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Natural vs. financial insurance in the management of public-good ecosystems

Martin F. Quaas[1,*] and Stefan Baumgärtner[2]

[1] Department of Ecological Modelling, UFZ – Helmholtz-Centre for Environmental Research, Leipzig, Germany
[2] Centre for Sustainability Managment, Leuphana University of Lüneburg, Germany

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Abstract: In the face of uncertainty, ecosystems can provide natural insurance to risk averse users of ecosystem services. We employ a conceptual ecological-economic model in which ecosystem management has a private insurance value and, through ecosystem processes at higher hierarchical levels, generates a positive externality on other ecosystem users. We analyze the allocation of (endogenous) risk and ecosystem quality by risk averse ecosystem managers who have access to financial insurance, and study the implications for individually and socially optimal ecosystem management, and policy design. We show that while an improved access to financial insurance leads to lower ecosystem quality, the effect on the extent of the public-good problem and on welfare is determined by ecosystem properties. We derive conditions on ecosystem functioning under which, if financial insurance becomes more accessible, (i) the extent of optimal regulation increases or decreases; and (ii) welfare, in the absence of environmental regulation, increases or decreases.

JEL-Classification: Q57, H23, D81, D62

Keywords: ecosystem services, ecosystem management, endogenous environmental risk, insurance, multi-scale ecosystem functioning, risk-aversion, uncertainty

*Corresponding author: Martin Quaas, Department of Ecological Modelling, UFZ – Helmholtz Centre for Environmental Research, Permoser Str. 15, D-04318 Leipzig, Germany. Email: martin.quaas@ufz.de.

1 Introduction

Ecosystems provide many valuable services, including goods such as food, fuel or fiber, and services such as pollination or the regulation of local climate, pests, diseases or water runoff from a watershed (Daily 1997, Millennium Ecosystem Assessment 2005). 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 statistical distribution. Biodiversity can reduce the variance at which desired ecosystem services are provided. This means, biodiversity can provide a natural insurance to risk averse users of ecosystem services. Since increasing biodiversity generates such an insurance value for ecosystem managers, they tend to employ more conservative management strategies in the face of uncertainty (Baumgärtner 2007, Baumgärtner and Quaas 2006).

On the other hand, rather than making use of natural insurance, ecosystem users can also use financial insurance to hedge their income risk. For example, in the USA for over one hundred years crop yield insurance is offered to manage agricultural risk. Since traditional crop yield insurance is particularly vulnerable to classical insurance problems such as moral hazard and adverse selection (e.g. Luo et al. 1994), considerable effort is recently spent to develop alternative possibilities of financial insurance for farmers, e.g. index-based insurance contracts (Miranda and Vedenov 2001, Skees et al. 2002, World Bank 2004).

While this effort to develop instruments of financial insurance is motivated by the idea that reducing income risk is beneficial for ecosystem users, some studies have shown that financial insurance tends to have ecologically negative effects. Horowitz and Lichtenberg (1993) show that financially insured farmers are likely to undertake riskier production – with higher nitrogen and pesticide use – than uninsured farmers do. A similar result is pointed out in Mahul (2001), assuming a weather-based insurance. Wu (1999) empirically estimates the impact of insurance on the crop mix and its negative results on soil erosion in Nebraska (USA).

In this paper, we analyze how risk-averse ecosystem managers make use of the natural insurance function of biodiversity and of financial insurance. We address the question of how the availability of financial insurance affects the overuse of natural resources and social welfare when ecosystem management measures generate both a private benefit and, via ecosystem processes at higher hierarchical levels, positive externalities on other ecosystem users.

Our analysis of biodiversity and the provision of ecosystem services captures important insights about ecosystem functioning that emerged from recent theoretical, experimental and observational research in ecology (Hooper et al. 2005, Kinzig et al. 2002, Loreau et al. 2001, 2002, Holling 2001, Levin 2000, Peterson et al. 1998, Tilman 1994, O'Neill 1986).[1] Among other insights two 'stylized facts' about biodiversity and ecosystem functioning emerged which are of crucial importance for the issue studied here:

1. *Local biodiversity is affected by ecosystem processes at different hierarchical scales.* Ecosystems are hierarchically structured, with processes operating at different spatial and temporal scales and interacting across scales. Species diversity is typically influenced differently by processes at different scales. Accordingly, biodiversity management measures at different scales have different impact on local biodiversity.

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

These stylized ecological facts are of economic relevance.[2] Biodiversity increasing management provides users with natural insurance in terms of a reduced variance of ecosystem services. In particular, an individual manager's action affects biodiversity via ecosystem processes at different scales. At a lower scale, benefits accrue exclusively to him. At a higher scale his action can contribute to increasing local biodiversity for other users, thereby generating a positive externality. For example, by setting aside land on his farm as habitat for insects, an individual farmer increases the local level of biodiversity on his farm and also contributes – via metapopulation dynamics (Hanski 1999, Levins 1969) – to biodiversity on other farms.

Our analysis of environmental risk, ecosystem management and purchase of financial insurance brings together three separate strands in the literature: (i) In the environmental economics literature, Crocker and Shogren (1999, 2001, 2003) and Shogren and Crocker (1999) 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

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

[2]For a more detailed and encompassing discussion of these findings, and references to the literature, see Baumgärtner (2007), Baumgärtner and Quaas (2006) and Hooper et al. (2005).

under uncertainty in this context by conceptualizing ecosystems as lotteries. (ii) In the literature on the use (or provision) of a public good under uncertainty, the conventional wisdom seems to be that the higher the uncertainty or the risk aversion of individual decision makers, the less severe is the problem of overuse (or under-provision) of the public good (Bramoullé and Treich 2005, Sandler and Sterbenz 1990, Sandler et al. 1987). The focus in this literature is on the properties of the utility function, while the production of the public good (or public bad) is typically modeled in a trivial way, i.e. one unit of money spent on providing the public good equals one unit of the public good provided. (iii) In the insurance economics literature, the analysis of the trade-off between 'self insurance' (by acting such as to reduce a potential income loss) or 'self protection' (by acting such as to reduce the probability of an income loss) on the one hand, and 'market insurance' on the other hand goes back to Ehrlich and Becker (1972). One standard result is that self insurance and market insurance are substitutes, with the result that market insurance, as it becomes cheaper, may drive out self insurance. In this paper, we bring together these three lines of argument.

We study a conceptual ecological-economic model of agro-ecosystem management where the direct economic use of some ecosystem service (e.g. crop yield) relies on other ecosystem services (e.g. pollination or pest control) from natural or semi-natural ecosystems. The directly used ecosystem service (crop yield) is random because of exogenous sources of risk (e.g. weather conditions or pests outbreaks); its distribution (mean and variance) is determined by ecosystem quality (biodiversity). Ecosystem quality, in turn, can be influenced by management action (e.g. setting aside land as habitat to enhance biodiversity) that affects ecosystem processes at different scales (e.g. farm scale and landscape scale).

A typical example of such a system is a highland coffee plantation. Fruit set of coffee plants (*coffea arabica*) is highly variable and related to bee pollination. Ecological evidence shows that the variability of coffee fruit set decreases with on-plantation bee diversity (Klein et al. 2003a,b). Arthropods and leaf damage are controlled by insectivory birds (Greenberg et al. 2000, Kellermann et al. 2006). Both types of species (bees and birds) rely on rainforest as habitat, but their activity range is at different spatial scales: while (social) bees visit coffee plants at a distance of 1.5 kilometers and less (Klein et al. 2003a,b), birds easily visit also neighboring plantations, even if there would be no contiguous forest cover (Greenberg et al. 2000). The diversity of both bee and bird species together constitutes ecosystem quality which reduces the variance of coffee yield by stabilizing pollination and controlling coffee pests.

In our model, ecosystem users are risk-averse and choose a management action such as to maximize expected utility from ecosystem use (e.g. income from crop farming). Individual ecosystem managers face a trade-off between obtaining natural insurance from ecosystem management and hedging income risk with financial insurance.

We show that natural insurance by conservative ecosystem management and financial insurance coverage are substitutes. Hence, availability of financial insurance reduces the demand for natural insurance from ecosystems and, thus, leads to a less conservative management action which results in lower ecosystem quality. In particular, the lower the costs of financial insurance are (i.e. the more actuarially fair the premium of financial insurance is), the less conservative are the individually optimal management actions and the lower is the resulting ecosystem quality.

Yet, the effect of an improved access to financial insurance on the extent of the public-good problem is ambiguous. We show that this relationship crucially depends on the ecosystem's properties, and that the extent of the optimal regulatory intervention may decrease or increase depending on the relative effects of management measures on biodiversity via the lower, i.e. on-farm, and the higher, i.e. landscape, scale. We further derive a condition on ecosystem functioning under which increasing costs of financial insurance decrease or increase welfare in the laissez-faire equilibrium. These results are highly policy relevant: while at first sight the introduction of, or improved access to, financial insurance seems to be beneficial from a welfare point of view, our results demonstrate that – depending on ecosystem properties – it may have adverse welfare effects.

The paper is organized as follows. In Section 2, we specify the ecological-economic model. The analysis and results are presented in Section 3, with all proofs and formal derivations contained in the Appendix. Section 4 discusses the results and concludes.

2 Ecological-economic model

We consider an ecosystem which is managed for some ecosystem service it provides. As an example, one may think of highland coffee plantations (see Section 1). Due to stochastic fluctuations in environmental conditions the provision of the ecosystem service is uncertain. Its statistical distribution depends on the state of the ecosystem in terms of 'ecosystem quality' (biodiversity), which is influenced by how the system is being managed. As a result, the statistical distribution of ecosystem service and, hence, of income depend on ecosystem management. We capture these relationships in a stylized ecological-economic model as follows.

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 individual effort to improve ecosystem quality. To be specific, we think of x_i as an area of land which is protected as habitat for the species relevant for the provision of the ecosystem service under consideration.

We consider two spatial scales in the model: the farm scale which is solely influenced by individual conservation effort x_i of user i, and the landscape scale on which the aggregate effort $X = x_1 + \ldots + x_n$ of all n ecosystem users matters.

The level of ecosystem quality q_i is specific to user i. It is a function of the biodiversity of two types of species whose dynamics are being governed by ecosystem processes at the farm scale and the landscape scale respectively. For instance, the first type could be species with small activity range (e.g. bees) while the second type could be species with relatively large activity range (e.g. birds).

For both types of species, a species-area relationship holds: the species number is a power function of the land area set aside as habitat (McArthur and Wilson 1967, Rosenzweig 1995). Thus, the species numbers are x_i^α for the species type for which local management is relevant and X^β for the species type for which aggregate management efforts at the landscape scale matter. In the ecological literature, the exponents α and β are usually referred to as the 'slope' of the species-area relationship (i.e., the slope of the corresponding curve on a double-logarithmic scale). In general, α and β will differ; the slopes lie between 0.1 and 0.6 for different ecosystems with values around 0.25 for most of the observed ecosystems (Durrett and Levin 1996, Hanski and Gyllenberg 1997, Rosenzweig 1995).

Local ecosystem quality q_i depends on individual and aggregate management effort in the following way:[3]

$$q_i = q(x_i, X) = \left[\gamma \; [x_i^\alpha]^\zeta + (1-\gamma) \; \left[X^\beta\right]^\zeta\right]^{1/\zeta} \qquad (1)$$

where α, β, $\gamma \in [0, 1]$ and $\zeta \leq 1$. All ecosystem users are assumed to face the same type of local ecosystem, so that the function $q(\cdot, \cdot)$ has no index i.

Assumption (1) expresses the idea that the level of ecosystem quality relevant to user i is determined by both individual management effort x_i taken by user i and positive externalities from the joint effort X of all ecosystem managers. How the function q_i depends on x_i and X reflects the hierarchical structure of the ecosystem: it captures how individual effort x_i affects local ecological processes, how aggregate

[3]Similar specifications have been used in other environmental economics studies. Eppink and Withagen (2006) use the sum of local and global biodiversity, which is a special case of (1) for $\zeta = 1$. Barbier and Rauscher (2006) use the special case of (1) with $\alpha = \beta = 1$.

effort X affects ecological processes at the landscape scale, and how these processes interact to determine local ecosystem quality. In the extreme, $\beta = 0$, corresponds to a situation where only local ecological processes are relevant and therefore management effort is purely private with no spill-overs to others. In the other extreme, $\alpha = 0$ corresponds to a situation where local ecosystem quality is completely determined by higher-scale ecological processes, so that management effort is a pure public good.

The parameter ζ measures the substitutability of the two species types for local ecosystem quality. For $\zeta = 1$, both types are perfect substitutes and all that matters is the sum of species richness of both types. For $\zeta \to -\infty$, the two species types are perfect complements and local ecosystem quality is limited by the species richness of the type with less biodiversity. In many cases, negative values of ζ seem plausible, reflecting some degree of complementarity between the two types of species (Tilman 1997).

Given ecosystem quality q_i, the ecosystem provides user i with the ecosystem service at a level s_i which is random. For simplicity we assume that the ecosystem service directly translates into monetary income and that the mean level $\mathcal{E} s_i = \mu$ of ecosystem service is independent of ecosystem quality and constant.[4] The variance of ecosystem services depends on ecosystem quality q_i as follows

$$\operatorname{var} s_i = \sigma^2(q_i) = \max\{(\eta - \epsilon\, q_i)^{1/\epsilon}, 0\}, \tag{2}$$

where $\eta > 0$ and $\epsilon < 1$. Again, since all managers face the same type of local ecosystem, the probability distribution of the ecosystem service is the same for all users who have the same ecosystem quality q.

Specification (2) includes (for different ϵ) a large variety of functions which are compatible with the ecological evidence discussed in the introduction: for each user, the variance of ecosystem service provision decreases with ecosystem quality q. This effect decrease in magnitude with the level of ecosystem quality. For $\epsilon > 0$, it is possible to obtain the ecosystem service at zero variance, provided ecosystem quality is high enough. This is not possible for $\epsilon < 0$. In the case $\epsilon = 0$, the specification (2) becomes $\sigma^2(q) = \exp(-q/\eta)$. In any case, a larger ϵ describes an ecosystem with higher natural insurance function.

[4]Ecological evidence suggests that for natural ecosystems μ increases with q (Hooper et al. 2005, Loreau et al. 2001, 2002, Tilman 1997), while in managed agricultural and silvicultural systems μ may decrease with q. We explored the impact of such relationships in previous versions of the model. Here, we neglect such a dependence of μ on q as it complicates the analysis while not adding further insights.

2.2 Financial insurance

In order to analyze the influence of availability of financial insurance on the ecosystem managers' choice of activity level x_i, we introduce financial insurance in a simple and stylized way. We assume that manager i has the option of buying financial insurance under the following contract: (i) The insurant chooses the fraction $a_i \in [0,1]$ of insurance coverage. (ii) He receives (pays)

$$a_i\left(\mathcal{E}s_i - s_i\right) \tag{3}$$

from (to) the insurance company as an actuarially fair indemnification benefit (insurance premium) if his realized income is below (above) the mean income.[5] In order to abstract from any problems related to informational asymmetry, we assume that the statistical distribution as well as the actual level s_i of ecosystem service are observable to both insurant and insurance company. (iii) In addition to (3), the insurant pays the transaction costs of insurance. The costs of insurance over and above the actuarially fair insurance premium, which are a measure of the 'real' costs of insurance to the insurant, are assumed to follow the cost function

$$\delta\, a_i \operatorname{var} s_i \ , \tag{4}$$

where the parameter $\delta \geq 0$ describes how actuarially unfair is the insurance contract. The costs increase linearly with the insured part of income variance. This captures in the simplest way the idea that the costs of insurance increase with the 'extent' of insurance. Throughout the analysis we assume $\delta < \rho$ to exclude corner solutions where a change in δ would have no effect.

The main focus of our analysis will lie in the comparative statics with respect to the parameter δ. Thereby we interpret a decrease in δ as an improvement in the access to, or reduction of the costs of, financial insurance.[6]

2.3 Income, preferences and decision

Each ecosystem manager i chooses the level of ecosystem management effort x_i and financial insurance coverage a_i. Improving ecosystem quality carries costs $c > 0$ per

[5]This benefit/premium-scheme is actuarially fair, because the insurance company has an expected net payment stream of $\mathcal{E}[a_i\left(\mathcal{E}s_i - s_i\right)] = 0$. This model of insurance is fully equivalent to the traditional model of insurance (e.g. Ehrlich and Becker 1972:627) where losses compared with the maximum income are insured against and one pays a constant insurance premium irrespective of actual income. In this traditional model, the *net* payment would exactly amount to (3), cf. Appendix A.1.

[6]The parameter δ could be treated as a policy variable, as it could be influenced by subsidies or taxes. Yet, we will treat δ as an exogenous parameter.

unit of management effort, which are purely private. Adding up income components, the manager's (random) income y_i is given by

$$y_i = (1 - a_i)\, s_i - c\, x_i + a_i\, \mathcal{E} s_i - \delta\, a_i \operatorname{var} s_i \ . \tag{5}$$

Since the ecosystem service s_i is a random variable, net income y_i is a random variable, too. The uncertain part of income is captured by the first term in Equation (5), while the other components are certain. Obviously, increasing a_i to one allows one to reduce the uncertain income component down to zero.

The mean $\mathcal{E} y_i$ and the variance $\operatorname{var} y_i$ of the manager's income y_i are determined by the mean and variance of ecosystem service, which depend on the individual and aggregate management efforts (Equation 2),

$$\mathcal{E} y_i = \mu - c\, x_i - \delta\, a_i\, \sigma^2(q(x_i, X)) \quad \text{and} \tag{6}$$

$$\operatorname{var} y_i = (1 - a_i)^2\, \sigma^2(q(x_i, X)) \ . \tag{7}$$

Mean income is given by the mean ecosystem service μ, minus the costs of ecosystem management effort $c\, x_i$ and the costs of financial insurance $\delta\, a_i\, \sigma^2(q(x_i, X))$. For an actuarially fair financial insurance contract ($\delta = 0$), the mean income equals mean net income from ecosystem use, $\mu - c\, x_i$. The variance of income vanishes for full insurance coverage, $a_i = 1$, and equals the variance of ecosystem service, $\sigma^2(q(x_i, X))$, without any financial insurance coverage, $a_i = 0$.

All ecosystem managers are assumed to have identical preferences over their uncertain income y_i, and to be risk-averse. From ecology (at best) the mean and the variance of ecosystem services are known, but rarely their full probability distribution. This restricts the class of risk preferences which can meaningfully be represented in our ecological-economic model to utility functions which depend only on the first and second moment of the probability distribution, i.e., on the mean and the variance. Specifically, we assume the following expected utility function, where $\rho > 0$ is a parameter describing the manager's degree of risk aversion (Arrow 1965, Pratt 1964):[7]

$$U_i = \mathcal{E} y_i - \frac{\rho}{2} \operatorname{var} y_i \ . \tag{8}$$

3 Analysis and results

The analysis proceeds in three steps: First, we discuss the laissez-faire equilibrium which arises if the n different ecosystem managers individually optimize their management effort taking the actions of the other managers as given (Section 3.1).

[7]More general utility functions of the mean-variance type would complicate the analysis without generating further insights.

Second, we derive the (symmetric) Pareto-efficient allocation (Section 3.2). Finally, we investigate how policy measures to internalize the externalities and welfare are influenced by the access to financial insurance, as described by the parameter δ (Section 3.3).

3.1 Laissez-faire equilibrium

As laissez-faire equilibrium, we consider the allocation which results as Nash-equilibrium without regulating intervention. Each ecosystem manager's decision problem is to maximize his expected utility, taking the actions of all other ecosystem managers as given subject to constraints (6) and (7). Formally, manager i's decision problem is

$$\max_{x_i, a_i} \mu - c\, x_i - \delta\, a_i\, \sigma^2(q(x_i, X)) - \frac{\rho}{2}\,(1-a_i)^2\, \sigma^2(q(x_i, X)) \;, \tag{9}$$

$$= \max_{x_i, a_i} \mu - c\, x_i - \left[\delta\, a_i + \frac{\rho}{2}\,(1-a_i)^2\right] \left[\eta - \epsilon \left[\gamma\, x_i^{\alpha\,\zeta} + (1-\gamma)\, X^{\beta\,\zeta}\right]^{\frac{1}{\zeta}}\right]^{\frac{1}{\epsilon}}$$

where $X = x_1 + \ldots + x_n$; all x_j for $j \neq i$ are treated as given.

The equilibrium allocation, consisting of the equilibrium levels $x_i^\star$ of management efforts, $q_i^\star$ of ecosystem qualities, and $a_i^\star$ of financial insurance coverages, has the following properties.

Proposition 1
An (interior) laissez-faire equilibrium exists, is unique and symmetric, that is, all ecosystem managers choose the same level $x^\star$ of ecosystem management and the same fraction $a^\star$ of financial insurance coverage. The equilibrium levels $x^\star$ of ecosystem management effort and $q^\star$ of ecosystem quality increase, and the equilibrium level $a^\star$ of financial insurance coverage decreases with the costs of financial insurance:

$$\frac{dx^\star}{d\delta} > 0, \quad \frac{dq^\star}{d\delta} > 0 \quad \text{and} \quad \frac{da^\star}{d\delta} < 0 \;.$$

Proof: see Appendix A.2.
The intuition behind the result is as follows. In the absence of transaction costs, i.e. for $\delta = 0$, the representative ecosystem manager chooses full insurance, i.e. $a^\star = 1$. If transaction costs are present, i.e. for $\delta > 0$, he chooses partial coverage by financial insurance ($a^\star < 1$).[8] Since natural insurance by conservative ecosystem management can be employed as a substitute for financial insurance, the equilibrium values of ecosystem management effort and of ecosystem quality are influenced by

[8] If transaction costs were prohibitively high, i.e. for $\delta \geq \rho$, the insurant would choose no financial insurance coverage ($a^\star = 0$).

the transaction costs of financial insurance: the higher the transaction costs of financial insurance are, the higher are ecosystem management effort and ecosystem quality in equilibrium.

Similarly, the equilibrium levels of ecosystem management effort, $x^\star$, ecosystem quality, $q^\star$, and financial insurance coverage, $a^\star$, all increase with the degree of risk aversion, ρ.

3.2 Efficient allocation

The next step is to study the efficient allocation. Since we are interested in comparing the efficient allocation to the laissez-faire equilibrium, we concentrate on the symmetric Pareto-optimum in which all ecosystem managers make the same effort. To obtain this allocation we define social welfare as the sum of the utilities of all n ecosystem managers, $W = \sum_{i=1}^{n} U_i$.

The efficient allocation is derived by choosing the individual levels of management effort x_i and financial insurance coverage a_i, such as to maximize social welfare subject to Constraints (6) and (7),

$$\max_{x_1,\dots,x_n;a_1,\dots,a_n} \sum_{i=1}^{n} \mu - c\,x_i - \delta\,a_i\,\sigma^2(q(x_i,X)) - \frac{\rho}{2}\,(1-a_i)^2\,\sigma^2(q(x_i,X)) \ , \tag{10}$$

$$= \max_{x_1,\dots,x_n;a_1,\dots,a_n} \sum_{i=1}^{n} \mu - c\,x_i - \left[\delta\,a_i + \frac{\rho}{2}\,(1-a_i)^2\right] \left[\eta - \epsilon\,\left[\gamma\,x_i^{\alpha\,\zeta} + (1-\gamma)\,X^{\beta\,\zeta}\right]^{\frac{1}{\zeta}}\right]^{\frac{1}{\epsilon}} .$$

Proposition 2
An (interior) efficient allocation exists, is unique and symmetric, that is, all ecosystem managers make the same management effort $\hat{x}$ and have the same fraction $\hat{a}$ of financial insurance coverage. The efficient levels $\hat{x}$ of ecosystem management effort and $\hat{q}$ of ecosystem quality increase, and the efficient level $\hat{a}$ of financial insurance coverage decreases with the costs of financial insurance:

$$\frac{d\hat{x}}{d\delta} > 0, \quad \frac{d\hat{q}}{d\delta} > 0, \quad \textit{and} \quad \frac{d\hat{a}}{d\delta} < 0 \ .$$

Proof: see Appendix A.3
The difference between the efficient and the equilibrium allocation is that in the efficient allocation the positive externality, which each ecosystem manager's effort has on the other ecosystem managers due to reduced variance of ecosystem service provision, is fully internalized. This changes the effect that an increase in the transaction costs of financial insurance has on the management effort and financial insurance coverage in magnitude, but not in sign. Hence, the same arguments hold which

support Proposition 1: with increasing transaction costs δ of financial insurance it is optimal to substitute financial insurance by natural insurance.

As in the laissez-faire equilibrium, the efficient levels of ecosystem management effort, $\hat{x}$, ecosystem quality, $\hat{q}$, and financial insurance coverage, $\hat{a}$, all increase with the degree of risk aversion, ρ.

3.3 Welfare effects of improved access to financial insurance

Due to the externalities of individual ecosystem management effort, the laissez-faire equilibrium is not efficient. In equilibrium, ecosystem managers spend too little effort to improve ecosystem quality, because they do not take into consideration the positive externality on other ecosystem users. In order to implement the efficient allocation as an equilibrium, a regulator could impose a Pigouvian subsidy on individual management effort. Denoting by τ the subsidy per unit of x_i, the optimization problem of ecosystem manager i under regulation then reads

$$\max_{x_i,\, a_i} \mu - c\, x_i - \delta\, a_i\, \sigma^2(q(x_i, X)) - \frac{\rho}{2}\,(1-a_i)^2\, \sigma^2(q(x_i, X)) + \tau\, x_i \ . \tag{11}$$

Comparing the first order conditions for the efficient allocation (i.e. the first order condition of problem (10) for x_i) and for the regulated equilibrium (i.e. the first order condition of problem (11) for x_i), we obtain the optimal subsidy $\hat{\tau}$.

Proposition 3

The efficient allocation is implemented as an equilibrium if a subsidy $\hat{\tau}$ on individual ecosystem management effort is set with

$$\hat{\tau} = -(n-1)\, \left[\delta\, \hat{a} + \frac{\rho}{2}\,(1-\hat{a})^2\right]\, q_X(\hat{x}, n\,\hat{x})\, \sigma^{2\prime}(q(\hat{x}, n\,\hat{x})) > 0 \ . \tag{12}$$

The optimal subsidy decreases / is unchanged / increases with the costs δ of financial insurance, i.e. $d\hat{\tau}/d\delta \lesseqgtr 0$, if and only if

$$(\beta - \alpha)\, \zeta \lesseqgtr 0. \tag{13}$$

Proof: see Appendix A.4.

The Pigouvian subsidy $\hat{\tau}$ captures the positive externality of ecosystem manager i's contribution to ecosystem quality. It comprises the insurance value that the higher ecosystem quality has for the $n-1$ other ecosystem managers and the (pecuniary) effect that the individual ecosystem manager's conservation effort has on the insurance costs of the other ecosystem managers: due to the decrease in variance, the markups on their insurance premiums decrease. The Pigouvian subsidy $\hat{\tau}$ can be interpreted as a measure of the extent of regulation necessary to internalize the externality of individual management effort, i.e. to solve the public-good problem. Thus, it can also be interpreted as a measure of the size of the positive externality that each unit of individual management effort has on the other ecosystem users in the efficient allocation.

Clearly, the size of the externality depends on the costs δ of financial insurance. However, the effect of higher costs of financial insurance on the public-good problem is in general ambiguous. The overall effect depends on the balance of two effects: (i) The higher δ, the higher is the positive (pecuniary) externality of individual management effort on other ecosystem managers' insurance costs. (ii) Individual management effort in the efficient allocation increases with δ (cf. Proposition 2). This effect decreases the size of the externality.

Whether the overall effect is negative or positive crucially depends on whether the marginal rate of substitution between individual and aggregate management effort in ecosystem quality, q_X/q_x, decreases or increases with the level x of individual management effort (see Equation A.20 in Appendix A.4). This marginal rate of substitution measures the potential for free-riding on other ecosystem managers' effort. It specifies the amount of aggregate management effort X that could be saved, holding q at a constant level, if one individual ecosystem managers' effort x increased by one marginal unit. If this potential for free-riding decreases with individual management effort the overall effect is negative, such that an increase in financial insurance costs δ decreases the size of the externality. Conversely, if the potential for free-riding increases with x the size of the externality increases with δ.

Condition (13) specifies, in terms of ecological parameters, if one or the other is the case. If the two species types – governed by farm-scale and landscape-scale processes, respectively – are ecological complements for local ecosystem quality, $\zeta < 0$, the size of the externality, measured by the Pigouvian subsidy $\hat{\tau}$, decreases with δ if $\beta > \alpha$ (increases if $\beta < \alpha$), i.e. if the slope of the species-area relationship is larger (smaller) at the landscape scale than at the farm scale. Conversely, if both types of species are ecological substitutes, $\zeta > 0$, the size of the externality decreases with δ if $\beta < \alpha$ and increases if $\beta > \alpha$. In the limiting case $\zeta = 0$, both effects equal out: the size of the externality is independent of the costs δ of financial insurance.

After having studied the effect of financial insurance on the size of the externality, we now turn to the question of how costs of financial insurance influence welfare. In a first-best economy, where the external effect is perfectly internalized, e.g. by the Pigouvian subsidy (12), the answer to this question is simple: higher costs of financial insurance are always welfare decreasing in the first best.[9]

This is not necessarily the case in the second best of the laissez-faire equilibrium where the externality of ecosystem management efforts is present. Whether welfare $W^\star = n\,[\mu - c\,x^\star - [\delta\,a^\star + (\rho/2)\,(1-a^\star)^2]\;\sigma^2(q(x^\star, n\,x^\star))]$ decreases or increases with δ depends on the relative size of two effects: (i) the direct effect of increased costs of insurance is always negative (this is the only effect present in the first best); (ii) the indirect effect that increased costs of financial insurance lead to increased individual ecosystem management efforts is positive (Proposition 1). The condition for whether the overall effect is negative or positive is given in the following proposition.

Proposition 4

With increasing costs of financial insurance, welfare in the laissez-faire equilibrium decreases / is unchanged / increases, i.e. $dW^\star/d\delta \lesseqgtr 0$, if and only if

$$\tau^\star\,\frac{dx^\star}{d\delta} \lesseqgtr a^\star\,\sigma^2(q(x^\star, n\,x^\star)), \tag{14}$$

where

$$\tau^\star = -(n-1)\,\left[\delta\,a^\star + \frac{\rho}{2}\,(1-a^\star)^2\right]\,q_X\,[x^\star, n\,x^\star]\;\sigma^{2\prime}(q(x^\star, n\,x^\star)) > 0. \tag{15}$$

In the special case $\alpha = \beta = 1$ and $\zeta = 0$, i.e. $q(x, X) = x^\gamma\,X^{1-\gamma}$, this condition simplifies to

$$n\,(\epsilon - \gamma) \lesseqgtr 1 - \gamma. \tag{16}$$

Proof: see Appendix A.5.

The right hand side of Condition (14) expresses the direct effect that expenditures for financial insurance increase with δ. This effect decreases welfare. The left hand side captures the indirect effect that individual effort $x^\star$ to improve ecosystem quality increases with δ (Proposition 1). Welfare is improved by the increase in $x^\star$ weighted by a factor of $\tau^\star$, which quantifies the positive externality of individual ecosystem management effort on the other ecosystem managers. The overall welfare effect depends on the balance between these two effects. In particular, laissez-faire welfare may even increase with the costs of financial insurance if the indirect effect is sufficiently large.

In order to better understand under which condition the indirect effect outweighs the direct effect, so that welfare actually increases with costs of financial insurance,

[9] By the envelope theorem, one only has to determine the partial derivative of the welfare function with respect to δ, which is unambiguously negative.

we consider the special case $\alpha = \beta = 1$ and $\zeta = 0$. In this case, Condition (14) simplifies to (16) which shows that laissez-faire welfare decreases with the costs of financial insurance δ if $\epsilon < \gamma$, i.e. when the natural insurance function of the ecosystem (measured by ϵ) is smaller than the relative importance of individual to aggregate management effort in producing ecosystem quality (measured by γ). The case that the positive indirect effect of an increase in δ outweighs the negative direct effect is also possible: laissez-faire welfare increases with δ if the natural insurance function of the ecosystem is sufficiently high, i.e. $\epsilon > \gamma$, and the number n of ecosystem managers is sufficiently large, i.e. $n > (1 - \gamma)/(\epsilon - \gamma)$.

4 Discussion and Conclusions

We have analyzed how risk-averse ecosystem users manage an ecosystem for the services it provides. The ecosystem model captures two stylized facts, as identified in the ecological literature: (i) Biodiversity is influenced by ecosystem processes operating at different hierarchical scales. We have considered two such scales: individual management action affects ecological processes at the farm scale, while aggregate action affects processes at the landscape scale. Thus, individual management effort has not only a private benefit but also exerts a positive externality on other ecosystem users. Considering land set aside for habitat as the management action, biodiversity at each scale can be described by a species-area relationship, with different 'slopes' at the farm and the landscape scales. (ii) The variance of ecosystem services decreases with biodiversity. Thus, biodiversity enhancing ecosystem management has a natural insurance function.

Financial insurance is a substitute for natural insurance from ecosystem quality, i.e. biodiversity. As a consequence, higher costs of financial insurance lead to a higher demand for natural insurance, and thus, to a higher level of biodiversity. Put the other way around, introducing institutions for, or improving access to, financial insurance leads to a lower level of ecosystem quality, as ecosystem managers substitute natural insurance from ecosystem quality by financial insurance.

Due to the externality of individual management effort, the laissez-faire equilibrium is not efficient. In order to study how the public-good problem is affected by financial insurance we have analyzed how (i) the extent of regulation necessary to implement an efficient allocation and (ii) welfare in the laissez-faire equilibrium depend on the costs of financial insurance.

How the Pigouvian subsidy, as a measure of the extent of efficient regulation, is affected by financial insurance depends on how exactly individual and aggregate management effort contribute to local ecosystem quality (Condition 13). In particular, the Pigouvian subsidy increases with improved access to, that is, decreasing costs of, financial insurance if (i) biodiversity at the farm and landscape scales are ecological complements and (ii) the slope of the species-area relationship is higher at the landscape scale.

While the condition of ecological complementarity holds for many ecosystems (Tilman 1997), there is no clear ecological evidence on whether the 'slope' of the species-area relationship is higher at the higher or the lower scale. Durrett and Levin (1996) argue that the slope of the species-area relationship is higher, the higher the rate is at which new species enter the system, either by in-migration or by mutation. It seems plausible that this rate and, correspondingly, the slope of the species-area relationship, is higher at the higher scale. This would imply that improved access to financial insurance increases the size of the externality and the extent of regulation necessary to solve the public-good problem.

If such regulation does not exist, or is not properly enforced, it is even possible that improved access to financial insurance decreases welfare. While this is, in principle, well-known from second-best theory, we have derived a specific condition on ecosystem functioning under which this happens (Condition 14). In particular, the following properties contribute to this condition being fulfilled: (i) the ecosystem has a very high natural insurance function and (ii) the number of ecosystem users is large, i.e. external benefits of ecosystem management are high.

While it is generally accepted that ecosystems do have a natural insurance function, empirical data on this natural insurance function only exists for a small number of systems. Yet, even there it is too sparse and insufficient to quantitatively estimate whether Condition (14) is fulfilled or not. More empirical ecological research on ecosystems' natural insurance function is needed from an ecological-economic point of view.

Our results are highly relevant for environmental and development policy. In so far as it is one aim of development policy to introduce, and improve access to, financial insurance markets, our analysis has shown that such a policy has negative implications for ecosystem quality and that ecosystem properties determine whether welfare increases or decreases under such a policy. Unless a sound environmental policy is in place, improving ecosystem users' access to financial insurance markets regardless of ecosystem properties may have adverse welfare effects.

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A Appendix

A.1 Fair insurance premium

Define the probability density function (pdf)

$$\tilde{f}(y) = \begin{cases} f(y)/\int_0^{\tilde{y}} f(\nu)\,d\nu & \text{if} \quad y \leq \tilde{y} \\ 0 & \text{if} \quad y > \tilde{y} \end{cases}, \tag{A.1}$$

where $f(y)$ is the pdf of a normal distribution with mean $\mathcal{E}y$ and variance $\operatorname{var} y$. Clearly, $\lim_{\tilde{y}\to\infty} \tilde{f}(y) = f(y)$. Consider the insurance contract under the probability density function (A.1) that losses compared to $\tilde{y}$ are insured against, i.e. if $y_i < \tilde{y}$, the insurance company pays an amount $a_i\,(\tilde{y} - y_i)$ of money to the insurant. (The contract considered in this paper is the particular case $\tilde{y} \to \infty$.) The fair premium π_i, i.e. the premium, which equals the expected payoff, of such a contract is

$$\pi_i = \mathcal{E}_{z_i}\,\left[a_i\,(\tilde{y} - y_i)\right]\ . \tag{A.2}$$

This premium has to be paid in any event. If the actual income y_i is below $\tilde{y}$, however, the insurant additionally receives the indemnification benefit. The net payment to (or from) the insurance company amounts to

$$\mathcal{E}_{z_i}\,\left[a_i\,(\tilde{y} - y_i)\right] - a_i\,(\tilde{y} - y_i) = -\mathcal{E}_{z_i}\,\left[a_i\,y_i\right] + a_i\,y_i = a_i\,(y_i - \mathcal{E}y_i)\ . \tag{A.3}$$

This expression does not depend on $\tilde{y}$, but only on the mean $\mathcal{E}y_i$ of the probability distribution of incomes. In particular, we obtain the same expression in the limit $\tilde{y} \to \infty$.

A.2 Proof of Proposition 1

The first order conditions of Problem (9) are

$$-\left(\delta\,a_i + \frac{\rho}{2}\,(1-a_i)^2\right)\,\sigma^{2\prime}(q(x_i,X))\,\left(q_x(x_i,X) + q_X(x_i,X)\right) = c \tag{A.4}$$

$$a_i = (\rho - \delta)/\rho, \tag{A.5}$$

where a_i is the same for all decision makers. We denote by $\tilde{X}$ the aggregate effort of all ecosystem managers except for manager i, i.e. $\tilde{X} = X - x_i$. Using (A.5), the first order condition with respect to x_i is

$$-\sigma^{2\prime}(q(x_i, x_i + \tilde{X}))\,\left(q_x(x_i, x_i + \tilde{X}) + q_X(x_i, x_i + \tilde{X})\right) = 2\,\rho\,c/\left(\delta\,\left(2\,\rho - \delta\right)\right) \tag{A.6}$$

To prove that there is a unique symmetric Nash equilibrium, we proceed in three steps: (i) we prove that a solution $x^\star$ to (A.4) is unique, (ii) we prove that $x_i = x^\star$ for all $i = 1, \ldots, n$ is a Nash-equilibrium. This is done by showing that $x_i = x^\star$ solves (A.6), if $\tilde{X} = (n-1)\,x^\star$. And (iii) we prove that no asymmetric Nash-equilibrium exists.

Ad (i). A solution $x^\star$ of (A.4) is unique, because the right hand side c is constant, while the left hand side is decreasing with $x^\star$;

$$-\frac{d}{dx^\star}\sigma^{2\prime}\,(q_x + q_X) = -\sigma^{2\prime\prime}\,(q_x + q_X)\,(q_x + n\,q_X) - \sigma^{2\prime}\,(q_{xx} + (n+1)\,q_{xX} + n\,q_{XX}) \leq 0\ , \tag{A.7}$$

where we omitted arguments for the sake of a clearer exposition.

Ad (ii). To show that the symmetric allocation $x_i = x^\star$ for all $i = 1, \ldots, n$ is a Nash equilibrium, we assume $\tilde{X} = (n-1)\,x^\star$ is given for manager i. In this case, the optimal effort for manager i is $x^\star$, because $x_i = x^\star$ solves Condition (A.4) uniquely. By symmetry, $x_i = x^\star$ for all $i = 1, \ldots, n$.

Ad (iii). Consider the two cases (a) $\tilde{X} > (n-1)\,x^\star$ and (b) $\tilde{X} < (n-1)\,x^\star$. In case (a), the optimal effort for manager i is $x_i < x^\star$. To prove this, we differentiate Condition (A.6) w.r.t. $\tilde{X}$, which yields

$$\frac{dx_i}{d\tilde{X}} = -\frac{\sigma^{2\prime\prime}\,(q_x + q_X)\,q_X + \sigma^{2\prime}\,(q_{xX} + q_{XX})}{\sigma^{2\prime\prime}\,(q_x + q_X)^2 + \sigma^{2\prime}\,(q_{xx} + 2\,q_{xX} + q_{XX})}, \tag{A.8}$$

which is negative. 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 (b). Hence, $x_i = x^\star$ for all $i = 1, \ldots, n$ is the unique equilibrium.

Differentiating the first order conditions (A.4) implicitly with respect to δ, we obtain

$$\frac{dx^\star}{d\delta} = a^\star\,\sigma^{2\prime}\,(q_x + q_X)\,\frac{1}{A^\star} > 0 \tag{A.9}$$

$$\frac{da^\star}{d\delta} = -\frac{1}{\rho} < 0\ , \tag{A.10}$$

where

$$A^\star = -\frac{\delta\,(2\,\rho - \delta)}{2\,\rho}\,\Big(\sigma^{2\prime\prime}\,(q_x + q_X)\,(q_x + n\,q_X) + \sigma^{2\prime}\,(q_{xx} + (n+1)\,q_{xX} + n\,q_{XX})\Big)\,.$$

$dq^\star/d\delta > 0$ follows from $dx^\star/d\delta > 0$ and Equation (1).

A.3 Proof of Proposition 2

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

$$\frac{1}{n}\sum_{i=1}^{n} \mu - c\,x_i - \delta\,a_i\,\sigma^2(q(x_i, X)) - \frac{\rho}{2}\,(1-a_i)^2\,\sigma^2(q(x_i, X)) \\ \leq \mu\big(q(\frac{X}{n}, X)\big) - \frac{\rho}{2}\,\theta\,\sigma^2\big(q(\frac{X}{n}, X)\big) - c\big(\frac{X}{n}\big)\ , \tag{A.11}$$

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.[10] Hence, we have to find the level x of effort to improve ecosystem quality, which maximizes

$$n\Big(\mu - c\,x - \delta\,a_i\,\sigma^2(q(x, n\,x)) - \frac{\rho}{2}\,(1-a)^2\,\sigma^2(q(x, n\,x))\Big) \tag{A.12}$$

Since this is a strictly concave function of both x and a, the solution is uniquely determined by the first order conditions

$$-\Big(\delta\,a + \frac{\rho}{2}\,(1-a)^2\Big)\,\sigma^{2\prime}(q(x, n\,x))\,\left(q_x(x, n\,x) + n\,q_X(x, n\,x)\right) = c \tag{A.13}$$

$$a = \frac{\rho - \delta}{\rho} \tag{A.14}$$

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

Differentiating these conditions implicitly with respect to δ, we obtain

$$\frac{d\hat{x}}{d\delta} = -\,\hat{a}\,\sigma^{2\prime}\,(q_x + n\,q_X)\,\frac{1}{\hat{A}} > 0 \tag{A.15}$$

$$\frac{d\hat{a}}{d\delta} = -\,\frac{1}{\rho} < 0\ , \tag{A.16}$$

where

$$\hat{A} = -\frac{\delta\,(2\,\rho - \delta)}{2\,\rho}\,\Big(\sigma^{2\prime\prime}\,(q_x + n\,q_X)^2 + \sigma^{2\prime}\,(q_{xx} + 2\,n\,q_{xX} + n^2\,q_{XX})\Big) < 0\ . \tag{A.17}$$

$d\hat{q}/d\delta > 0$ follows from $d\hat{x}/d\delta > 0$ and Equation (1).

A.4 Proof of Proposition 3

Ad 1. In order to derive the comparative statics of $\hat{\tau}$ with respect to δ, we differentiate (12) with respect to δ. This yields (omitting arguments)

$$\begin{aligned}\frac{d\hat{\tau}}{d\delta} = &-(n-1)\,\frac{\rho-\delta}{\rho}\,q_X\,\sigma^{2\prime} \\ &-(n-1)\,\delta\,\frac{2\,\rho-\delta}{2\,\rho}\,\Big((q_{xX} + n\,q_{XX})\,\sigma^{2\prime} + q_X\,\sigma^{2\prime\prime}\,(q_x + n\,q_X)\Big)\,\frac{d\hat{x}}{d\delta}\end{aligned} \tag{A.18}$$

Plugging in $\hat{a} = (\rho - \delta)/\rho$ and $d\hat{x}/d\delta$ from Equation (A.15) yields

$$\begin{aligned}\frac{d\hat{\tau}}{d\delta} = &-\frac{(n-1)\,\hat{a}\,\sigma^{2\prime}}{\sigma^{2\prime\prime}\,(q_x + n\,q_X)^2 + \sigma^{2\prime}\,(q_{xx} + 2\,n\,q_{xX} + n^2\,q_{XX})}\cdot \\ &\cdot\Big[q_X\,\Big(\sigma^{2\prime\prime}\,(q_x + n\,q_X)^2 + \sigma^{2\prime}\,\big(q_{xx} + 2\,n\,q_{xX} + n^2\,q_{XX}\big)\Big) \\ &\quad + (q_x + n\,q_X)\,\Big((q_{xX} + n\,q_{XX})\,\sigma^{2\prime} + q_X\,\sigma^{2\prime\prime}\,(q_x + n\,q_X)\Big)\Big]\end{aligned} \tag{A.19}$$

$$= (n-1)\,\hat{a}\,\sigma^{2\prime}\,q_X\,q_x\,\frac{\frac{q_x(\hat{x},n\,\hat{x})}{q_X(\hat{x},n\,\hat{x})}\,\frac{d}{dx}\,\frac{q_X(\hat{x},n\,\hat{x})}{q_x(\hat{x},n\,\hat{x})}}{\frac{\sigma^{2\prime\prime}}{\sigma^{2\prime}}\,(q_x + n\,q_X)^2 + q_{xx} + 2\,n\,q_{xX} + n^2\,q_{XX}} \tag{A.20}$$

Since the denominator of this expression is negative and $\sigma^{2\prime}$ is negative, too, the change of $\hat{\tau}$ following an increase in δ has the same sign as the numerator, which is is the elasticity of the marginal rate of substitution between individual and aggregate effects on local ecosystem quality. Using the specification (1), this elasticity is $(\beta-\alpha)\,\zeta/x$. Condition (13) follows, because $x > 0$.

A.5 Proof of Proposition 4

Part 1. is proven by differentiating laissez-faire welfare $W^\star$ with respect to δ, and plugging in the equilibrium conditions (A.4).

Ad 2.: Using $\alpha = \beta = 1$ and $\zeta = 0$ in Equation (1), with obtain $q(x, X) = x^{\gamma} X^{1-\gamma}$. Plugging this into Equations (A.4) and (A.5) yields

$$\sigma^2(q(x^\star, n\, x^\star)) = \left(\frac{\frac{2\rho}{\delta\,(2\rho-\delta)}\, n^{\gamma}\, c}{1 + \gamma\,(n-1)} \right)^{\frac{1}{1-\epsilon}} \tag{A.21}$$

$$x^\star = \frac{1}{\epsilon\, n^{1-\gamma}} \left(\eta - \left(\frac{\frac{2\rho}{\delta\,(2\rho-\delta)}\, n^{\gamma}\, c}{1 + \gamma\,(n-1)} \right)^{\frac{\epsilon}{1-\epsilon}} \right) \tag{A.22}$$

Using these results and $a^\star = (\rho - \delta)/\rho$, laissez-faire welfare can be expressed as

$$W^\star = n\,\mu - \frac{n^{\gamma}\, c}{\epsilon}\,\eta + \left(\frac{\delta\,(2\rho - \delta)}{2\rho} \right)^{-\frac{\epsilon}{1-\epsilon}} \left(\frac{n^{\gamma}\, c}{1 + \gamma\,(n-1)} \right)^{\frac{1}{1-\epsilon}} \left(\frac{1 + \gamma\,(n-1)}{\epsilon} - n \right) \tag{A.23}$$

Hence,

$$\frac{dW^\star}{d\delta} = -\frac{\epsilon}{1-\epsilon}\,\frac{\rho - \delta}{\rho} \left(\frac{\delta\,(2\rho - \delta)}{2\rho} \right)^{-\frac{\epsilon}{1-\epsilon}-1} \left(\frac{n^{\gamma}\, c}{1 + \gamma\,(n-1)} \right)^{\frac{1}{1-\epsilon}} \left(\frac{1 + \gamma\,(n-1)}{\epsilon} - n \right) \tag{A.24}$$

Because $\delta < \rho$, and $\epsilon < 1$, this sign of this expression is determined by

$$-\,(1 + \gamma\,(n-1) - \epsilon\, n) = n\,(\epsilon - \gamma) - (1 - \gamma). \tag{A.25}$$

This expression is negative for $\epsilon \leq 0$ and positive (only) for $\epsilon > \gamma$ and large n, i.e. $n > \frac{1-\gamma}{\epsilon-\gamma}$.