THE INSURANCE VALUE OF BIODIVERSITY IN THE PROVISION OF ECOSYSTEM SERVICES

STEFAN BAUMGÄRTNER
Centre for Sustainability Management
University of Lüneburg
P.O. Box 2440
D-21314 Lüneburg, Germany
E-mail: `baumgaertner@uni-lueneburg.de`

ABSTRACT. Biodiversity provides insurance against the uncertain provision of ecosystem services which are being used by risk-averse economic agents. I present a conceptual ecological-economic model that combines (i) current results from ecology about the relationships between biodiversity, ecosystem functioning, and the provision of ecosystem services with (ii) economic methods to study decision-making under uncertainty. In this framework I (1) determine the insurance value of biodiversity, (2) study the optimal allocation of funds in the trade-off between investing into biodiversity protection and the purchase of financial insurance, and (3) analyze the effect of different institutional regimes in the market for financial insurance on biodiversity protection. I conclude that biodiversity acts as a form of natural insurance for risk-averse ecosystem managers against the over- or under-provision with ecosystem services. Therefore, biodiversity has an insurance value, which is a value component in addition to the usual value arguments, such as direct or indirect use or non-use values. In this respect, biodiversity and financial insurance are substitutes. Hence, the availability, and exact institutional design, of financial insurance influence the level of biodiversity protection.

KEY WORDS: Biodiversity, ecosystem functioning, ecosystem services, insurance, risk aversion, uncertainty.

1. Introduction. In the face of uncertainty, diversity provides insurance for risk averse economic agents. For example, investors in financial markets diversify their asset portfolio in order to hedge their risk; firms diversify their activities, products or services when facing an uncertain market environment; farmers traditionally grow a variety of crops in order to decrease the adverse impact of uncertain environmental and market conditions. In this paper, I argue that

biological diversity plays a similar role: it can be interpreted as an insurance against the uncertain provision of ecosystem services, such as biomass production, control of water run-off, pollination, control of pests and diseases, nitrogen fixation, soil regeneration, etc. Such ecosystem services are generated by ecosystems and are used by utility-maximizing and risk averse economic agents (Daily [1997], Millennium Ecosystem Assessment [2005]).

In order to explore the hypothesis that biodiversity has an insurance value in the provision of ecosystem services, I take an interdisciplinary approach and study a conceptual ecological-economic model that combines (i) current results from ecology about the relationships between biodiversity, ecosystem functioning, and the provision of ecosystem services with (ii) economic methods to study decision-making of risk averse agents under uncertainty. The focus here is on how to model the ecology-economy-interface. Relevant economic and policy questions that arise from this view on biodiversity are only briefly sketched and are discussed in more detail elsewhere (Baumgärtner and Quaas [2005], Quaas and Baumgärtner [2005], Quaas et al. [2004]).

Although ecologists usually stress the large extent of ignorance about the detailed mechanisms of ecosystem functioning, e.g., Holling et al. [1995], Loreau et al. [2001], Schulze and Mooney [1993], there now seems to be a consensus about some of the basic mechanisms through which biodiversity influences ecosystem functioning and the provision of ecosystem services (Hooper et al. [2005], Kinzig et al. [2002], Loreau et al. [2001, 2002b]). Among other insights, it has become clear that biodiversity may decrease the variability of these services. This result has led economists to suggest that biodiversity may be seen as a form of insurance, for instance in agriculture or medicine (Perrings [1995], Schläpfer et al. [2002], Swanson and Goeschl [2003], Weitzman [2000]). On the other hand, availability of financial insurance against the over- or under-provision with ecosystem services, or other financial products that allow the hedging of income risk, may be seen as substitutes for the natural insurance provided by biodiversity (Baumgärtner and Quaas [2005], Ehrlich and Becker [1972]). The implications of this idea for both economic well-being and the state of ecosystems in terms of biodiversity, however, have hardly been explored so far.

One notable exception is to be found in the field of agricultural economics. A number of studies have analyzed the contribution of

crop diversity to the mean and variance of agricultural yields (Smale et al. [1998], Schläpfer et al. [2002], Widawsky and Rozelle [1998], Zhu et al. [2000]) and to the mean and variance of farm income (Di Falco and Perrings [2003, 2005], Di Falco et al. [2005]). It has been conjectured that risk averse farmers use crop diversity in order to hedge their income risk (Birol et al. [2005a, 2005b], Di Falco and Perrings [2003]) and that this may be affected by agricultural policies such as subsidized crop yield insurance or direct financial assistance (Di Falco and Perrings [2005]).[1]

With this analysis, I want to look into these issues in greater generality and with a particular focus on modeling the ecology-economy interface. In order to study the role of biodiversity as a form of natural insurance, I employ a conceptual model that captures the relevant ecological and economic relationships in a stylized way. While such a simple model cannot offer any quantitative predictions or detailed policy prescriptions, it can clarify the underlying theoretical structure of the problem: The ecosystem generates a valuable ecosystem service at a level that is uncertain because of environmental stochasticity. Its probability distribution is influenced by the level of biodiversity, which is measured by a suitable index. In line with evidence from ecology, I posit a monotonically increasing and concave relationship between biodiversity and the mean absolute level of the ecosystem service provided by the ecosystem, and a monotonically decreasing and convex relationship between biodiversity and the variance of ecosystem service. The ecosystem service is being used by an ecosystem manager, say, a farmer, who is assumed to be a risk averse expected utility maximizer. Protection of biodiversity is costly. There exists a financial form of insurance against over- or under-provision with the ecosystem service. The ecosystem manager decides upon (i) the level of biodiversity and (ii) the level of financial insurance coverage.

In this framework, I analyze the optimal allocation of biodiversity as a choice of endogenous environmental risk in mean-variance space.[2] In particular, I

• determine the insurance value of biodiversity, i.e., the marginal value of biodiversity in its function to reduce the risk premium of the ecosystem manager's income risk from using ecosystem services under uncertainty,

- study the optimal allocation of funds in the trade-off between investing into natural capital, that is, biodiversity protection, and the purchase of financial insurance, and

- analyze the effect of different institutional regimes in the market for financial insurance (e.g., availability, transaction costs and profitability of financial insurance) on biodiversity protection.

I conclude that biodiversity acts as a form of natural insurance for risk averse ecosystem managers against the over- or under-provision with ecosystem services. Therefore, biodiversity has an insurance value, which is a value component in addition to the usual value arguments (such as direct or indirect use or non-use values, or existence values) which hold in a world of certainty. In this respect, biodiversity and financial insurance are substitutes. Hence, the availability, and the exact institutional design, of financial insurance, influence the level of biodiversity protection.

The paper is organized as follows. Section 2 discusses the ecological background and surveys the relevant literature. Section 3 introduces a formal ecological-economic model. The model analysis and results are presented in Section 4, with all formal derivations and proofs given in the Appendix. Section 5 critically discusses the limitations and the generality of the results, and Section 6 concludes.

2. Ecological background: Biodiversity and the provision of ecosystem services. Over the past 15 years, there has been intensive research in ecology on the role of biodiversity for ecosystem functioning and the provision of ecosystem services. *Biodiversity* has been defined as 'the variability among living organisms from all sources ... and the ecological complexes of which they are part' (CBD [1992]), which encompasses a wide spectrum of biotic scales, from genetic variation within species to biome distribution on the planet (Gaston [1996], Purvis and Hector [2000], Wilson [1992]). Biodiversity can be described in terms of numbers of entities, (e.g., genotypes, species, or ecosystems), the evenness of their distribution, the differences in their functional traits, and their interactions. The simplest measure of biodiversity at, say, the species level is therefore simply the number of different species ('species richness'). Much of ecological research has relied on this

measure when quantifying 'biodiversity,' although more encompassing information has also been employed.[3]

Research on the role of biodiversity for ecosystem functioning and the provision of ecosystem services built on (i) observations of existing ecosystems, (ii) controlled experiments both in the laboratory and in the field ('pots and plots') and (iii) theory and model analysis. While the discussion of results has been, at times, heated and controversial, there now seems to be a consensus over some of the basic results from this research (Hooper et al. [2005], Kinzig et al. [2002], Loreau et al. [2001, 2002b]).[4] Among other insights two 'stylized facts' about biodiversity and ecosystem functioning emerged which are of crucial importance for the issue studied here:

1. *Biodiversity may enhance ecosystem productivity.* In many instances, an increase in the level of biodiversity monotonically increases the mean absolute level at which certain ecosystem services, e.g., biomass production or nutrient retention, are provided. This effect decreases in magnitude with the level of biodiversity.

2. *Biodiversity may enhance ecosystem stability.* In many instances, an increase in the level of biodiversity monotonically decreases the temporal variability of the level at which these ecosystem services are provided under changing environmental conditions. This effect decreases in magnitude with the level of biodiversity.

These two stylized facts are now discussed in turn.[5]

2.1 *Biodiversity may enhance ecosystem productivity.* The absolute level of a certain ecosystem service, e.g., biomass production, carbon sequestration or nitrogen fixation, may be influenced by species or functional diversity in several ways.[6] Indeed, more than 50 potential response patterns have been proposed (Loreau [1998a], Naeem [2002]). There are two primary mechanisms through which biodiversity may increase the mean absolute level at which certain ecosystem services are provided, Figure 1:

(i) Only one or a few species might have a large effect on any given ecosystem service. Increasing species richness, i.e., the number of different species, increases the likelihood that those key species would be present in the system (Aarssen [1997], Huston [1997], Loreau [2000],

Tilman et al. [1997b]). This is known as the 'sampling effect' or the 'selection probability effect', Figure 1A.[7]

(ii) Species or functional richness could increase the level of ecosystem services through complementarity, i.e., species use different resources, or the same resources but at different times or different points in space and facilitation, i.e., positive interactions among species so that, e.g., certain species alleviate harsh environmental conditions or provide a critical resource for other species. Both complementarity and facilitation lead to an 'overyielding effect,' Figure 1B, in which biomass production in mixtures exceeds expectations based on monoculture yields (Ewel [1986], Harper [1977], Hector et al. [1999], Loreau [1998b], Trenbath [1974], Vandermeer [1989]).

Complementarity, facilitation and sampling effects will all lead to a saturating average impact of species richness on the level of some ecosystem service, Figure 1A, B.
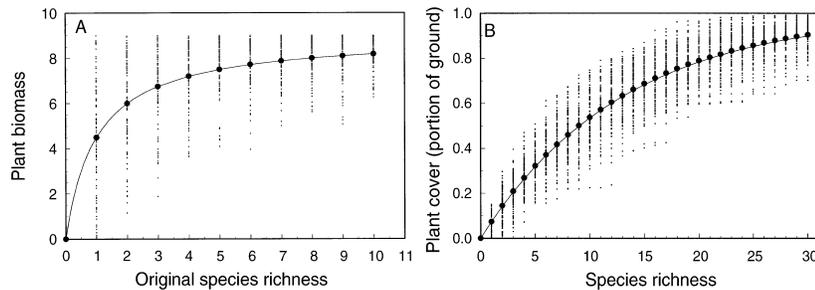

FIGURE 1. Ecological theory has suggested two basic mechanisms of how biodiversity could increase the mean absolute level of ecosystem services: sampling or selection probability effect (A), and complementarity or facilitation (B). Points show individual treatments, and lines show the average response. (Figures are taken from Tilman [1997], as compiled by Hooper et al. [2005].)

Experiments have confirmed the important role of these two primary mechanisms through which biodiversity may increase the mean absolute level of certain ecosystem services. This holds, in particular, for experiments with herbaceous plants, in which average primary production and nutrient retention were found to increase with increasing plant species or functional richness, at least within the range of species

richness tested and over the relatively short duration of the experiments (Fridley [2003], Hector et al. [1999], Loreau and Hector [2001], Niklaus et al. [2001], Reich et al. [2001], Tilman et al. [1996, 1997a, 2001, 2002]).[8] In these experiments, the responses to changing diversity are strongest at low levels of species richness and generally saturate at 5–10 species. It has also become evident that complementarity, facilitation and sampling/selection effects are all relevant and can be observed in experiments.[9] They are not necessarily mutually exclusive, but they may be simultaneously or sequentially at work in one system. The strength of species complementarity and interspecific facilitation and, thus, the quantitative response in the level of ecosystem services to changes in species richness varies with both the functional characteristics of the species involved and the biotic as well as abiotic environmental context.

These general findings need to be qualified in a number of respects:

• Experiments have shown that the exact response of ecosystem services on changes in biodiversity is determined at least as much by differences in species composition, i.e., which species and functional traits are lost and remain behind, as by species richness, i.e., how many species are lost.

• Patterns of response to experimental manipulation of species richness vary for different ecosystem processes and services, different ecosystems, and even different compartments within ecosystems.

• Varying multitrophic diversity and composition, i.e., the diversity and composition of an ecological community at more than one trophic level, can lead to more idiosyncratic behavior than varying diversity of primary producers alone.

The different patterns found under experimental conditions may or may not reflect actual patterns seen for a particular ecosystem under a particular scenario of species loss or invasion, which will depend not only on the functional traits of the species involved, but also on the exact pattern of environmental change and the species traits that determine how species respond to changes in environmental conditions (Lavorel and Garnier [2002], Schläpfer et al. [2005], Symstad and Tilman [2001]).

2.2 *Biodiversity may enhance ecosystem stability.* The debate about
whether (or not) biodiversity enhances ecosystem stability, i.e., whether
(or not) ecosystem properties are more stable in response to environ-
mental fluctuations as diversity increases, has a long tradition in ecol-
ogy (McCann [2000]). This so-called 'diversity-stability-debate' has
been initiated in the 1950s by observations from natural ecosystems
which were found to be more productive and more stable when more
diverse (Elton [1958], Odum [1953], MacArthur [1955]). This early
diversity-stability hypothesis has been shaken in the early 1970s by
computer simulations of ecosystems which demonstrated that these sys-
tems were more *un*stable when more diverse (May [1972, 1974]). How-
ever, because the simulated model systems were randomly and purely
fictional, the diversity-stability-question for real ecosystems remained
open.[10] In the 1990s, the debate gained new momentum and research
was organized and discussed more systematically, with results coming
from controlled laboratory experiments, field studies and theoretical
analysis.

The diversity-stability debate is generally clouded by inconsistent ter-
minology, as 'stability' is an umbrella term that denotes a large number
of potential phenomena, including, but not limited to, resistance to dis-
turbance, resilience to disturbance, temporal variability in response to
fluctuating abiotic conditions, and spatial variability in response to dif-
ferences in either abiotic conditions or the biotic community (Chesson
[2000], Chesson et al. [2002], Cottingham et al. [2001], Grimm and Wis-
sel [1997], Holling [1986], Lehmann and Tilman [2000], Loreau et al.
[2002a], May [1974], McNaughton [1993], Peterson et al. [1998], Pimm
[1984]). Most research so far has focused on temporal variability, but
some of the results may also apply to other measures of ecosystem
stability.

Theory, both via simple ecological reasoning and via mathematical
models, has led to the understanding that a diversity of species with
different sensitivities to a suite of environmental conditions should lead
to greater stability of ecosystem properties. The basic idea is that,
with increasing number of functionally different species, the probability
increases that some of these species can react in a functionally differ-
entiated manner to external disturbance of the system and changing
environmental conditions. In addition, the probability increases that
some species are functionally redundant, such that one species can take

over the role of another species when the latter goes extinct. This is what ecologists have been calling an 'insurance effect' of biodiversity in carrying out ecological processes (Borrvall et al. [2000], Elton [1958], Chapin and Shaver [1985], Hooper et al. [2002], Lawton and Brown [1993], MacArthur [1955], Naeem [1998], Naeem and Li [1997], Petchey et al. [1999], Trenbath 1999, Walker [1992], Walker et al. [1999], Yachi and Loreau [1999]).[11] With this logic, processes that are carried out by a relatively small number of species are hypothesized to be most sensitive to changes in diversity (Hooper et al. [1995]). Also, the number of species or functional traits necessary to maintain ecosystem processes under changing environmental conditions increases with spatial and temporal scales (Casperson and Pacala [2001], Chesson et al. [2002], Field [1995], Pacala and Deutschman [1995]).

Several mathematical models generally support these hypotheses (see McCann [2000], Cottingham et al. [2001], Loreau et al. [2002a] for reviews) and highlight the role of statistical averaging, the so-called 'portfolio effect,' for the result (Doak et al. [1998], Tilman et al. [1998]): if species abundances are negatively correlated or vary randomly and independently from one another, then overall ecosystem properties are likely to vary less in more diverse communities than in species-poor communities.[12] The strength of the modeled effects of diversity depends on many parameters, including the degree of correlation among different species' responses (Chesson et al. [2002], Doak et al. [1998], Lehman and Tilman [2000], Tilman [1999], Tilman et al. [1998], Yachi and Loreau [1999]), the evenness of distribution among species' abundances (Doak et al. [1998]), and the extent to which the variability in abundances scales with the mean (Cottingham et al. [2001], Tilman [1999], Yachi and Loreau [1999]).[13]

While theory is well developed and predicts that increased diversity will lead to lower variability of ecosystem properties under those conditions in which species respond in a differentiated manner to variations in environmental conditions, it cannot tell us how important the underlying basic mechanisms are in the real world or whether they saturate at high or low levels of species richness. This requires experimental investigations. However, controlled experiments are very difficult to carry out, because one needs to make sure that the effect of species diversity is not confounded by other variables, such as, e.g., soil fertility or disturbance regime. Nevertheless, considerable evidence exists

from field studies in a variety of ecosystems that in diverse communities, redundancy of functional traits and compensation among species can buffer ecosystem processes in response to changing conditions and species loss. Examples include studies of arctic tundra (Chapin and Shaver [1985]), Minnesota grasslands (Tilman [1996, 1999], Tilman et al. [2002]), deserts (Ernest and Brown [2001]), lakes (Frost et al. [1995], Schindler et al. [1986]), and soil ecosystems (de Ruiter et al. [2002], Griffiths et al. [2000], Ingham et al. [1985], Liiri et al. [2002]). As an example, Figure 2 shows experimental results for aboveground plant biomass production in response to climatic variability in a Minnesota grassland, Figure 2A, and net ecosystem CO_2 flux in a microbial microcosm, Figure 2B. While the overall stability patterns found are as predicted from theory, the experiments so far give little insights about the underlying basic mechanisms. Also, mechanisms other than compensation among species can affect stability in response to changing species richness.

Several experiments that manipulate diversity in the field and in microcosms generally support theoretical predictions that increasing species richness increases stability of ecosystem properties. For instance, stability of plant production, as measured by resistance and/or resilience to nutrient additions, drought and grazing, increased with the Shannon-Wiener index of diversity[14] in a variety of successional
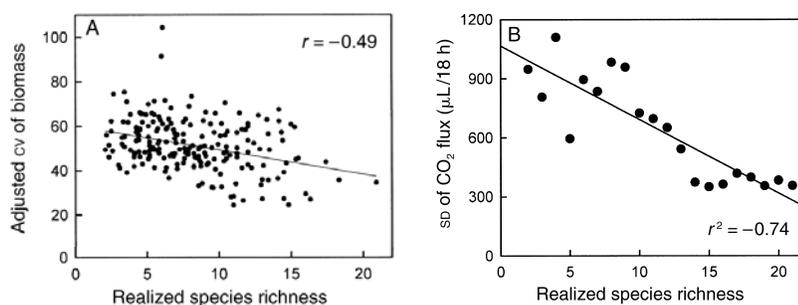

FIGURE 2. Ecological experiments found that species richness may decrease the variability of ecosystem services, such as, e.g., aboveground plant biomass production in response to climatic variability in a Minnesota grassland (A), or net ecosystem CO_2 flux in a microbial microcosm (B). (Figures are taken from Tilman [1999] [A] and McGrady-Steed et al. [1997] [B], as compiled by Hooper et al. [2005] and Loreau et al. [2001].)

and herbivore-dominated grasslands (McNaughton [1977, 1985, 1993]). And in Minnesota grasslands, resistance to loss of plant productivity to drought increased with increasing plant species richness (Tilman and Downing [1994]). However, results of these experiments may be confounded by a variety of variables other than species richness or diversity, which has raised considerable controversy over the interpretation of these results (e.g., Givnish [1994], Grime [1997], Grime et al. [2000], Huston [1997], Huston et al. [2000], Pfisterer and Schmid [2002]). Experiments in microcosms and grasslands suggest that increased species richness, either in terms of numbers of different functional groups, or numbers of species within trophic functional groups, can lead to decreased temporal variability in ecosystem properties (Emmerson et al. [2001], McGrady-Steed et al. [1997], Naeem and Li [1997], Petchey et al. [1999], Pfisterer et al. [2004]; but see also Pfisterer and Schmid [2002]). But while species richness or the Shannon-Wiener index of species diversity was statistically significant in all these experiments, species composition (where investigated) had an at least equally strong effect on stability.

In sum, the experimental work provides qualified support for the hypothesis that species richness can increase the stability of ecosystem processes and services, although the underlying mechanisms can differ from theoretical predictions and in many cases still need to be fully resolved (Loreau et al. [2001]).

3. Ecological-economic model. In order to study the economic implications of the insights from ecology about how biodiversity affects ecosystem functioning and the provision of ecosystem services, I shall cast them into a simple and stylized ecological-economic model.

3.1 *Biodiversity and the provision of ecosystem services.* For notational simplicity, consider only one ecosystem service and let s be the amount generated of that service. As an example, think of insects providing pollination service to an orchard farmer. Because of environmental stochasticity the level s, at which the ecosystem service is provided, is a random variable. Assume, for analytical simplicity (and lack of specific ecological evidence on this point), that s is normally distributed with mean μ_s and standard deviation σ_s.

As discussed in the previous section, ecological research provides evidence that the level of biodiversity affects the statistical distribution of the ecosystem service. Let $v \in [0, \infty]$ be an appropriate index of biodiversity.[15] The two stylized facts about the relationship between biodiversity and the provision of ecosystem services, which emerged from ecological research (cf. Section 2), can then formally be expressed as:

(1) $\qquad\qquad \mu_s = \mu_s(v) \quad \text{with} \quad \mu_s'(v) > 0, \quad \mu_s''(v) \leq 0,$

(2) $\qquad\qquad \sigma_s = \sigma_s(v) \quad \text{with} \quad \sigma_s'(v) < 0, \quad \sigma_s''(v) \geq 0,$

where the prime denotes a derivative. That is, the mean level of ecosystem service increases and the standard deviation decreases with the level of biodiversity. Both effects decrease in magnitude with the level of biodiversity. While biodiversity, thus, is beneficial in a twofold manner—by increasing the mean level, at which the ecosystem service is being provided, and by decreasing its standard deviation—its provision is costly. Assume that the (direct and opportunity) costs of biodiversity are given by a cost function

(3) $\qquad\qquad\qquad C(v) \quad \text{with} \quad C'(v) > 0, \quad C''(v) \geq 0.$

In the example of an orchard farmer using insects' pollination services, the costs of biodiversity could result from setting aside land from agricultural cultivation and leaving it in a natural state, so that hedges and wetlands can provide habitat for insects.[16]

3.2 *Ecosystem manager.* The ecosystem manager, who manages the system for the services s it provides, chooses the level of biodiversity $v \in [0, \infty]$.[17] On the one hand, the choice of v implies costs as given by equation (3). On the other hand, biodiversity is essential for ecosystem functioning and the provision of ecosystem services. The ecosystem manager has benefits from ecosystem services, $B(s)$. For simplicity, assume that:

(4) $\qquad\qquad\qquad\qquad B(s) = s.$

Since ecosystem services s are a random variable (normally distributed with mean μ_s and standard deviation σ_s) and the level of biodiversity v

determines the distribution of this random variable according to (1) and (2), the benefits are also a random variable normally distributed with mean $\mu_s(v)$ and standard deviation $\sigma_s(v)$. The ecosystem manager's net income y is then given by

$$(5) \qquad y = B(s) - C(v) = s - C(v),$$

which is a random variable normally distributed with mean μ_y and standard deviation σ_y:

$$(6) \qquad \mu_y(v) = \mu_s(v) - C(v)$$

and

$$(7) \qquad \sigma_y(v) = \sigma_s(v).$$

Hence, by choosing the level of biodiversity v, the ecosystem manager chooses a particular (normal) distribution $N(\mu_y(v), \sigma_y(v))$ of net income. That is, he chooses a particular income 'lottery' (Crocker and Shogren [2001]).

The ecosystem manager's preferences over his uncertain net income y are represented by a von Neumann-Morgenstern expected utility function

$$(8) \qquad U = \mathcal{E}[u(y)],$$

where $\mathcal{E}$ is the expectancy operator and $u(y)$ is a Bernoulli utility function which is assumed to be increasing $(u' > 0)$ and strictly concave $(u'' < 0)$, i.e., the ecosystem manager is non-satiated and risk averse.[18] In order to obtain simple closed-form solutions, assume that $u(y)$ is the constant absolute risk aversion Bernoulli utility function

$$(9) \qquad u(y) = -e^{-\rho y},$$

where $\rho > 0$ is a parameter describing the ecosystem manager's Arrow-Pratt measure of risk aversion (Arrow 1965, Pratt [1964]). The ecosystem manager's von Neumann-Morgenstern expected utility function (8) is then given by, see Appendix A.1,

$$(10) \qquad U = \mu_y - \frac{\rho}{2}\sigma_y^2,$$

which is the simplest expected utility function of the mean-variance type.

3.3 *Financial insurance.* In order to analyze the influence of availability of financial insurance products on the ecosystem manager's choice of biodiversity, in subsection 4.4, financial insurance is introduced in a simple and stylized way.[19] I assume that the manager does or does not have the option of buying financial insurance under the following contract:

- The insurant chooses the fraction $a \in [0, 1]$ of insurance coverage.

- He receives (pays)

$$(11) \qquad\qquad a\,(s - \mu_s)$$

from (to) the insurance company as an actuarially fair indemnification benefit (risk premium) if his realized income is below (above) the mean income.[20]

- In addition, he pays a mark-up for the transaction costs of insurance and the insurance company's profit:

$$(12) \qquad\qquad \frac{\delta}{2}\,a^2\,\sigma_s^2,$$

where $\delta \geq 0$ is a parameter describing how actuarially unfair is the insurance contract. Thus, the costs of insurance over and above the actuarially fair risk premium, which are a measure of the 'real' costs of insurance to the insurant,[21] are assumed to follow a quadratic cost function.

This is a highly idealized form of financial insurance which captures in the most simple way the essence of financial insurance with an actuarially fair risk premium and some mark-up (due to transaction costs and profits) on top. The higher the insurance coverage a, the lower the effective income risk; and the effective income risk can be continuously reduced down to zero by increasing a to one. This follows the 'Venetian Merchant' model of insurance: there exists an insurance company (the 'Venetian Merchant') which is ready to (fully or partially) take over the income risk from the insurant. In order to abstract from any problems related to informational asymmetry I assume that the

statistical distribution $N(\mu_s, \sigma_s)$ and actual level s of ecosystem service are observable to both insurant and insurance company.

4. Analysis and results. When analyzing the insurance value of biodiversity, subsection 4.2, the optimal allocation of biodiversity, subsection 4.3, and the effect of different institutional settings in the market for financial insurance products on biodiversity protection, subsection 4.4, the idea is to treat the level of biodiversity v as the choice variable and to analyze the choice of biodiversity as the choice of an income lottery.

4.1 *The choice set.* To start with, neglect the option to buy financial insurance and focus on biodiversity as the natural insurance. Financial insurance will be taken into account in subsection 4.4. As v can range from zero to infinity, the resulting feasible and efficient distributions of net income y, equation (5), in μ_y-σ_y space can be depicted by an income-possibility frontier as in Figure 3. Income distributions above the income-possibility-frontier are not feasible; income distributions below the income-possibility-frontier may be feasible, but are not efficient.

The right-hand end of the curve corresponds to very low levels of biodiversity v: the standard deviation σ_y of income is high. As v increases, one moves left along the curve: the standard deviation of income is reduced due to the stabilizing effect of biodiversity, equations (2) and (7) and the mean income increases, because the mean level of ecosystem service increases with biodiversity while the costs of biodiversity are not too important at low levels of biodiversity, equations (1), (3) and (6). As the level v of biodiversity increases further, i.e., moving left along the curve even further, the additional mean benefits from additional ecosystem service become smaller and smaller, equation (1) while the additional costs of biodiversity become greater and greater, equation (3), thus eventually causing additional mean net benefits y from biodiversity to become negative. This corresponds to the left-hand end of the curve: as biodiversity v increases, i.e., moving left along the curve, the standard deviation σ_y of income still decreases while the mean income μ_y decreases. Overall, the income possibility frontier in
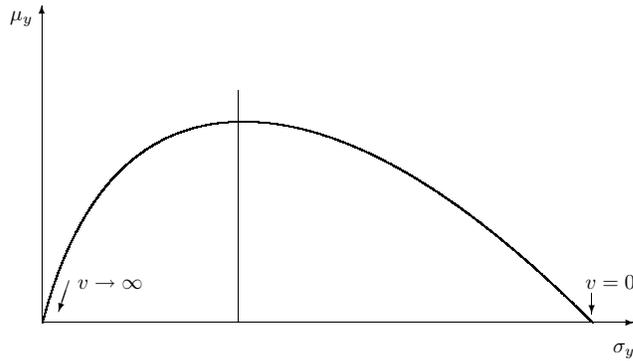
FIGURE 3. Feasible and efficient distributions of net income y, equation (5), in μ_y-σ_y space are represented by the income possibility frontier (solid line). The vertical line separates the domain with a trade-off between mean and standard deviation of income (left) from the domain without such a trade-off (right).

μ_y-σ_y space has two parts: in the left-hand part (corresponding to high levels v of biodiversity) the mean income μ_y increases with increasing standard deviation σ_y; in the right-hand part (corresponding to low levels v of biodiversity) the mean income μ_y decreases with increasing standard deviation σ_y. Given the ecosystem manager's expected utility function (10), according to which a high mean income and a low standard deviation of income are desirable, this means that for low levels of biodiversity there does not exist any economic problem. For, increasing the level of biodiversity at low v (right-hand part of the curve) has a double desirable effect: it increases the mean income and it reduces the standard deviation of income. In contrast, for high levels of biodiversity (left-hand part of the curve) when (opportunity) costs of biodiversity become important, the ecosystem manager faces a trade-off: increasing the level of biodiversity reduces the standard deviation of income, but reduces mean income, too.

It is the left part of the curve which suggests the interpretation that biodiversity provides insurance. As with buying financial insurance, increasing the level of biodiversity reduces the standard deviation of income but reduces mean income, too. In this domain, a choice has to be made in order to optimally balance the two opposing goals of a high mean income and a low standard deviation of income.

4.2 *The insurance value of biodiversity.* In order to precisely define the insurance value of biodiversity, let me come back to the idea that the ecosystem can be seen as an infinite set of lotteries (Crocker and Shogren [2001]). By choosing the level of biodiversity v, the ecosystem manager determines the distribution $N(\mu_s(v), \sigma_s(v))$ of ecosystem service, equations (1) and (2), which then determines the distribution $N(\mu_y(v), \sigma_y(v))$ of income, equations (6) and (7). Thus, by choosing the level of biodiversity v, he chooses a particular income lottery. In the model employed here, this lottery is uniquely characterized by the level of biodiversity v. Therefore, one may speak of 'the lottery v.'

One standard method of how to value the riskiness of a lottery to a decision maker is to calculate the *risk premium* R of the lottery, which is defined by (e.g., Kreps [1990], Varian [1992, p. 181])[22]

$$u\left(\mathcal{E}[y] - R\right) = \mathcal{E}\left[u(y)\right]. \tag{13}$$

The risk premium R is the amount of money that leaves a decision maker equally well-off, in terms of utility, between the two situations of (1) receiving for sure the expected pay-off from the lottery $\mathcal{E}[y]$ minus the risk premium R, and (2) playing the risky lottery with random pay-off y.[23] In general, if the utility function u characterizes a risk averse (risk neutral, risk loving) decision maker, the risk premium R is positive (zero, negative).

In the model employed here, the risk premium of the lottery v depends on the level of biodiversity and is given by, see Appendix A.2,

$$R(v) = \frac{\rho}{2}\,\sigma_s^2(v). \tag{14}$$

The insurance value of biodiversity can now be defined based on the risk premium of the lottery v (Baumgärtner and Quaas [2005]).

Definition 1. The *insurance value V* of biodiversity v is given by the change of the risk premium R of the lottery v due to a marginal change in the level of biodiversity v:

$$V(v) := -R'(v). \tag{15}$$

Thus, the insurance value of biodiversity is the marginal value of biodiversity in its function to reduce the risk premium of the ecosystem
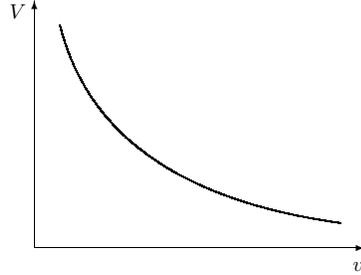
FIGURE 4. The insurance value V of biodiversity, equation (16), as a function of existent biodiversity v.

manager's income risk from using ecosystem services under uncertainty. Being a marginal value, it depends on the existing level of biodiversity v. The minus sign in the defining equation (15) serves to express biodiversity's ability to *reduce* the risk premium of the lottery v as a *positive* value. Applying Definition 1 to equation (14), one obtains the following result for the insurance value of biodiversity in this model.

Proposition 1. *The insurance value $V(v)$ of biodiversity is given by*

(16) $$V(v) = -\,\rho\,\sigma_s(v)\,\sigma_s{}'(v) > 0.$$

From this equation it is apparent that the insurance value of biodiversity has an objective and a subjective dimension. The objective dimension is captured by the sensitivity of the standard deviation of ecosystem services to changes in biodiversity, σ_s and $\sigma_s{}'$; the subjective dimension is captured by the ecosystem manager's degree of risk aversion, ρ. The insurance value V increases

• with the degree ρ of the ecosystem manager's risk aversion and

• with the sensitivity of the standard deviation of ecosystem services to changes in biodiversity, σ_s and $|\sigma_s^{2\,\prime}|$.

As a function of biodiversity v, the insurance value $V(v)$ decreases, Figure 4: as biodiversity becomes more abundant (scarcer), its insurance value decreases (increases).

4.3 *The optimal level of biodiversity.* In order to study how the ecosystem manager will make use of the insurance function of biodiversity, consider first the situation in which there is no financial insurance available. The ecosystem manager chooses a level of biodiversity v such as to maximize his expected utility (10):

$$(17) \qquad \max_v \ U(v).$$

With no financial insurance available, income y is given by equation (5), such that the mean income μ_y and the standard deviation of income σ_y are given by equations (6) and (7). The following proposition states the properties of the optimal solution to problem (17).

Proposition 2. (i) *The optimal level of biodiversity $v^\star$, which solves the ecosystem manager's optimization problem* (17)*, is characterized by the necessary and sufficient condition*

$$(18) \qquad \mu_s'(v^\star) + V(v^\star) = C'(v^\star).$$

(ii) *The higher the ecosystem manager's degree of risk aversion ρ, the higher the optimal level of biodiversity $v^\star$:*

$$(19) \qquad \frac{dv^\star}{d\rho} > 0.$$

Proof. See Appendix A.3.

Condition (18) states that the optimal level of biodiversity $v^\star$ is chosen such that the marginal benefits of biodiversity equal its marginal costs. The marginal benefits here are composed of two additive components: the marginal gain in the mean level of ecosystem service and the insurance value $V(v^\star)$ of biodiversity. Hence, the insurance value of biodiversity is a value component in addition to the usual value arguments (such as direct or indirect use or non-use values, or existence values) which hold in a world of certainty. It leads to choosing a higher level of biodiversity than without taking the insurance value into account.

The second part of the proposition states that the higher the degree of risk aversion ρ, the higher the optimal level of biodiversity $v^\star$. This

is intuitively obvious, and confirms the idea that biodiversity is being used by a risk averse ecosystem manager as a form of natural insurance.

4.4 *The effect of financial insurance.* Consider now the situation in which there is financial insurance available. As an example, think again of the orchard farmer, who crucially depends on the pollination service provided by insects and who can manage his agro-ecosystem by choosing the level of biodiversity, e.g., by setting aside land for hedges and wetlands. As we have seen above, this farmer can manage his income risk from the random level of ecosystem service by choosing the level of biodiversity. On the other hand, the farmer may also have access to commercial crop yield insurance. Hence, his risk management now comprises two instruments. The ecosystem manager chooses a level of biodiversity v and a fraction of financial insurance coverage a such as to maximize his expected utility (10):

$$(20) \qquad \max_{v,\,a} U(v,a).$$

Income y is now given by

$$(21) \qquad y = s - C(v) - a(s - \mu_s(v)) - \frac{\delta}{2}\, a^2\, \sigma_s^2(v).$$

The first two components represent the benefits and costs of ecosystem management, equation (5), the third component is the actuarially fair insurance premium/indemnification benefit, equation (11), and the fourth component are the real costs of financial insurance, equation (12). While the real costs of both ecosystem management and financial insurance, i.e., the second and fourth component, are certain, the benefits, i.e., the first and third component, are random. As a result, the mean and standard deviation of income are given by

$$(22) \qquad \mu_y(v,a) = \mu_s(v) - C(v) - \frac{\delta}{2}\, a^2\, \sigma_s^2(v)$$

and

$$(23) \qquad \sigma_y(v,a) = (1 - a)\, \sigma_s(v).$$

Since the actuarially fair insurance premium/indemnification benefit corresponds to an expected payment of exactly zero, the mean income,

equation (22), is given by the mean benefits of ecosystem service minus the real costs of ecosystem management and financial insurance. The standard deviation of income, equation (23), is given by the standard deviation of ecosystem service, reduced by a factor of $0 \leq (1 - a) \leq 1$. This should be compared to the case without financial insurance, where the standard deviation of income is given by the full standard deviation of ecosystem service, equation (7). Equation (23) expresses the fact that the ecosystem manager can reduce the standard deviation of his income, besides by increasing the level of biodiversity v and thus lowering $\sigma_s(v)$, by increasing the fraction a of financial insurance coverage. In the extreme, with full coverage by financial insurance, $a = 1$, the standard deviation of income vanishes. With (22) and (23), the expected utility (10) is given by

$$(24) \qquad U(v, a) = \mu_s(v) - C(v) - \frac{\delta}{2} a^2 \sigma_s^2(v) - \frac{\rho}{2} (1 - a)^2 \sigma_s^2(v).$$

The following proposition states the properties of the optimal solution to problem (20).

Proposition 3. (i) *The optimal level of biodiversity $\hat{v}$ and the optimal fraction of financial insurance coverage $\hat{a}$, which solve the ecosystem manager's optimization problem* (20), *are characterized by the necessary and sufficient conditions*

$$(25) \qquad\qquad \mu_s'(\hat{v}) + \frac{\delta}{\rho + \delta} V(\hat{v}) = C'(\hat{v})$$

and

$$(26) \qquad\qquad\qquad \hat{a} = \frac{\rho}{\rho + \delta}.$$

(ii) *The higher the real costs of financial insurance, as measured by δ, the lower the optimal fraction $\hat{a}$ of coverage by financial insurance and the higher the optimal level $\hat{v}$ of biodiversity:*

$$(27) \qquad\qquad \frac{d\hat{a}}{d\delta} < 0 \quad \text{and} \quad \frac{d\hat{v}}{d\delta} > 0.$$

(iii) *A risk averse ecosystem manager chooses*

• *full coverage by financial insurance, $\hat{a} = 1$, if $\delta = 0$,*

• *partial coverage by financial insurance, $0 < \hat{a} < 1$, if $0 < \delta < +\infty$,* *and*

• *no coverage by financial insurance, $\hat{a} \to 0$, if $\delta \to +\infty$.*

(iv) *A risk averse ecosystem manager chooses $\hat{v} < v^\star$.*

Proof. See Appendix A.4.

The optimal allocation of biodiversity $\hat{v}$ and financial insurance coverage $\hat{a}$ is characterized by conditions (25) and (26). Condition (25) states, similarly to condition (18) in the absence of financial insurance, that the optimal level of biodiversity $\hat{v}$ is chosen such that the marginal benefits of biodiversity equal its marginal costs. The marginal benefits, again, are composed of two additive components: the marginal gain in the mean level of ecosystem service and the natural insurance value $V(\hat{v})$ of biodiversity, which is, however, not fully taken into account but only to a fraction $\delta/(\rho + \delta) < 1$. That is, biodiversity's natural insurance function is only partly taken into account when determining the optimal allocation.

The reason is that, of course, part of the income risk is now covered by financial insurance. Condition (26) specifies the optimal level of financial insurance coverage. It is obvious that $\hat{a}$ and the factor in front of $V(\hat{v})$ in condition (25) add up to one. This means, biodiversity as the natural form of insurance and financial insurance together provide the optimal coverage of income risk.[24] Indeed, the two forms of insurance are substitutes: whatever part of the risk is not covered by biodiversity is covered by financial insurance. And what part of the risk is covered by financial insurance is determined by the real costs of financial insurance. Part (ii) of the proposition details this result: the higher the real costs of financial insurance, i.e., costs over and above the actuarially fair risk premium, the lower is the fraction of income risk covered by financial insurance and the higher is the fraction covered by the natural insurance, i.e., biodiversity.

Part (iii) of the proposition describes this in more detail. A risk averse ecosystem manager, $\rho > 0$, chooses full coverage by financial insurance, $\hat{a} = 1$, if it is available at actuarially fair conditions, $\delta = 0$;

he chooses only partial coverage by financial insurance, $0 < \hat{a} < 1$, if financial insurance comes at additional costs over and above the actuarially fair risk premium, $0 < \delta < +\infty$; and he chooses no coverage by financial insurance, $\hat{a} \to 0$, if financial insurance becomes infinitely costly, $\delta \to +\infty$. These three cases imply, respectively, that the fraction of biodiversity's insurance value $V(\hat{v})$ which is taken into account according to condition (25), which is also the fraction of income risk covered by the natural insurance of biodiversity, is zero if financial insurance is available at actuarially fair conditions; it is in between zero and one if financial insurance is available at actuarially unfair conditions; and it goes to one for infinitely unfair financial insurance.

Part (iv) of the proposition states that, in any case, a risk averse ecosystem manager chooses a lower level of biodiversity if financial insurance is available compared to a situation where no financial insurance is available: $\hat{v} < v^\star$. That is, financial insurance crowds out biodiversity as the natural from of insurance.

5. Discussion. Although the results have been derived from a very simple and specific model, they are robust to a fair amount of generalization. For instance, while the choice of the preference representation (9) served to obtain simple closed-form solutions, all results thus obtained are qualitatively robust to generalizations to expected utility functions of the type $U(\mu_y, \sigma_y^2)$ with $\partial U/\partial \mu_y > 0$ and $\partial U/\partial \sigma_y^2 < 0$. Also, while the specific form of financial insurance contract assumed here, subsection 3.3, served to obtain simple closed-form solutions, all results thus obtained are qualitatively robust to generalizations to more general financial insurance contracts with an actuarially fair insurance premium plus a transaction costs/profit mark-up on top (Baumgärtner and Quaas [2005]). And while I have assumed for simplicity that the level of biodiversity is the only determinant of the statistical distribution of the ecosystem service, equations (1), (2), one could easily generalize the analysis so that the stochastic production of the ecosystem service depends also on inputs other than biodiversity, say labor, capital, fertilizer or chemical pest control. This could be formalized with the help of a Just-Pope production function (Just and Pope [1978, 1979]), which is well suited for mean-variance analysis of stochastic production and would not qualitatively alter the basic results about the role of biodiversity for income risk.

Of particular importance are Assumptions (1), (2) and (3) about the benefits and costs of biodiversity. While Assumptions (1) and (2) represent the best available ecological knowledge and describe a relevant problem, it is an interesting question whether these assumptions are actually necessary in order to arrive at the main result, i.e., biodiversity's insurance value, or whether this result holds under more general conditions. It turns out that the crucial assumption is $\sigma'_s < 0$, while $\mu'_s > 0$ is not necessary. If biodiversity did depress the mean level of ecosystem services, $\mu'_s < 0$, then this could be considered as costs of biodiversity and could be included in the function $C(v)$. This assumption would therefore not lead to a different result. If, however, biodiversity did increase the variance of ecosystem services, $\sigma'_s > 0$, then it would obviously not have any insurance value. Clearly, this would fundamentally alter the main results of the paper. As for the assumption on second derivatives ($\mu'_s \leq 0$, $\sigma'_s \geq 0$, $C' \geq 0$), their role is mainly technical, making sure that second order conditions are fulfilled and that one has an interior solution. Without these assumptions, the main results would not change fundamentally but would require a more elaborate formulation and proof of results.

So, the crucial assumptions which ultimately limit the generality of results are the following:

• The ecosystem manager is risk averse and maximizes his expected utility from an uncertain income which is determined by the random level of some ecosystem service.

• The level of biodiversity determines the probability distribution of the ecosystem service and, thus, of income. Taking into account the (direct or opportunity) costs of biodiversity, there is a positive correlation between expected income and standard deviation of income in the relevant range of feasible income distributions.

• A financial insurance contract specifies only the state dependent redemption payment and the corresponding risk premium. In particular, it is not explicitly contingent on the particular level of biodiversity chosen by the ecosystem manager.[25]

• Both insurant and insurance company have the same ex ante knowledge about the probability distribution of ecosystem services. Both can observe ex post the actual state of nature.

While these assumptions limit the generality of the results obtained here, they describe, in a very stylized way, a realistic scenario of managing stochastic ecosystems under uncertainty for the ecosystem services they provide. Hence, this analysis yields relevant insights into the issue.

6. Conclusion. I have presented a conceptual ecological-economic model that combines (i) ecological results about the relationships between biodiversity, ecosystem functioning, and the provision of ecosystem services with (ii) economic methods to study decision-making under uncertainty. In this framework I have (1) determined the insurance value of biodiversity, (2) studied the optimal allocation of funds in the trade-off between investing into biodiversity protection and the purchase of financial insurance, and (3) analyzed the effect of different institutional settings in the market for financial insurance on biodiversity protection. The focus was on how to model the ecology-economy interface. Relevant economic and policy questions that arise from this view on biodiversity, e.g., the public good character of the problem, the dynamics of the problem or implications for environmental and development policies, are discussed in more detail elsewhere (Baumgärtner and Quaas [2005], Quaas and Baumgärtner [2005], Quaas et al. [2004]).

The conclusion from this analysis is that biodiversity can be interpreted as a form of natural insurance for risk averse ecosystem managers against the over- or under-provision with ecosystem services, such as biomass production, control of water run-off, pollination, control of pests and diseases, nitrogen fixation, soil regeneration, etc. Thus, biodiversity has an insurance value, which is a value component in addition to the usual value arguments (such as direct or indirect use or non-use values, or existence values) holding in a world of certainty. This insurance value should be taken into account when deciding upon how much to invest into biodiversity protection. It leads to choosing a higher level of biodiversity than without taking the insurance value into account, with a higher degree of risk aversion leading to a higher optimal level of biodiversity. As far as the insurance function is concerned, biodiversity and financial insurance against income risk, e.g., crop yield insurance, may be seen as substitutes. If financial insurance is available, a risk averse ecosystem manager, say, a farmer, will partially or fully substitute biodiversity's insurance function by financial insurance, with the

extent of substitution depending on the costs of financial insurance. Hence, the availability, and exact institutional design, of financial insurance influence the level of biodiversity protection.

<div align="center">APPENDIX</div>

A.1. *Expected utility function* (10). With

$$(A.1) \qquad f(y) = \frac{1}{\sqrt{2\pi\sigma_y^2}}\, e^{-(y-\mu_y)^2/(2\sigma_y^2)}$$

as the probability density function of the normal distribution of income y with mean μ_y and variance σ_y^2, the von (Neumann-Morgenstern) expected utility from the (Bernoulli) utility function (9) is

$$(A.2) \qquad \widetilde{U} = \mathcal{E}[u(y)] = -\int e^{-\rho\, y} f(y)\, dy = -e^{-\rho\left[\mu_y - (\rho/2)\,\sigma_y^2\right]}.$$

Using a simple monotonic transformation of $\widetilde{U}$, one obtains the expected utility function U, equation (10).

A.2 *Risk premium* (14). The risk premium R has been defined in equation (13) as

$$(A.3) \qquad u\left(\mathcal{E}[y] - R\right) = \mathcal{E}\left[u(y)\right].$$

With the Bernoulli utility function (9) and $\mathcal{E}[y] = \mu_y$, the left-hand side of this equation is given by

(A.4)
$$u\left(\mathcal{E}[y] - R\right) = -e^{-\rho\,[\mu_y - R]},$$

and the right-hand side is given by equation (A.2). Hence, we have

(A.5)
$$-e^{-\rho\,[\mu_y - R]} = -e^{-\rho\,\left[\mu_y - (\rho/2)\,\sigma_y^2\right]}.$$

Rearranging, and observing that $\sigma_y^2 = \sigma_s^2$, equation (7), yields the result stated in equation (14).

A.3 *Proof of Proposition* 2. ad (i). In Problem 17, the objective function to be maximized over v is

(A.6)
$$U(v) = \mu_s(v) - C(v) - \frac{\rho}{2}\,\sigma_s^2(v),$$

such that the first order condition for a solution $v^\star$ is

(A.7)
$$\mu_s'(v^\star) - C'(v^\star) - \rho\,\sigma_s(v^\star)\,\sigma_s'(v^\star) = 0.$$

Observing that $-\rho\,\sigma_s(v^\star)\,\sigma_s'(v^\star) = V(v^\star)$, equation (16) yields equation (18). With Assumptions (1), (2) and (3) about the curvature of these functions, the second order condition for a maximum,

(A.8)
$$\mu_s''(v^\star) - C''(v^\star) - \rho\left(\sigma_s'(v^\star)\right)^2 - \rho\,\sigma_s(v^\star)\,\sigma_s''(v^\star) < 0,$$

is satisfied, such that the necessary first order condition is also sufficient.

ad (ii). The total derivative of first order condition (18) with respect to ρ is

(A.9)
$$\mu_s''\,\frac{dv^\star}{d\rho} - C''\,\frac{dv^\star}{d\rho} + V'\,\frac{dv^\star}{d\rho} - \sigma_s\sigma_s' = 0.$$

This can be rearranged into

(A.10)
$$\frac{dv^\star}{d\rho} = \frac{\sigma_s\,\sigma_s'}{\mu_s'' - C'' + V'} > 0,$$

which is strictly positive due to Assumptions (1), (2), (3) and $V' < 0$, Proposition 1.

A.4 *Proof of Proposition* 3. ad (i). In Problem (20), the objective function to be maximized over v and a is

$$(A.11) \qquad U(v, a) = \mu_s(v) - C(v) - \frac{\delta}{2} a^2 \sigma_s^2(v) - \frac{\rho}{2} (1 - a)^2 \sigma_s^2(v),$$

such that the first order conditions for a solution $(\hat{v}, \hat{a})$ are

$$(A.12)$$
$$U_v(\hat{v}, \hat{a}) = \mu_s'(\hat{v}) - C'(\hat{v}) - \delta \hat{a}^2 \sigma_s(\hat{v}) \sigma_s'(\hat{v}) - \rho(1-\hat{a})^2 \sigma_s(\hat{v}) \sigma_s'(\hat{v}) = 0,$$

$$(A.13)$$
$$U_a(\hat{v}, \hat{a}) = - \delta \hat{a} \sigma_s^2(\hat{v}) + \rho(1 - \hat{a}) \sigma_s^2(\hat{v}) = 0.$$

As $\sigma_s^2(v) > 0$ for all v, Condition (A.13) can be solved to yield

$$(A.14) \qquad\qquad\qquad \hat{a} = \frac{\rho}{\rho + \delta},$$

which is the result stated in the proposition, equation (26). This can be inserted into Condition (A.12), which yields, after rearranging,

$$(A.15) \qquad\qquad \mu_s'(\hat{v}) + \frac{\delta}{\rho + \delta} \left(-\rho \, \sigma_s(\hat{v}) \, \sigma_s'(\hat{v}) \right) = C'(\hat{v}).$$

Observing that $-\rho \, \sigma_s(\hat{v}) \, \sigma_s'(\hat{v}) = V(\hat{v})$, equation (16) yields equation (25). As for the second order condition, note that

$$(A.16) \quad U_{vv}(\hat{v}, \hat{a}) = \mu_s''(\hat{v}) - C''(\hat{v}) - \delta \, \hat{a}^2 \, (\sigma_s'(\hat{v}))^2 - \delta \, \hat{a} \, \sigma_s(\hat{v}) \, \sigma_s''(\hat{v})$$
$$- \rho \, (1 - \hat{a})^2 \, (\sigma_s'(\hat{v}))^2 - \rho \, (1 - \hat{a})^2 \, \sigma_s(\hat{v}) \, \sigma_s''(\hat{v}) < 0,$$
$$(A.17) \quad U_{aa}(\hat{v}, \hat{a}) = - (\delta + \rho) \, \sigma_s^2(\hat{v}) < 0,$$
$$(A.18) \quad U_{va}(\hat{v}, \hat{a}) = - 2\delta \hat{a} \, \sigma_s(\hat{v}) \, \sigma_s^p(\hat{v}) + 2\rho(1 - \hat{a}) \, \sigma_s(\hat{v}) \, \sigma_s'(\hat{v}) = 0,$$

where the last equality follows from using first order condition (A.14). Hence, $U_{vv} U_{aa} - U_{va}^2 > 0$, so that the second order condition for a

maximum is satisfied and the necessary first order conditions are also sufficient.

ad (ii). The total derivative of first order condition (25) with respect to δ is

$$(A.19) \qquad \mu_s'' \frac{d\hat{v}}{d\delta} + \frac{\rho}{(\rho + \delta)^2} V + \frac{\delta}{\rho + \delta} V' \frac{d\hat{v}}{d\delta} - C'' \frac{d\hat{v}}{d\delta} = 0,$$

which can be rearranged into

$$(A.20) \qquad \frac{d\hat{v}}{d\delta} = - \frac{\rho/(\rho + \delta)^2 V}{\mu_s'' + \delta/(\rho + \delta)V' - C''} > 0,$$

which is strictly positive due to Assumptions (1), (3) and $V' < 0$, Proposition 1. The result about $d\hat{a}/d\delta$ follows immediately from Condition (26).

Part (iii) of the proposition follows immediately from Condition (26).

ad (iv). Compare Conditions (18) and (25) for $v^\star$ and $\hat{v}$, respectively, in a slightly rearranged version:

$$(A.21) \qquad \mu_s'(v^\star) - C'(v^\star) = \qquad\quad -V(v^\star),$$

$$(A.22) \qquad \mu_s'(\hat{v}) - C'(\hat{v}) = \frac{\delta}{\rho + \delta} \left(-V(v^\star) \right).$$

From Assumptions (1) and (3) it follows that $\mu_s'(v) - C'(v)$ is a decreasing function of v, while it follows from Proposition 1 that $-V(v)$ is an increasing function of v, so that $v^\star$ and $\hat{v}$ are determined by the intersection of the decreasing curve representing the left-hand side and the increasing curve representing the right-hand side of Conditions (A.21) and (A.22) respectively. The difference between these two conditions is that for every v the function on the right-hand side of Condition (A.22) yields smaller values than the one in Condition (A.21), as $0 < \delta/(\rho + \delta) < 1$, so that the intersection determining the optimal v in Condition (A.22) is further to the left than the one in Condition (A.21), i.e, $\hat{v} < v^\star$.

ENDNOTES

1. In this respect, biodiversity plays a similar role for farmers as other risk changing production factors, such as, e.g., nitrogen fertilizer or pesticides (Horowitz and Lichtenberg [1993, 1994a, b]).

2. This procedure has been inspired by Crocker and Shogren [1999, 2001, 2003] and Shogren and Crocker [1999]. It is also employed by Baumgärtner and Quaas [2005] and Quaas and Baumgärtner [2005].

3. The question of how to construct an aggregate and encompassing measure of biodiversity has been extensively discussed and is still subject to on-going research (Baumgärtner [2004], Crozier [1992], Magurran [1988], May [1990], Nehring and Puppe [2004], Peet [1974], Purvis and Hector [2000], Vane-Wright [1991], Weitzman [1992, 1998], Whittaker [1972]).

4. The article by Hooper et al. [2005] is a committee report commissioned by the Governing Board of the Ecological Society of America. Some of its authors have previously been on opposite sides of the debate. This report surveys the relevant literature, identifies a consensus of current knowledge as well as open questions, and can be taken to represent the best currently available ecological knowledge about biodiversity and ecosystem functioning.

5. This discussion is compiled from the report of Hooper et al. [2005, Sections II.A and II.B], with large parts being original quotes from this report. For a more detailed and encompassing discussion see Hooper et al. [2005].

6. The patterns depend on the degree of dominance of the species lost or gained, the strength of their interactions with other species, the order in which species are lost, the functional traits of both the species lost and those remaining, and the relative amount of biotic and abiotic control over process rates (Lawton [1994], Naeem [1998], Naeem et al. [1995], Sala et al. [1996], Vitousek and Hooper [1993]).

7. There is still disagreement over whether sampling effects are relevant to natural ecosystems, or whether they only occur in artificially assembled systems (Huston [1997], Loreau [2000], Mouquet et al. [2002], Schläpfer et al. [2005], Tilman et al. [1997b], Wardle [1999]). Much of the experimental work has focused on the effect of plant diversity on primary production and nutrient retention. Recently, evidence for ecosystem services other than biomass production and from ecosystems other than grasslands has begun to accumulate as well. Important insights come from research on intercropping and agroforestry (Ewel [1986], Fridley [2001], Harper [1977], Hector et al. [2002], Loreau [1998b], Smale et al. [1998], Trenbath [1974], Vandermeer [1990], Zhu et al. [2000]).

9. Identifying the exact mechanisms by which experimental manipulation of species leads to increased levels of ecosystem processes has led to substantial debate (Aarssen [1997], Garnier et al. [1997], Hector et al. [2000], Huston [1997], Huston and McBride [2002], Huston et al. [2000], Schmid et al. [2002], van der Heijden et al. [1999], Wardle [1999]), as many experiments were originally designed to test general patterns, rather than to test the underlying mechanisms.

10. The simulated model systems in the analysis of May [1972, 1974] were randomly constructed by putting together a given number of system elements (species) and, in particular, linking them by randomly assigned interaction strengths which were taken from a uniform distribution over all possible interaction strengths. This is in contrast to recent empirical evidence that in real ecosystems the vast majority of pairwise interactions are weak (Paine [1992], Wootton [1997], McCann et al. [1998]).

11. In such cases, there is compensation among species: as some species do worse, others do better due to differences in their functional traits. As a result,

unstable individual populations stabilize properties of the ecosystem as a whole. Hence, instability of the community composition is no contradiction to, but may actually support stability of ecosystem processes (Ernest and Brown [2001], Hughes and Roughgarden [1998], Ives et al. [1999], Landsberg [1999], Lehman and Tilman [2000], McNaughton [1977], Tilman [1996, 1999], Walker et al. [1999]).

12. This is similar to the effect of diversifying a portfolio of financial assets, e.g., stocks.

13. It is generally acknowledged that the underlying assumptions of the mathematical models as to these parameters need further investigation and more experimental confirmation. Also, the role of the stability measures used and other mechanisms built into the models (such as, e.g., overyielding) need further clarification.

14. See Endnote 3.

15. According to the discussion in the previous section, 'biodiversity' could in many instances simply be measured by the number of different species ('species richness'). However, the discussion in the previous section also suggests that in some instances it should be measured by a more sophisticated index which takes into account the functional traits and relative abundances of different species as well as their interactions (see Endnote 3).

16. According to the well established species-area relationships, the level of biodiversity v increases with the area l of land as $v \sim l^z$, where z, with $0 < z < 1$, is a characteristic constant for the type of ecosystem (MacArthur and Wilson [1967], Rosenzweig [1995], Gaston [2000]). Assuming constant per-hectare costs of land, this leads to a strictly convex cost function.

17. Of course, it is a major simplification to assume that one can directly choose a certain level of biodiversity. Actually, one would choose some instrumental variable, such as area of protected land, or investment in some species protection/recovery plan, which then results in a certain level of biodiversity.

18. While risk-aversion is a natural and standard assumption for farm *households* (Besley [1995], Dasgupta [1993, Chapter 8]), it appears as an induced property in the behavior of (farm) *companies* which are fundamentally risk neutral but act as if they were risk averse when facing, e.g., external financing constraints or bankruptcy costs (Caillaud et al. [2000], Mayers and Smith [1990]).

19. This stylized insurance institution is a special case of the one studied by Baumgärtner and Quaas [2005].

20. This benefit/premium-scheme is actuarially fair, because the insurance company has an expected net payment stream of $\mathcal{E}[a(s - \bar{s})] = 0$. To the insurant, this actuarially fair benefit/premium-scheme does not come at any real costs, as $\mathcal{E}[a(s - \bar{s})] = 0$. It is fully equivalent to the traditional model of insurance, e.g., Ehrlich and Becker [1972, p. 627], where losses compared with the maximum income are insured against and one pays a constant insurance premium irrespective of actual income.

21. Since the actuarially fair risk premium does not cause any expected payoff/costs to the insurant, only the price component over and above the actuarially fair risk premium (the so-called 'loading' of the premium) constitutes real costs of insurance to the insurant (Ehrlich and Becker [1972, pp. 626–627]).

22. By equation (13), $\mathcal{E}[y] - R$ is the *certainty equivalent* of lottery v, as it yields the expected utility $\mathcal{E}[u(y)]$. According to equations (3) and (5), $y \in Y$ with Y as an interval of $\mathbf{R}$, and according to equation (9), u is continuous and strictly increasing, so that a risk premium R uniquely exists for every lottery v (Kreps [1990, p. 84]).

23. In the simple model employed here, the risk premium is equivalent to the so-called 'option price' of risk reduction, that is, the amount of money that a decision maker would be willing to pay for getting the expected pay-off from the lottery, $\mathcal{E}[y]$, for sure instead of playing the risky lottery with random pay-off y.

24. Note that this does *not* necessarily mean that in the optimal allocation there is no more income risk, i.e., $\sigma_y^2(\hat{v}, \hat{a}) = 0$. It only means that the overall amount of income variance that the decision maker wishes to avoid in the optimum is covered by both natural and financial insurance. This may still leave the decision maker with some positive income risk in the optimum, i.e., $\sigma_y^2(\hat{v}, \hat{a}) > 0$.

25. This gives rise to what is known in the insurance economics literature as 'moral hazard' (Kreps [1990]). As long as the behavior of the economic agent (here: the level of biodiversity chosen by the ecosystem manager) cannot be observed by the insurance company, but only the resulting outcome can be observed (here: the provision of some ecosystem service), the existence of insurance will induce the insurant to choose a riskier behavior than if insurance was not available. Moral hazard is a problem for many insurance markets, e.g., health insurance or car insurance, and has been identified as a major reason for the absence of private insurance markets for most agricultural risks (Chambers [1989]). Because of the moral hazard problem, most insurance contracts intentionally do not allow for full coverage at actuarially fair premiums but contain deductibles or upper limits in either the degree of coverage or the amount to be insured. Other insurance policies try to include a specification of the insurant's behavior (or observable proxies thereof) into the contract. These mechanisms serve to diminish the moral hazard problem, yet they cannot eliminate it completely.

REFERENCES

L.W. Aarssen [1997], *High Productivity in Grassland Ecosystems: Affected by Species Diversity or Productive Species?*, Oikos **80**, 183–184.

K.J. Arrow [1965], *Aspects of the Theory of Risk-Bearing*, Yrjö Jahnssonin Säätio Lecture, Helsinki, reprinted with modifications, in *Essays in the Theory of Risk Bearing* (K.J. Arrow, ed.), Markham, Chicago, 1971.

S. Baumgärtner [2004], *Measuring the Diversity of What? And for What Purpose? A Conceptual Comparison of Ecological and Economic Biodiversity Indices*, Paper presented at Annual Conf. of the Euro. Assoc. of Environmental and Resource Economists (Budapest) and Biennial Conf. of the Internat. Soc. for Ecological Economics (Montréal).

S. Baumgärtner and M. Quaas [2005], *Natural vs. Financial Insurance in the Management of Public-Good Ecosystems*, Working paper, Department of Economics, University of Heidelberg.

T. Besley [1995], *Savings, credit and insurance*, in *Handbook of Development Economics* (H.B. Chenery and T.N. Srinivasan, eds.), Vol. III, North Holland, Amsterdam, pp. 2123–2207.

E. Birol, A. Kontoleon and M. Smale [2005a], *Using a Choice Experiment to Estimate the Demand of Hungarian Farmers for Food Security and Agrobiodiversity During Economic Transition*, Paper presented at 7th BIOECON Conf., 20–21 September 2005, Cambridge, UK.

E. Birol, M. Smale and A. Gyovoi [2005b], *Farmer Management of Agricultural Biodiversity in Hungary's Transition Economy*, in *Valuing Crop Biodiversity*: *On-Farm Genetic Resources and Economic Change* (M. Smale, ed.), CAB Internat. Publishing, Wallingford, UK.

C. Borrvall, B. Ebenman and T. Jonsson [2000], *Biodiversity Lessens the Risk of Cascading Extinction in Model Food Webs*, Ecol. Letters **3**, 131–136.

J.H. Brown, T.G. Whitham, S.K. Morgan Ernest and C.A. Gehring [2001], *Complex Species Interactions and the Dynamics of Ecological Systems*: *Long-Term Experiments*, Science **293**, 643–650.

B. Caillaud, G. Dionne and B. Jullien [2000], *Corporate Insurance with Optimal Financing Contracts*, Econ. Theory **16**, 77–105.

J.P. Casperson and S.W. Pacala [2001], *Successional Diversity and Forest Ecosystem Function*, Ecol. Research **16**, 895–904.

[CBD] *Convention on Biological Diversity*, United Nations Conf. on Environ. and Development, Rio de Janeiro, Brazil, 1992.

R.G. Chambers [1989], *Insurability and Moral Hazard in Agricultural Insurance Markets*, Amer. J. Ag. Econ. **71**, 604–616.

F.S. Chapin, III and G.R. Shaver [1985], *Individualistic Growth Response of Tundra Plant Species to Environmental Manipulations in the Field*, Ecol. **66**, 564–576.

P.L. Chesson [2000], *Mechanisms of Maintenance of Species Diversity*, Annual Rev. Ecol. Syst. **31**, 343–366.

P. Chesson, S. Pacala and C. Neuhauser [2002], *Environmental Niches and Ecosystem Functioning*, in *Functional Consequences of Biodiversity*: *Experimental Progress and Theoretical Extensions* (A. Kinzig, D. Tilman and S. Pacala, eds.), Princeton Univ. Press, Princeton, pp. 213–245.

K.C. Cottingham, B.L. Brown and J.T. Lennon [2001], *Biodiversity May Regulate the Temporal Variability of Ecological Systems*, Ecol. Letters **4**, 72–85.

T.D. Crocker and J.F. Shogren [1999], *Endogenous Environmental Risk*, in *Handbook of Environmental and Resource Economics* (J.C.J.M. van den Bergh, ed.), Cheltenham, UK and Edward Elgar, Northampton, MA, pp. 215–222.

T.D. Crocker and J.F. Shogren [2001], *Ecosystems as Lotteries*, in *Frontiers of Environmental Economics* (H. Folmer, H.L. Gabel, S. Gerking and A. Rose, eds.), Cheltenham, UK and Edward Elgar, Northampton, MA, pp. 250–271.

T.D. Crocker and J.F. Shogren [2003], *Choosing Environmental Risks*, in *The International Yearbook of Environmental and Resource Economics* 2003/04 (H. Folmer and T. Tietenberg, eds.), Cheltenham, UK and Edward Elgar, Northampton, MA, pp. 36–81.

R.H. Crozier [1992], *Genetic Diversity and the Agony of Choice*, Biol. Conserv. **61**, 11–15.

G.C. Daily (ed.) [1997], *Nature's Services. Societal Dependence on Natural Ecosystems*, Island Press, Washington, DC.

P. Dasgupta [1993], *An Inquiry into Well-Being and Destitution*, Clarendon Press, Oxford.

P.C. de Ruiter, B. Griffiths and J.C. Moore [2002], *Biodiversity and Stability in Soil Ecosystems: Patterns, Processes and the Effects of Disturbance*, in *Biodiversity and Ecosystem Functioning*: *Synthesis and Perspectives* (M. Loreau, S. Naeem and P. Inchausti, eds.), Oxford Univ. Press, Oxford, pp. 102–11.

S. Di Falco, J.-P. Chavas and M. Smale [2005], *Farmer Management of Production Risk on Degraded Lands*: *Wheat Diversity in Tigray Region, Ethiopia*, Paper presented at 7th BIOECON Conf., 20–21 September 2005, Cambridge, UK.

S. Di Falco and C. Perrings [2003], *Crop Genetic Diversity, Productivity and Stability of Agroecosystems*: *A Theoretical and Empirical Investigation*, Scottish J. Polit. Econ. **50**, 207–216.

S. Di Falco and C. Perrings [2005], *Crop Biodiversity, Risk Management and the Implications of Agricultural Assistance*, Ecol. Econ. **55**, 459–466.

D.F. Doak, D. Bigger, E.K. Harding, M.A. Marvier, R.E. O'Malley and D. Thomson [1998], *The Statistical Inevitability of Stability-Diversity Relationships in Community Ecology*, The Amer. Naturalist **151**, 264–276.

J. Ehrlich and G.S. Becker [1972], *Market Insurance, Self-Insurance and Self-Protection*, J. Polit. Econ. **80**, 623–648.

C.S. Elton [1958], *Ecology of Invasions by Animals and Plants*, Methuen, London.

M.C. Emmerson, M. Solan, C. Emes, D.M. Peterson and D. Raffaelli [2001], *Consistent Patterns and the Idiosyncratic Effects of Biodiversity in Marine Ecosystems*, Nature **411**, 73–77.

S.K.M. Ernest and J.H. Brown [2001], *Delayed Compensation for Missing Keystone Species by Colonization*, Science **292**, 101–104.

J.J. Ewel [1986], *Designing Agroecosystems for the Humid Tropics*, Annual Rev. Ecol. System. **17**, 245–271.

C.B. Field [1995], *Productive Capacity and Biomass Accumulation*, in *Global Biodiversity Assessment* (United Nations Environment Programme (UNEP), ed.), Cambridge Univ. Press, Cambridge, UK, pp. 402–406.

J.D. Fridley [2001], *The Influence of Species Diversity on Ecosystem Productivity*: *How, Where and Why?*, Oikos **93**, 514–526.

J.D. Fridley [2003], *Diversity Effects on Production in Different Light and Fertility Environments: An Experiment with Communities of Annual Plants*, J. Ecol. **91**, 396–406.

T.M. Frost, S.R. Carpenter, A.R. Ives and T.K. Kratz [1995], *Species Compensation and Complementarity in Ecosystem Function*, in *Linking Species and Ecosystems* (C.G. Jones and J.H. Lawton, eds.), Chapman and Hall, San Diego, CA, pp. 224–239.

E. Garnier, M.-L. Navas, M.P. Austin, J.M. Lilley and R.M. Gifford [1997], *A Problem for Biodiversity-Productivity Studies*: *How to Compare the Productivity of Multispecific Plant Mixtures to that of Monocultures?*, Acta Oecolog. **18**, 657–670.

K.J. Gaston [1996], *Biodiversity. A Biology of Numbers and Difference*, Blackwell, Oxford, UK.

K.J. Gaston [2000], *Global Patterns in Biodiversity*, Nature **405**, 220–227.

T.J. Givnish [1994], *Does Diversity Beget Stability?*, Nature **371**, 113–114.

B.S. Griffiths, K. Ritz, R.D. Bardgett, R. Cok, S. Christensen, F. Ekelund, S.J. Sorenson, E. Baath, J. Bloem, P.C. De Ruiter, J. Dolfing and B. Nicolardot [2000], *Ecosystem Response of Pasture Soil Communities to Fumigation-Induced Microbial Diversity Reductions*: *An Examination of the Biodiversity-Ecosystem Function Relationship*, Oikos **90**, 279–294.

J.P. Grime [1997], *Biodiversity and Ecosystem Function*: *The Debate Deepens*, Science **277**, 1260–1261.

J.P. Grime, V.K. Brown, K. Thompson, G.J. Masters, S.H. Hillier, I.P. Clarke, A.P. Askew, D. Corker and P. Kielty [2000], *The Response of Two Contrasting Limestone Grasslands to Simulated Climate Change*, Science **289**, 762–765.

V. Grimm and C. Wissel [1997], *Babel, or the Ecological Stability Discussions*: *An Inventory and Analysis of Terminology and a Guide for Avoiding Confusion*, Oecologia **109**, 323–334.

J.L. Harper [1977], *Population Biology of Plants*, Academic Press, London.

A. Hector, E. Bazeley-White, M. Loreau, S. Otway and B. Schmid [2002], *Overyielding in Plant Communities*: *Testing the Sampling Effect Hypothesis with Replicated Biodiversity Experiments*, Ecol. Letters **5**, 502–511.

A. Hector, B. Schmid, C. Beierkuhnlein, M.C. Caldeira, M. Diemer, P.G. Dimitrakopoulos, J.A. Finn, H. Freitas, P.S. Giller, J. Good, R. Harris, K. Huss-Danell, J. Joshi, A. Jumpponen, C. Korner, P. Leadley, M. Loreau, A. Minns, C. Mulder, G. O'Donovan, S. Otway, J. Pereira, A. Prinz, D. Read, M. Scherer-Lorenzen, E. Schulte, A. Siamantziouras, E. Spehn, A. Terry, A. Troumbis, F. Woodward, S. Yachi and J. Lawton [1999], *Plant Diversity and Productivity Experiments in European Grasslands*, Science **286**, 1123–1127.

A. Hector, B. Schmid, C. Beierkuhnlein, M.C. Caldeira, M. Diemer, P.G. Dimitrakopoulos, J.A. Finn, H. Freitas, P.S. Giller, J. Good, R. Harris, K. Huss-Danell, J. Joshi, A. Jumpponen, C. Korner, P. Leadley, M. Loreau, A. Minns, C. Mulder, G. O'Donovan, S. Otway, J. Pereira, A. Prinz, D. Read, M. Scherer-Lorenzen, E. Schulte, A. Siamantziouras, E. Spehn, A. Terry, A. Troumbis, F. Woodward, S. Yachi and J. Lawton [2000], *No Consistent Effect of Plant Diversity on Productivity? Response*, Science **289**, 1255a.

C.S. Holling [1986], *Resilience of Ecosystems*: *Local Surprise and Global Change*, in *Sustainable Development of the Biosphere* (W.C. Clark and R.E. Munn, eds.), Cambridge Univ. Press, Cambridge, UK, pp. 292–317.

C.S. Holling, D.W. Schindler, B.W. Walker and J. Roughgarden [1995], *Biodiversity in the Functioning of Ecosystems*: *An Ecological Synthesis*, in *Biodiversity Loss. Economic and Ecological Issues* (C. Perrings, K.-G. Mäler, C. Folke, C.S. Holling and B.-O. Jansson, eds.), Cambridge Univ. Press, Cambridge, UK, pp. 44–83.

D. Hooper, D. Hawksworth and S. Dhillion [1995], *Microbial Diversity and Ecosystem Processes*, in *Global Biodiversity Assessment* (U.N. Environment Programme (UNEP), ed.), Cambridge Univ. Press, Cambridge, UK, pp. 433–443.

D.U. Hooper, F.S. Chapin, III, J.J. Ewel, A. Hector, P. Inchausti, S. Lavorel, J.H. Lawton, D.M. Lodge, M. Loreau, S. Naeem, B. Schmid, H. Setälä, A.J. Symstad, J. Vandermeer and D.A. Wardle [2005], *Effects of Biodiversity on Ecosystem Functioning*: *A Consensus of Current Knowledge*, Ecol. Monogr. **75**, 3–35.

D.U. Hooper, M. Solan, A. Symstad, S. Díaz, M.O. Gessner, N. Buchmann, V. Degrange, P. Grime, F. Hulot, F. Mermillod-Blondin, J. Roy, E. Spehn and L. van Peer [2002], *Species Diversity, Functional Diversity and Ecosystem Functioning*, in *Biodiversity and Ecosystem Functioning*: *Synthesis and Perspectives* (M. Loreau, S. Naeem and P. Inchausti, eds.), Oxford Univ. Press, Oxford, UK, pp. 195–208.

J.K. Horowitz and E. Lichtenberg [1993], *Insurance, Moral Hazard and Chemical Use in Agriculture*, Amer. J. Ag. Econ. **75**, 926–935.

J.K. Horowitz and E. Lichtenberg [1994a], *Crop Insurance and Agricultural Chemical Use*, in *Economics of Agricultural Crop Insurance*: *Theory and Evidence* (D. Hueth and H. Furtan, eds.), Kluwer, Norwell, MA.

J.K. Horowitz and E. Lichtenberg [1994b], *Risk-Increasing and Risk-Reducing Effects of Pesticides*, J. Ag. Econ. **45**, 82–89.

J.B. Hughes and J. Roughgarden [1998], *Aggregate Community Properties and the Strength of Species' Interactions*, Proc. Natl. Acad. Sci. **95**, 6837–6842.

M.A. Huston [1997], *Hidden Treatments in Ecological Experiments*: *Re-Evaluating the Ecosystem Function of Biodiversity*, Oecologia, **110**, 449–460.

M.A. Huston, L.W. Aarssen, M.P. Austin, B.S. Cade, J.D. Fridley, E. Garnier, J.P. Grime, J. Hodgson, W.K. Lauenroth, K. Thompson, J.H. Vandermeer and D.A. Wardle [2000], *No Consistent Effect of Plant Diversity on Productivity*, Science **289**, 1255.

M.A. Huston and A.C. McBride [2002], *Evaluating the Relative Strengths of Biotic versus Abiotic Controls on Ecosystem Processes*, in *Biodiversity and Ecosystem Functioning*: *Synthesis and Perspectives* (M. Loreau, S. Naeem and P. Inchausti, eds.), Oxford Univ. Press, Oxford, pp. 47–60.

R.E. Ingham, J.A. Trofymow, E.R. Ingham and D.C. Coleman [1985], *Interactions of Bacteria, Fungi, and Their Nematode Grazers*: *Effects on Nutrient Cycling and Plant Growth*, Ecol. Monogr. **55**, 119–140.

A.R. Ives, K. Gross and J.L. Klug [1999], *Stability and Variability in Competitive Communities*, Science **286**, 542–544.

R.E. Just and R.D. Pope [1978], *Stochastic Specification of Production Functions and Econometric Implications*, J. Econometrics **7**, 67–86.

R.E. Just and R.D. Pope [1979], *Production Function Estimation and Related Risk Considerations*, Amer. J. Ag. Econ. **61**, 267–284.

A. Kinzig, S. Pacala and D. Tilman [2002], *The Functional Consequences of Biodiversity*: *Empirical Progress and Theoretical Extensions*, Princeton Univ. Press, Princeton.

D.M. Kreps [1990], *A Course in Microeconomic Theory*, Harvester Wheatsheaf, New York.

J. Landsberg [1999], *Response and Effect*: *Different Reasons for Classifying Plant Functional Types under Grazing*, in *People and Rangelands*: *Building the Future* (D. Eldridge and D. Freudenberger, eds.), Proc. of VI Internat. Rangeland Congress, Townsville, Australia, pp. 911–915.

S. Lavorel and E. Garnier [2002], *Predicting the Effects of Environmental Changes on Plant Community Composition and Ecosystem Functioning*: *Revisiting the Holy Grail*, Funct. Ecol. **16**, 545–556.

J.H. Lawton [1994], *What Do Species Do in Ecosystems?*, Oikos **71**, 367–374.

J.H. Lawton and V.K. Brown [1993], *Redundancy in Ecosystems*, in *Biodiversity and Ecosystem Functions* (E.-D. Schulze and H.A. Mooney, eds.), Springer, Heidelberg, pp. 255–270.

C.L. Lehman and D. Tilman [2000], *Biodiversity, Stability, and Productivity in Competitive Communities*, The Amer. Naturalist **156**, 534–552.

M. Liiri, H. Setälä, J. Haimi, T. Pennanen and H. Fritze [2002], *Relationship between Soil Microarthropod Species Diversity and Plant Growth Does Not Change When the System is Disturbed*, Oikos **96**, 137–149.

M. Loreau [1998a], *Biodiversity and Ecosystem Functioning*: *A Mechanistic Model*, Proc. Natl. Acad. Sci. **95**, 5632–5636.

M. Loreau [1998b], *Separating Sampling and Other Effects in Biodiversity Experiments*, Oikos **82**, 600–602.

M. Loreau [2000], *Biodiversity and Ecosystem Functioning*: *Recent Theoretical Advances*, Oikos **91**, 3–17.

M. Loreau, A. Downing, M.C. Emmerson, A. Gonzalez, J. Hughes, P. Inchausti, J. Joshi, J. Norberg and O. Sala [2002a], *A New Look at the Relationship between Diversity and Stability*, in *Biodiversity and Ecosystem Functioning*: *Synthesis and Perspectives* (M. Loreau, S. Naeem and P. Inchausti, eds.), Oxford Univ. Press, Oxford, pp. 79–91.

M. Loreau and A. Hector [2001], *Partitioning Selection and Complementarity in Biodiversity Experiments*, Nature **412**, 72–76.

M. Loreau, S. Naeem, P. Inchausti, J. Bengtsson, J.P. Grime, A. Hector, D.U. Hooper, M.A. Huston, D. Raffaelli, B. Schmid, D. Tilman and D.A. Wardle [2001], *Biodiversity and Ecosystem Functioning*: *Current Knowledge and Future Challenges*, Science **294**, 804–808.

M. Loreau, S. Naeem and P. Inchausti [2002b], *Biodiversity and Ecosystem Functioning*: *Synthesis and Perspectives*, Oxford Univ. Press, Oxford.

R.H. MacArthur [1955], *Fluctuations of Animal Populations and a Measure of Community Stability*, Ecol. **36**, 533–536.

R.H. MacArthur and E.O. Wilson [1967], *The Theory of Island Biogeography*, Princeton Univ. Press, Princeton.

A.E. Magurran [1988], *Ecological Diversity and Its Measurement*, Princeton Univ. Press, Princeton.

R.M. May [1972], *Will a Large Complex System Be Stable?*, Nature **238**, 413–414.

R.M. May [1974], *Stability and Complexity in Model Ecosystems*, 2nd ed., Princeton Univ. Press, Princeton.

R.M. May [1990], *Taxonomy as Destiny*, Nature **347**, 129–130.

D. Mayers and C.W. Smith, Jr. [1990], *On the Corporate Demand for Insurance: Evidence from the Reinsurance Market*, J. Business **63**, 19–40.

K.S. McCann [2000], *The Diversity-Stability Debate*, Nature **405**, 228–233.

K. McCann, A. Hastings and G.R. Huxel [1998], *Weak Trophic Interactions and the Balance of Nature*, Nature **395**, 794–798.

J. McGrady-Steed, P.M. Harris and P.J. Morin [1997], *Biodiversity Regulates Ecosystem Predictability*, Nature **390**, 162–164.

S.J. McNaughton [1977], *Diversity and Stability of Ecological Communities: A Comment on the Role of Empiricism in Ecology*, The Amer. Naturalist **111**, 515–525.

S.J. McNaughton [1985], *Ecology of a Grazing Ecosystem: The Serengeti*, Ecol. Monogr. **55**, 259–294.

S.J. McNaughton [1993], *Biodiversity and Function of Grazing Ecosystems*, in *Biodiversity and Ecosystem Function* (E.-D. Schulze and H.A. Mooney, eds.), Springer, Heidelberg, pp. 361–383.

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

N. Mouquet, J.L. Moore and M. Loreau [2002], *Plant Species Richness and Community Productivity: Why the Mechanism that Promotes Coexistence Matters*, Ecol. Letters **5**, 56–65.

S. Naeem [1998], *Species Redundancy and Ecosystem Reliability*, Conserv. Biol. **12**, 39–45.

S. Naeem [2002], *Ecosystem Consequences of Biodiversity Loss: The Evolution of a Paradigm*, Ecol. **83**, 1537–1552.

S. Naeem and S. Li [1997], *Biodiversity Enhances Reliability*, Nature **390**, 507–509.

S. Naeem, L.J. Thompson, S.P. Lawler, J.H. Lawton and R.M. Woodfin [1995], *Empirical Evidence that Declining Species Diversity May Alter the Performance of Terrestrial Ecosystems*, Philos. Trans. Royal Soc. London **347**, 249–262.

K. Nehring and C. Puppe [2004], *Modelling Phylogenetic Diversity*, Resource Energy Econ. **26**, 205–235.

P.A. Niklaus, E. Kandeler, P.W. Leadley, B. Schmid, D. Tscherko and C. Körner [2001], *A Link between Plant Diversity, Elevated* CO_2 *and Soil Nitrate*, Oecologia **127**, 540–548.

E. Odum [1953], *Fundamentals of Ecology*, Saunders, Philadelphia.

S.W. Pacala and D.H. Deutschman [1995], *Details that Matter: The Spatial Distribution of Individual Trees Maintains Forest Ecosystem Function*, Oikos **74**, 357–365.

R.T. Paine [1992], *Food-Web Analysis through Field Measurements of Per Capita Interaction Strengths*, Nature **355**, 73–75.

R.K. Peet [1974], *The Measurement of Species Diversity*, Annual Rev. Ecol. Syst. **5**, 285–307.

C. Perrings [1995], *Biodiversity Conservation as Insurance*, in *The Economics and Ecology of Biodiversity Decline. The Forces Driving Global Change* (T.M. Swanson, ed.), Cambridge Univ. Press, Cambridge, pp. 69–77.

O.L. Petchey, P.T. McPhearson, T.M. Casey and P.J. Morin [1999], *Environmental Warming Alters Food-Web Structure and Ecosystem Function*, Nature **402**, 69–72.

G. Peterson, C.R. Allen and C.S. Holling [1998], *Ecological Resilience, Biodiversity and Scale*, Ecosyst. **1**, 6–18.

A.B. Pfisterer, J. Joshi, B. Schmid and M. Fischer [2004], *Rapid Decay of Diversity-Productivity Relationships after Invasion in Experimental Plant Communities*, Basic Appl. Ecol. **5**, 5–14.

A.B. Pfisterer and B. Schmid [2002], *Diversity-Dependent Production Can Decrease the Stability of Ecosystem Functioning*, Nature **416**, 84–86.

S.L. Pimm [1984], *The Complexity and Stability of Ecosystems*, Nature **307**, 321–326.

A. Purvis and A. Hector [2000], *Getting the Measure of Biodiversity*, Nature **405**, 212–219.

J.W. Pratt [1964], *Risk Aversion in the Small and in the Large*, Econometrica **32**, 122–136.

M. Quaas and S. Baumgärtner [2005], *The Insurance Value of Ecosystem Management*, Working paper, Dept. of Economics, University of Heidelberg.

M. Quaas, S. Baumgärtner, C. Becker, B. Müller and K. Frank [2004], *Uncertainty and Sustainability in the Management of Semi-Arid Rangelands*, Discussion paper No. 414, Dept. of Economics, University of Heidelberg.

P.B. Reich, et al. [2001], *Plant Diversity Enhances Ecosystem Responses to Elevated CO_2 and Nitrogen Deposition*, Nature **410**, 809–812.

M.L. Rosenzweig [1995], *Species Diversity in Space and Time*, Cambridge Univ. Press, Cambridge, UK.

O.E. Sala, W.K. Lauenroth, S.J. McNaughton, G. Rusch and X. Zhang [1996], *Biodiversity and Ecosystem Function in Grasslands*, in *Functional Roles of Biodiversity*: *A Global Perspective* (H.A. Mooney, J.H. Cushman, E. Medina, O.E. Sala and E.-D. Schulze, eds.), John Wiley, Chichester, pp. 129–149.

D.W. Schindler, M.A. Turner, M.P. Stainton and G.A. Linsey [1986], *Natural Sources of Acid Neutralizing Capacity in Low Alkalinity Lakes of the Precambrian Shield*, Science **232**, 844–847.

F. Schläpfer, B. Pfisterer and B. Schmid [2005], *Non-Random Species Extinction and Plant Production: Implications for Ecosystem Functioning*, J. Appl. Ecol. **42**, 13–24.

F. Schläpfer, M. Tucker and I. Seidl [2002], *Returns from Hay Cultivation in Fertilized Low Diversity and Non-Fertilized High Diversity Grassland*, Environ. Resource Econ. **21**, 89–100.

B. Schmid, A. Hector, M.A. Huston, P. Inchausti, I. Nijs, P.W. Leadley and D. Tilman [2002], *The Design and Analysis of Biodiversity Experiments*, in *Biodiversity and Ecosystem Functioning. Synthesis and Perspectives* (M. Loreau, S. Naeem and P. Inchausti, eds.), Oxford Univ. Press, Oxford, UK, pp. 61–75.

E.-D. Schulze and H.A. Mooney, eds. [1993], *Biodiversity and Ecosystem Functions*, Springer, Heidelberg.

J.F. Shogren and T.D. Crocker [1999], *Risk and Its Consequences*, J. Environ. Econ. Manage. **37**, 44–51.

M. Smale, J. Hartell, P.W. Heisey and B. Senauer [1998], *The Contribution of Genetic Resources and Diversity to Wheat Production in the Punjab of Pakistan*, Amer. J. Ag. Econ. **80**, 482–493.

T.M. Swanson and T. Goeschl [2003], *Pests, Plagues, and Patents*, J. Euro. Econ. Assoc. **1**, 561–575.

A.J. Symstad and D. Tilman [2001], *Diversity Loss, Recruitment Limitation, and Ecoystem Functioning*: *Lessons Learned from a Removal Experiment*, Oikos **92**, 424–435.

D. Tilman [1996], *Biodiversity*: *Population versus Ecosystem Stability*, Ecol. **77**, 350–363.

D. Tilman [1997], *Distinguishing between the Effects of Species Diversity and Species Composition*, Oikos **80**, 185.

D. Tilman [1999], *The Ecological Consequences of Changes in Biodiversity*: *A Search for General Principles*, Ecol. **80**, 1455–1474.

D. Tilman and J.A. Downing [1994], *Biodiversity and Stability in Grasslands*, Nature **367**, 363–365.

D. Tilman, J. Knops, D. Wedin and P. Reich [2002], *Experimental and Observational Studies of Diversity, Productivity, and Stability*, in *Functional Consequences of Biodiversity*: *Empirical Progress and Theoretical Extensions* (A. Kinzig, S. Pacala and D. Tilman, eds.), Princeton Univ. Press, Princeton, pp. 42–70.

D. Tilman, J. Knops, D. Wedin, P. Reich, M. Ritchie and E. Siemann [1997a], *The Influence of Functional Diversity and Composition on Ecosystem Processes*, Science **277**, 1300–1302.

D. Tilman, C.L. Lehman and C.E. Bristow [1998], *Diversity-Stability Relationships*: *Statistical Inevitability or Ecological Consequence?*, The Amer. Naturalist **151**, 277–282.

D. Tilman, C.L. Lehman and K.T. Thomson [1997b], *Plant Diversity and Ecosystem Productivity: Theoretical Considerations*, Proc. Natl. Acad. Sci. **94**, 1857–1861.

D. Tilman, P.B. Reich, J. Knops, D. Wedin, T. Mielke and C. Lehman [2001], *Diversity and Productivity in a Longterm Grassland Experiment*, Science **294**, 843–845.

D. Tilman, D. Wedin and J. Knops [1996], *Productivity and Sustainability Influenced by Biodiversity in Grassland Ecosystems*, Nature **379**, 718–720.

B.R. Trenbath [1974], *Biomass Productivity of Mixtures*, Adv. Agronomy **26**, 177–210.

B.R. Trenbath [1999], *Multispecies Cropping Systems in India*, in *Agriculture as a Mimic of Natural Systems* (E.C. Lefroy, R.J. Hobbs, M.H. O'Connor and J.S. Pate, eds.), Kluwer, Dordrecht, pp. 381–405.

M.G.A. van der Heijden, J.N. Klironomos, M. Ursic, P. Moutoglis, R. Streitwolf-Engel, T. Boller, A. Wiemken and I.R. Sanders [1999], *'Sampling Effect, a Problem in Biodiversity Manipulation?', a Reply to David A. Wardle*, Oikos **87**, 408–410.

J.H. Vandermeer [1989], *The Ecology of Intercropping*, Cambridge Univ. Press, Cambridge.

J.H. Vandermeer [1990], *Intercropping*, in *Agroecology* (C.R. Carrol, J.H. Vandermeer and P.M. Rosset, eds.), McGraw Hill, New York, pp. 481–516.

R.I. Vane-Wright, C.J. Humphries and P.H. Williams [1991], *What to Preserve? Systematics and the Agony of Choice*, Biol. Conserv. **55**, 235–254.

H.R. Varian [1992], *Microeconomic Analysis*, 3rd ed., W.W. Norton, New York.

P.M. Vitousek and D.U. Hooper [1993], *Biological Diversity and Terrestrial Ecosystem Biogeochemistry*, in *Biodiversity and Ecosystem Function* (E.-D. Schulze and H.A. Mooney, eds.), Springer, Heidelberg, pp. 3–14.

B. Walker [1992], *Biodiversity and Ecological Redundancy*, Conserv. Biol. **6**, 18–23.

B. Walker, A. Kinzig and J. Langridge [1999], *Plant Attribute Diversity, Resilience, and Ecosystem Function*: *The Nature and Significance of Dominant and Minor Species*, Ecosyst. **2**, 95–113.

D.A. Wardle [1999], *Is "Sampling Effect" a Problem for Experiments Investigating Biodiversity-Ecosystem Function Relationships?*, Oikos **87**, 403–407.

M. Weitzman [1992], *On Diversity*, Quart. J. Econ. **107**, 363–406.

M. Weitzman [1998], *The Noah's Ark Problem*, Econometrica **66**, 1279–1298.

M. Weitzman [2000], *Economic Profitability versus Ecological Entropy*, Quart. J. Econ. **115**, 237–263.

R.H. Whittaker [1972], *Evolution and Measurement of Species Diversity*, Taxon. **21**, 213–251.

D. Widawsky and S.D. Rozelle [1998], *Varietal Diversity and Yield Variability in Chinese Rice Production*, in *Farmers, Gene Banks, and Crop Breeding, Economic Analyses of Diversity in Wheat, Maize, and Rice* (M. Smale, ed.), Kluwer, Boston, pp. 159–172.

E.O. Wilson [1992], *The Diversity of Life*, W.W. Norton, New York.

J.T. Wootton [1997], *Estimates and Tests of Per Capita Interaction Strength*: *Diet, Abundance, and Impact of Intertidally Foraging Birds*, Ecol. Monogr. **67**, 45–64.

S. Yachi and M. Loreau [1999], *Biodiversity and Ecosystem Productivity in a Fluctuating Environment*: *The Insurance Hypothesis*, Proc. Natl. Acad. Sci. **96**, 1463–1468.

Y. Zhu, H. Chen, J. Fan, Y. Wang, Y. Li, J. Chen, J.X. Fan, S. Yang, L. Hu, H. Leung, T.W. Mew, P.S. Teng, Z. Wang and C.C. Mundt [2000], *Genetic Diversity and Disease Control in Rice*, Nature **406**, 718–722.