levels for the probabilities; and (iv) which is the relevant time horizon.

We call the set of all feasible projects that are viable for a given system and given viability criteria $(\bar{f}, p, \bar{s}, q, T)$ the *viability set* of the system.

Definition 3 (viability set)

The *viability set* $\mathcal{V}_E$ is the set of all feasible projects $x \in X$ which are viable in E:

$$\mathcal{V}_E(\bar{f}, p, \bar{s}, q, T) := \left\{ x \in X \,\middle|\, x \text{ is } (\bar{f}, p, \bar{s}, q, T) - \text{viable in } E \right\}. \tag{3}$$

Note that the viability set, according to this definition, may well be empty. Depending on the threshold values for stocks, $\bar{f}$, services, $\bar{s}$, or the corresponding probability thresholds, p and q, the initial state $f(0)$ of the system or the dynamic allocation mechanism α may be such that no viable project exists.

On the other hand, under Definition 2, for any given ecological-economic system E and for given viability criteria $(\bar{f}, p, \bar{s}, q, T)$, many different projects may turn out to be viable, so that the viability set contains many projects. Then we may go one step further and exclude from the set of all viable projects those which are dominated by others in terms of viability. To define dominance, we consider for a give system the set of all possible dynamic trajectories that have a non-zero probability weight for a given project, $\Psi(x) = \{\xi \in \Xi | \text{Prob}(\xi) > 0 \text{ in system } E \text{ under project } x\}$. Using this notation, dominance is defined in the following way.

Definition 4 (dominance)

Given an ecological-economic system E, a selection of funds and services $G, I, J \subseteq \{1, \ldots, n\}$, $H \subseteq \{1, \ldots, l\}$, $K \subseteq \{1, \ldots, m\}$, and a time horizon T, the project $\hat{x} \in X$ *dominates* the project $x \in X$ in system E if and only if for all $(\hat{\xi}, \xi) \in \Psi(\hat{x}) \times \Psi(x)$ the following holds:

$$
\begin{array}{lll}
1. & \hat{f}_g^h(t) \geq f_g^h(t) \quad \text{and} \quad \hat{s}_{ij}^k(t) \geq s_{ij}^k(t) & \\
 & \qquad\qquad \text{for all } (g,h,i,j,k) \in G \times H \times I \times J \times K \text{ and all } t \in [0,T] & \\
\text{and} & & (4) \\
2. & \hat{f}_g^h(t) > f_g^h(t) \quad \text{or} \quad \hat{s}_{ij}^k(t) > s_{ij}^k(t) & \\
 & \qquad\qquad \text{for at least one } (g,h) \in G \times H \text{ or one } (i,j,k) \in I \times J \times K, & \\
 & \qquad\qquad \text{and at least one } t \in [0,T]\ . &
\end{array}
$$

This notion of dominance is very strong. In particular, if $\Psi(\hat{x}) \cup \Psi(x) \neq \emptyset$, that is, if there exist dynamic trajectories that have non-zero probability weight under both projects $\hat{x}$ and x, $\hat{x}$ cannot dominate x because when considering one of those trajectories the strict inequality of Condition (4) would be violated.

Definition 2 of viability as well as the dominance criterion (Definition 4), constitute ordinal criteria of viability: they establish a partial rank ordering among all feasible projects. They do not, by themselves, allow one to make quantitative comparisons among projects in terms of viability, or even to establish, in general, a full rank ordering among all feasible projects. For making quantitative sustainability assessments, and for ordering projects that do not dominate one another, it is therefore helpful to also have a cardinal measure of viability. Based on Definition 2, the following cardinal measure of viability appears plausible.

Definition 5 (degree of viability)

Given an ecological-economic system E, thresholds $\bar{f} \equiv \left\{\bar{f}_g^h\right\}_{g \in G}^{h \in H}$, thresholds $\bar{s} \equiv \left\{\bar{s}_{ij}^k\right\}_{i \in I, j \in J}^{k \in K}$, where $G, I, J \subseteq \{1, \ldots, n\}$, $H \subseteq \{1, \ldots, l\}$, $K \subseteq \{1, \ldots, m\}$, and a time horizon T, the *degree of viability* $v(x)$ of project $x \in X$ in system E is given by

$$
v(x) = \min \left\{ \left\{ \text{Prob}\left[f_g^h(t) \geq \bar{f}_g^h \right] \right\}^{(g,h) \in G \times H,\ t \in [0,T]} \right.
\left. \cup \left\{ \text{Prob}\left[s_{ij}^k(t) \geq \bar{s}_{ij}^k \right] \right\}^{(i,j,k) \in I \times J \times K,\ t \in [0,T]} \right\}. \quad (5)
$$

The function $v(\cdot)$ is called *viability function.*

In general, the viability function will yield values between 0 (not viable at all) and 1 (fully viable). It can be used to quantitatively assess individual projects, and to rank two projects in terms of their viability even if there is no dominance relation between them. Using the minimum function, with the threshold conditions for the various funds and services as arguments, expresses the idea of strong sustainability that each fund and service should be maintained separately. So, only the minimal degree of threshold fulfillment is counted for the overall value of the viability function.[8]

Under conditions of certainty the viability function can be either one or zero, $v(x) = 1$ or $v(x) = 0$, because either the threshold values are exceeded or not for a certain dynamic trajectory. In other words, under conditions of certainty a project can be either viable, i.e. strongly sustainable, or not, i.e. unsustainable.

There are some obvious relationship between the cardinal degree of viability (Definition 5) and absolute viability as defined in Definition 2. First of all, a project can only be viable (in the absolute sense of Definition 2) if its (cardinal) degree of viability is greater than some minimum value. This minimum degree of viability that is necessary (yet, not sufficient) for a project to be viable in the absolute sense is simply given by the smallest probability threshold employed for defining absolute viability.

Lemma 1

Given an ecological-economic system E, thresholds $\bar{f} \equiv \left\{\bar{f}_g^h\right\}_{g\in G}^{h\in H}$ with corresponding probability thresholds $p \equiv \left\{p_g^h\right\}_{g\in G}^{h\in H}$, thresholds $\bar{s} \equiv \left\{\bar{s}_{ij}^k\right\}_{i\in I, j\in J}^{k\in K}$ with corresponding probability thresholds $q \equiv \left\{q_{ij}^k\right\}_{i\in I, j\in J}^{k\in K}$, where $G, I, J \subseteq \{1, \ldots, n\}$, $H \subseteq \{1, \ldots, l\}$, $K \subseteq \{1, \ldots, m\}$, and a time horizon T, a necessary – yet, not sufficient – condition for project $x \in X$ to be viable in system E is that

$$v(x) \geq \min \left\{p_g^h, q_{ij}^k\right\}_{(g,i,j)\in G\times I\times J}^{(h,k)\in H\times K} \quad . \tag{6}$$

Proof: see Appendix A.1.

[8]Obviously, writing the viability function $v(\cdot)$ as a simple (normalized) sum of these arguments would express the idea of *weak* sustainability were the preservation of individual funds or services can be traded off against each other.

Moreover, a sufficient condition for a project to be viable (in the absolute sense of Definition 2) is that its (cardinal) degree of viability exceeds some minimum value that is higher than the one specified in Condition (6). In fact, the minimum degree of viability that is sufficient (yet, not necessary) for a project to be viable in the absolute sense is simply given by the largest probability threshold employed for defining absolute viability.

Lemma 2

Given an ecological-economic system E, thresholds $\bar{f} \equiv \left\{\bar{f}_g^h\right\}_{g\in G}^{h\in H}$ with corresponding probability thresholds $p \equiv \left\{p_g^h\right\}_{g\in G}^{h\in H}$, thresholds $\bar{s} \equiv \left\{\bar{s}_{ij}^k\right\}_{i\in I, j\in J}^{k\in K}$ with corresponding probability thresholds $q \equiv \left\{q_{ij}^k\right\}_{i\in I, j\in J}^{k\in K}$, where $G, I, J \subseteq \{1, \ldots, n\}$, $H \subseteq \{1, \ldots, l\}$, $K \subseteq \{1, \ldots, m\}$, and a time horizon T, a sufficient – yet, not necessary – condition for project $x \in X$ to be viable in system E is that

$$v(x) \geq \max\left\{p_g^h, q_{ij}^k\right\}_{(g,i,j)\in G\times I\times J}^{(h,k)\in H\times K} \quad . \tag{7}$$

Proof: see Appendix A.2.

4 Illustrative example: Livestock grazing management in semi-arid rangelands

In order to illustrate the conceptual framework and the concept of viability, and to demonstrate that it is operational and useful, we now consider the example of livestock grazing management in semi-arid rangelands. This is a prime object of study for ecological economics, as the ecological and economic systems are tightly coupled (e.g. Beukes et al. 2002, Heady 1999, Janssen et al. 2004, Perrings 1997, Perrings and Walker 1997, Perrings and Walker 2004, Westoby et al. 1989). The grass biomass is directly used as forage for livestock, which is the main source of income; and the grazing pressure from livestock farming directly influences the ecological dynamics. The crucial link is the grazing management.

Uncertainty plays a major role in semi-arid rangelands, as the dynamics of ecosystems in semi-arid regions are essentially driven by low and highly variable precipitation

(Behnke et al. 1993, Sullivan and Rhode 2002, Westoby et al. 1989). Uncertain precipitation also is of major economic significance, as it poses an income risk to the farmer. In this respect, the grazing management constitutes some form of ecological-economic risk management (Quaas et al. 2007).

In a given managed rangeland system a particular change in the grazing management strategy can be considered as a 'project', and we shall assess here whether such a project is viable or not. The grazing management strategy we consider is a specific rotational resting scheme (Heady 1999, Müller et al. 2007, Quaas et al. 2007): in years with high precipitation a certain fraction of the pasture is given a rest, i.e. the stocking rate is less than the carrying capacity of the pasture in that year. In years with low precipitation stocking is adapted to the available forage on the whole pasture.

The rotational resting strategy with resting in years with high rainfall combines two advantages: (i) It provides a form of 'natural insurance' to the farmer – income is shifted from good years to bad years by building up the vegetation's stock of reserve biomass in years with sufficient rainfall, which can then be used in years with insufficient rainfall. (ii) Resting in years with high rainfall is particularly effective in building up reserve biomass. Thus, a strategy with resting in years with sufficient rainfall improves the sustainability of rangeland management (Quaas et al. 2007).

4.1 The ecological-economic system

The essential funds for this system are the the climate (fund F_1), the vegetation of palatable grasses (fund F_2), the population of livestock (fund F_3), and the farmer's household (fund F_4). The essential services are precipitation (s^1_{12}), livestock feed (s^2_{23}), grazing pressure (s^3_{32}), stocking or destocking of livestock (s^4_{43}), and the ecosystem services provided by the livestock that yield the farmer's income (s^5_{34}). Figure 2 illustrates the funds and how they are interrelated by the services they provide. The essential human action in this ecological-economic system is the grazing management strategy x. It directly determines the stocking or destocking of livestock and, thus, the production of farm income. It also indirectly governs the way in which livestock grazing affects the

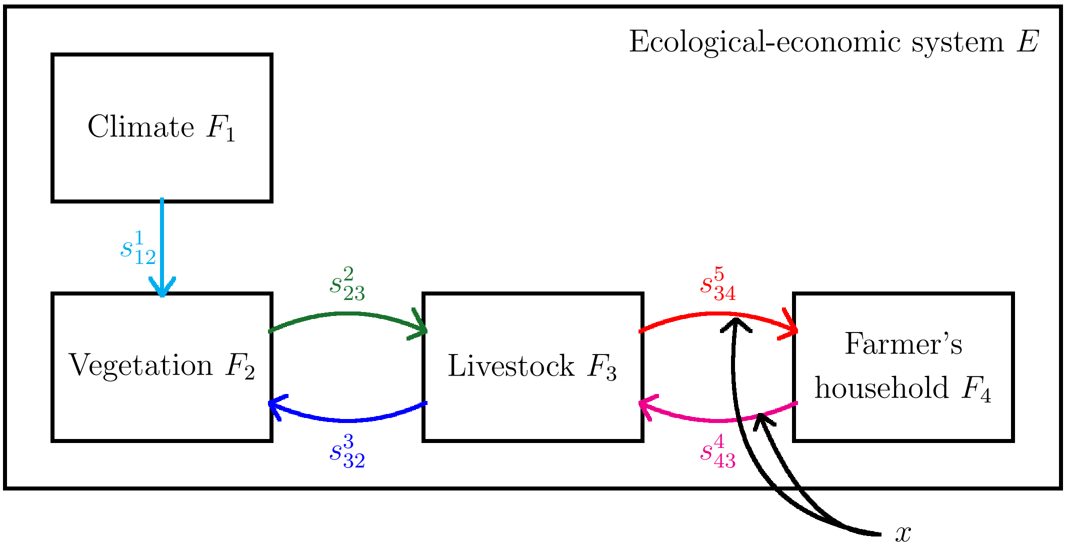

Figure 2: Funds and services in the example of the semi-arid rangeland system.

vegetation dynamics and how forage is being produced by the vegetation.

The analysis is based on an integrated dynamic and stochastic ecological-economic model which captures essential aspects and principles of grazing management in semi-arid regions.[9] Uncertainty is introduced into the model by the stochasticity of the service rainfall, $s^1_{12}(t) = r(t)$, which is assumed to be a log-normally distributed random variable with mean μ_r and variance σ^2_r,[10]

$$r(t) \propto \text{Log-N}(\mu_r, \sigma^2_r). \tag{8}$$

The key feature of the grazing management strategy is that in dry years the whole pasture is used, while in years with high rainfall a pre-specified fraction of the pasture is rested. Whether resting takes place, and to what extent, are the defining elements of what we call the farmer's grazing management strategy: A *grazing management strategy* $x = (\gamma, \underline{r})$ is a rule of which fraction of the pasture is not grazed in a particular year given the actual rainfall in that year, where $\gamma \in [0, 1]$ is the fraction of pasture rested if rainfall exceeds the threshold value $\underline{r} \in [0, \infty)$. This rule determines the fraction $g(t)$ of

[9] The details of the model and its analysis are described in Quaas et al. (2007).

[10] The dynamics of the fund 'climate', F_1 is not explicitly modeled.

pasture that is used for grazing in year t:

$$g(t) = \begin{cases} 1 & \text{if } r(t) \leq \underline{r} \quad \text{(no resting)} \\ 1-\gamma & \text{if } r(t) > \underline{r} \quad \text{(resting)} \end{cases}, \tag{9}$$

which constitutes the impact (s_{32}^3) of the fund 'livestock' (F_3) on the fund 'vegetation' (F_2).

We describe the fund F_2 'vegetation' by two stock variables: the reserve biomass and the green biomass of a representative grass species. While the green biomass $f_2^1(t) = G(t)$, which serves as feed for the livestock, captures all photosynthetic ('green') parts of the plants, the reserve biomass $f_2^2(t) = R(t)$ captures the non-photosynthetic reserve organs ('brown' parts) of the plants below or above ground. The internal dynamics of the stock of reserve biomass is described by

$$R(t+1) = R(t) - d \cdot R(t) \cdot \left(1 + \frac{R(t)}{K}\right) + w_R \cdot (1 - c \cdot g(t)) \cdot G(t) \cdot \left(1 - \frac{R(t)}{K}\right), \tag{10}$$

where w_R is a growth parameter and d is a constant intrinsic death rate of the reserve biomass. A density dependence of reserve biomass growth is captured by the factors containing the capacity limits K: the more reserve biomass, the slower it grows. The variable $s_{32}^3 = g$ captures the impact of grazing on the stock of reserve biomass. The parameter c (with $0 \leq c \leq 1$) describes the amount by which reserve biomass growth is reduced due to grazing pressure.

The amount $G(t)$ of green biomass available in year t after the end of the growing season depends on rainfall $r(t)$ in the current year, on the reserve biomass $R(t)$ and on a growth parameter w_G:

$$G(t) = w_G \cdot r(t) \cdot R(t). \tag{11}$$

The fund livestock, F_3, is described by the herd size $f_3^3 = S(t)$ that is kept on the farm at time t. This herd size is limited by total available forage. We normalize the units of green biomass in such a way that one unit of green biomass equals the need of one livestock unit per year. Thus, in any period available green biomass on the farm, $G(t)$, determines the maximum number of livestock that can be held on the farm. In general, the farmer will not stock up to this carrying capacity in every year. Rather, the herd size kept on the farm in period t is given by

$$S(t) = g(t) \cdot G(t) \ . \tag{12}$$

That is, stocking $s^4_{43} = S(t)$, is determined by the total green biomass available on the fraction of pasture used for grazing (i.e. not rested) in that year. For the sake of the analysis, we assume that the farmer can exactly adapt the actual herd size to the available forage and to his chosen grazing management strategy.[11] Accordingly, the service livestock feed equals the amount of green biomass used by grazing, $s^2_{23} = g(t)\, G(t)$.

The farm household, fund F_4, receives an income, $s^5_{34} = y(t)$, from the products of the livestock, fund F_3. For simplicity we assume that this income equals the herd size $S(t)$ kept on the farm in year t,

$$y(t) = S(t). \tag{13}$$

Since the herd size $S(t)$ is a random variable, income $y(t)$ is a random variable, too.

As in Quaas et al. (2007), we will only consider 'efficient' strategies that yield the minimal standard deviation of income for a given mean income. These are given by (Quaas et al. 2007, Lemma 1):

$$\gamma^*(\underline{r}) = \frac{\int_{\underline{r}}^{\infty} r\,(r - \underline{r})\, f(r)\, dr}{\int_{\underline{r}}^{\infty} r\,(r - \underline{r}/2)\, f(r)\, dr} \quad \text{for all} \quad \underline{r} \in [0, \infty), \tag{14}$$

where $f(r)$ is the log-normal probability density function. In the following, strategies are simply denoted by γ^*, implying that they are efficient in that they fulfill Condition (14). To summarize, the ecological-economic system (sensu Definition 1) is given by

- the funds climate F_1, without explicit representation, vegetation F_2, represented by the stocks of green biomass $f^1_2 = G(t)$ and reserve biomass $f^2_2 = R(t)$, livestock F_3, represented by the herd size $f^3_3 = S(t)$, and the farmer's household F_4, also without explicit representation

[11] Hence, the herd size $S(t)$ does not follow its own dynamics, but it is determined by precipitation and the chosen strategy.

- the services precipitation $s^1_{12} = r$, livestock feed $s^2_{23} = g\,G$, grazing pressure $s^3_{32} = g$, stocking $s^4_{43} = g$, and income $s^5_{34} = y$,
- the project 'grazing management strategy' $x = \gamma^*$ subject to efficiency condition (14),
- the dynamic allocation mechanism described by Equations (8), (10), (11), (12) and (13).

4.2 Viability as a criterion of strong sustainability

In order to assess the viability of different grazing management strategies we consider their impact on the ecological stock 'reserve biomass', R, and the economic service 'income', y. By requiring the viability of an ecological (stock) variable *and* an economic (service) variable, we consider a criterion of strong sustainability here. According to Definition 2, a grazing management strategy is viable if these two quantities exceed given thresholds ($\bar{R}$ and $\bar{y}$) with probabilities greater than given probability thresholds (p and q) over a given time horizon T. Formally, the strategy $\gamma^* \in [0, 1]$ is viable if and only if for given $\bar{R}, p, \bar{y}, q$, and T,

$$\text{Prob}\,[R(t) \geq \bar{R}] \geq\ p \quad \text{and} \quad \text{Prob}\,[y(t) \geq \bar{y}] \geq\ q \quad \text{for all } t \in [0, T]\ . \tag{15}$$

Figure 3 illustrates how the viability of different strategies (described by the fraction of resting $\gamma^\star$) depends on the probability thresholds, p and q, and the time horizon, T. The figure shows the probabilities that given levels of the stock of reserve biomass ($\bar{R} = 1000$, left) and the service income ($\bar{y} = 350$, right) are reached over different time horizons ($T \in \{1, 10, 40, 70, 100\}$) for different (efficient) grazing management strategies. In the example shown in Figure 3 a strategy $\gamma^\star$ is viable for a time horizon T if the probability $\text{Prob}\,[R(T) \geq \bar{R}]$ is higher than $p = 0.7$ and if the probability $\text{Prob}\,[y(T) \geq \bar{y}]$ is higher than $q_1 = 0.7$ or $q_2 = 0.5$, as examples of a high and a low probability threshold, respectively.[12]

[12]It is sufficient to consider the probabilities at the end of the time horizon here, because under the assumptions of the model we have $\text{Prob}\,[R(t) \geq \bar{R}] > p$ and $\text{Prob}\,[y(t) \geq \bar{y}] > q$ for all $t \in [0, T]$ provided

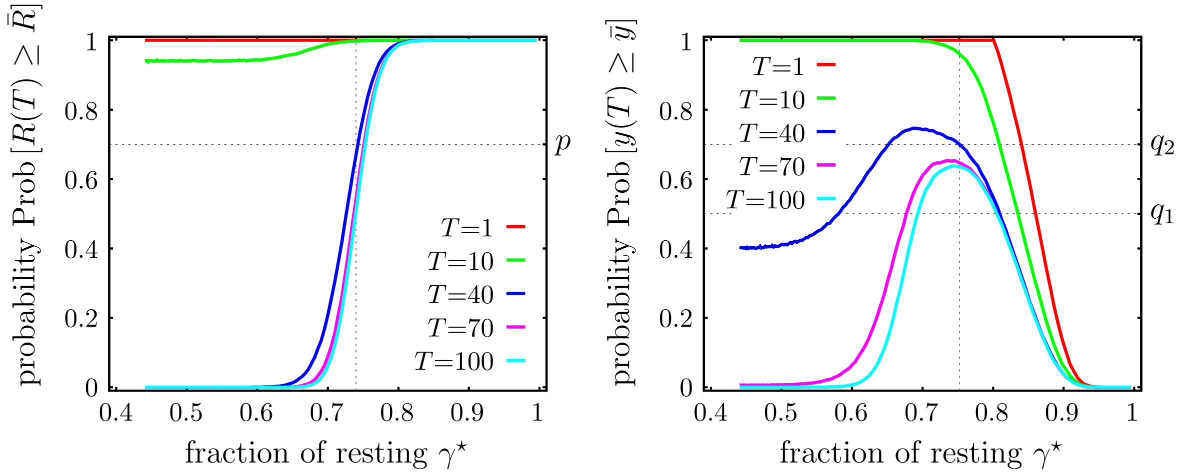

Figure 3: The probabilities that given levels of the stock of reserve biomass ($\bar{R} = 1000$, left) and the service income ($\bar{y} = 350$, right) are reached at different points in time ($T \in \{1, 10, 40, 70, 100\}$) for different (efficient) grazing management strategies, described by the fraction of resting. The parameters for the calculations were $\mu_r = 1.2$, $\sigma_r = 0.7$, $d = 0.15$, $w_G = 1.2$, $w_R = 0.2$, $c = 0.5$, $R_0 = 2400$, $K = 8000$.

According to Definition 3, the viability set is given by the set of all strategies $\gamma^\star$ for which the curve for the time horizon under consideration in Figure 3 lies above the horizontal lines depicting the probability thresholds under consideration.

For the high probability threshold q_2, the viability set is empty for long time horizons ($T \geq 70$), because the probability that the threshold level $\bar{y}$ of income is exceeded is smaller than the required probability threshold q_2 for all strategies γ^*.

For a comparatively short time horizon of T=40 the viability set is small when probability thresholds for both reserve biomass and income are high. The reason is that viability with regard to the economic criterion 'income' requires a grazing management strategy with little resting. In the example, less than about 75% of the pasture has to be rested to exceed the threshold level $\bar{y}$ of income with a probability of at least q_2 for a time horizon of T=40. By contrast, viability with regard to the ecological criterion 'reserve biomass' requires a substantial amount of resting. In the example, more than

that at the end of the time horizon it holds that Prob $[R(T) \geq \bar{R}] > p$ and Prob $[y(T) \geq \bar{y}] > q$.

about 74% of the pasture has to be rested to exceed the threshold level $\bar{R}$ of reserve biomass with a probability of at least p for a time horizon of T=40. Only strategies fulfilling both the economic and the ecological criterion at the same time are viable. In the example, these are only the strategies with fractions of resting between 74% and 75%.

For the low probability threshold of $q_1 = 0.5$ the viability set is non-empty also for a very long time horizon. Interestingly, a certain minimal amount of resting is necessary for the viability with regard to the economic criterion 'income', too. The reason is that in the long-run, in the context of rangelands, ecological viability is a prerequisite for economic viability.

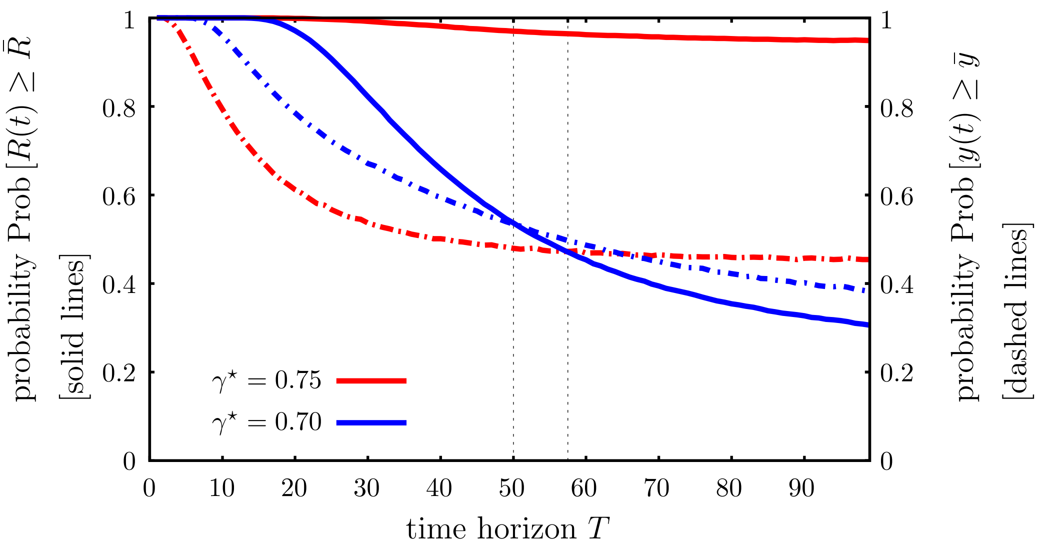

Figure 4: The probability that given levels $\bar{R} = 700$ of the stock of reserve biomass (solid lines, left axis) and $\bar{y} = 450$ of the service income (dashed lines, right axis) are reached for different time horizons T and for two strategies, $\gamma^\star = 0.75$ and $\gamma^\star = 0.70$. Other parameters are as in Figure 3.

Figure 4 shows that it depends on the time horizon which of the two strategies is more viable according to Definition 5.[13] This figure shows the probabilities that the stock reserve biomass ($\bar{R} = 700$) and the service income ($\bar{y} = 450$) exceed given thresholds for different time horizons T and for two strategies, one with a smaller fraction of resting than the other ($\gamma^\star = 0.70$ vs. $\gamma^\star = 0.75$). The degree of viability $v(\gamma^*)$ for each of the two strategies $\gamma^* = 0.70$ and $\gamma^* = 0.75$ is given by the smaller of the two probabilities that the stock reserve biomass and the service income exceed their respective threshold values. Hence, in the figure, the degree of viability for each strategy can be read off as the lower of the solid and dashed lines for this strategy. For the strategy with more resting ($\gamma^\star = 0.75$, red lines), the degree of viability is simply the probability that the service income exceeds the threshold $\bar{y}$, $v(\gamma^\star = 0.75) = \text{Prob}\,[y \geq \bar{y}]$ (dashed line), as this probability is smaller than the probability that the stock reserve biomass exceeds the threshold value $\bar{R}$ (solid line) for all time horizons T. This expresses that with high resting viability is for all time horizons limited by the income criterion.

In contrast, for the strategy with less resting ($\gamma^\star = 0.70$, blue lines), the degree of viability is given by the the probability that the service income exceeds the threshold $\bar{y}$ (dashed line) for short time horizons $T \leq 50$, and by the the probability that the stock reserve biomass exceeds the threshold $\bar{R}$ (solid line) for long time horizons $T > 50$. Hence, $v(\gamma^\star = 0.70) = \text{Prob}\,[y \geq \bar{y}]$ for $T \leq 50$, and $v(\gamma^\star = 0.70) = \text{Prob}\,[R \geq \bar{R}]$ for $T > 50$. This expresses that with little resting in the short term viability is limited by the income criterion, while in the long term viability is limited by the reserve biomass criterion.

Comparing the two strategies in terms of their degree of viability, Figure 4 shows that $v(\gamma^\star = 0.70) > v(\gamma^\star = 0.75)$ for $T \leq 58$, i.e. the strategy with a small fraction of resting ($\gamma^\star = 0.70$, blue lines) is more viable than the strategy with a large fraction of resting ($\gamma^\star = 0.75$, red lines) for short time horizons, while $v(\gamma^\star = 0.75) > v(\gamma^\star = 0.70)$ for $T > 58$, i.e the strategy with a large fraction of resting is more viable than the strategy with a small fraction of resting for long time horizons.

For given viability criteria $(\bar{R}, p, \bar{y}, q, T)$ one can classify whether a strategy γ^* is viable or not (Definition 2). One can also take the reverse perspective and ask, under what

[13] Of course, this also depends on the threshold values $\bar{R}$ and $\bar{y}$.

viability criteria is a given strategy γ^* viable? Figure 5 illustrates the answer to this question for the example of the strategy $\gamma^\star = 0.70$ considered already in Figure 4. This strategy is viable over a time horizon $T = 40$ for all $(\bar{R}, p, \bar{y}, q)$ with the combination $(\bar{R}, p)$ of the threshold level for the stock of reserve biomass and the corresponding probability threshold to the south west of the green line (Figure 5, left) and the combination $(\bar{y}, q)$ of the threshold level for the service income and the corresponding probability threshold to the south west of the blue line (Figure 5, right).

We see that the strategy under consideration, $\gamma^\star = 0.70$, is viable over the time horizon $T = 40$ for many different combinations of thresholds $\bar{R}$ and $\bar{y}$ in the physical quantities and corresponding probability thresholds p and q: for instance, a viable strategy is still viable under a lower threshold in the service or stock and a higher corresponding probability threshold. This is a property of the particular system dynamics of

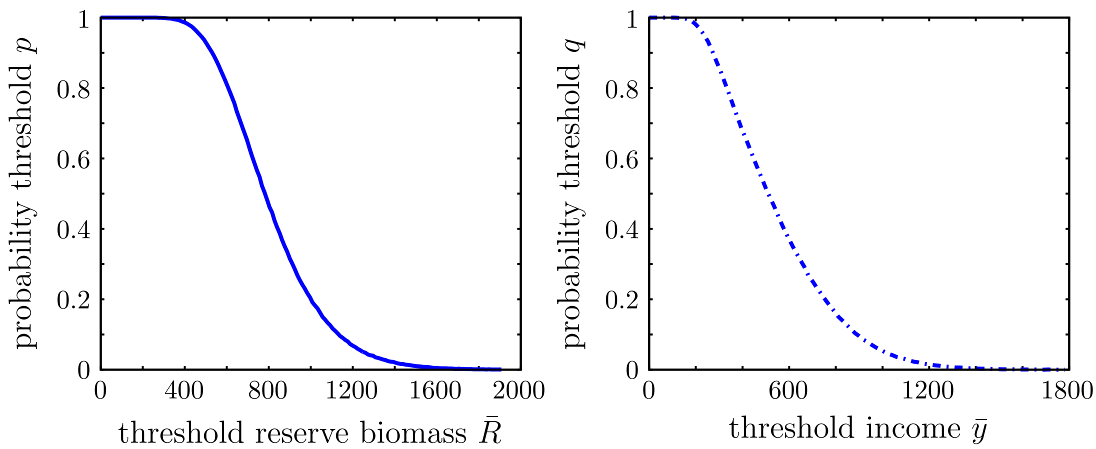

Figure 5: The strategy $\gamma^\star = 0.70$ is viable over a time horizon $T = 40$ whenever the combination $(\bar{R}, p)$ of the threshold level for the stock of reserve biomass and the corresponding probability threshold is to the south west of the green line (left) and the combination $(\bar{y}, q)$ of the threshold level for the service income and the corresponding probability threshold is to the south west of the blue line (right). The parameters are as in Figure 3.

managed semi-arid rangelands. We conjecture that such a relationship exists for many reasonably well behaved systems. Nevertheless, in defining viability we believe that it is reasonable and useful to separate the thresholds in the level of physical quantities (stocks and services) and in the probabilities: the threshold in the quantities has to be set according to society's value judgments on these quantities while the thresholds in the probabilities have to be set according to society's valuation of risks. In line with the logic of strong sustainability, one could argue that these judgments should be made separately.

5 Conclusion and discussion

In this paper, we have developed a general formalization of ecological-economic systems as stochastic dynamic networks of funds and services. To this end, we have generalized the framework of Arrow et al. (2003) in two respects. First, in addition to considering different natural and economic (capital) stocks, we have explicitly included the various services rendered by ecological and economic funds. Second, we have included uncertainty about the future development of the system.

Based on this formalization of ecological-economic systems, we have conceptualized strong sustainability under uncertainty as ecological-economic viability. In particular, we have developed a unifying and general concept of viability that encompasses the traditional ecological and economic notions of viability – continued existence of funds and of services, respectively – as special cases. This concept of ecological-economic viability provides an operational criterion of strong sustainability under conditions of uncertainty.

Our analysis yields several insights into the normative prerequisites for, and the implications of, demanding strong sustainability when future development is uncertain. First of all, our formal definition of ecological-economic viability clarifies conceptually what has to be specified in order to assess whether a project is sustainable or not. It thereby highlights the different normative judgments that necessarily enter a sustainability assessment under conditions of uncertainty. In particular, the following questions have to be answered:

1. What should be sustained? – The answer to this question specifies the selection of relevant stocks f_i^h and services s_{ij}^k.

2. At what level? – The answer to this question specifies the threshold levels $\bar{f}_i^h$ and $\bar{s}_{ij}^k$ at which the selected stocks and services shall be maintained.

3. For how long? – The answer to this question specifies the time horizon T.

4. To what extent of (un)certainty? – The answer to this question specifies the probability thresholds p_i^h and q_{ij}^k, i.e. the minimum probabilities with which the selected stocks and services shall be maintained above their respective threshold levels.

This emphasizes that viability is not a purely objective property of some system that could be determined on purely scientific grounds, as it appears to be in some ecological applications. Rather, viability is a normative criterion specified for a given ecological-economic system, reflecting societal norms and values.

Second, our analysis shows that strong sustainability under conditions of uncertainty cannot be as 'strong' as it is appears to be under certainty. Under uncertainty, it is in general not possible to maintain all relevant stocks of natural capital with 100% probability because the stocks may decline by chance irrespectively of management activities, for example because of a stochastic event such as an earthquake or volcano eruption. Therefore, from an *ex-ante* perspective a given project leads to an *ex post* sustainable outcome only with a probability which is in general less than one. In other words, even a project that is considered viable *ex ante* may actually turn out to be unsustainable *ex post*. It is for this reason that an ex-ante sustainability criterion under uncertainty necessarily has to be weaker than under certainty. The probabilities that selected funds and services are maintained above given threshold values lead to a continuous measure of sustainability, i.e. the *degree of viability*. In order to make an unambiguous statement as to whether a project is sustainable (i.e. viable) or not, it is necessary to define also thresholds for these probabilities.

Third, as a viability assessment should provide guidance for societal choices and policy making towards sustainability under uncertainty, it is important that the underlying criterion is plausible, transparent and operational. We believe that the formalization and definition of viability developed in this paper exactly fulfills these desiderata, as the definition of thresholds is a process that is easily accessible for public debate and communication between scientists, policy makers and the public.

Fourth, taken as a criterion of societal choice, the viability criterion by itself will, in general, not yield unique recommendations, as several projects may turn out to be viable. Therefore, a sustainability assessment based on the viability criterion may be complemented by a cost-benefit analysis. Among the many viable projects one may choose the one that generates the highest net benefit. In this approach, cost-benefit analysis would not be used to choose among all feasible projects but only among the viable ones ('tolerable window'). In other words, viability is taken as a constraint on net-benefit maximization. This procedure yields what may be called the 'optimal sustainable' project.

Acknowledgments

We are grateful to Christian Becker, Christoph Böhringer, Udo Ebert, Malte Faber, Karin Frank, Lutz Göhring, Anja Humburg, Klara Stumpf, Heinz Welsch and Christian Wissel for helpful discussion and comments. Financial support from the Volkswagen Foundation under grants II/79 628 and II/82 883 and the German Federal Ministry of Education and Research under grant 01UN0607 is gratefully acknowledged.

Appendix

A.1 Proof of Lemma 1

To proof that Condition (6) is *necessary* for viability, consider a project $x \in X$ that is viable for given ecological-economic system E, thresholds $\bar{f} \equiv \left\{\bar{f}_g^h\right\}_{g\in G}^{h\in H}$ with corresponding probability thresholds $p \equiv \left\{p_g^h\right\}_{g\in G}^{h\in H}$, thresholds $\bar{s} \equiv \left\{\bar{s}_{ij}^k\right\}_{i\in I, j\in J}^{k\in K}$ with corresponding probability thresholds $q \equiv \left\{q_{ij}^k\right\}_{i\in I, j\in J}^{k\in K}$, where $G, I, J \subseteq \{1,\ldots,n\}$, $H \subseteq \{1,\ldots,l\}$, $K \subseteq \{1,\ldots,m\}$, and time horizon T. By Definition 2 of viability, this implies that Condition (2) is met. That is, for all $(g,h,i,j,k) \in G\times H\times I\times J\times K$ and all $t\in[0,T]$

$$\tilde{p}_g^h(t) \geq p_g^h \quad \text{and} \quad \tilde{q}_{ij}^k(t) \geq q_{ij}^k \ , \tag{A.16}$$

$$\text{where} \qquad \tilde{p}_g^h(t) := \text{Prob}\left[f_g^h(t) \geq \bar{f}_g^h\right] \quad \text{and} \quad \tilde{q}_{ij}^k(t) := \text{Prob}\left[s_{ij}^k(t) \geq \bar{s}_{ij}^k\right] \ . \tag{A.17}$$

The degree of viability of project x as defined in Definition 5 (function 5) is then

$$\begin{aligned} v(x) \quad &= \quad \min\Bigg\{\left\{\text{Prob}\left[f_g^h(t) \geq \bar{f}_g^h\right]\right\}^{(g,h)\in G\times H,\ t\in[0,T]} \\ &\qquad \cup \left\{\text{Prob}\left[s_{ij}^k(t) \geq \bar{s}_{ij}^k\right]\right\}^{(i,j,k)\in I\times J\times K,\ t\in[0,T]}\Bigg\} \\ &= \quad \min\left\{\tilde{p}_g^h(t), \tilde{q}_{ij}^k(t)\right\}_{(g,i,j)\in G\times I\times J}^{(h,k)\in H\times K; t\in[0,T]} \\ &\overset{\text{Cond. (6)}}{\geq} \quad \min\left\{p_g^h, q_{ij}^k\right\}_{(g,i,j)\in G\times I\times J}^{(h,k)\in H\times K} \ , \end{aligned}$$

which is the necessary condition stated in the lemma (Equation 6).

To proof that Condition (6) is *not sufficient* for viability, consider the following counter example of a project $x \in X$ that fulfills Condition (6) but is not viable. In an ecological-economic system with $l = 1$, i.e. one single stock variable characterizing all funds, so that the index h can be suppressed, the viability analysis is in terms of $G = \{1,2\}$, $H = \{1\}$, $I, J, K = \emptyset$ over some time horizon T with thresholds $\bar{f}_1$, $\bar{f}_2$ and corresponding probability thresholds $p_1 = 0.1$ and $p_2 = 0.4$. The dynamic allocation mechanism is such that project x leads to $\text{Prob}\left[f_1(t) \geq \bar{f}_1\right] = 0.2$ and $\text{Prob}\left[f_2(t) \geq \bar{f}_2\right] = 0.3$ for all $t \in [0,T]$. Then

$$\begin{aligned} v(x) \ &= \ \min\left\{\text{Prob}\left[f_1(t) \geq \bar{f}_1\right], \text{Prob}\left[f_2(t) \geq \bar{f}_2\right]\right\}_{t\in[0,T]} = \min\{0.2, 0.3\} = 0.2 \\ &> \ \min\{p_1, p_2\} = \min\{0.1, 0.4\} = 0.1 \ , \end{aligned}$$

so that Condition (6) is fulfilled. Yet, project x is not viable as

$$\text{Prob}\left[f_2(t) \geq \bar{f}_2\right] = 0.3 \quad < \quad p_2 = 0.4 \ ,$$

which violates Condition (2) in Definition 2 of viability.

A.2 Proof of Lemma 2

Consider any $h \in H$, $g \in G$ and $t \in [0,T]$. By Definition 5 and Condition (7), we have

$$\text{Prob}\left[f_g^h(t) \geq \bar{f}_g^h\right] \overset{\text{Def. 5}}{\geq} v(x) \overset{\text{Cond. (7)}}{\geq} p_g^h. \tag{A.18}$$

Similarly, consider any $k \in K$, $i \in I$, $j \in J$ and $t \in [0,T]$. Again, by Definition 5 and Condition (7), we have

$$\text{Prob}\left[s_{ij}^k(t) \geq \bar{s}_{ij}^k\right] \overset{\text{Def. 5}}{\geq} v(x) \overset{\text{Cond. (7)}}{\geq} q_{ij}^k. \tag{A.19}$$

Because Conditions (A.18) and (A.19) hold for all $(g,h,i,j,k) \in G \times H \times I \times J \times K$ and all $t \in [0,T]$, project x is viable in the sense of Definition 2.

References

Arrow, K. J., P. Dasgupta and K.-G. Mäler (2003). Evaluating Projects and Assessing Sustainable Development in Imperfect Economies. *Environmental and Resource Economics*, **26**(4): 647–685.

Asheim, G. B. (1994). Net national product as an indicator of sustainability. *Scandinavian Journal of Economics*, **96**: 257–265.

Asheim, G. B. and K. Brekke (2002). Sustainability when capital management has stochastic consequences. *Social Choice and Welfare*, **19**: 921–940.

Aubin, J. (1991). *Viability Theory*. Systems & Control: Foundations & Applications. Birkhäuser, Boston.

Baumgärtner, S., M. Faber and J. Schiller (2006). *Joint Production and Responsibility in Ecological Economics. On the Foundations of Environmental Policy*. Edard Elgar, Cheltenham.

Behnke, R. H., I. Scoones and C. Kerven (1993). *Range ecology at disequilibrium: New models of natural variability and pastoral adaption in African savannas*. Overseas Development Institute, London.

Beissinger, S. and D. McCullough (eds.) (2002). *Population Viability Analysis*. University of Chicago Press, Chigaco.

Beltratti, A., G. Chichilnisky and G. Heal (1998). Uncertain future preferences and conservation. In G. Chichilnisky, G. Heal and A. Vercelli (eds.), *Sustainability: Dynamics and Uncertainty*, pp. 257–275. Kluwer Academic Publishers, Dordrecht.

Béné, C. and L. Doyen (2000). Storage and viablity of a fishery with resource and market dephased seasonalities. *Environmental and Resource Economics*, **15**: 1–26.

Béné, C., L. Doyen and D. Gabay (2001). A viability analysis for a bio-economic model. *Ecological Economics*, **36**: 385–396.

Beukes, P. C., R. M. Cowling and S. Higgins (2002). An ecological economic simulation model of a non-selective grazing system in the Nama Karoo, South Africa. *Ecological Economics*, **42**: 221–242.

Bruckner, T., G. Petschel-Held, F.L. Tóth, H.-M. Füssel, C. Helm, M. Leimbach and H.-J. Schellnhuber (1999). Climate-change decision support and the tolerable windows approach. *Environmental Modeling and Assessment*, **4**: 217–234.

Bruckner, T., G. Petschel-Held, M. Leimbach and F.L. Tóth (2003). Methodological aspects of the tolerable windows approach. *Climatic change*, **56**: 73–89.

Costanza, R., L. Wainger, C. Folke and K.-G. Mäler (1993). Modeling complex ecological economic systems: toward an evolutionary, dynamic understanding of people and nature. *BioScience*, **43**: 545–555.

Daly, H.E. and J.B. Cobb (1989). *For the Common Good.* Beacon Press, Boston.

Daily, G. (1997). What are ecosystem services? In G. Daily (ed.), *Nature's Services. Societal Dependence on Natural Ecosystems*. Island Press, Washington, D.C, pp. 1–10.

Dasgupta, P., S. Levin and J. Lubchenco (2000). Economic pathways to sustainability. *BioScience*, **50**: 339–345.

Doyen, L. and C. Béné (2003). Sustainability of fisheries through marine reserves: a robust modelling analysis. *Journal of Environmental Management*, **69**: 1–13.

Eichner and Pethig (2005). Ecosystem and economy: an integrated dynamic general equilibrium approach. *Journal of Economics*, **85**(3): 213–249.

Eichner and Pethig (2006). Economic land use, ecosystem services and microfounded species dynamics. *Journal of Environmental Economics and Management*, **52**(3): 702–720.

Eichner and Pethig (2007). Harvesting in an integrated general equilibrium model. *Environmental and Resource Economics*, **37**(1): 233–252.

Eisenack, K., J. Sheffran and J. Kropp (2006). The viability analysis of management frameworks for fisheries. *Environmental Modeling and Assessment*, **11**(1): 69–79.

Ekins, P., S. Simon, L. Deutsch, C. Folke and R. D. Groot (2003). A framework for the practical application of the concepts of critical natural capital and strong sustainability. *Ecological Economics*, **44**(2): 165–185.

Faber, M., K. Frank, B. Klauer, R. Manstetten, J. Schiller and C. Wissel (2005). On the foundation of a general theory of stocks. *Ecological Economics*, **55**(2): 155–172.

Faber, M. and R. Manstetten (1998). Produktion, Konsum und Dienste in der Natur – Eine Theorie der Fonds. In F. Schweitzer and G. Silverberg (eds.), *Evolution und Selbstorganisation in der Ökonomie*, pp. 209–236. Duncker & Humblot, Berlin.

Faber, M. and R. Manstetten (2003). *Mensch–Natur–Wissen. Grundlagen der Umweltbildung*. Vandenhoeck & Ruprecht, Göttingen.

Faber, M., R. Manstetten and J. Proops (1992). Humankind and the environment: an anatomy of surprise and ignorance. *Environmental Values*, **1**(3): 217–242.

Faber, M., R. Manstetten and J. Proops (1995). On the conceptual foundations of ecological economics: a teleological approach. *Ecological Economics*, **12**: 41–54.

Faber, M., R. Manstetten and J. Proops (1996). *Ecological Economics: Concepts and Methods*. Edward Elgar, Cheltenham.

Finnoff, D. and J. Tschirhart (2003). Harvesting in an eight-species ecosystem. *Journal of Environmental Economics and Management*, **45**: 589–611.

Frank, K. (2005). Metapopulation persistence in heterogeneous landscapes: lessons about the effect of stochasticity. *The American Naturalist*, **165**: 374–388.

Georgescu-Roegen, N. (1971). *The Entropy Law and the Economic Process*. Harvard University Press, Cambridge.

Hamilton, K. (1994). Green adjustments to GDP. *Resources Policy*, **20**: 155–168.

Heady, H. (1999). Perspectives on Rangeland Ecology and Management. *Rangelands*, **21**: 23–33.

Heal, G. (1998). Interpreting Sustainability. In G. Chichilnisky, G. Heal and A. Vercelli (eds.), *Sustainability: Dynamics and Uncertainty*, pp. 257–275. Kluwer Academic Publishers, Dordrecht.

Howarth, R. B. (1995). Sustainability under uncertainty: a deontological approach. *Land Economics*, **71**(4): 417–427.

Janssen, M. A., J. M. Anderies and B. H. Walker (2004). Robust strategies for managing rangelands with multiple stable attractors. *Journal of Environmental Economics and Management*, **47**: 140–162.

Jansson, A.-M. (ed.) (1994). *Investing in Natural Capital. The Ecological Economics Approach to Sustainability*. Island Press, Washington, D.C.

Klauer, B. (1999). Defining and achieving sustainable development. *International Journal of Sustainable Development and World Ecology*, **6**(2): 114–121.

Knight, F. (1921). *Risk, Uncertainty and Profit*. Houghton Mifflin, Boston.

Martinet, V. and L. Doyen (2007). Sustainability of an economy with an exhaustible resource: a viable control approach. *Resource and Energy Economics*, **29**: 17–39.

Millennium Ecosystem Assessment (2005). *Ecosystems and Human Well-Being: Synthesis Report*. Island Press, Washington DC.

Müller, B., K. Frank and C. Wissel (2007). Relevance of rest periods in non-equilibrium rangeland systems: A modelling analysis. *Agricultural Systems*, **92**: 295–317.

Neumayer, E. (2003). *Weak Versus Strong Sustainability: Exploring the Limits of Two Opposing Paradigms*. Edward Elgar, Cheltenham, UK.

Norgaard, R. B. (1981). Sociosystem and ecosystem coevolution in the Amazon. *Journal of Environmental Economics and Management*, **8**: 238–254.

Ott, K. and R. Döring (2004). *Theorie und Praxis starker Nachhaltigkeit*. Metropolis-Verlag, Marburg.

Pearce, D. and G. Atkinson (1993). Capital theory and the measurement of sustainable development: an indicator of 'weak' sustainability. *Ecological Economics*, **8**(2): 103–108.

Pearce, D., A. Markandya and E. Barbier (1989). *Blueprint for a Green Economy.* Earthscan, London.

Pereau, L. D. J. (submitted). Viable management of a renewable resource with a quota market. *Journal of Environmental Economics and Management*.

Perrings, C. (1997). Stress, shock and the sustainability of resource use in semi-arid environments. In C. Perrings (ed.), *Economics of Ecological Resources*, pp. 142–175. Edward Elgar, Cheltenham, UK.

Perrings, C. (1998). Resilience in the dynamics of economy-environment systems. *Environmental and Resource Economics*, **11**(3-4): 503–520.

Perrings, C. and B. Walker (1997). Biodiversity, resilience and the control of ecological-economic systems: the case of fire-driven rangelands. *Ecological Economics*, **22**: 73–83.

Perrings, C. and B. Walker (2004). Conservation in the optimal use of rangelands. *Ecological Economics*, **49**: 119–128.

Pezzey, J. (1992). *Sustainable Development Concepts. An Economic Analysis*. World Bank, Washington, DC.

Pezzey, J. and C. Withagen (1995). The rise, fall and sustainability of capital-resource economies. *Scandinavian Journal of Economics*, **100**: 513–527.

Quaas, M. F., S. Baumgärtner, C. Becker, K. Frank and B. Müller (2007). Uncertainty and sustainability in the management of rangelands. *Ecological Economics*, **62**: 213–234.

Settle, C., T. Crocker and J. Shogren (2002). On the joint determination of biological and economic systems. *Ecological Economics*, **42**: 301–311.

Soulé, M. (ed.) (1987). *Viable Populations for Conservation*. Cambridge University Press, Cambridge.

Sullivan, S. and R. Rhode (2002). On non-equilibrium in arid and semi-arid grazing systems. *Journal of Biogeography*, **29**: 1595–1618.

Tóth, F.L., T. Bruckner, H.-M. Füssel, M. Leimbach, G. Petschel-Held and H.-J. Schellnhuber (2002). Exploring options for global climate policy: a new analytical framework. *Environment*, **44**(5): 22–34.

Tschirhart, J. (2000). General equilibrium of an ecosystem. *Journal of Theoretical Biology*, **203**: 13–23.

Tschirhart, J. (2003). Resource competition among plants: from maximizing individuals to community structure. *Ecological Modelling*, **148**: 191–212.

Tucci, M. (1998a). Stochastic sustainability. In G. Chichilnisky, G. Heal and A. Vercelli (eds.), *Sustainability: Dynamics and Uncertainty*, pp. 257–275. Kluwer Academic Publishers, Dordrecht.

Tucci, M. (1998b). Stochastic sustainability in the presence of unknown parameters. In G. Chichilnisky, G. Heal and A. Vercelli (eds.), *Sustainability: Dynamics and Uncertainty*, pp. 257–275. Kluwer Academic Publishers, Dordrecht.

Ulanowizc, R. (1986). *Growth and Development – Ecosystem Phenomenology*. Springer, New York.

Ulanowizc, R. (1997). *Ecology – The Ascendant Perspective*. Columbia University Press, New York.

Westoby, M., B. H. Walker and I. Noy-Meir (1989). Opportunistic management for rangelands not at equilibrium. *Journal of Range Management*, **42**: 266–274.

Woodward, R. (2000). Sustainability as intergenerational fairness: efficiency, uncertainty, and numerical methods. *American Journal of Agricultural Economics*, **82**: 581–593.

Wulff, F., J. Field and K. Mann (eds.) (1989). *Network Analysis in Marine Biology: Methods and Applications*. Springer, Berlin.

Working Paper Series in Economics

(see www.leuphana.de/vwl/papers for a complete list)

No.66: *Kathrin Michael:* Überbrückungsgeld und Existenzgründungszuschuss – Ergebnisse einer schriftlichen Befragung drei Jahre nach Gründungsbeginn, November 2007

No.65: *The International Study Group on Export and Productivity:* Exports and Productivity – Comparable Evidence for 14 Countries, November 2007

No.64: *Lena Koller, Claus Schnabel und Joachim Wagner:* Freistellung von Betriebsräten – Eine Beschäftigungsbremse?, November 2007

No.63: *Anne-Kathrin Last:* The Monetary Value of Cultural Goods: A Contingent Valuation Study of the Municipal Supply of Cultural Goods in Lueneburg, Germany, October 2007

No.62: *Thomas Wein und Heike Wetzel:* The Difficulty to Behave as a (regulated) Natural Monopolist – The Dynamics of Electricity Network Access Charges in Germany 2002 to 2005, September 2007

No.61: *Stefan Baumgärtner und Martin F. Quaas:* Agro-biodiversity as natural insurance and the development of financial insurance markets, September 2007

No.60: *Stefan Bender, Joachim Wagner, Markus Zwick:* KombiFiD - Kombinierte Firmendaten für Deutschland, September 2007

No.59: *Jan Kranich*: Too much R&D? - Vertical differentiation in a model of monopolistic competition, August 2007

No.58: *Christian Papilloud und Ingrid Ott:* Convergence or mediation? Experts of vulnerability and the vulnerability of experts' discourses on nanotechnologies – a case study, July 2007

No.57: *Ingrid Ott und Susanne Soretz:* Governmental activity, integration and agglomeration, July 2007

No.56: *Nils Braakmann:* Struktur und Erfolg von Ich-AG-Gründungen: Ergebnisse einer Umfrage im Arbeitsagenturbezirk Lüneburg, Juli 2007

No.55: *Nils Braakmann:* Differences in the earnings distribution of self- and dependent employed German men – evidence from a quantile regression decomposition analysis, July 2007

No.54: *Joachim Waagner:* Export entry, export exit, and productivity in German Manufacturing Industries, June 2007
[forthcoming in:International Journal of the Economics of Business]

No.53: *Nils Braakmann:* Wirkungen der Beschäftigungspflicht schwerbehinderter Arbeitnehmer – Erkenntnisse aus der Einführung des „Gesetzes zur Bekämpfung der Arbeitslosigkeit Schwerbehinderter", Juni 2007

No.52: *Jan Kranich und Ingrid Ott:* Regionale Spitzentechnologie auf internationalen Märkten, Juni 2007

No.51: *Joachim Wagner:* Die Forschungspotenziale der Betriebspaneldaten des Monatsberichts im Verarbeitenden Gewerbe, Mai 2007

No.50: *Stefan Baumgärtner, Frank Jöst und Ralph Winkler:* Optimal dynamic scale and structure of a multi-pollution economy, May 2007

No.49: *Helmut Fryges und Joachim Wagner:* Exports and productivity growth – First evidence from a continuous treatment approach, May 2007

No.48: *Ulrich Kaiser und Joachim Wagner:* Neue Möglichkeiten zur Nutzung vertraulicher amtlicher Personen- und Firmendaten, April 2007
[erscheint in: Perspektiven der Wirtschaftspolitik]

No.47: *Joachim Wagner:* Jobmotor Mittelstand? Arbeitsplatzdynamik und Betriebsgröße in der westdeutschen Industrie, April 2007
[publiziert in: Vierteljahrshefte zur Wirtschaftsforschung, 76 (2007), 3, 76-87]

No.46: *Christiane Clemens und Maik Heinemann:* Credit Constraints, Idiosyncratic Risks, and the Wealth Distribution in a Heterogenous Agent Model, March 2007

No.45: *Jan Kranich:* Biotechnologie und Internationalisierung. Ergebnisse der Online-Befragung, März 2007

No.44: *Joachim Wagner:* Entry, exit and productivity. Empirical results for German manufacturing industries, March 2007

No.43: *Joachim Wagner:* Productivity and Size of the Export Market Evidence for West and East German Plants, 2004, March 2007

No.42: *Joachim Wagner:* Why more West than East German firms export, March 2007

No.41: *Joachim Wagner:* Exports and Productivity in Germany, March 2007

No.40: *Lena Koller, Klaus Schnabel und Joachim Wagner:* Schwellenwerte im Arbeitsrecht. Höhere Transparenz und Effizienz durch Vereinheitlichung, Februar 2007
[publiziert in: Perspektiven der Wirtschaftspolitik, 8 (2007), 3, 242-255]

No.39: *Thomas Wein und Wiebke B. Röber:* Sind ausbildende Handwerksbetriebe erfolgreicher?, Januar 2007

No.38: *Joachim Wagner:* Institut für Volkswirtschaft: Forschungsbericht 2006, Januar 2007

No.37: *Nils Braakmann:* The impact of September 11th, 2001 on the job prospects of foreigners with Arab background – Evidence from German labor market data, January 2007

No.36: *Jens Korunig:* Regulierung des Netzmonopolisten durch Peak-load Pricing?, Dezember 2006

No.35: *Nils Braakmann:* Die Einführung der fachkundigen Stellungnahme bei der Ich-AG, November 2006

No.34: *Martin F. Quaas and Stefan Baumgärtner:* Natural vs. financial insurance in the management of public-good ecosystems, October 2006
[forthcoming in: Ecological Economics]

No.33: *Stefan Baumgärtner and Martin F. Quaas:* The Private and Public Insurance Value of Conservative Biodiversity Management, October 2006

No.32: *Ingrid Ott and Christian Papilloud:* Converging institutions. Shaping the relationships between nanotechnologies, economy and society, October 2006
[forthcoming in: Bulletin of Science, Technology & Society]

No.31: *Claus Schnabel and Joachim Wagner:* The persistent decline in unionization in western and eastern Germany, 1980-2004: What can we learn from a decomposition analysis?, October 2006
[published in: Industrielle Beziehungen/The German Journal of Industrial Relations 14 (2007), 118-132]

No.30: *Ingrid Ott and Susanne Soretz:* Regional growth strategies: fiscal versus institutional governmental policies, September 2006
[forthcoming in: Economic Modelling]

No.29: *Christian Growitsch and Heike Wetzel:* Economies of Scope in European Railways: An Efficiency Analysis, July 2006

No.28: *Thorsten Schank, Claus Schnabel and Joachim Wagner:* Do exporters really pay higher wages? First evidence from German linked employer-employee data, June 2006
[published in in: Journal of International Economics 72 (2007), 1, 52-74]

No.27: *Joachim Wagner:* Markteintritte, Marktaustritte und Produktivität
Empirische Befunde zur Dynamik in der Industrie, März 2006
[erscheint in: Allgemeines Statistisches Archiv, Heft 3/2007]

No.26: *Ingrid Ott and Susanne Soretz:* Governmental activity and private capital adjustment, March 2006
[forthcoming in: Icfai Journal of Managerial Economics]

No.25: *Joachim Wagner:* International Firm Activities and Innovation:
Evidence from Knowledge Production Functions for German Firms, March 2006

No.24: *Ingrid Ott und Susanne Soretz:* Nachhaltige Entwicklung durch endogene Umweltwahrnehmung, März 2006
publiziert in: Clemens, C., Heinemann, M. & Soretz, S., Auf allen Märkten zu Hause (Gedenkschrift für Franz Haslinger), Marburg: Metropolis, 2006, 233-256

No.23: *John T. Addison, Claus Schnabel, and Joachim Wagner:* The (Parlous) State of German Unions, February 2006
[forthcoming in: Journal of Labor Research 28 (2007), 3-18]

No.22: *Joachim Wagner, Thorsten Schank, Claus Schnabel, and John T. Addison:* Works Councils, Labor Productivity and Plant Heterogeneity: First Evidence from Quantile Regressions, February 2006
[published in: Jahrbücher für Nationalökonomie und Statistik 226 (2006), 505 - 518]

No.21: *Corinna Bunk:* Betriebliche Mitbestimmung vier Jahre nach der Reform des BetrVG: Ergebnisse der 2. Befragung der Mitglieder des Arbeitgeberverbandes Lüneburg Nordostniedersachsen, Februar 2006

No.20: *Jan Kranich:* The Strength of Vertical Linkages, July 2006

No.19: *Jan Kranich und Ingrid Ott:* Geographische Restrukturierung internationaler Wertschöpfungsketten – Standortentscheidungen von KMU aus regionalökonomischer Perspektive, Februar 2006

No.18: *Thomas Wein und Wiebke B. Röber:* Handwerksreform 2004 – Rückwirkungen auf das Ausbildungsverhalten Lüneburger Handwerksbetriebe?, Februar 2006

No.17: *Wiebke B. Röber und Thomas Wein:* Mehr Wettbewerb im Handwerk durch die Handwerksreform?, Februar 2006

No.16: *Joachim Wagner:* Politikrelevante Folgerungen aus Analysen mit wirtschaftsstatistischen Einzeldaten der Amtlichen Statistik, Februar 2006
[publiziert in: Schmollers Jahrbuch 126 (2006) 359-374]

No.15: *Joachim Wagner:* Firmenalter und Firmenperformance
Empirische Befunde zu Unterschieden zwischen jungen und alten Firmen in Deutschland, September 2005
[publiziert in: Lutz Bellmann und Joachim Wagner (Hrsg.), Betriebsdemographie (Beiträge zur Arbeitsmarkt- und Berufsforschung, Band 305), Nürnberg: IAB der BA, 83-111]

No.14: *Joachim Wagner:* German Works Councils and Productivity:
First Evidence from a Nonparametric Test, September 2005
[forthcoming in: Applied Economics Letters]

No.13: *Lena Koller, Claus Schnabel und Joachim Wagner:* Arbeitsrechtliche Schwellenwerte und betriebliche Arbeitsplatzdynamik: Eine empirische Untersuchung am Beispiel des Schwerbehindertengesetzes, August 2005
[publiziert in: Zeitschrift für ArbeitsmarktForschung/ Journal for Labour Market Research 39 (2006), 181-199]

No.12: *Claus Schnabel and Joachim Wagner:* Who are the workers who never joined a union? Empirical evidence from Germany, July 2005
[published in: Industrielle Beziehungen/ The German Journal of Industrial Relations 13 (2006), 118-131]

No.11: *Joachim Wagner:* Exporte und Produktivität in mittelständischen Betrieben
Befunde aus der niedersächsischen Industrie (1995 – 2004), June 2005
[publiziert in: Niedersächsisches Landesamt für Statistik, Statistische Berichte Niedersachsen, Sonderausgabe: Tagung der NLS am 9. März 2006, Globalisierung und regionale Wirtschaftsentwicklung - Datenlage und Datenbedarf in Niedersachsen. Hannover, Niedersächsisches Landesamt für Statistik, Juli 2006, 18 – 29]

No.10: *Joachim Wagner:* Der Noth gehorchend, nicht dem eignen Trieb.
Nascent Necessity and Opportunity Entrepreneurs in Germany.
Evidence from the Regional Entrepreneurship Monitor (REM), May 2005
[published in: RWI: Mitteilungen. Quarterly 54/ 55 (2003/04), 287-303
{published June 2006}]

No. 9: *Gabriel Desgranges and Maik Heinemann:* Strongly Rational Expectations Equilibria with Endogenous Acquisition of Information, March 2005

No. 8: *Joachim Wagner:* Exports, Foreign Direct Investment, and Productivity: Evidence from German Firm Level Data, March 2005
[published in: Applied Economics Letters 13 (2006), 347-349]

No. 7: *Thomas Wein:* Associations' Agreement and the Interest of the Network Suppliers – The Strategic Use of Structural Features, March 2005

No. 6: *Christiane Clemens and Maik Heinemann:* On the Effects of Redistribution on Growth and Entrepreneurial Risk-Taking, March 2005

No. 5: *Christiane Clemens and Maik Heinemann:* Endogenous Redistributive Cycles – An overlapping Generations Approach to Social Conflict and Cyclical Growth, March 2005

No. 4: *Joachim Wagner: Exports and Productivity:* A Survey of the Evidence from Firm Level Data, March 2005
[published in: The World Economy 30 (2007), 1, 60-82]

No. 3: *Thomas Wein and Reimund Schwarze:* Is the Market Classification of Risk Always Efficient? - Evidence from German Third Party Motor Insurance, March 2005

No. 2: *Ingrid Ott and Stephen J. Turnovsky:* Excludable and Non-Excludable Public Inputs: Consequences for Economic Growth, June 2005 (Revised version)
[published in: Economica 73 (2006), 292, 725-742
also published as CESifo Working Paper 1423]

No. 1: *Joachim Wagner:* Nascent and Infant Entrepreneurs in Germany.
Evidence from the Regional Entrepreneurship Monitor (REM), March 2005
[published in: Simon C. Parker (Ed.), The Life Cycle of Entrepreneurial Ventures (International Handbook Series on Entrepreneurship, Volume 3), New York etc.: Springer, 2006, 15-37]

Universität Lüneburg
Institut für Volkswirtschaftslehre
Postfach 2440
D-21314 Lüneburg
Tel.: ++49 4131 677 2321
email: brodt@leuphana.de
www.leuphana.de/vwl/papers