The economic insurance value of ecosystem resilience

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Abstract: Ecosystem resilience, i.e. an ecosystem's ability to maintain its basic functions and controls under disturbances, is often interpreted as insurance: by decreasing the probability of future drops in the provision of ecosystem services, resilience insures risk-averse ecosystem users against potential welfare losses. Using a general and stringent definition of 'insurance' and a simple ecological-economic model, we derive the economic insurance value of ecosystem resilience and study how it depends on ecosystem properties and the risk preferences of the ecosystem user. We show that (i) the insurance value of resilience is negative (positive) for low (high) levels of resilience, (ii) it increases monotonically with the level of resilience, and (iii) it is one additive component of the total economic value of resilience.

JEL-Classification: Q57, Q56, D81, G22

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1 Introduction

Ecosystems that are used and managed by humans for the ecosystem services they provide may exhibit multiple stability domains ("basins of attraction") that differ in fundamental system structure and behavior. As a result of exogenous natural disturbances or human management, a system may flip from one stability domain into another one with different basic functions and controls (Holling 1973, Levin et al. 1998, Scheffer et al. 2001). As a consequence, also the level, composition and quality of ecosystem services may abruptly and irreversibly change. Examples encompass a diverse set of ecosystem types that are highly relevant for economic use, such as boreal forests, semi-arid rangelands, wetlands, shallow lakes, coral reefs, or high-seas fisheries (Gunderson and Pritchard 2002).

The term "resilience" has been used to denote an ecosystem's ability to maintain its basic functions and controls under disturbances (Holling 1973, Carpenter et al. 2001). The economic relevance of ecosystem resilience is obvious, as a system flip may entail huge welfare losses.[1] For example, a combination of drought, fire and ill-adapted livestock grazing management in sub-Saharan Africa, central Asia and Australia have lead to severe degradation and desertification of semi-arid rangelands, which provide subsistence livelihood for more than one billion people worldwide. Once degraded, these grassland ecosystems cannot be used as pasture anymore (Perrings and Walker 1995, Perrings and Stern 2000). In Africa alone, almost 75 % of semi-arid regions are threatened by degradation and desertification (UNO 2002). Worldwide, the income loss associated with desertification of agricultural land is estimated to some 42 billion US dollars per year (UNCCD 2005).

An ecosystem's resilience in a given stability domain can be measured by the probability that exogenous perturbations make the system flip into another stability domain.

[1] Accordingly, some have included a reference to the provision of desired ecosystem services right into the definition of ecosystem resilience as the capacity of an ecosystem "to maintain desired ecosystem services in the face of a fluctuating environment and human use" (Brand and Jax 2007: 3, referring to Folke et al. 2002).

Therefore, enhancing the resilience of a particular (desired) domain reduces the likelihood of a flip into another (less desired) domain. It is for this reason that ecosystem resilience has been referred to as "insurance", e.g. in the following manner:

> "Resilience can be regarded as an insurance against flips of the system into different basins of stability." (Mäler 2008: 17)

> "[R]esilience [...] provides us with a kind of insurance against reaching a non-desired state." (Mäler et al. 2009: 48)

> "The link between biodiversity, ecosystem resilience and insurance should now be transparent. [...] It follows that the value of biodiversity conservation lies in the value of that protection: the insurance it offers against catastrophic change." (Perrings 1995: 72)

> "The resilience of the ecological system provides 'insurance' within which managers can affordably fail and learn while applying policies and practices." (Holling et al. 2002: 415)

So far in the literature, the term "insurance" is employed in a rather metaphoric manner – as a metaphor for "keeping an ecosystem in a desirable domain". It is used to convey the message that resilience is a desirable property of some ecosystem since it helps to prevent catastrophic and irreversible reductions in ecosystem service flows. While ecosystem resilience obviously and undoubtedly includes an insurance aspect, no explicit attempt has been made so far to use a clearly defined concept of "insurance" from the established literature on insurance and financial economics. As a result, it remains unclear what exactly constitutes the economic insurance value of ecosystem resilience, how it depends on ecosystem properties and on the ecosystem user's risk preferences, and how it relates to the total economic value of ecosystem resilience.

In an attempt to conceptually determine and to empirically capture the economic value of ecosystem resilience, Mäler et al. (2007) and Walker et al. (2007) have suggested to use the shadow price of resilience as a measure of its economic value. They calculate the present discounted value of future improvements in welfare from ecosystem services, where these future improvements accrue from reduced risks of a system flip due to a unit increase in the initial level of resilience. While this procedure establishes the total economic value of resilience, it does not explicitly relate it to any idea of "insurance".

In this paper, we aim to close that gap and to provide some conceptual clarification. Any idea of "insurance" fundamentally refers to a combination of three elements: (i) the objective characteristics of risk in terms of different possible states of nature, (ii) people's subjective risk preferences over these states, and (iii) a mechanism that allows mitigation of (i) in view of (ii). We believe that the ongoing discussion of resilience as an insurance could be clarified and fruitfully advanced if reference to these three elements was made explicit and rigorous, and we propose an analytical framework for that purpose. We adopt a clear and generally accepted definition of "insurance" from the risk and finance literature, according to which *insurance* is an action or institution that mitigates the influence of uncertainty on a person's well-being (McCall 1987). Based on this definition, we conceptualize resilience's economic insurance value as the value of one very specific function of resilience: to reduce an ecosystem user's income risk from using ecosystem services under uncertainty. We also analyze how exactly the insurance value of ecosystem resilience depends on ecosystem properties and on the ecosystem user's risk preferences.

Our analysis yields several interesting and important results. First, the insurance value of resilience is negative for low levels of resilience and positive for high levels of resilience. That is, ecosystem resilience actually functions as an economic insurance only at sufficiently high levels of resilience; it does *not* function as an economic insurance at low levels of resilience. Second, the (marginal) insurance value of resilience increases monotonically with the level of resilience. This is in contrast to normal economic goods, the (marginal) value of which *de*creases with their quantity. Third, the insurance value of resilience is one additive component of its total economic value. That is, the total economic value of resilience is larger than just its insurance value. While the latter may be negative, the total economic value of resilience turns out to be always positive.

The remainder of the paper is organized as follows. In Section 2, we present a stylized model of an ecological-economic system that describes how different degrees of ecosystem resilience are related to different system outcomes. In Section 3, we then clarify what exactly we mean by "insurance" and "insurance value". On this basis, in Section 4, we then present our results about the economic insurance value and the total value of ecosystem resilience, with all proofs and formal derivations contained in the Appendix. In Section 5, we discuss these findings and draw conclusions.

2 Model

To discuss the economic insurance value of ecosystem resilience, we propose the following simple and stylized model of an ecological-economic system. Consider an ecosystem that potentially exhibits two different stability domains with respective levels of ecosystem services-production. One domain is characterized by a high level of ecosystem service provision and corresponding net income $y_H \in Y$; the other domain is characterized by a low level of ecosystem service provision and corresponding net income $y_L \in Y$; with $Y \subseteq \mathrm{I\!R}_+$ and $y_L < y_H$, so that

$$\Delta y := y_H - y_L > 0 \ . \tag{1}$$

From the perspective of human ecosystem use, the former ecosystem state is therefore preferred over the latter.

Initially, the ecosystem is in the preferred high-production stability domain. In this domain, exogenous stochastic disturbances threaten to trigger a shift to the undesirable low-production stability domain. Such a shift may occur with a probability p with $0 \leq p \leq 1$. Conversely, the ecosystem stays in the high-production domain with probability $1-p$.

In line with Holling's (1973) notion of resilience as the maximum amount of disturbance a system can absorb in a given stability domain while still remaining in that stability domain, we measure resilience as a continuous state variable $R \in [0, \bar{R}]$ that determines the probability of the system flipping into another stability domain "given

(a) its current state and (b) the disturbance regime" (Perrings and Walker 2004: 121):

$$p = p(R) \qquad \text{with} \qquad p'(R) < 0 \text{ for all } R \tag{2}$$

$$\text{and} \qquad p(0) = 1,\ p(\bar{R}) = 0\ . \tag{3}$$

In words, the higher the ecosystem's resilience in the high-production domain, the lower the probability that it flips into the low-production domain due to exogenous disturbance; with zero resilience, it flips for sure; and with a maximum resilience of $\bar{R}$ it will not flip at all.

The ecosystem user thus faces a binary income lottery $\{y_L, y_H; p(R), (1-p(R))\}$. That is, given that the system is initially in the high-production stability domain and is characterized by a level R of resilience, the system will provide net income y_L with probability $p(R)$ and net income y_H with probability $1-p(R)$. Obviously, with changing level of resilience R the statistical distribution of income will also change. As in our simple analytical framework only the level of resilience R may vary, R uniquely characterizes the income lottery. One may thus speak of "the income lottery R".

We assume that the ecosystem user only cares about (uncertain) income, and not directly about the underlying states of nature in terms of resilience. The ecosystem user's preferences over income lotteries are represented by a von Neumann-Morgenstern expected utility function

$$U = \mathcal{E}_R[u(y)] \qquad \text{with} \qquad u'(y) > 0 \text{ and } u''(y) < 0 \text{ for all } y\ , \tag{4}$$

where $\mathcal{E}_R$ is the expectancy operator based on the probabilities of lottery R, y is net income,[2] and $u(y)$ is a continuous and differentiable Bernoulli utility function which is assumed to be increasing and strictly concave, i.e. the ecosystem user is non-satiated and risk averse.[3] In order to study in the most simple way how the insurance value of

[2]For notational simplicity, y denotes both the random variable income and income in a particular state of the world.

[3]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).

resilience depends on the ecosystem user's degree of risk aversion, we assume that the ecosystem user is characterized by constant absolute risk aversion in the sense of Arrow (1965) and Pratt (1964), i.e. $-u''(y)/u'(y) \equiv$ const., so that the Bernoulli utility $u(y)$ function is

$$u(y) = -e^{-\rho y} \qquad \text{with} \qquad \rho > 0 \ , \tag{5}$$

where the parameter ρ measures the ecosystem user's risk aversion.

3 Conceptual clarification: insurance and insurance value

Before we derive results about the economic insurance value of ecosystem resilience in the next section, in this section we provide some conceptual clarification about the exact and general definition of "insurance" and "insurance value". Adopting a very general and widely accepted definition, insurance may be defined in the following way (cf. McCall 1987).

Definition 1
Insurance is an action or institution that mitigates the influence of uncertainty on a person's well-being or on a firm's profitability.

In the concrete setting described in the previous section, the term "insurance" takes on a more concrete meaning. As a person's (here: the ecosystem user's) *well-being* is determined by a preference relation over income lotteries, insurance is about the mitigation of income uncertainty, and the person's risk preferences specify what changes in the income lottery actually constitute a "mitigation". Thereby, *uncertainty* exists due the existence of many potential future states of the world (here: high and low ecosystem-service production), in each of which the state-specific income is known (y_H and y_L) and the probability of which is also known ($1-p(R)$ and $p(R)$). That is, uncertainty comes in the form of *risk* in the sense of Knight (1921).

In this more concrete understanding of the term, insurance may come in many forms.

One example is the classic insurance contract that an insuree signs with an insurance company under private law, and which specifies that the insuree pays an insurance premium to the insurance company in all states of the world and in exchange obtains from the insurance company an indemnification payment if and only if one particular unfavorable state of the world should occur. Another example is so-called “self-protection” (Ehrlich and Becker 1972), which means that a person undertakes some real action that reduces the probability by which an unfavorable – in terms of net income – state of the world occurs. In this terminology, an increase in an ecosystem’s resilience by the ecosystem manager may be interpreted as insurance because it is a real action that may provide self-protection in terms of net income obtained from the ecosystem.

In order to precisely define and measure the economic insurance value of some act of self-protection (here: an increase in the ecosystem’s resilience), we follow Baumgärtner (2007: 103–104). One standard method of how to value the riskiness of an income lottery to a decision maker in monetary terms is to calculate the *risk premium* RP of the lottery, which is defined by (e.g. Kreps 1990, Varian 1992: 181)[4]

$$u\left(\mathcal{E}_R[y] - RP\right) = \mathcal{E}_R\left[u(y)\right] \ . \tag{6}$$

In words, the risk premium RP is the amount of money that leaves a decision maker equally well-off, in terms of utility, between the two situations of (i) receiving for sure the expected pay-off from the income lottery R, $\mathcal{E}_R[y]$, minus the risk premium RP, and (ii) playing the risky income lottery R with random pay-off y.[5] In the model employed here, the risk premium as defined by Equation (6) uniquely exists because, by assumption (cf. Section 2), $y \in Y$ with Y as an interval of $\mathbb{R}$, and u is continuous and strictly increasing (Kreps 1990: 84). In general, if the Bernoulli utility function u characterizes a risk averse decision maker, i.e. if $\rho > 0$ in Equation (5), the risk premium RP is strictly positive.

[4]By Equation (6), $\mathcal{E}_R[y] - RP$ is the *certainty equivalent* of lottery R, as it yields exactly the same expected utility as playing the risky lottery, $\mathcal{E}_R\left[u(y)\right]$.

[5]The risk premium is, thus, the maximum amount of money that a decision maker would be willing to pay for getting the expected pay-off from the income lottery, $\mathcal{E}[y]$, for sure instead of playing the risky income lottery with random pay-off y.

The economic insurance value of resilience can now be defined based on the risk premium of the income lottery R as follows (Baumgärtner 2007: 103).

Definition 2

The *insurance value* V of resilience is given by the change of the risk premium RP of the income lottery R due to a marginal change in the level of resilience R:

$$IV(R) := -\frac{dRP(R)}{dR} \ . \tag{7}$$

Thus, the economic insurance value of ecosystem resilience is the marginal value of its function to reduce the risk premium of the ecosystem user's income risk from using ecosystem services under uncertainty. Being a marginal value, it depends on the existing level of resilience R. The minus sign in the defining Equation (7) serves to express a *reduction* of the risk premium as a *positive* value.

As it is apparent already from Definition 2 (and as it will become more explicit in the following section), the economic insurance value of ecosystem resilience has, in general, an objective and a subjective dimension. The objective dimension is captured by the ecosystem's sensitivity of the flip probability $p(R)$ to changes in the level of resilience R; the subjective dimension is captured by the ecosystem user's degree of risk aversion, ρ. If the flip probability would not vary with the level of resilience (i.e. $p'(R) \equiv 0$), or if the ecosystem user was risk-neutral (i.e. $\rho = 0$), the risk premium RP of income lottery R would not vary with R, thus yielding a vanishing insurance value of resilience.

The insurance value of resilience is only a fraction of resilience's total economic value, namely the value of its function to reduce the risk premium of the ecosystem user's income risk from using ecosystem services under uncertainty. Beyond its insurance value, resilience also has economic value in its function to increase the ecosystem user's expected income from ecosystem services. In order to characterize the insurance value of resilience as a fraction of its total economic value, we adopt the following general and widely accepted definition of total economic value under uncertainty (e.g. Freeman 2003: Chap. 8).

Definition 3

The *total economic value* TEV of resilience is given by the maximum willingness to pay WTP per unit for a marginal increase of ΔR in the level of resilience R:

$$TEV(R) := \lim_{\Delta R \to 0} \frac{WTP(\Delta R)}{\Delta R} \ , \tag{8}$$

where WTP is defined through

$$\mathcal{E}_R \left[u(y) \right] = \mathcal{E}_{R+\Delta R} \left[u(y - WTP(\Delta R)) \right] \ . \tag{9}$$

In words, we measure the total economic value of a change ΔR in resilience as the maximum willingness to pay (WTP) for that change, more exactly as the WTP per marginal unit of resilience. The maximum willingness to pay for the increase ΔR in resilience is the amount of money that leaves an individual indifferent, in terms of expected utility, between the two situations of (i) resting in the original position with resilience R and (ii) paying the amount WTP and getting into a situation with resilience $R+\Delta R$.[6] As value is typically expressed as a per-unit quantity characterizing a marginal change, we divide WTP by ΔR and let $\Delta R \to 0$ to obtain the total economic value of resilience. Being a marginal value, it depends on the existing level of resilience R.

In the simple model studied here, with no other constraints or alternative options for action in place, the total economic value of resilience as defined by Definition 3 is exactly equivalent to its shadow price (as measured e.g. by Mäler et al. 2007).

[6] In the language of welfare measurement, WTP is the Hicksian compensating surplus for a finite change of ΔR in the level of resilience (Hicks 1943, Freeman 2003: Chap. 3). Alternatively, one could also use the Hicksian equivalent surplus to measure the monetary value of the welfare change associated with a finite change of ΔR in the level of resilience, that is, the minimum amount of monetary compensation to the individual ("willingness to accept", WTA) that leaves the individual indifferent between the two situations of (i) resting in the original position with resilience R and receiving a monetary payment of WTA and (ii) getting into a situation with resilience $R + \Delta R$. In general, WTP and WTA will differ for finite changes of ΔR. However, for the marginal changes studied here, i.e. $\Delta R \to 0$, WTP and WTA coincide, so that the value of $TEV(R)$ does not depend upon whether WTP or WTA is used in the defining Equation (8).

4 Results

Using the concepts defined in Section 3, we can make the following statements about the model described in Section 2, and, thus, about the economic insurance value of ecosystem resilience.

Lemma 1

The risk premium $RP(R)$ of the income lottery characterized by the level of resilience R is given by

$$RP(R) = -p(R)\Delta y + \frac{1}{\rho} \ln \left[1 + p(R)\left(e^{\rho \Delta y} - 1\right)\right] \;, \tag{10}$$

which has the following properties:

(i)

$$RP(0) = RP(\bar{R}) = 0 \quad \text{and} \quad RP(R) > 0 \text{ for all } R \in (0, \bar{R}) \;. \tag{11}$$

(ii)

$$RP'(R) \left\{ \begin{array}{c} > \\ = \\ < \end{array} \right\} 0 \qquad \text{for} \qquad R \left\{ \begin{array}{c} < \\ = \\ > \end{array} \right\} \tilde{R} \;, \tag{12}$$

$$\text{where} \quad \tilde{R} := p^{-1} \left(\frac{1}{\rho \Delta y} - \frac{1}{e^{\rho \Delta y} - 1} \right) \;, \tag{13}$$

$$\text{so that} \quad 0 < \tilde{R} < \bar{R} \quad \text{and} \quad \frac{d\tilde{R}}{d\rho}, \frac{d\tilde{R}}{d\Delta y} > 0 \tag{14}$$

(iii)

$$\frac{dRP(R)}{d\rho} > 0 \quad \text{and} \quad \lim_{\rho \to 0} RP(R) = 0 \quad \text{for all } R \in (0, \bar{R}) \;. \tag{15}$$

(iv)

$$\frac{dRP(R)}{d\Delta y} > 0 \quad \text{and} \quad \lim_{\Delta y \to 0} RP(R) = 0 \quad \text{for all } R \in (0, \bar{R}) \;. \tag{16}$$

Proof. See Appendix A.1. □

Result (11) states that the risk premium of income lottery R is strictly positive at all levels of resilience in between 0 and the maximum level of $\bar{R}$, and is zero at the extreme levels of 0 and $\bar{R}$. That is, income is risky at all levels of resilience in between 0 and $\bar{R}$;

and only at the extreme levels of 0 and $\bar{R}$ does the income risk vanish, as in the case $R = 0$ the system will flip into the low-productivity domain with income y_L for certain, and at $R = \bar{R}$ the system will remain in the high-productivity domain with income y_L for certain.

As a consequence of Result (11), the risk premium varies with the level of resilience in a non-monotonic way (Figure 1, orange line). Result (12) states that there uniquely exists a level of the domain's resilience, $\tilde{R}$ ($\tilde{R} = 0.647$ in Figure 1), at which the risk premium is maximal, that is, the income lottery is most risky. For $R > \tilde{R}$ a marginal increase in resilience reduces the risk premium, and for $R < \tilde{R}$ a marginal increase in resilience raises the risk premium. This maximum-income-risk level of resilience $\tilde{R}$, according to Equation (13), is strictly in between 0 and $\bar{R}$, and increases with the degree of risk aversion ρ and the potential income loss Δy.

The more risk-averse the ecosystem user is, the larger the perceived riskiness of the income lottery R and the larger the associated risk premium (Result 15). For a risk-neutral individual, on the other hand, the risk premium would be 0 for all R. Similarly, for the potential income loss Δy (Result 16): the risk premium raises with an increasing potential income loss Δy. For equal income levels in both stability domains, which means no income loss in case of a system flip ($\Delta y = 0$), the risk premium would be 0 over the whole range of R.

Having explored the effect of the ecosystem user's risk preferences and ecosystem properties on the risk premium of income lottery R, we can now discuss the insurance value of resilience as introduced in Definition 2.

Proposition 1

The insurance value of resilience, $IV(R)$, is given by

$$IV(R) = p'(R) \left\{ \Delta y - \frac{1}{\rho} \frac{e^{\rho \Delta y} - 1}{1 + p(R)\left(e^{\rho \Delta y} - 1\right)} \right\} , \tag{17}$$

which has the following properties:

(i)

$$IV(R)\left\{\begin{array}{c}<\\=\\>\end{array}\right\}0 \quad \text{for} \quad R\left\{\begin{array}{c}<\\=\\>\end{array}\right\}\tilde{R}\text{ , where }\tilde{R}\text{ is given by Equation (13) .} \tag{18}$$

(ii)

$$IV'(R) > 0 \quad \text{for all } R \quad \text{if} \quad p''(R) \quad \text{not too large.}^{7} \tag{19}$$

(iii)

$$\frac{dIV(R)}{d\rho}\left\{\begin{array}{c}<\\=\\>\end{array}\right\}0 \quad \text{for} \quad R\left\{\begin{array}{c}<\\=\\>\end{array}\right\}\tilde{R}\ , \quad \text{and} \quad \lim_{\rho\to 0} IV(R) = 0 \quad \text{for all } R\ . \tag{20}$$

(iv)

$$\frac{dIV(R)}{d\Delta y}\left\{\begin{array}{c}<\\=\\>\end{array}\right\}0 \quad \text{for} \quad R\left\{\begin{array}{c}<\\=\\>\end{array}\right\}\tilde{R}\ , \quad \text{and} \quad \lim_{\Delta y\to 0} IV(R) = 0 \quad \text{for all } R\ . \tag{21}$$

Proof. See Appendix A.2. □

Result (18) states that the insurance value of resilience may be negative or positive, depending on the level of resilience R. If resilience is below the maximum-income-risk level $\tilde{R}$, an increases in resilience raises the risk premium (Result 12) and therefore, as the insurance value is defined as the reduction in the risk premium (Definition 2), resilience has a negative insurance value for all $R < \tilde{R}$. Only if $R > \tilde{R}$, an increase in resilience reduces the risk premium and the insurance value is positive (Figure 1, green line).

[7] $p''(R) \gg 0$ would imply a relationship between p and R such that the first marginal units of resilience starting from $R = 0$ had a huge impact on the reduction of the flip probability p, whereas all later units of resilience only had a negligible effect. Under such circumstances, the insurance value of resilience steeply increases in the vicinity of $R = 0$ from a negative value to its maximum (positive) value and then slightly descreases again as R increases. We reckon that $p''(R) > 0$ might be a plausible assumption and, indeed, Result (19) does hold also for a considerable range of parameter values where $p''(R) > 0$. The restriction that p'' not be "too large" only concerns an extreme case.

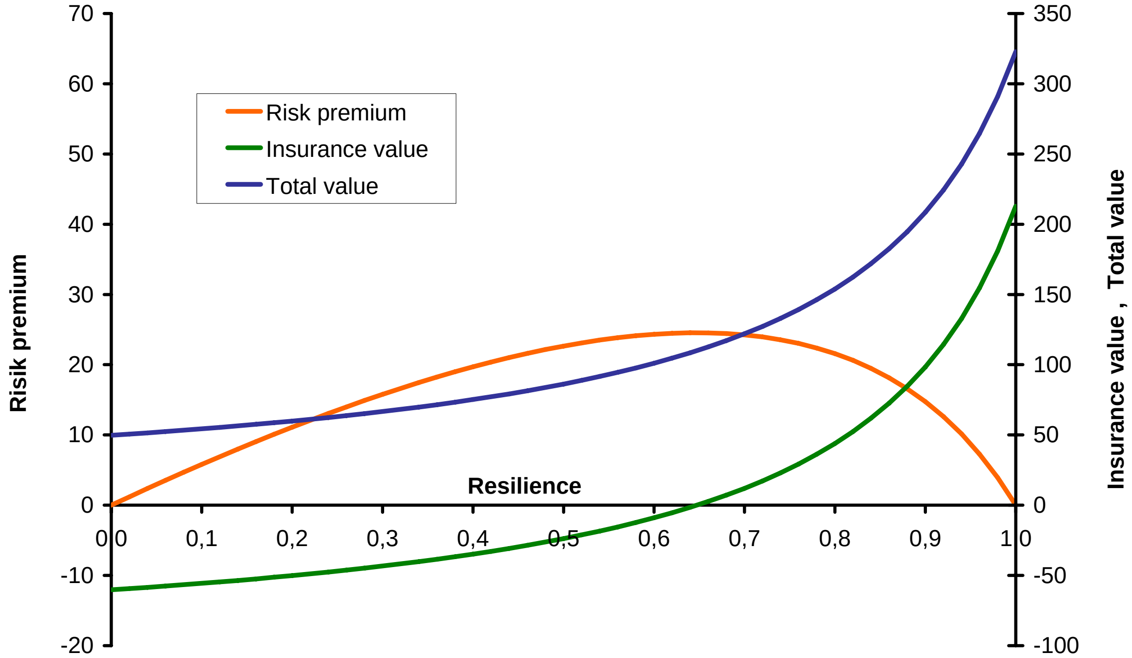

Figure 1: Risk premium, insurance value and total value as a function of resilience. Parameter values: $\bar{R} = 1$, $\Delta y = 110$, $\rho = 0.017$.

Result (19) states that the insurance value of ecosystem resilience increases with the level of resilience. That is, the higher the level of resilience, the more valuable – as an insurance – is a marginal increase in resilience. This is unusual and in contrast to normal economic goods, the marginal value of which decreases with their amount: normally, the more abundant a good, the less valuable the next marginal unit.

Result (20) states how the ecosystem user's degree of risk-aversion affects the insurance value. If the ecosystem user was risk neutral ($\rho = 0$), the insurance value would vanish for all levels of resilience R. With increasing risk-aversion, the insurance value raises for high levels of $R < \tilde{R}$ and decreases for low levels of $R < \tilde{R}$. Thus, the more risk-averse the ecosystem user is, the steeper the curve for IV (green line in Figure 1). The same goes for the potential income loss Δy (Result 21). For equal income levels in both stability domains, which means no income loss in case of a system flip ($\Delta y = 0$), the insurance value would vanish for all levels of resilience R. With increasing potential income loss Δy, the IV-curve gets steeper, as the insurance value decreases for $R < \tilde{R}$

and raises for $R > \tilde{R}$.

Also, $\tilde{R}$ shifts to the right with both increasing risk-aversion ρ and increasing potential income loss Δy. For very high values of ρ or Δy the IV-curve appears to be sharply bended around $\tilde{R}$, since the insurance value raises faster with ρ or Δy in the range of $R > \tilde{R}$ than it decreases in the range of $R < \tilde{R}$.

Having discussed the effect of the ecosystem user's risk preferences and ecosystem properties on the insurance value of resilience, we now turn to discussing how the insurance value of ecosystem resilience relates to its total economic value (Definition 3).

Proposition 2

The total economic value of resilience, $TEV(R)$, is given by

$$TEV(R) = -p'(R)\frac{1}{\rho}\frac{e^{\rho\Delta y} - 1}{1 + p(R)\left(e^{\rho\Delta y} - 1\right)} = -p'(R)\Delta y + IV(R) \ , \qquad (22)$$

which has the following properties:

(i)

$$TEV(R) > 0 \quad \text{for all } R. \qquad (23)$$

(ii)

$$TEV'(R) > 0 \quad \text{for all } R \quad \text{if} \quad p''(R) \quad \text{not too large.}^{8} \qquad (24)$$

(iii)

$$\frac{dTEV(R)}{d\rho} = \frac{dIV(R)}{d\rho}\left\{\begin{array}{c} < \\ = \\ > \end{array}\right\} 0 \quad \text{for} \quad R\left\{\begin{array}{c} < \\ = \\ > \end{array}\right\}\tilde{R} \qquad (25)$$

$$\text{and} \quad \lim_{\rho\to 0} TEV(R) = -p'(R)\Delta y \quad \text{for all } R \ . \qquad (26)$$

(iv)

$$\frac{dTEV(R)}{d\Delta y} > 0 \quad \text{and} \quad \lim_{\Delta y\to 0} TEV(R) = 0 \quad \text{for all } R \ . \qquad (27)$$

Proof. See Appendix A.3. □

[8] See Footnote 7.

From Equation (22) it becomes obvious that the total economic value of resilience is the sum of two components: the expected increase in income due to a marginal increase in resilience, $-p'(R)\Delta y$, which is always positive, and the insurance value of increased resilience, which may be negative or positive (cf. Proposition 1). This reflects the fact that an increase in ecosystem resilience has two effects on the ecosystem user's income: (i) it raises the expected income; (ii) it may raise or lower the riskiness of income, i.e. deviations from expected income. Thus, the total value of resilience is more than its insurance value, or, put the other way round, the insurance value is a value component over and above the usually acknowledged mean-increasing effect.

Figure 1 shows the total economic value as a function of resilience (blue line). In the figure, the expected value of resilience, $-p'(R)\Delta y$, is just the difference between the curves for IV (green) and TEV (blue). Whereas the insurance value $IV(R)$ of resilience may be positive or negative, depending on the level of resilience R, the expected value of resilience, $-p'(R)\Delta y$, is positive and constant at all levels of resilience R. As a consequence, for $R < \tilde{R}$ where the insurance value is negative, the total economic value of resilience is smaller than its expected value. Yet, at all levels of resilience the total value is strictly positive (Result 23). That means, even if the insurance value should be negative, the mean-increasing value of resilience is large enough to offset this negative effect on the total value.

Result (24) states that the total economic value raises with the level of resilience. This unusual result – for the marginal value of a good to increase with its abundance – is exclusively due to $IV'(R) > 0$ (Result 19). The expected value of an additional unit of resilience stays constant over the whole range of $R \in [0, \bar{R}]$. Hence, it is the insurance value that is the driving force behind the shape of TEV-curve in Figure 1.

Results (25), (26) and (27) explore how the ecosystem user's risk aversion and the potential income loss from a system flip affect the total economic value. Since it is the insurance value that mainly determines how changes in the parameters ρ and Δy affect tho total value, the results are similar to those of Proposition 1. For a risk-neutral ecosystem user, resilience's insurance function of reducing income uncertainty is not valuable and the total economic value converges towards the expected value (Result 26).

With increasing risk-aversion the total economic value raises sharply for levels of R above $\tilde{R}$ but decreases for all R below $\tilde{R}$ (Result 25).

For equal income levels in both stability domains, which means no income loss in case of a system flip ($\Delta y = 0$), the total economic value of an additional unit of resilience would obviously be 0 for all levels of R. With increasing potential income loss Δy, the insurance value may increase or decrease depending on the level of resilience (Result 21), but the expected value $-p'(R)\Delta y$ will always increase, with the latter effect always dominating the former, so that the total economic value increases with Δy for all levels of resilience R (Result 27).

Again, for increasing parameter values of ρ or Δy, the maximum-income-risk level of resilience $\tilde{R}$, where the insurance value vanishes and the total economic value equals just the expected value of resilience, increases and the TEV-curve in Figure 1 appears more and more sharply bended around $\tilde{R}$.

5 Discussion and Conclusion

In this paper we have provided a conceptual clarification of the economic insurance value of ecosystem resilience. We have adopted a general and widely accepted definition of *insurance* as mitigation of the influence of uncertainty on a person's well-being (McCall 1987), and of *insurance value* as a reduction in the risk premium of the person's income risk lottery (Baumgärtner 2007). That way, we have clearly distinguished the insurance value of ecosystem resilience, which is due to its function to reduce the *riskiness* of income ("risk mitigation"), from other components of its total economic value, which are due to resilience's function to raise the *expected* income from ecosystem services.

Our analysis has yielded several interesting and important results. First, the insurance value of resilience is negative for low levels of resilience and positive for high levels of resilience. That is, ecosystem resilience actually functions as an economic insurance, i.e. it reduces the riskiness of income from ecosystem services, only at sufficiently high levels of resilience; it does *not* function as an economic insurance but – just on the contrary – increases the riskiness of income at low levels of resilience.

Second, the (marginal) insurance value as well as the (marginal) total value of resilience increase monotonically with the level of resilience: the higher the level of resilience, the more valuable is another unit of resilience. This is in contrast to normal economic goods, the (marginal) value of which *de*creases with their quantity. As unusual as this increasing-returns property may be for normal economic goods, it is not implausible and also known from other goods which are of systemic importance and thus give rise to a non-concavity in the social objective function, such as e.g. information (Radner and Stiglitz 1984) or biodiversity conservation (Hunter 2009).

Third, the insurance value of resilience is one additive component of its total economic value. The other component is the rise in expected income due to a higher level of resilience. So, the insurance value of resilience, which is due to its risk-mitigation function, is a value component over and above the change in the expected value of the income lottery. While the former may be positive or negative, the latter is always positive, and the total economic value of resilience is always positive. One reason for distinguishing between the two value components of ecosystem resilience, and for studying the insurance value separately, might be that in an encompassing management-and-decision context the different functions of resilience may have different substitutes. For example, in many rural areas of developing countries there is no substitute for agro-ecosystem resilience in enhancing the mean level of farming income, but there is now more and more financial insurance available that serves as a substitute for resilience's function to mitigate income risks (Quaas and Baumgärtner 2008).

While we have made one specific assumption about risk preferences, i.e. constant absolute risk aversion, actually all of our results qualitatively hold more generally for all risk preferences satisfying the von-Neumann-Morgenstern axioms. These axioms, including continuity and context-independence, appear plausible for standard small-risk situations. But one may doubt that they adequately describe people's risk preferences when it comes to catastrophic (i.e. discontinuous) risk that irreversibly threatens the subsistence level of income, as it is the case for many threats to the resilience of life-supporting ecosystems. For such risks, it may be interesting to study how resilience provides insurance under, e.g., safety-first preferences (Roy 1952, Telser 1955, Kataoka

1963).

One general lesson from our analysis for further discussions of resilience as an insurance is that the concept of insurance fundamentally refers to both the objective characteristics of risk in terms of different possible states of nature and people's subjective risk preferences over these states. In particular, explicit reference to people's risk preferences is needed to meaningfully discuss insurance, to specify the economic insurance value of resilience, and to meaningfully distinguish the insurance value from other components of the total economic value of ecosystem resilience.

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Appendix

A.1 Proof of Lemma 1

Explicating the general definition of the risk premium (Equation 6) by the CARA-utility function (Equation 5) yields

$$-e^{-\rho(\mathcal{E}_R[y]-RP(R))} = -(1-p(R))e^{-\rho y_H} - p(R)e^{-\rho y_L} \ , \tag{A.28}$$

which can be rearranged into

$$e^{\rho RP(R)} = \frac{-(1-p(R))e^{-\rho y_H} - p(R)e^{-\rho y_L}}{-e^{-\rho \mathcal{E}_R[y]}} \ . \tag{A.29}$$

Using $\mathcal{E}_R[y] = p(R)y_L + (1 - p(R))y_H$ and (1), (A.29) can be solved for $RP(R)$ and finally leads to Result (10).

ad (i). Inserting $p(0) = 1$ or $p(\bar{R}) = 0$ into (10) immediately yields 0 (Result 11a). Strict positivity of $RP(R)$ for all $R \in (0, \bar{R})$ (Result 11b) can be demonstrated by

Taylor expansion of expression (10) and identifying 0 as a lower bound:

$$e^{\rho\Delta y} > 1 + \rho\Delta y + (\rho\Delta y)^2/2, \quad \text{(A.30)}$$

$$p(R)\left(e^{\rho\Delta y} - 1\right) > p(R)\left[\rho\Delta y + (\rho\Delta y)^2/2\right], \quad \text{(A.31)}$$

$$\ln\left[1 + p(R)\left(e^{\rho\Delta y} - 1\right)\right] > p(R)\rho\Delta y, \quad \text{(A.32)}$$

$$-p(R)\Delta y + \frac{1}{\rho}\ln\left[1 + p(R)\left(e^{\rho\Delta y} - 1\right)\right] > 0 \ . \quad \text{(A.33)}$$

ad (ii). Differentiating Result (10) with respect to R yields

$$\frac{dRP(R)}{dR} = -p'(R)\left\{\Delta y - \frac{1}{\rho}\frac{e^{\rho\Delta y} - 1}{1 + p(R)\left(e^{\rho\Delta y} - 1\right)}\right\} \ . \quad \text{(A.34)}$$

By Assumption (2), p' is strictly negative for all R. Hence, a necessary condition for $dRP(\tilde{R})/dR = 0$ is

$$\Delta y = \frac{1}{\rho}\frac{e^{\rho\Delta y} - 1}{1 + p(\tilde{R})\left(e^{\rho\Delta y} - 1\right)}\} \ . \quad \text{(A.35)}$$

which can be solved for $p(\tilde{R})$,

$$p(\tilde{R}) = \frac{1}{\rho\Delta y} - \frac{1}{e^{\rho\Delta y} - 1} \ , \quad \text{(A.36)}$$

which is equivalent to Result (13). To check the second-order condition for $\tilde{R}$, differentiate (A.34) again with respect to R:

$$\frac{d^2RP(R)}{dR^2} = -p''(R)\left\{\Delta y - \frac{1}{\rho}\frac{e^{\rho\Delta y} - 1}{p(R)(e^{\rho\Delta y} - 1) + 1}\right\} - \frac{[p'(R)]^2}{\rho}\frac{(e^{\rho\Delta y} - 1)^2}{[p(R)(e^{\rho\Delta y} - 1) + 1]^2} \ . \quad \text{(A.37)}$$

For $p''(R) \equiv 0$ the first term on the right hand side vanishes. As the second term is strictly negative for all R, $d^2RP(R)/dR^2 < 0$ and $\tilde{R}$ is a maximum of $RP(R)$.

In order to study the properties of $\tilde{R}$ (Equation 13) introduce $x \equiv \rho\Delta y$ and

$$F(x) = \frac{1}{x} - \frac{1}{e^x - 1} \ , \quad \text{(A.38)}$$

so that (A.36) and (13) can be rewritten as

$$p(\tilde{R}) \equiv F(x) \quad \text{and} \quad \tilde{R} \equiv p^{-1}\left(F(x)\right) \ . \quad \text{(A.39)}$$

Note that

$$F'(x) = -\frac{1}{x^2} + \frac{e^x}{(e^x - 1)^2} = \frac{x^2 e^x - (e^x - 1)^2}{x^2(e^x - 1)^2} < 0 \ , \quad \text{(A.40)}$$

so that, with (A.39) and Assumption 2 ($p'(R) < 0$ for all R),

$$\frac{d\tilde{R}}{dx} = \frac{1}{p'(\tilde{R})} F'(x) > 0 \ . \tag{A.41}$$

From that, with $x \equiv \rho \Delta y$ it follows immediately that $d\tilde{R}/d\rho > 0$ and $d\tilde{R}/d\Delta y > 0$.

As $x < e^x - 1$ for all x, $1/x > 1/(e^x - 1)$ and therefore $F(x) > 0$ for all x. Hence, $p(\tilde{R}) > 0$ for all x, which implies, with $p'(R) < 0$ for all R, that $\tilde{R} < \bar{R}$ for all x. On the other hand, as (apply l'Hôpital's rule twice)

$$\begin{aligned} \lim_{x \to 0} F(x) &= \lim_{x \to 0} \frac{e^x - x - 1}{x(e^x - 1)} \\ &= \lim_{x \to 0} \frac{e^x - 1}{(1 + x)e^x - 1} \\ &= \lim_{x \to 0} \frac{1}{2 + x} = \frac{1}{2} \ , \end{aligned} \tag{A.42}$$

and $F'(x) < 0$ for all $x > 0$, one has that $F(x) < 1/2$ for all $x > 0$. Hence, $p(\tilde{R}) < 1/2$ for all x, which implies, with $p'(R) < 0$ for all R, that $\tilde{R} > \hat{R} > 0$ for all x, where $\hat{R}$ is defined through $p(\hat{R}) = 1/2$. This establishes Result (14).

ad (iii). By definition, the risk premium is zero for a risk-neutral decision-maker ($\rho = 0$) and increases with her degree of risk-aversion ρ (eg. Varian 1992), which yields Result (15).

ad (iv). Setting $\Delta y = 0$ in Expression (10) for $RP(R)$ obviously yields $RP(R) \equiv 0$. That the risk premium raises with Δy can be seen from the first derivative of $RP(R)$ with respect to Δy:

$$\begin{aligned} \frac{dRP(R)}{d\Delta y} &= p(R) \left[\frac{e^{\rho \Delta y}}{1 + p(R)\left(e^{\rho \Delta y} - 1\right)} - 1 \right] \\ &= p(R) \left[\frac{1}{p(R) + (1 - p(R))e^{-\rho \Delta y}} - 1 \right] \ . \end{aligned} \tag{A.43}$$

As $e^{-\rho \Delta y} \leq 1$ and $0 \leq p(R) \leq 1$, the denominator in this expression is smaller than 1, so that the term in brackets is positive and the whole expression is positive.

A.2 Proof of Proposition 1

Differentiating $-RP(R)$ with respect to R immediately yields Result (17).

ad (i). Result (18) follows immediately from Definition (7) and Result (12).

ad (ii). Differentiating $IV(R)$ with respect to R yields

$$\frac{dIV(R)}{dR} = p''(R)\left\{\Delta y - \frac{1}{\rho}\frac{e^{\rho\Delta y}-1}{p(R)(e^{\rho\Delta y}-1)+1}\right\} + (p'(R))^2\frac{(e^{\rho\Delta y}-1)^2}{\rho[p(R)(e^{\rho\Delta y}-1)+1]^2} \ . \tag{A.44}$$

For $p''(R) = 0$, the first term on the right hand side vanishes and

$$\frac{dIV(R)}{dR} = (p'(R))^2\frac{(e^{\rho\Delta y}-1)^2}{\rho[p(R)(e^{\rho\Delta y}-1)+1]^2} \tag{A.45}$$

which is positive and proves Result (19).

ad (iii) *and* (iv). Results (20) and (21) follow immediately from Definition (7) and Results (15) and (16).

A.3 Proof of Proposition 2

Explicating Definition (9) of the ecosystem user's WTP by the CARA-utility function (Equation 5) yields

$$\mathcal{E}_R\left[u(y)\right] = -\left[p(R+\Delta R)e^{-\rho(y_L - WTP(\Delta R))} + (1-p(R+\Delta R))e^{-\rho(y_H - WTP(\Delta R))}\right] \tag{A.46}$$

$$= -e^{\rho WTP(\Delta R)}\left[p(R+\Delta R)e^{-\rho y_L} + (1-p(R+\Delta R))e^{-\rho y_H}\right] \ . \tag{A.47}$$

Rearranged and reformulated in more general terms this becomes

$$e^{\rho WTP(\Delta R)} = \frac{\mathcal{E}_R\left[u(y)\right]}{\mathcal{E}_{R+\Delta R}\left[u(y)\right]} \ . \tag{A.48}$$

Inserting the CARA-utility function (5) and solving for $WTP(\Delta R)$ finally yields

$$WTP(\Delta R) = \frac{1}{\rho}\ln[(1-p)+pe^{\rho\Delta y}] - \frac{1}{\rho}\ln[(1-p(R+\Delta R)) + p(R+\Delta R)e^{\rho\Delta y}] \ . \tag{A.49}$$

Following Definition (3)

$$TEV(R) := \lim_{\Delta R\to 0}\frac{WTP(\Delta R)}{\Delta R} \tag{A.50}$$

and using l'Hôpital's rule to evaluate the limit leads to

$$TEV(R) = -p'(R)\frac{1}{\rho}\frac{e^{\rho\Delta y}-1}{1+p(R)\left(e^{\rho\Delta y}-1\right)} \ . \tag{A.51}$$

Comparison with Result (17) proves that $TEV(R) = -p'(R)\Delta y + IV(R)$ (Result 22).

ad (i). Expression (A.51) for TEV is positive, since $-p'(R)$ and the term $(e^{\rho\Delta y} - 1)$ are strictly positive. Hence, Result (23) holds.

ad (ii). Since it follows from Result (22) that $dTEV(R)/dR = dIV(R)/dR$, Result (24) follows immediately from Result (19).

ad (iii). Since it follows from Result (22) that $dTEV(R)/d\rho = dIV(R)d\rho$, Result (25) follows immediately from Result (20). Result (26) follows directly from Results (20) and (22).

ad (iv). Differentiating Expression (A.51) for $TEV(R)$ with respect to Δy yields

$$\frac{dTEV(R)}{d\Delta y} = -p'(R)\frac{e^{\rho\Delta y}}{[1 + p(R)(e^{\rho\Delta y} - 1)]^2} \tag{A.52}$$

which is positive and proves Result (27).

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