The Insurance Value of Conservative Biodiversity Management

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Abstract. The ecological literature suggests that improved ecosystem quality leads to a lower variance of ecosystem services. Thus, quality-improving ecosystem management has an insurance value to risk-averse decision makers. We analyze a conceptual ecological-economic model in which such management measures generate both a private benefit and positive externalities on other ecosystem users. We study the implications of risk and risk-aversion for optimal ecosystem management and policy design. Extending the literature which concentrates on the shape of the utility function, we show that with increasing risk and risk-aversion the private efforts to improve ecosystem quality increase, but whether the market distortion improves or worsens depends on how the ecosystem functions. The extent of market failure decreases if (i) the elasticity of marginal quality improvement from joint effort is higher than from private effort and (ii) the effect of improved quality on provision of ecosystem services is high.

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1 Introduction

Human well-being depends in manifold ways on ecosystem services, which are understood as the various benefits provided by natural or managed ecosystems (Daily 1997, Millennium Ecosystem Assessment 2005). Examples include goods such as food, fuel and fibre; and services such as pollination or the regulation of nutrient cycling, local climate, pests and diseases. In a world of uncertainty, human well-being depends not only on the mean level at which such services are being provided, but also on their variability. Quality-improving ecosystem management can provide insurance to risk averse users of these systems, e.g. livestock farmers managing a rangeland. This means, ecosystem management can reduce the variability at which desired ecosystem services are provided, at the expense of a reduced mean level of provision. In this paper, we analyze how risk-averse ecosystem managers make use of this insurance function of ecosystems when management measures generate both a private benefit and positive externalities on other ecosystem users. We study the implications of risk and risk-aversion for optimal ecosystem management and policy design, based on a conceptual ecological-economic model.

Our modelling of ecosystem quality and the provision of ecosystem services captures essential insights from recent theoretical, experimental and observational research in ecology (which is surveyed by Hooper et al. 2005, Kinzig et al. 2001, Loreau et al. 2001, 2002). Ecosystem services (e.g. the production of forage on a pasture) are random because of exogenous sources of risk (e.g. stochastic precipitation); their distribution (mean and variance) is determined by ecosystem quality (e.g. biodiversity or reserve biomass level). Ecosystem quality, in turn, can be influenced by management action (e.g. stocking with livestock, or implementing conservational measures such as de-bushing or irrigation). Management actions have both a private and a public benefit. That is, by taking a certain management action the manager creates benefits that, on the one hand, accrue exclusively to him and, on the other hand, contribute to the aggregate level of management effort that also determines ecosystem quality for all users. Hence, management effort is an impure public good. The ecosystem is being used by a number of people under an open access regime (e.g. subsistence farmers on communal land). All users are risk-averse and choose a management action such as to maximize their expected individual utility from using ecosystem services (e.g. income from livestock farming). For the special case of one single user, this corresponds to a commercial farmer on private land.

Our analysis of endogenous environmental risk and ecosystem management is inspired by works by Crocker and Shogren (1999, 2001, 2003) and Shogren and Crocker (1999), who have developed the idea that environmental risk is endogenous, that is, economic decision makers bearing environmental risk may influence their risk through their actions. They have formalized decision making under uncertainty in this context by conceptualizing ecosystems as lotteries. The methodological innovation of our analysis is the concept of *insurance value* of some action, which allows us to conceptualize ecosystem management as a form of natural insurance.

The conventional wisdom in the literature on the use (or provision) of a public good under uncertainty (Aronsson and Blomquist 2003, Bramoullé and Treich 2005, Sandler and Sterbenz 1990, Sandler et al. 1987) seems to be that the more uncertainty and the higher the risk aversion of individual decision makers, the less severe is the problem of overuse (or under-provision) of the public good. In a sense, this literature suggests that private uncertainty and risk-aversion are good for the socially optimal management of public goods. In contrast, our analysis indicates that the effect of uncertainty and risk-aversion on the extent of market failure is ambiguous. One crucial difference between the existent literature and our analysis is that the literature so far, while focusing on a detailed discussion of the shape of the utility function, assumes a very simple relationship between individual actions and (private or public) benefits. In contrast, our analysis employs a more differentiated model of how individual actions translate – via ecosystem functioning – into private or public benefits. Our ambiguity result ultimately stems from the existence of different such mechanisms in natural ecosystems. Also, while the literature so far only analyzes the problem in terms of the allocation variables (i.e. effort to contribute to the public good), our analysis explicitly employs a measure of social welfare to study the extent of market distortion.

We show that with increasing risk and risk-aversion the private efforts to improve ecosystem quality increase, because ecosystem managers, when choosing a management action under uncertainty, take into account the ecosystem's insurance value and manage the ecosystem such as to obtain the optimal balance between high expected yield and insurance. Consequently, the higher the risk and the more risk-averse the ecosystem managers are, the higher is the resulting ecosystem quality. Thus, under uncertainty the ecosystem management is more conservative, and the resulting ecosystem quality is higher, than it would be in a world of certainty. But whether the market distortion, which stems from the public good character of ecosystem management, improves or worsens depends on exactly how the ecosystem functions. The extent of market failure decreases if (i) the elasticity of marginal quality improvement from joint effort is higher than from private effort and (ii) the effect of improved quality on provision of ecosystem services is high.

The paper is organized as follows. In Section 2 we specify an ecological-economic model of an ecosystem which is managed for the ecosystem services that it provides. The analysis and results are presented in Section 3, with all proofs and formal derivations contained in the Appendix. Section 4 concludes.

2 Ecological-economic model

We consider an ecosystem which is managed for some ecosystem service that it provides. A typical example would be livestock grazing in semi-arid rangelands (e.g. Beukes et al. 2002, Heady 1999, Janssen et al. 2004, Perrings and Walker 1997, 2004, Quaas et al. 2004). The dynamics of such systems are driven by stochastic events, such as rainfall or fire. This translates into a highly variable provision of the ecosystem service, e.g. production of forage on the pasture, depending on the state, termed 'quality', of the ecosystem. The quality of the ecosystem is influenced by how the system is being managed. As a result, the variability of ecosystem service and, hence, income from ecosystem use, i.e. livestock farming, depends on ecosystem management. We capture these relationships in a stylized ecological-economic model.

When outlining the model in the following, we will refer to the example of semi-arid rangelands. A good measure of ecosystem quality in this example is the richness of grass species, i.e. the number of grass species on a given farm.

2.1 Ecosystem management

There are n ecosystem managers, numbered by $i = 1, \ldots, n$. Each ecosystem manager can choose a level x_i of private effort to improve ecosystem quality.

In the case of rangelands, this effort could be measured by the area of land, on which measures are taken to increase species richness (e.g. by de-stocking or de-bushing).

The level of ecosystem quality q_i, which is specific to user i, increases with user i's private effort x_i and the aggregate effort X:

$$q_i = q(x_i, X) \quad \text{with} \quad \begin{array}{lll} q_x \geq 0 \ , & q_{xx} \leq 0 \ , & \\ q_X \geq 0 \ , & q_{XX} \leq 0 \ , & q_{xX} = q_{Xx} \leq 0 \ , \end{array} \tag{1}$$

where

$$X = \sum_{i=1}^{n} x_i \tag{2}$$

and subscripts x and X denote partial derivatives with respect to x_i and X respectively. We assume that $q_x > 0$, if $q_X = 0$ and that $q_X > 0$ if $q_x = 0$ (otherwise results are trivial).

Assumption (1) expresses the idea that the level of ecosystem quality that is relevant to user i is determined by both the private management action x_i taken by user i and positive externalities from the joint effort X of all ecosystem managers.

With respect to rangelands, it seems plausible to consider two groups of species: species with low range of dispersal and species with long range of dispersal. The former mainly benefit from the local area x_i under treatment, while for the latter the total area (which is X) is relevant: species with high dispersal colonize areas on other farms and, the other way around, areas on the farm under consideration become recolonized by similar species from areas on neighboring farms. From the ecological literature, we know that the relation between habitat area and species richness is given by a power-relationship, where the exponent is determined by the ecosystem under consideration, but typically is well below one (Begon et al. 1990, Hanski 1994, Drechsler and Wätzold 2002).[1] Hence, the number of grass species on farm i can be described by the sum of the number of species with short- and with long-range dispersal, both of which depend on the area which is relevant to the respective group by a power-relationship.

Hence, ecosystem quality, which we assume to equal the total number of species is given by

$$q_i^r = q^r(x_i, X) = a_s\, x_i^{\chi_s} + a_l\, X^{\chi_l} \ . \tag{3}$$

[1] A similar relationship governs the mean lifetime of metapopulations (Frank and Wissel 2002, Frank 2004).

The superscript r refers to the rangelands-example. The exponent χ_s (χ_l) applies for the short-range (long-range) dispersal, and a_s (a_l) are positive constants. Provided $0 < \chi_s < 1$ and $0 < \chi_l < 1$, which is an assumption supported by the ecological literature (e.g., Begon et al. 1990:778), the specification (3) fulfills Conditions (1).

In the extreme, $q_x > 0$ and $q_X \equiv 0$ corresponds to a situation where management effort is purely private with no spill-overs to others; and $q_x \equiv 0$ and $q_X > 0$ corresponds to a situation where management effort is a pure public good. We assume that all individuals manage the same ecosystem, so that the function $q(\cdot, \cdot)$ has no index i.

Given ecosystem quality q_i, the ecosystem provides user i with the ecosystem service (e.g. production of forage on a pasture) at level s_i which is a random variable that follows a normal distribution. Its mean $\bar{s}_i$ and variance Δs_i depend on ecosystem quality q_i:

$$\bar{s}_i = \mu(q_i) \quad \text{and} \quad \Delta s_i = \sigma^2(q_i) \ . \tag{4}$$

Again, since all individuals manage the same ecosystem, the probability distribution of the ecosystem service is the same for all users who have the same ecosystem quality q. The functions μ and σ^2 are assumed to have the following properties:

$$\begin{array}{lll} \mu' > 0, & \mu'' \leq 0 & \text{and} \\ \sigma^{2\prime} < 0, & \sigma^{2\prime\prime} \geq 0 & , \end{array} \tag{5}$$

where the prime denotes a derivative. For each user, the mean level of ecosystem service provision increases, and its variance decreases, with ecosystem quality q. Both effects decrease in magnitude with the level of ecosystem quality. For a number of important ecosystem types, these assumptions capture the current state of ecological knowledge. For instance, there is now a consensus among ecologists that biodiversity under certain circumstances influences ecosystem functioning and services in this manner (Baumgärtner 2005, Hooper et al. 2005, Kinzig et al. 2001, Loreau et al. 2001, 2002). Also, semi-arid grasslands are regulated by the stock of 'reserve biomass' in this manner (Behnke et al. 1993, Hein and Weikard 2004, Müller et al. 2004, Stephan et al. 1998, Sullivan and Rhode 2002).

2.2 Income

Improving ecosystem quality carries costs, which are purely private and are described by the cost function

$$c(x_i) \quad \text{with} \quad c' > 0, \quad c'' \geq 0 \; . \tag{6}$$

Balancing the benefits from ecosystem services and the costs of ecosystem management, manager i's net income from ecosystem use is

$$y_i = s_i - c(x_i) \; , \tag{7}$$

where we have assumed that the ecosystem service directly translates into monetary income. Since the ecosystem service s_i is a random variable, net income y_i is a random variable, too. With the normal distribution of ecosystem service s_i, where the mean and variance are given by $\bar{s}_i = \mu\left(q(x_i, X)\right)$ and $\Delta s_i = \sigma^2\left(q(x_i, X)\right)$ (Equations 4 and 1), the manager's income y_i is normally distributed as well, with mean $\bar{y}_i$ and variance Δy_i:

$$\bar{y}_i = \bar{s}_i - c(x_i) \qquad = \mu(q(x_i, X)) - c(x_i) \quad \text{and} \tag{8}$$

$$\Delta y_i = \Delta s_i \qquad = \sigma^2(q(x_i, X)) \; . \tag{9}$$

That is, the mean income is given by the mean ecosystem service minus the costs of managing ecosystem quality; the variance of income equals the variance of ecosystem service.

2.3 Preferences

All ecosystem managers are assumed to have identical preferences over their uncertain income y_i. These are represented by a von Neumann-Morgenstern expected utility function

$$U_i = \mathcal{E}[u(y_i)] \; , \tag{10}$$

where $\mathcal{E}$ is the expectancy operator. It depends on the action x_i taken by the decision maker himself and on his conjectures about the aggregate effort X. We assume that each decision maker is perfectly informed, so that his conjectures coincide with the actual outcome in equilibrium. The Bernoulli utility function $u(y_i)$ is increasing ($u' > 0$) and strictly concave ($u'' < 0$), i.e. the decision maker is non-satiated and risk-averse.[2] In order to obtain simple closed-form solutions, we assume that manager i's preferences are given by the constant absolute risk aversion Bernoulli utility function

$$u(y_i) = -e^{-\rho\, y_i}, \tag{11}$$

where $\rho > 0$ is a parameter describing the manager's Arrow-Pratt measure of absolute risk aversion (Arrow 1965, Pratt 1964). Since income follows a normal distribution with mean $\bar{y}_i$ and variance Δy_i, the von Neumann-Morgenstern expected utility function (10) is

$$U_i = \bar{y}_i - \frac{\rho}{2}\,\Delta y_i \ , \tag{12}$$

which is of the mean-variance type (see Appendix A.1).

3 Analysis and results

After having introduced our notion of *insurance value* in Section 3.1, the analysis proceeds in three steps: First, we discuss the laissez-faire equilibrium, which arises if the n different ecosystem managers optimize their management effort taking the actions of the other managers as given (Section 3.2). Second, we derive the (symmetric) Pareto-efficient allocation and derive its comparative static properties (Section 3.3). Finally, we investigate, how the efficient allocation can be implemented as an equilibrium by means of a Pigouvian subsidy on management efforts. We derive results on how the optimal subsidy depends on the risk and the degree of risk aversion (Section 3.4).

3.1 The insurance value of conservative ecosystem management

In order to demonstrate how conservative ecosystem management acts as an insurance, consider a single ecosystem manager in isolation, i.e. the special case of $n = 1$. By choosing an action x, the ecosystem manager chooses a particular income lottery (Crocker

[2] 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).

and Shogren 2001, Shogren and Crocker 1999), which in our model is characterized by a normal distribution with mean $\bar{y} = \mu(q(x,x)) - c(x)$ and variance $\Delta y = \sigma^2(q(x,x))$ (Equations 8, 9). Therefore, one may speak of 'the lottery x'. One standard method of valuing the riskiness of a lottery to a decision maker is to calculate the *risk premium* R of the lottery x, which is defined by (e.g. Dasgupta and Heal 1979: 381, Kreps 1990: 84, Varian 1992: 181)[3]

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

The risk premium R is the amount of money that leaves the decision maker equally well of, in terms of utility, between the two situations of (i) receiving for sure the expected pay-off from the lottery $\mathcal{E}[y]$ minus the risk premium R, and (ii) playing the risky lottery with random pay-off y.[4]

In general, the idea of an *insurance* is that it reduces the (income) risk to which one is exposed. In the extreme, under *full insurance* one does not have any income risk at all. For the sake of this analysis, we conceptualize this notion of insurance by employing the risk premium as a measure of riskiness. A change in the action x such that, as a result, the risk premium R is reduced, therefore has an *insurance value* equal to $-dR/dx$.

With utility function (12), the risk premium R of a lottery with mean pay-off $\bar{y}$ and variance Δy is simply given by (see Appendix A.2):

$$R = \frac{\rho}{2}\,\Delta y \ . \tag{14}$$

We will come back to this, when discussing the properties of the equilibrium and the efficient allocation later on.

3.2 Laissez-faire equilibrium

We consider as laissez-faire case the allocation, which results as Nash-equilibrium without regulating intervention. The representative ecosystem manager's decision problem in

[3]Note that by Equation (13), $\mathcal{E}[y] - R$ is the *certainty equivalent* of lottery x, as it yields the expected utility $\mathcal{E}\left[u(y)\right]$. If $y \in Y$ with Y as an interval of $\mathbb{R}$, and if u is continuous and strictly increasing, a risk premium R uniquely exists for every lottery x (Kreps 1990: 84).

[4]In general, if the Bernoulli utility function u characterizes a risk-averse (risk-neutral, risk-loving) decision maker, the risk premium R is positive (zero, negative).

this setting is to maximize his expected utility taking the actions of all other ecosystem managers as given

$$\max_{x_i} \mu(q(x_i, X)) - c(x_i) - \frac{\rho}{2} \sigma^2(q(x_i, X)) , \tag{15}$$

where $X = x_1 + \ldots + x_n$ and all x_j for $j \neq i$ are treated as given in the optimization by decision maker i.

Lemma 1

An interior laissez-faire equilibrium has the following properties: (i) it is unique, (ii) all ecosystem managers choose the same level of ecosystem management $x^\star$ and (iii) it is characterized by the condition

$$\mu'(q(x^\star, n\, x^\star)) \; [q_x(x^\star, n\, x^\star) + q_X(x^\star, n\, x^\star)] \\ - \frac{\rho}{2} \sigma^{2\prime}(q(x^\star, n\, x^\star)) \; [q_x(x^\star, n\, x^\star) + q_X(x^\star, n\, x^\star)] = c'(x^\star) \; . \tag{16}$$

Proof: see Appendix A.3.

While the right hand side of (16) captures the marginal costs of the measures to improve ecosystem quality, the left hand side contains the marginal benefits. Of particular interest is the second term $-\rho/2\, \sigma^{2\prime}(q(x^\star, n\, x^\star)) \; [q_x(x^\star, n\, x^\star) + q_X(x^\star, n\, x^\star)]$. This is the *insurance value* of improving ecosystem quality, i.e. the marginal reduction of the risk-premium due to a marginal increase in x_i in the optimum for manager i. This insurance value captures (i) the ecosystem manager's subjective valuation of risk, measured by the absolute risk-aversion ρ; (ii) the response of the ecosystem on an increased quality in terms of reduced variance of ecosystem service provision (given by the factor $\sigma^{2\prime}(q(x^\star, n\, x^\star))$); and (iii) how ecosystem quality improves due to both the private and the public efforts, given by the last factor $q_x(x^\star, n\, x^\star) + q_X(x^\star, n\, x^\star)$. Note that (i) captures a subjective aspect, while (ii) and (iii) capture objective aspects of the insurance value. Both are tightly interwoven.

How the equilibrium levels of ecosystem management effort depend on the risk-related parameters of the model, mainly depends on the properties of the insurance value. They comparative static results are given in the following proposition.

Proposition 1

1. *The equilibrium levels $x^\star$ ecosystem management effort and $q^\star$ of ecosystem quality*

increase with the ecosystem manager's degree ρ of risk aversion:

$$\frac{dx^\star}{d\rho} > 0 \qquad \textit{and} \qquad \frac{dq^\star}{d\rho} > 0 \ . \tag{17}$$

2. *Consider a mean-preserving spread of variance in ecosystem services, such that the variance becomes $\tilde{\sigma}^2 = \theta\,\sigma^2$, where $\theta > 1$. Equilibrium levels $x^\star$ ecosystem management effort and $q^\star$ of ecosystem quality increase:*

$$\frac{dx^\star}{d\theta} > 0 \qquad \textit{and} \qquad \frac{dq^\star}{d\theta} > 0 \ . \tag{18}$$

Proof: see Appendix A.4.

The way to model increased risk employed in Part 2 of the proposition is a particular case of a mean-preserving spread as defined in Rothschild Stiglitz (1970). It allows us to discuss the effects of increased risk in a convenient way. The result that increased risk leads to higher contribution to a public good (given the utility function (11), for which $u'''(y) > 0$, and absolute risk-aversion is constant) has been derived by Sandler et al. (1987). Sandler and Sterbenz (1990) show in a similar setting that increased risk leads to less exploitation of a renewable resource; Bramoullé and Treich (2005, Propositions 4 and 8) show that increased risk leads to less polluting CO_2-emissions in a Nash-equilibrium when individuals are risk-averse with $u''' \geq 0$.

In the setting of our model, increased risk-aversion and increased risk, i.e., a mean preserving spread of risk, have the same qualitative effect on the equilibrium allocation. Since the individuals are risk-averse, the risk-premium increases if either the degree of risk-aversion or the risk as such increase. As a consequence, the insurance value of improving ecosystem quality increases. The resulting higher marginal utility leads to a higher level of management action x and to improved ecosystem quality.

3.3 Efficient allocation

The next step is to derive the optimal allocation. Since we are interested in comparing the optimum to the laissez-faire equilibrium, we will concentrate on that particular Pareto-optimum, in which all ecosystem managers do the same. This allocation could be derived by selecting that particular allocation out of the set of all Pareto-optima.[5] The same

[5]Conditions for the general Pareto-optimum are derived in Appendix A.5.

result is obtained by maximizing social welfare which we define to be the sum of the utilities of all n ecosystem managers, i.e. the welfare function is

$$W = \sum_{i=1}^{n} \mu\big(q\big(x_i, \sum_{j=1}^{n} x_j\big)\big) - \frac{\rho}{2}\,\sigma^2\big(q\big(x_i, \sum_{j=1}^{n} x_j\big)\big) - c(x_i)\ . \tag{19}$$

The optimal allocation is derived by choosing the effort of improving ecosystem quality for each ecosystem manager, such that social welfare, as defined by Equation (19), is maximized,

$$\max_{x_1,\ldots,x_n} W\ . \tag{20}$$

This problem has a unique solution.

Lemma 2

A in interior efficient allocation has the following properties: (i) it is unique, (ii) all ecosystem managers spend the same effort $\hat{x}$ to improve ecosystem quality and (iii) it is characterized by the condition

$$\mu'(q(\hat{x}, n\,\hat{x}))\ [q_x(\hat{x}, n\,\hat{x}) + n\,q_X(\hat{x}, n\,\hat{x})] \\ - \frac{\rho}{2}\,\sigma^{2\prime}(q(\hat{x}, n\,\hat{x}))\ [q_x(\hat{x}, n\,\hat{x}) + n\,q_X(\hat{x}, n\,\hat{x})] = c'(\hat{x})\ . \tag{21}$$

Proof: see Appendix A.6.

Like in the laissez-faire equilibrium, the insurance value of improving ecosystem quality plays an important role. The insurance value which is considered by the central planner consists of similar components as the insurance value considered by the individual ecosystem managers, but the contribution of the public effort on ecosystem quality is augmented by a factor n.

The properties of the efficient allocation are stated in the following proposition.

Proposition 2

1. *The optimal levels $\hat{x}$ ecosystem management effort and $\hat{q}$ of ecosystem quality increase with the representative ecosystem manager's degree ρ of risk aversion:*

$$\frac{d\hat{x}}{d\rho} > 0 \qquad \text{and} \qquad \frac{d\hat{q}}{d\rho} > 0\ . \tag{22}$$

2. *Consider a mean-preserving spread of variance in ecosystem services, such that the variance becomes $\tilde{\sigma}^2 = \theta\,\sigma^2$, where $\theta > 1$. Optimal levels $\hat{x}$ ecosystem management effort and $\hat{q}$ of ecosystem quality increase:*

$$\frac{d\hat{x}}{d\theta} > 0 \qquad \text{and} \qquad \frac{d\hat{q}}{d\theta} > 0\ . \tag{23}$$

Proof: see Appendix A.7.

A change in the risk-aversion of the representative ecosystem manager increases the insurance value of improving ecosystem quality concerning both, the pure private and the public effort. Hence, the marginal benefits of investment into ecosystem quality increase and, due to the shape of the objective function (19), the optimal level of x increases (Part 1 of Proposition 2). As a consequence, ecosystem quality increases. The effects go in the same direction as in the laissez-faire equilibrium. However, they are differ in their quantity in general, since in the efficient allocation, the public insurance value is fully taken into account.

3.4 Optimal environmental policy

Due to the external effects of the ecosystem management efforts, the laissez-faire equilibrium clearly is not efficient – in equilibrium, ecosystem managers will spend too few effort in improving ecosystem quality, because they do not take into consideration the positive externality on the other ecosystem users. If a regulator wishes to implement the first-best allocation as an equilibrium, he has to impose a Pigouvian subsidy on the private efforts of improving ecosystem quality. Denoting the subsidy per unit x_i with τ, the optimization problem of ecosystem manager i reads

$$\max_{x_i} \mu\left(q(x_i, X)\right) - c(x_i) - \frac{\rho}{2}\,\sigma^2\left(q(x_i, X)\right) + \tau\, x_i \ . \tag{24}$$

Comparing the first order conditions for the efficient allocation (Equation 21) and for the regulated equilibrium (i.e. the first order condition of maximizing (24) with respect to x_i), we derive the optimal subsidy, which is given in the following lemma.

Lemma 3

The efficient allocation is implemented as an equilibrium, if a subsidy on ecosystem quality improvement effort is set with a rate

$$\hat{\tau} = (n-1)\, q_X(\hat{x}, n\,\hat{x})\, \left[\mu'(q(\hat{x}, n\,\hat{x})) - \frac{\rho}{2}\,\sigma^{2\prime}(q(\hat{x}, n\,\hat{x}))\right] \ . \tag{25}$$

Clearly, the optimal subsidy increases with $q_X(\hat{x}, n\,\hat{x})$, i.e. it is higher, the higher the marginal benefits of aggregate effort is in terms of ecosystem quality improvement. The different contributions to the optimal subsidy rate, which are captured by the terms in brackets, deserve some comments. In the case of risk-neutrality, $\rho = 0$, only the first term in brackets remains. Then, the optimal subsidy is $(n-1)\, q_X\, \mu'$, it just internalizes the positive externality that the increase in ecosystem quality has on the expected payoff of the $n-1$ other ecosystem managers. If $\rho > 0$ the second term in brackets captures the positive externality of ecosystem manager $i's$ contribution to ecosystem quality, which is due to the insurance value that the higher ecosystem quality has for the $n-1$ remaining ecosystem managers.

The optimal subsidy rate $\hat{\tau}$ can be interpreted as a measure for the market failure due to the public good problem. It has become clear from the above discussion that this market failure depends on the degree ρ of risk-aversion of the representative ecosystem manager. The question is, does the market failure become better or worse, if (i) the degree of risk-aversion, (ii) the variability of ecosystem services or (iii) the number of ecosystem managers increase? This question is answered by the following proposition.

Proposition 3

1. *If, and only if, the following condition holds,*

$$\left[\frac{\hat{x}\, q_{xx}}{q_x} + \frac{\hat{X}\, q_{xX}}{q_x} - \frac{\hat{x}\, q_{xX}}{q_X} - \frac{\hat{X}\, q_{XX}}{q_X}\right] \left[\mu' - \frac{\rho}{2}\, \sigma^{2\prime}\right] q_x > \hat{x}\, c'' \;, \tag{26}$$

the optimal subsidy rate decreases with the degree ρ of risk-aversion,

$$\frac{d\hat{\tau}}{d\rho} < 0 \;. \tag{27}$$

2. *Consider a mean-preserving spread of variance in ecosystem services, such that the variance becomes $\tilde{\sigma}^2 = \theta\, \sigma^2$, where $\theta > 1$. If and only if Condition (26) holds, the optimal subsidy rate decreases,*

$$\frac{d\hat{\tau}}{d\theta} < 0 \;. \tag{28}$$

Proof: see Appendix A.8.

If the inequality in Condition (26) is reversed, the effects of increased risk-aversion and a mean-preserving spread on the optimal subsidy are also reversed. In that case, increased risk or increased risk-aversion lead to an increase in the market distortion.

Although both increased risk and increased risk-aversion have an unambiguously positive effect on the equilibrium values of efforts to improve ecosystem quality, the effect on the market distortion can go either way. The literature suggests that whether increased risk improves or worsens the public-good problem depends on the curvature properties of marginal utility (Sandler et al. 1987, Bramoullé and Treich 2005). In our model, however, the utility function is given and exhibit curvature properties that promote an alleviation of the commons problem. Nevertheless, the effect of increased risk is ambiguous.

According to Condition (26), the direction of the effect depends on (i) the costs and the improvement in ecosystem quality due to increased effort, (ii) how improved quality translates into higher mean and less variability of ecosystem services and (iii) the exact utility function. We shall discuss this condition in some detail.

In order to interpret this Condition (26), consider the rangeland example, where ecosystem quality is given by (3). Using this functional form, Condition (26) simplifies to

$$[\chi_s - \chi_l] \left[\mu' - \frac{\rho}{2}\,\sigma^{2\prime}\right] q_x > \hat{x}\, c'' \; . \tag{29}$$

A necessary condition for the market distortion to decrease with increased risk, is, that due to a marginal increase in area managed for species conservation the relative increase in species number with short dispersal range is higher than the relative increase in the species number with a long dispersal range. Whatever is the case, depends on the exact ecosystem under consideration. The sign of the effect does not depend on the relative size of the two sub-groups of species, but only on the ecological factors affecting the relation between habitat area and species number in the respective group.

4 Conclusions

We have analyzed how risk-averse ecosystem managers make use of the insurance function of ecosystems when management measures generate both a private benefit and positive externalities on other ecosystem users. We have shown that with increasing risk and risk-aversion the private efforts to improve ecosystem quality increase, because ecosystem managers, when choosing a management action under uncertainty, take into account the ecosystem's insurance value and manage the ecosystem such as to obtain the optimal balance between high expected yield and insurance. Consequently, the higher the risk and the more risk-averse the ecosystem managers are, the higher is the resulting ecosystem quality. Thus, under uncertainty the ecosystem management is more conservative, and the resulting ecosystem quality is higher, than it would be in a world of certainty. But whether the market distortion, which stems from the public good character of ecosystem management, improves or worsens depends on exactly how the ecosystem functions. The extent of market failure decreases if (i) the elasticity of marginal quality improvement from joint effort is higher than from private effort and (ii) the effect of improved quality on provision of ecosystem services is high.

Appendix

A.1 Expected utility function (12)

With

$$f(y) = \frac{1}{\sqrt{2\pi\Delta y}}\, e^{-\frac{(y-\bar{y})^2}{2\Delta y}} \tag{A.1}$$

as the probability density function of the normal distribution of income y with mean $\bar{y}$ and variance Δy, the von Neumann-Morgenstern expected utility from the Bernoulli utility function (11) is

$$\tilde{U} = \mathcal{E}[u(y)] = -\int e^{-\rho\, y} f(y) dy = -e^{-\rho \left[\bar{y} - \frac{\rho}{2}\, \Delta y\right]} \ . \tag{A.2}$$

Using a simple monotonic transformation of $\tilde{U}$, one obtains the expected utility function U (Equation 12).

A.2 Risk premium (14)

The risk premium R has been defined in Equation (13) as

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

With the Bernoulli utility function (11) and $\mathcal{E}[y] = \bar{y}$ the left hand side of this equation is given by

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

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

$$-e^{-\rho\, [\bar{y} - R]} = -e^{-\rho \left[\bar{y} - \frac{\rho}{2}\, \Delta y\right]} \ . \tag{A.5}$$

Rearranging yields the result stated in Equation (14).

A.3 Proof of Lemma 1

The first order condition of Problem (15) is

$$\left[\mu'(q(x_i,X)) - \frac{\rho}{2}\,\sigma^{2\prime}(q(x_i,X))\right]\,[q_x(x_i,X) + q_X(x_i,X)] = c'(x_i)\ . \tag{A.6}$$

Denote by $\tilde{X}$ the aggregate effort of all ecosystem managers except for manager i, i.e. $\tilde{X} = x_1 + \ldots + x_{i-1} + x_{i+1} + \ldots + x_n$. Hence, we can write

$$\left[\mu'(q(x_i,x_i+\tilde{X})) - \frac{\rho}{2}\,\sigma^{2\prime}(q(x_i,x_i+\tilde{X}))\right]\,\left[q_x(x_i,x_i+\tilde{X}) + q_X(x_i,x_i+\tilde{X})\right] = c'(x_i)\ . \tag{A.7}$$

First, we show that Equation (16), which is identical to (A.7) in the case $x_i = x^\star$ and $\tilde{X} = (n-1)\,x^\star$, has a unique solution $x^\star$. Provided it has a solution at all, this solution is unique, because, by assumption (6), the right hand side c' is increasing with x_i, while the left hand side is decreasing with x_i;

$$\begin{aligned}&\frac{d}{dx^\star}\left[\mu' - \frac{\rho}{2}\,\sigma^{2\prime}\right]\,[q_x + q_X]\\ &= \left[\mu'' - \frac{\rho}{2}\,\sigma^{2\prime\prime}\right]\,[q_x + q_X]\,[q_x + n\,q_X] + \left[\mu' - \frac{\rho}{2}\,\sigma^{2\prime}\right]\,[q_{xx} + (n+1)\,q_{xX} + n\,q_{XX}] \le 0\ ,\end{aligned} \tag{A.8}$$

where we omitted arguments for the sake of a clearer exposition. The sign of this expression is negative by assumptions (1) and (5).

Second, we show that the symmetric allocation $x_i = x^\star$ for all $i = 1,\ldots,n$ is a Nash equilibrium. Assume therefore $\tilde{X} = (n-1)\,x^\star$ is given for manager i. In this case, the optimal effort for manager i is $x^\star$, because $x_i = x^\star$ solves Condition (16) uniquely. By symmetry, $x_i = x^\star$ for all $i = 1,\ldots,n$.

Third, we show that no other Nash equilibrium exists. Consider the two cases (i) $\tilde{X} > (n-1)\,x^\star$ and (ii) $\tilde{X} < (n-1)\,x^\star$. In case (i), the optimal effort for manager i is $x_i < x^\star$. To prove this, we differentiate Condition (A.7) w.r.t. $\tilde{X}$, which yields

$$\frac{dx_i}{d\tilde{X}} = -\,\frac{\left[\mu'' - \frac{\rho}{2}\,\sigma^{2\prime\prime}\right]\,[q_x + q_X]\,q_X + \left[\mu' - \frac{\rho}{2}\,\sigma^{2\prime}\right]\,[q_{xX} + q_{XX}]}{\left[\mu'' - \frac{\rho}{2}\,\sigma^{2\prime\prime}\right]\,[q_x + q_X]^2 + \left[\mu' - \frac{\rho}{2}\,\sigma^{2\prime}\right]\,[q_{xx} + 2\,q_{xX} + q_{XX}] - c''}, \tag{A.9}$$

which is negative by assumptions (1) and (5). Since $x_i = x^\star$ for $\tilde{X} = (n-1)\,x^\star$, $x_i < x^\star$ for $\tilde{X} > (n-1)\,x^\star$. Due to the symmetry, this contradicts the assumption $\tilde{X} > (n-1)\,x^\star$, since *all* ecosystem managers would choose $x_i < x^\star$. Hence, there is no equilibrium where $\tilde{X} > (n-1)\,x^\star$. With a similar argument, we can rule out case (ii). Hence, $x_i = x^\star$ for all $i = 1,\ldots,n$ is the unique equilibrium.

A.4 Proof of Proposition 1

Ad 1. Differentiating (16) with respect to ρ yields (omitting arguments):

$$\left[\left[\mu'' - \frac{\rho}{2}\,\sigma^{2''}\right]\,[q_x + q_X]\,[q_x + n\,q_X] + \left[\mu' - \frac{\rho}{2}\,\sigma^{2'}\right]\,[q_{xx} + (n+1)\,q_{xX} + n\,q_{XX}] - c''\right]\,\frac{dx^\star}{d\rho}$$
$$= \frac{\sigma^{2'}}{2}\,[q_x + q_X]\ . \quad \text{(A.10)}$$

Because the term in brackets on the left hand side of this equation is negative and because the right hand side of the equation is negative (both by assumptions (1), (5) and (6)), we conclude $dx^\star/d\rho > 0$. $dq^\star/d\rho > 0$ follows, because

$$\frac{dq(x^\star, n\,x^\star)}{dx^\star} = q_x + n\,q_X > 0\ . \quad \text{(A.11)}$$

Ad 2. Replacing σ^2 by $\theta\,\sigma^2$ in Condition (16) and differentiating with respect to θ yields:

$$\left[\left[\mu'' - \frac{\rho}{2}\,\sigma^{2''}\right]\,[q_x + q_X]\,[q_x + n\,q_X] + \left[\mu' - \frac{\rho}{2}\,\sigma^{2'}\right]\,[q_{xx} + (n+1)\,q_{xX} + n\,q_{XX}] - c''\right]\,\frac{dx^\star}{d\theta}$$
$$= \frac{\rho\,\sigma^{2'}}{2}\,[q_x + q_X]\ . \quad \text{(A.12)}$$

The same arguments as in Part 1 of the proof lead to the conclusion $dx^\star/d\theta > 0$ and $dq^\star/d\theta > 0$.

A.5 Pareto-efficient allocations

We consider the social planner's problem

$$\max_{x_1,\ldots,x_n}\ \mathcal{E}[u(y_1)] \quad \text{s.t. (1), (2), (5), (8), (9), and } \mathcal{E}[u(y_i)] \geq U_i\ \forall\, i \neq 1.$$

The Lagrangian for this problem reads

$$\begin{aligned}\mathcal{L} &= \mu(q(x_1, X)) - c(x_1) - \frac{\rho}{2}\,\sigma^2(q(x_1, X)) + \sum_{k=2}^{n} \lambda_i\,[\mathcal{E}[u(y_i)] - U_i] \\ &= \sum_{i=1}^{n} \lambda_i\,\left[\mu(q(x_i, X)) - c(x_i) - \frac{\rho}{2}\,\sigma^2(q(x_i, X)) - U_i\right] + U_1,\end{aligned}$$

where $\lambda_1 = 1$. The first order condition of this problem read for all $i \in \{1, \ldots, n\}$:

$$\lambda_i\,\left[\mu'(q(\hat{x}_i, \hat{X})) - c'(\hat{x}_i) - \frac{\rho}{2}\,\sigma^{2'}(q(\hat{x}_i, \hat{X}))\right]\,q_x(\hat{x}_i\,\hat{X})$$
$$\stackrel{!}{=} -\sum_{k=1}^{n} \lambda_k\,\left[\mu'(q(\hat{x}_k, \hat{X})) - \frac{\rho}{2}\,\sigma^{2'}(q(\hat{x}_k, \hat{X}))\right]\,q_X(\hat{x}_k, \hat{X})\ . \quad \text{(A.13)}$$

Dividing the i-th equation by the first one yields:

$$\lambda_i = \frac{\mu'(q(\hat{x}_1, \hat{X}))\, q_x(\hat{x}_1, \hat{X}) - c'(\hat{x}_1) - \frac{\rho}{2}\,\sigma^{2\prime}(q(\hat{x}_1, \hat{X}))\, q_x(\hat{x}_1, \hat{X})}{\mu'(q(\hat{x}_i, \hat{X}))\, q_x(\hat{x}_i, \hat{X}) - c'(\hat{x}_i) - \frac{\rho}{2}\,\sigma^{2\prime}(q(\hat{x}_i, \hat{X}))\, q_x(\hat{x}_i, \hat{X})} \; .$$

Using this in Equation (A.13) leads to

$$1 = -\sum_{k=1}^{n} \frac{\mu'(q(\hat{x}_k, \hat{X})) - \frac{\rho}{2}\,\sigma^{2\prime}(q(\hat{x}_k, \hat{X}))}{\mu'(q(\hat{x}_i, \hat{X}))\, q_x(\hat{x}_i, \hat{X}) - c'(\hat{x}_i) - \frac{\rho}{2}\,\sigma^{2\prime}(q(\hat{x}_i, \hat{X}))\, q_x(\hat{x}_i, \hat{X})}\, q_X(\hat{x}_k\, \hat{X}) \; . \quad \text{(A.14)}$$

In the symmetric case, i.e. $x_i = \hat{x}$ for all $i \in \{1, \ldots, n\}$, it is $c'(x_1) = c'(x_i)$, and Equation (A.14) simplifies to

$$-c'(\hat{x}) + [q_x(\hat{x}, n\,\hat{x}) + n\, q_X(\hat{x}, n\,\hat{x})] \left[\mu'(q(\hat{x}, n\,\hat{x})) - \frac{\rho}{2}\,\sigma^{2\prime}(q(\hat{x}, n\,\hat{x}))\right] = 0 \; . \quad \text{(A.15)}$$

A.6 Proof of Lemma 2

First, we show that it is optimal to choose the same management for all n ecosystem managers, i.e. that

$$\frac{1}{n}\sum_{i=1}^{n} \mu\big(q\big(x_i, X\big)\big) - \frac{\rho}{2}\,\sigma^2\big(q\big(x_i, X\big)\big) - c(x_i) \le \mu\big(q\big(\frac{X}{n}, X\big)\big) - \frac{\rho}{2}\,\sigma^2\big(q\big(\frac{X}{n}, X\big)\big) - c\big(\frac{X}{n}\big) \; , \quad \text{(A.16)}$$

where $X = \sum_{j=1}^{n} x_j$. This is true by Jensen's inequality, because the welfare function is concave in x_i for any given X.[6] Hence, we have to find the level x of effort to improve ecosystem quality, which maximizes

$$n\,\left[\mu(q(x, n\,x)) - \frac{\rho}{2}\,\sigma^2(q(x, n\,x)) - c(x)\right] \; . \quad \text{(A.17)}$$

This is a strictly concave function of x, since

$$\begin{aligned} &\frac{d^2}{dx^2}\left[n\,\left[\mu(q(x, n\,x)) - \frac{\rho}{2}\,\sigma^2(q(x, n\,x)) - c(x)\right]\right] \\ &= \left[\mu'' - \frac{\rho}{2}\,\sigma^{2\prime\prime}\right]\,[q_x + n\,q_X]^2 + \left[\mu' - \frac{\rho}{2}\,\sigma^{2\prime}\right]\,\left[q_{xx} + 2\,n\,q_{xX} + n^2\,q_{XX}\right] - c'' < 0 \; . \quad \text{(A.18)} \end{aligned}$$

Hence, if an interior solution exists, it is uniquely determined by the first order condition

$$\left[\mu' - \frac{\rho}{2}\,\sigma^{2\prime}\right]\,[q_x + n\,q_X] = c' \; . \quad \text{(A.19)}$$

[6] The idea for this proof is taken from Bramoullé and Treich (2005).

A.7 Proof of Proposition 2

Ad 1. Differentiating (21) with respect to ρ yields (omitting arguments):

$$\left[\left[\mu'' - \frac{\rho}{2}\,\sigma^{2''}\right]\,[q_x + n\,q_X]^2 + \left[\mu' - \frac{\rho}{2}\,\sigma^{2'}\right]\,[q_{xx} + 2\,n\,q_{xX} + n^2\,q_{XX}] - c''\right]\frac{d\hat{x}}{d\rho} = \frac{\sigma^{2'}}{2}\,[q_x + n\,q_X]\ . \tag{A.20}$$

Because the term in brackets on the left hand side of this equation is negative and because the right hand side of the equation is negative (both by assumptions (1), (5) and (6)), we conclude $d\hat{x}/d\rho > 0$. $d\hat{q}/d\rho > 0$ follows, because

$$\frac{dq(\hat{x}, n\,\hat{x})}{d\hat{x}} = q_x + n\,q_X > 0\ . \tag{A.21}$$

Ad 2. Replacing σ^2 by $\theta\,\sigma^2$ in Condition (21) and differentiating with respect to θ yields:

$$\left[\left[\mu'' - \frac{\rho}{2}\,\sigma^{2''}\right]\,[q_x + n\,q_X]^2 + \left[\mu' - \frac{\rho}{2}\,\sigma^{2'}\right]\,[q_{xx} + 2\,n\,q_{xX} + n^2\,q_{XX}] - c''\right]\frac{d\hat{x}}{d\theta} = \frac{\rho\,\sigma^{2'}}{2}\,[q_x + n\,q_X]\ . \tag{A.22}$$

The same arguments as in Part 1 of the proof lead to the conclusion $d\hat{x}/d\theta > 0$ and $d\hat{q}/d\theta > 0$.

A.8 Proof of Proposition 3

Ad 1. In order to derive the comparative statics of $\hat{\tau}$ with respect to ρ, we differentiate (25) with respect to ρ. This yields (omitting arguments)

$$\frac{d\hat{\tau}}{d\rho} = (n-1)\left[\left[[q_{xX} + n\,q_{XX}]\,\left[\mu' - \frac{\rho}{2}\,\sigma^{2'}\right] + q_X\,\left[\mu'' - \frac{\rho}{2}\,\sigma^{2'''}\right]\,[q_x + n\,q_X]\right]\frac{d\hat{x}}{d\rho} - q_X\frac{\sigma^{2'}}{2}\right] \tag{A.23}$$

From Equation (A.20), we have

$$\frac{d\hat{x}}{d\rho} = \frac{\frac{\sigma^{2'}}{2}\,[q_x + n\,q_X]}{\left[\mu'' - \frac{\rho}{2}\,\sigma^{2''}\right]\,[q_x + n\,q_X]^2 + \left[\mu' - \frac{\rho}{2}\,\sigma^{2'}\right]\,[q_{xx} + 2\,n\,q_{xX} + n^2\,q_{XX}] - c''} \tag{A.24}$$

Using this in (A.23) and simplifying yields

$$\frac{d\hat{\tau}}{d\rho} = \frac{(n-1)\,\frac{\sigma^{2'}}{2}\,\left[\left[\mu' - \frac{\rho}{2}\,\sigma^{2'}\right]\,[-q_X\,q_{xx} - n\,q_{xX}\,q_X + n\,q_x\,q_{XX} + q_x\,q_{xX}] + q_X\,c''\right]}{\left[\mu'' - \frac{\rho}{2}\,\sigma^{2''}\right]\,[q_x + n\,q_X]^2 + \left[\mu' - \frac{\rho}{2}\,\sigma^{2'}\right]\,[q_{xx} + 2\,n\,q_{xX} + n^2\,q_{XX}] - c''}\ . \tag{A.25}$$

Since the denominator of this expression is negative and the first two facors of the numerator together are negative, too, the change of $\hat{\tau}$ following an increase in ρ is negative, if and only if

$$\left[\mu' - \frac{\rho}{2}\,\sigma^{2\prime}\right]\,\left[-q_X\,q_{xx} - n\,q_{xX}\,q_X + n\,q_x\,q_{XX} + q_x\,q_{xX}\right] + q_X\,c'' < 0\ . \tag{A.26}$$

Rearranging yields Condition (26).

Ad 2. With the mean-preserving spread, the optimal subsidy rate is

$$\hat{\tau} = (n-1)\,q_X(\hat{x}, n\,\hat{x})\,\left[\mu'(q(\hat{x}, n\,\hat{x})) - \frac{\rho}{2}\,\theta\,\sigma^{2\prime}(q(\hat{x}, n\,\hat{x}))\right]\ . \tag{A.27}$$

Differentiating with respect to θ leads to

$$\frac{d\hat{\tau}}{d\theta} = (n-1)\left[\left[[q_{xX} + n\,q_{XX}]\,\left[\mu' - \frac{\rho}{2}\,\sigma^{2\prime}\right] + q_X\,\left[\mu'' - \frac{\rho}{2}\,\sigma^{2\prime\prime\prime}\right]\,[q_x + n\,q_X]\right]\frac{d\hat{x}}{d\theta} - q_X\frac{\rho}{2}\sigma^{2\prime}\right] \tag{A.28}$$

Using (A.22) and rearranging yields

$$\frac{d\hat{\tau}}{d\theta} = \frac{(n-1)\,\frac{\rho}{2}\,\sigma^{2\prime}\,\left[\left[\mu' - \frac{\rho}{2}\,\sigma^{2\prime}\right]\,\left[-q_X\,q_{xx} - n\,q_{xX}\,q_X + n\,q_x\,q_{XX} + q_x\,q_{xX}\right] + q_X\,c''\right]}{\left[\mu'' - \frac{\rho}{2}\,\sigma^{2\prime\prime}\right]\,[q_x + n\,q_X]^2 + \left[\mu' - \frac{\rho}{2}\,\sigma^{2\prime}\right]\,[q_{xx} + 2\,n\,q_{xX} + n^2\,q_{XX}] - c''}\ , \tag{A.29}$$

which is negative, if and only if Condition (26) is fulfilled.

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