Ecosystem resilience as an economic insurance

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Zusammenfassung

In meiner Dissertation untersuche ich konzeptionelle und ökonomische Aspekte der Resilienz von Ökosystemen, also der Widerstandsfähigkeit von Systemen gegenüber exogenen Störungen. Hierbei stütze ich mich auf wissenschaftstheoretische Argumentation und ökologisch-ökonomische Modellierung. Ich zeige wie Resilienz als wichtige systemische Eigenschaft ökonomisch untersucht und bewertet werden kann.

Kapitel 1 geht der Frage nach ob konzeptionelle Vagheit in der Wissenschaft vorteilhaft oder problematisch ist. Hierzu wäge ich die in der Wissenschaftstheorie vorgebrachten Argumente pro und contra Vagheit ab und wende sie auf das Konzept der Resilienz an. Während die traditionelle Wissenschaftstheorie Präzision zur Bedingung guter Forschung erhebt, gestehen alternative Ansätze auch konzeptioneller Vagheit Vorteile zu. Ich argumentiere, dass es keine objektiv gültige Lösung des Zielkonflikts zwischen Präzision und Vagheit gibt und spreche mich für einen kontextabhängigen Grad an Vagheit aus.

Kapitel 2 untersucht inwieweit die in der Ökonomie gängige Annahme, dass das „self-protection“ Problem konvex ist, gerechtfertigt werden kann. Tatsächlich zieht die zentrale, formal notwendige Bedingung zur Stützung der Konvexitätsannahme unplausible Konsequenzen nach sich. Mithilfe üblicher Spezifikationen wird das „self-protection“ Problem analysiert. Selbst für standardmäßige Parameterwerte ist es nicht notwendigerweise konvex. Insbesondere ergeben numerische Simulationen, dass voller Selbstschutz oft die optimale Lösung des Problems darstellt. Darüberhinaus kann die Vernachlässigung solcher Randlösungen zu falscher Interpretation der komparativen Statik von inneren Maxima führen.

Kapitel 3 beschäftigt sich mit dem Versicherungswert von Ökosystemresilienz. Indem Resilienz die Wahrscheinlichkeit zukünftiger Verluste an Ökosystemdienstleistungen reduziert, versichert Resilienz Menschen gegen Wohlfahrtsverlust. Mithilfe einer allgemeinen und stringenten Definition von Versicherung als „Reduzierung von Einkommensunsicherheit“ wird der Versicherungswert von Resilienz in einem ökologisch-ökonomischen Modell ermittelt. Es wird gezeigt, dass der Versicherungswert (i) bei niedrigem Level von Resilienz negativ und bei hohem Level von Resilienz positiv ist, (ii) mit zunehmender Resilienz ansteigt und (iii) ein additiver Teil des gesamten ökonomischen Werts von Resilienz ist.

Kapitel 4 untersucht anhand eines ökologisch-ökonomischen Modells die Ursprünge von nichtlinearer Dynamik. Unter „open access“ Ressourcenernte werden die Resilienzeigenschaften des Systems durch die Präferenzen der Konsumenten für Ökosystemdienstleistungen bestimmt. Mit zunehmender Komplementarität der Ökosystemdienstleistungen im Konsum und zunehmender relativer Wichtigkeit für das Gesamtwohlbefinden der Konsumenten nimmt die Stabilität des Systems ab. Somit beschränkt sich die Rolle von Konsumenten und menschlichen Institutionen nicht nur auf die Anpassung an eine vorgegebene ökologische Dynamik. Vielmehr bestimmen Konsumenten und Institutionen selbst die grundlegenden dynamischen Eigenschaften eines gekoppelten ökologisch-ökonomischen Systems.

Kapitel 5 beschreibt wie „real options“ Techniken und „resilience thinking“ beim Management von Umweltrisiken in komplexen Systemen hilfreich sein können. In den Finanzwissenschaften werden Techniken zur Optionsbewertung bei der Entscheidungsfindung unter Unsicherheit angewendet. Das Konzept der Resilienz ist zur Darstellung von systemischen Risiken geeignet. Eine Kombination von „real options“ Techniken und dem Resilienz-Konzept ist somit ein vielversprechender Weg Umweltrisiken darzustellen und zu bewerten.

Contents

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Introduction

1 Motivation

Human civilization profoundly affects ecosystems on Earth. In fact, many ecosystems are degraded and the services they provide are critically at stake (MEA 2005). Making systems on all scales more resilient is deemed to be an appropriate way to mitigate these risks. For instance, The Economist (2011: 11) reflects on the human impact on ecosystems: “For humans to be intimately involved in many interconnected processes at a planetary scale carries huge risks. But it is possible to add to the planet’s resilience, often through simple and piece-meal actions […].” In other words, The Economist argues in favor of step-wise increasing the Earth’s resilience. Similarly, Folke et al. (2010) advocate investments in “Earth system resilience”. This implies that humans consciously assess and adjust their impact on ecosystems to address planetary challenges such as climate change or biodiversity loss.

While resilience proves a popular topic in discussions about planetary risks, research in this domain is only beginning (Rockström et al. 2009). Ever since Holling’s (1973) seminal article, the concept of resilience indicates non-linear system transitions. A widely cited definition of resilience is “the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks” (Walker et al. 2004: 2). If a system passes a tipping point and suddenly changes its functional structure, the consequences may be adverse or even catastrophic (Scheffer et al. 2001). Yet, while for many systems ample evidence exists on tipping points and non-linear transitions, examples on the planetary scale are scarce and difficult to demonstrate (Walker and Meyers 2004).

In fact, fundamental questions in the debate on resilience remain unanswered. What is the appropriate conceptual basis for resilience research? Should resilience necessarily be a precise concept? For instance, measuring resilience requires specifying resilience *of* what *to* what (Carpenter et al. 2001). However, while conceptual requirements are proposed in order to facilitate precise research, resilience is also embedded in a cluster of interrelated vague concepts (Gunderson and Holling 2002). Thus, the conceptual structure of resilience is open and contested (Brand and Jax 2007). Only by addressing these fundamental issues specific aspects of resilience can be investigated.

The crucial aspect I focus on is the insurance function of resilience. As resilient ecosystems are less prone to disturbances, they are less likely to exhibit disruptions in the flow of ecosystem services they provide (MEA 2005). Therefore, resilience insures humans by preventing welfare losses from reductions in ecosystem service flows. In consequence, precautionary investments in the capability of ecosystems to absorb shocks may be very valuable. Concerning this insurance aspect, specific questions arise. What exactly is the value of resilience as an insurance against reductions in ecosystem service flows? How much investment in resilience is optimal and what is the right time for an investment?

In my cumulative dissertation, I explore conceptual and economic aspects of resilience by addressing the aforementioned questions. Specifically, I contribute to economic resilience research on the abstract levels of the “comprehensive multi-level approach’’ (Baumgärtner et al. 2008). That is, I provide methodological considerations on the conceptual level and general insights derived from stylized models. I do not investigate a specific ecological-economic system but aim at advancing the conceptual basis on which empirical research can build.

In the remainder of this introduction, I present and discuss my thesis which consists of five research papers I (co-)authored. In Section 2, I summarize the five papers and set out their original contributions to the scientific discourse. Subsequently, in Section 3, I assume a meta-perspective and reflect on the scientific status and contribution of my thesis as a whole. To that end, I review the similarities and differences of the research papers and draw conclusions.

2 Research papers

In this Section, I sketch the five research papers of my thesis. The first paper investigates resilience research from a methodological point of view. The following four papers provide different approaches how to frame resilience so as to economically evaluate and analyze it as an important property of ecological-economic systems.

First, the paper **Is conceptual vagueness an asset? Arguments from philosophy of science and the concept of resilience (CV)** discusses the methodological question whether the scientific concept of resilience should be vague. To start with, the CV-paper contrasts two strands of resilience concepts, precise approaches and the vague perspective of “resilience thinking”. In the first strand, precise research establishes a polysemous concept of resilience, which means that similarities and differences between individual terms and meanings are clearly observable (Tuggy 1993). In the second strand, the vague perspective of “resilience thinking” expands the notion of ecosystem resilience to the social domain and complements it with a variety of other concepts. In contrast to the precise approaches, “resilience thinking” exhibits blurred conceptual boundaries, redundancies, metaphors and an implicit mix of descriptive and evaluative content. Thus, “resilience thinking” is a vague concept in the sense that its different meanings “have so much in common that it is difficult to separate them” (Tuggy 1993: 273).

These two diverging strands of resilience research may draw on different arguments from philosophy of science. Whereas traditional methodological arguments claim that conceptual clarity is essential for scientific research (e.g., Schlick 1936), post-normal and other views critical of traditional philosophy of science plead for conceptual vagueness (e.g, Feyerabend 1998). Which methodological arguments prevail? Arguably, there is not only one, generally appropriate level of vagueness. Rather, a trade-off between vagueness and precision exists, which might be solved differently depending on the specific research context. Applying this methodological argument to the specific case of “resilience thinking”, the CV-paper finds that the implicit mix of descriptive and normative aspects in “resilience thinking” is problematic. In order to address this issue, a coherent restructuring proposal along the lines of transdisciplinary research (Hirsch Hadorn 2006) is offered.

Thus, the CV-paper provides two original contributions. First, it systematically assesses the benefits and drawbacks of conceptual vagueness and thus fills a gap in the ecological economics literature, which hitherto neglects this question. It sketches how conflicting arguments from philosophy of science can be productively employed to determine whether conceptual vagueness is an asset or a liability. Second, the paper suggests a conceptual restructuring of „resilience thinking“. The proposal explicitly distinguishes between descriptive and normative aspects and thus provides a more coherent trade-off between vagueness and precision than the implicit emphasis on vagueness that characterizes “resilience thinking” so far. In sum, the CV-paper indicates how a methodological argument can facilitate advances on the conceptual level.

Second, the paper **Non-convexity of the self-protection problem (SPP)** derives from earlier work on optimal resilience management. Here, the basic idea is to interpret the ecological concept of resilience in terms of the economic self-protection framework. Self-protection is commonly defined as a real action that reduces the probability of a loss (Ehrlich and Becker 1972). Since an investment in resilience reduces the probability of an adverse ecosystem transition, it constitutes an act of self-protection. Thus, the decision on whether and how much to invest in ecosystem resilience can be modeled equivalent to the standard self-protection problem. While the SPP-paper contributes primarily to the economic literature on self-protection, its applicability to resilience management implies relevance for the wider range of interdisciplinary resilience research.

Specifically, the SPP-paper analyzes the condition for convexity of the self-protection problem given in the economic literature. While this literature claims a high degree of generality (e.g., Meyer and Meyer 2011), the condition it employs to assure convexity is implausible for a simple functional specification. In other words, the condition is much more restrictive than it purports to be. Furthermore, optimal self-protection often implies full self-protection, which contradicts the common economic presumption that the self-protection problem yields interior solutions (e.g., Jullien et al. 1999). The occurrence of boundary solutions such as “full self-protection is optimal” may also have consequences for the comparative statics of interior solutions: a particular parameter change may be misinterpreted if only interior maxima are analyzed but a global boundary optimum exists.

The SPP-paper demonstrates that an emphasis on high generality may have drawbacks. Whereas the economic literature on self-protection thoroughly investigates the comparative statics of the self-protection problem, it neglects other aspects. The SPP-paper’s original contribution is to indicate and address those hitherto overlooked aspects of the self-protection problem: the plausibility of second-order conditions, the relation between the effort to self-protect and the probability of a loss as well as the possibility of boundary solutions. As the SPP-paper’s framework can be interpreted in terms of "resilience thinking", it also provides an original contribution to resilience research: the paper demonstrates that full investment in resilience is often optimal even if ecosystem transitions are not catastrophic.

Third, the paper **The economic insurance value of ecosystem resilience (IV)** links two distinct strands of literature, the economics of risk and insurance on the one hand and the analysis of ecosystem resilience on the other hand.[1] Specifically, the IV-paper investigates in which respect ecosystem resilience can be interpreted as an economic insurance. So far, the resilience literature uses the term "insurance" in a loose, metaphoric way, in order to highlight the essential contribution of resilience to ecosystem functioning and the provision of ecosystem services. From a distinctively economic perspective, the IV-paper employs "insurance" in its specific meaning of mitigation of income uncertainty (McCall 1987). In that sense, insurance relates to a very specific function of ecosystem resilience, namely the reduction of some ecosystem manager's income uncertainty. Building on this conceptual framework, the IV-paper provides three salient results. First, the insurance value of ecosystem resilience may be negative (for low levels of resilience) or positive (for high levels of resilience). Intuitively, if resilience is very low and a system transition almost certain, small increases in resilience actually *raise* uncertainty; only if resilience is high enough do further increases reduce uncertainty. Second, the insurance value of resilience increases with the level of resilience. Third, the insurance value is one additive part of the total economic value of resilience, over and above the expected value of resilience.

The IV-paper thus analyzes the concept of resilience in the specific terms of the economic framework of binary risk prospects. This precise conceptual analysis yields results which may be rather unexpected following the vague colloquial meaning of the employed concepts. In particular, it may be astonishing that in some situations the insurance value of resilience is negative. Summing up, the IV-paper originally contributes to economic resilience research by conceptually separating the specific mitigation-of-uncertainty function of resilience from its overall contribution to human well-being.

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[1] In fact, the seminal references of both the resilience literature (Holling 1973) and the economics literature on risk and insurance (Ehrlich and Becker 1972) co-existed for almost 40 years without being related to one another.

Fourth, the paper **Consumer preferences determine resilience of ecological-economic systems (IPR)** shows that consumer preferences are important determinants of ecological-economic resilience. To that end, the paper models a stylized ecological-economic system. The coupled system consists of a multitude of individuals (“society”) who consume ecosystem services in the form of harvesting two competing species (“ecosystem”). Resilience emerges as a dynamic property of the system: if both species can be harvested and none of them goes extinct following a minor exogenous disturbance, the system is said to be resilient. If, in contrast, small disturbances lead to extinction of one of the species, the system has lost almost all its resilience. Numerical analysis shows that economic resource use and consumer preferences significantly influence the system’s degree of resilience. In particular, three destabilizing effects directly follow from consumer preferences. First, profit-maximizing harvesting under open access weakens the system’s resilience. Second, complementarity of ecosystem services in consumption reduces the system’s resilience. Third, relative importance of ecosystem services for the consumers’ overall well-being weakens the system’s resilience. Put another way, the more substitutable the ecosystem services and the lower their relative importance in consumption, the more stable the system.

The IPR-paper originally contributes to economic resilience research by clearly distinguishing the effects of economic resource use and consumer preferences from the effect of ecological interactions on a dynamic system’s resilience properties. So far, the existence of multiple stability domains has not been linked to consumer preferences. While it is an established result that species competition and, a fortiori, more complex ecological interaction eventually destabilize a dynamic system (e.g., Scheffer 2009), the IPR-paper shows that consumer preferences may induce similar effects. Thus, the IPR-paper originally demonstrates how the social dimension adds to ecological dynamics.

Finally, the overview paper **How real options and ecological resilience thinking can assist in environmental risk management (ROR)** investigates the prospect of combining real options techniques with “resilience thinking”. First, the ROR-paper demonstrates how resilience relates to the concepts of risk and uncertainty. In particular, the paper discusses three different concepts of resilience: the distance-to-threshold interpretation (Holling 1973), the speed-of-return interpretation (Pimm 1984) and the expected-time-until-flip interpretation (Hertzler and Harris 2010), which all have individual advantages and shortcomings. Second, the paper explains the real options framework, which is commonly employed to analyze dynamic investment decisions under uncertainty, in a non-technical way. Subsequently, a literature review shows how real options techniques have been applied in the context of environmental risk. Building on these considerations, the paper sets out the possibilities to use real options techniques to value resilience of ecosystems, of coupled ecological-economic or of purely social and economic systems. In particular, the real options approach might be used to determine the optimal timing and the optimal amount of investments in resilience. As an example, the classic case of eutrophication of shallow lakes is analyzed. Here, the option price of resilience indicates the maximum willingness to pay to avoid an adverse system transition.

Given that the ROR-paper is an overview paper, its original contribution consists of its broad integration of hitherto unrelated strands of research. Indeed, the real options literature on investment under uncertainty and “resilience thinking” display many similarities in their way of framing problems. Both strands of research focus on system transitions that are difficult to reverse (hysteresis) or even irreversible. Furthermore, both emphasize adaptability to exogenous changes and the value of flexibility as important factors for successful risk management. Hence, real options techniques could be productively employed within the resilience framework. In sum, the ROR-paper originally contributes to economic resilience research by highlighting the potential of an integrated research approach that uses real options to model dynamic investment decisions under risk of adverse system transitions.

3 Discussion

In this section, I assess the contribution to scientific knowledge of my thesis as a whole. To this end, I first compare the approaches of the individual papers. Subsequently, I interpret the findings by setting out complementarities and limitations.

Consider the different perspectives of the economic research papers. The SPP- and the IV-paper study resilience from the perspective of the ecosystem manager. Here, resilience figures as a control variable that may be directly chosen in a one-shot decision. Risk-aversion plays an important role in determining the optimal level (SPP) and the insurance value (IV) of resilience. In contrast, the IPR-paper abandons the ecosystem manager's perspective and conceptualizes resilience as emergent property of a dynamic ecological-economic system; it does not investigate the role of risk-preferences. While the ROR-paper does not set out a formal model, the real options approach in general applies a dynamic perspective and focuses on risk-neutral individuals. Thus, the ROR-paper demonstrates how to frame and evaluate dynamic investment decisions in ecological-economic systems.

Apart from these differences, the economic research papers display a fundamental similarity. They build on (SPP, IV, IPR) or suggest (ROR) stylized toy-models, which do not directly model empirical systems. Thus, the relevance of the ensuing results hinges not on empirical analyses but on their value for our conceptual understanding of resilience. In other words, the underlying similarity between the papers consists in their aim of advancing the conceptual discussion. By formalizing and devising a hypothetical setting, each of the papers focuses on some issues, leaving aside further aspects. Explicit assumptions specify a small set of variables and their relation. Here, I follow the idea of generic modeling (Baumgärtner et al. 2008). That is, the individual models frame resilience from different *perspectives* in accordance with their respective research aim.

What follows from these differences and similarities? On the one hand, the research papers are complementary on a conceptual level. This means that the models do not compete in explaining some phenomenon or solving a puzzle. Rather, the perspectives provide a more complete picture of the multifaced character of resilience. How do the different perspectives relate to each other? Following generic modeling, each perspective exists in its own right; the specific focus on a one-shot investment decision justifies the SPP-perspective, the focus on the economic insurance value of resilience justifies the IV-perspective, the focus on the right timing of an investment justifies the ROR-perspective and the focus on the determinants of resilience justifies the IPR-perspective. The CV-paper, in turn, provides the methodological background for this discussion of related perspectives. Using linguistic terminology (Tuggy 1993), the CV-paper demonstrates how similar but separable meanings yield a polysemous concept of resilience. The related but clearly distinguishable perspectives of my thesis conform very well to this polysemous picture.

Yet, on the other hand, the conceptual approach of my thesis displays clear limitations. As there is no empirical analysis, the research papers do not directly add to our understanding of a specific ecological-economic system. Another limitation arises from the papers’ narrow focus on some particular variables. For instance, the simple framework of resilience as a one-dimensional variable may not adequately represent more complex system structures. Also, while the SPP- and the IV-paper emphasize risk and risk-aversion, they do not address other aspects of risk preferences, such as aversion against ambiguity. Furthermore, the simplifying assumptions that help to generate analytically tractable models are very strong. For instance, the assumption that resilience is measurable and can directly be influenced (IV, SPP, ROR) presupposes very precise knowledge of an ecological-economic system, which might not be given.

While these are clear limitations, they necessarily arise in ongoing conceptual research. Deliberately simplifying and narrowing the focus on some key issues constitutes the core of abstract modeling. In other words, resilience remains a metaphor unless it is given a precise conceptual structure. Also, some of the limitations might be mitigated through subsequent research. For instance, the SPP- and the IV-papers’ frameworks might be extended to capture ambiguity-aversion as well. The aforementioned limitations, therefore, do not represent fundamental flaws in research design; rather, they are unavoidable in the stepwise process of better understanding resilience.

In conclusion, I demonstrate how to frame resilience so as to economically evaluate and investigate it as an important property of ecological-economic systems. Each of the research papers contributes a specific, limited perspective. I thus establish a polysemous concept of resilience, whose different aspects are clearly distinguishable. Overall, I aim to advance the conceptual discussion about ecosystem resilience as an economic insurance.

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Chapter 1: Is conceptual vagueness an asset? Arguments from philosophy of science and the concept of resilience

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Abstract: Is conceptual vagueness an asset or a liability? By weighing arguments from philosophy of science and applying them to the concept of resilience, I address this question. I first sketch the wide spectrum of resilience concepts that ranges from concise concepts to the vague perspective of "resilience thinking". Subsequently, I set out the methodological arguments in favor and against conceptual vagueness. While traditional philosophy of science emphasizes precision and conceptual clarity as precondition for empirical science, alternative views highlight vagueness as fuel for creative and pragmatic problem-solving. Reviewing this discussion, I argue that a trade-off between vagueness and precision exists, which is to be solved differently depending on the research context. In some contexts research benefits from conceptual vagueness while in others it depends on precision. Assessing the specific example of "resilience thinking" in detail, I propose a restructuring of the conceptual framework which explicitly distinguishes descriptive and normative knowledge.

JEL-Classification: B40, Q57

Keywords: vagueness, philosophy of science, precision, resilience thinking

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1 Introduction

> "*'But is a blurred concept a concept at all?' - Is an indistinct photograph a picture of a person at all? Is it even always an advantage to replace an indistinct picture by a sharp one? Isn't the indistinct one often exactly what we need?*"
>
> (Ludwig Wittgenstein, Philosophical Investigations, § 71)

In this paper, I discuss Wittgenstein's question about the (in-)desirability of sharp conceptual boundaries using the concept of resilience as an example. Does resilience exhibit conceptual vagueness, and, if so, is that beneficial? Can looseness in concepts and meanings lend itself to shedding light on unsolved problems? While resilience research has established that redundancy is an asset for complex adaptive systems, does a similar finding also hold for conceptual frameworks?

The question about the benefits of vagueness is not only of philosophical interest but also highly relevant within scientific discourse. For instance, ecologists regularly debate wether conceptual precision is found wanting in their discipline (McCoy and Shrader-Frechette 1992, Odenbaugh 2001, Davis and Thompson 2001, Hodges 2008a, Jax 2008, Hodges 2008b). Within ecological economics, several concepts are contested with respect to the appropriate degree of vagueness/precision. Most prominently, sustainable development carries a vague, broadly accepted meaning and many individual, contentious meanings (Jacobs 1999). A systematic discussion, however, about the potential benefits or drawbacks from vagueness is missing in ecological economics.

In order to fill this gap, I analyze the methodological question whether scientific concepts should be vague.[1] I contrast two conflicting positions within philosophy of science. First, the traditional view of science emphasizes precision and conceptual clarity as precondition for an empirical science that aims at generating valid, objective knowledge. This view relegates all vague concepts and statements to the realm of pseudo-science and belief. Second, alternative views highlight vagueness as fuel for creativity, means of communication across disciplinary boundaries and part of pragmatic problem-solving. Thus, the diverging positions derive from fundamental differences about the purposes of science. To put it pointedly, con-

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[1] I am not interested in the manifold disputes in philosophy and cognitive science whether concepts are objects or abilities, mental representations or abstract entities and so forth. I leave it at the observation that "[c]oncepts, pretheoretically, are the constituents of thoughts (Margolis and Laurence 2006)".

ceptual vagueness is seen as detrimental for achieving "truth" but it is perceived as beneficial for mitigating "wicked problems" (Rittel and Webber 1973). Assessing these methodological arguments, I propose that the advantages of precision and vagueness constitute a trade-off. A universal solution to this trade-off that perfectly balances the benefits and drawbacks of conceptual vagueness may not exist. Rather, the trade-off may be solved differently depending on the specific research context. By consciously approaching the trade-off and giving explicit justification for a particular solution, inappropriate degrees of vagueness/precision could be avoided.

I highlight the significance of this methodological discussion for ecological economics by applying it to the concept of social-ecological resilience. Resilience relates to a variety of topics, such as non-linear transitions in ecosystems or adaptive management. Hence, it sometimes appears as vast and fuzzy: "Resilience is a broad, multifaced, and loosely organized cluster of concepts, [...] a changing constellation of ideas [...]" (Carpenter and Brock 2008: 1). More systematically, a literature survey (Brand and Jax 2007) inventories the prevalent meanings of resilience in a typology comprising ten (!) different categories of concepts. Yet not every *individual* concept is vague. There is a wide spectrum of concepts with respect to the degree of vagueness. On the precise end of this spectrum different meanings and their relation are clearly distinguishable. On the vague end of the spectrum lies "resilience thinking", a holistic perspective on human-nature relationships (Folke et al. 2010, Kirchhoff et al. 2010, Walker and Salt 2006). It expands the original ecological definition of resilience (Holling 1973) to encompass social systems as well and complements it by a variety of other vague notions, such as adaptability, transformability (Walker et al. 2004) or panarchy (Gunderson and Holling 2002). Weighing the methodological arguments about vagueness with respect to the example of "resilience thinking", I argue that its implicit mix of descriptive and normative attributes is problematic. I thus suggest an explicit distinction between descriptive and normative aspects. By relating the concepts of resilience, sustainability, adaptability and transfomability in analogy to the approach of transdisciplinary research (Hirsch Hadorn et al. 2006), I show how "resilience thinking" could accomplish this.

Throughout this paper I use *vagueness* in the linguistic, purely descriptive sense of the word: *vagueness* refers to the phenomenon of a term that has several meanings which "have so much in common that it is difficult to separate them" (Tuggy 1993: 273). In contrast, *polysemy* refers to a term whose several meanings are similar but separable and *ambiguity* to a term whose several meanings have “little or nothing in common beyond the phonological structure they share” (ibid.). Although these categories themselves are vague because borderline cases may exist, they are helpful in shaping the focus of this paper: I am not concerned with ambiguity since I ignore meanings from completely different contexts, such as psychological resilience during childhood development. Rather, I concentrate on resilience in social-ecological systems and present how conceptually precise research establishes a polysemous concept of resilience whereas “resilience thinking” is based on a vague concept of resilience.

The paper is organized as follows. In Section 2, I give an introduction to the wide spectrum of current resilience concepts. In Section 3, I present arguments from philosophy of science in favor and against conceptual vagueness. I discuss the implications of this methodological dispute in Section 4 and propose a restructuring of the “resilience thinking” conceptual framework. Finally, in Section 5, I summarize and conclude.

2 Concepts of resilience: a wide spectrum

First, I demonstrate how precise definitions yield a polysemous concept of resilience. Second, I sketch the vague perspective of “resilience thinking”. In doing so, I set out the extreme end-points of the whole spectrum of vagueness/precision.

2.1 Resilience research: a polysemous concept

Rather than giving an encompassing literature overview, which recently has been provided in form of a typology (Brand and Jax 2007), I introduce three concise concepts of resilience in an exemplary manner.

First, Pimm’s (1984: 322) well-known concept of resilience refers to the time a system needs to recover from a disturbance: “How fast the variables return towards their equilibrium following a perturbation.” This definition is applicable only to stable systems with one equilibrium. It is a precise, one-dimensional measure. The faster a systems returns to equilibrium, the larger its resilience.

Second, Walker et al. (2010) measure the economic value of resilience. To that end, they define resilience theoretically as a stock variable where the height of the stock is equivalent to the system’s resilience. Applied to the problem of salinization in South-East Australia, they operationalize resilience as the distance of the groundwater table from a critical threshold value. Hence, resilience figures as a precise, one-dimensional measure. The bigger the groundwater table's distance to the critical salinization level, the bigger the system's resilience.

Third, Derissen et al. (2011: 10) define resilience in a relative way. They ask wether a system is persistent relative to a specific disturbance: a given state of a system is called resilient with respect to a specific disturbance "if and only if the disturbed system is in the same domain of attraction in which the system has been at the time of disturbance". Hence, the question wether a system is resilient or not can only be evaluated after a disturbance has occurred. Resilience, in this view, is an ex-post description of a dynamic system's trajectory. It is coupled to a precise, formally specified condition. This implies that resilience is not continuously measurable - either the condition is met and the system is resilient or the system fails to comply with the condition and is deemed not resilient. Thus, resilience boils down to a 0/1 decision.

These are three concise definitions of resilience. In some respects they are similar, in others they are different. In the first and second concept, resilience is continuously measurable, in the third it is a 0/1 decision. In the first and third concept, the resilience of a system is determined ex-post, after some perturbation occurred, in the second concept, current resilience is assessed in order to determine the consequences of future disturbances. Finally, concepts two and three are inspired by Holling's (1973) notion of resilience, whereas the first concept is not.

In sum, resilience research provides different specific definitions of resilience, which partly overlap in structure. The question which specific concept is adequate in what context has to be addressed accordingly. Crucially, the similarities and differences between these precise definitions are clearly observable. Resilience, then, is a polysemous concept in that its "meanings are clearly distinguishable, yet clearly related" (Tuggy 1993: 273). The possibility to clearly distinguish one meaning from another is what separates precise concepts of resilience research from the vague concept of "resilience thinking" presented in the next subsection.

2.2 Resilience thinking: a vague concept

"Resilience thinking addresses the dynamics and development of complex social-ecological systems" (Folke et al. 2010: 1). Here, "addressing" refers not only to scientific apprehending for "resilience thinking" is more than a research program. It is also a resource-management approach and a view of the world that is not necessarily tied to scientific discourse and academic institutions (Walker and Salt 2006). "Resilience thinking" moves away from the analysis of specific situations (Carpenter et al. 2001) and rather emphasizes the attitudes embodied by the perspective (Folke et al. 2010). Consequently, there is a whole cluster of concepts gathering under the umbrella "resilience thinking". Four characteristics mark "resilience thinking" as vague extreme of the spectrum of resilience concepts. "Resilience thinking" displays blurred boundaries of concepts (1), redundancy (2), metaphors (3) and an implicit mix of normative and positive aspects (4).

First, several other concepts are suggested as complementary to resilience. The boundaries between them are blurred. Consider the concepts adaptability and transformability, which are proposed as prerequisites for resilience (Walker et al. 2004, Folke et al. 2010). Adaptability is often defined as "the capacity of actors to influence resilience", transformability as "the capacity to transform the stability landscape itself to become a different kind of system" (Folke et al. 2010: 3). However, the capacities evoked in the definitions are roughly the same - both on the empirical and on the conceptual level. Empirically, adaptability and transformability of a social-ecological system rely on similar characteristics, such as institutional diversity, learning possibilities or openness to experimental change (Folke et al. 2010: 5). On the conceptual level the boundaries are also blurred. Both concepts refer to the ability to change the stability landscape, where adaptability indicates small changes and transformability large changes. The boundary between small and large changes is, of course, hard to pin down (Walker et al. 2004: 2).[2]

Second, not only are the boundaries between concepts blurred, but also is there redundancy. That is, concepts overlap in meaning up to the point of complete congruency. The use of the concepts of resilience and adaptive capacity illustrates. Adaptive capacity is often defined as one aspect of resilience, which refers to "learning, flexibility to experiment and adopt novel solutions" (Walker et al. 2002: 6). Following this view, adaptive capacity figures

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[2] This is also the root of the so-called "sorites-paradox" from classic Greek philosophy which arises from the impossibility to draw a precise boundary between such predicates as bald and not bald or tall and not tall.

(i) as an exclusively human attribute and (ii) as one component of the main concept of social-ecological resilience. However, the concepts are also used in ways contradicting both (i) and (ii). Contra (i), for instance, Scheffer (2009: 103) writes : "In ecosystems, adaptive capacity is determined largely by the (response) diversity of species". Here, adaptive capacity no longer exclusively represents human capabilities. Contra (ii), for instance, Bierman et al. (2010: 284) indicate "adaptiveness" as an "umbrella concept for a set of related concepts", among them resilience. In other words, adaptive capacity and resilience seem to mutually contain each other and converge to one social-ecological concept.

Third, "resilience thinking" includes two metaphorical concepts, "adaptive cycle" and "panarchy" (Gunderson and Holling 2002). Both metaphors refer to distinct aspects that, following "resilience thinking", are crucial for the resilience of complex, adaptive systems. The adaptive cycle metaphor highlights the time dimension of resilience and repeated circulation through different phases. The panarchy metaphor emphasizes the spatial dimension of resilience and the importance of scales below and above the system in question. Albeit these metaphors do not come down to a single hypothesis, they serve as "heuristic models" (Folke et al. 2010) that structure research.

Fourth, "resilience thinking" implicitly mixes normative and positive aspects. While resilience was introduced as a purely descriptive concept (Holling 1973), "resilience thinking" now carries heavy normative content (Brand and Jax 2007, Nykvist and Hahn 2011). In other words, "resilience thinking" replaces an initially "thin" concept of resilience with a "thick" concept that exhibits both description and evaluation (Williams 1985). This is not per se a problem; it just indicates the social relevance and therefore contested structure of resilience. If it is not clear whether a concept is used in a descriptive or evaluative way, however, this may lead to confusion over the type of knowledge that is generated. In Section 4.2, I deal with this point in more detail and suggest a possible remedy.

In sum, at the vague end of resilience research lies "resilience thinking". Individual meanings inside this cluster of concepts are not clearly distinguishable, partly redundant, metaphorical and evaluative.

3 Conceptual vagueness vs. precision

In the following, I present the methodological arguments pro and contra vagueness and precision, respectively. First, I set out the traditional view of science that emphasizes precision and conceptual clarity. Second, I present the arguments pro vagueness, which stem from various attacks on the traditional view.

3.1 Arguments pro conceptual precision and versus vagueness

In traditional philosophy of science, several arguments back the claim that conceptual clarity is essential for scientific research. (P 1) Conceptual precision sets science apart from faith. (P 2) Precise concepts reveal the limits of their validity. (P 3) Empirical testability necessarily presupposes conceptual precision. I will put forward arguments (P 1) and (P 2) by presenting Max Weber's reasoning. Subsequently, I introduce two rationalizations of argument (P 3) by presenting the dispute between the logical empiricists of the Vienna Circle and Karl Popper.

First, consider Weber's argument for conceptual precision as the main virtue of a researcher. Weber argues that scientists make value-judgments when choosing on how to deal with the "infinite multiplicity of successively and coexistently emerging and disappearing events" (Weber [1904] 1949: 72). The researcher's perspective is no less subjective than the individual actions she intends to explain. The establishment of ends-means relationships as a basis for understanding human actions is an inherently value-laden activity. Therefore, the researcher must state her own perspective as clearly as possible. She needs to disclose her own starting-point in order to distinguish her subjective value-judgments from the empirical knowledge delivered by the respective analysis. In other words, total *Wertfreiheit* (value-freedom) is impossible. Albeit the researcher should strive to distinguish her subjective view from empirical facts, she cannot attain a perspective-free point from where to conduct research. Value-judgments are unavoidable. They should be clearly indicated and recognizable as such – for if they are not made explicitly up front, they silently enter subsequent research. It is only a "hair-line which separates science from faith" (Weber [1904] 1949: 110). Hence, it is of uttermost importance for the researcher to make the normative foundation of her conceptual framework as explicit as possible.

Second, Weber argues that conceptual clarity is necessary to be aware of a concept's limits. In contrast, failing to clarify one's perspective and assumptions obfuscates the merits of a given research approach. Only by means of clear conceptual boundaries can the limits of produced empirical knowledge be established. Only by concise delineation of a concept's content can its applicability be judged. That reality is complex and multi-layered should not be a pretext for using soft and blurred concepts that accommodate reality more easily. Very broad concepts may tempt researchers to believe the concepts could explain everything. Then, however, they explain nothing. Weber concludes:

> "...the construction of sharp and unambiguous concepts relevant to the concrete individual viewpoint which directs our interest at any given time, affords the possibility of clearly realizing the limits of their validity." (Weber [1904] 1949: 107)

Hence, Weber suggests abstract *Idealtypen* (ideal types) which serve as instruments to structure social reality. Whether these theoretical constructs are mere intellectual games or useful categories cannot be determined a priori. It is through their capacity to provide meaningful empirical knowledge that they reveal their validity.

Third, the relationship between theories, concepts and the empirical world is at the core of the reasoning of the logical empiricists of the Vienna Circle and their critic Popper. Both sides contend that empirical testing constitutes the heart of science. This conviction builds on the dictum of 19th century physicist Mach [1883] (1960: 587) that "where neither confirmation nor refutation is possible, science is not concerned." In their assault on metaphysics the members of the Vienna Circle reject any statement that belongs neither to the realm of logic nor to the realm of empirical science. Since they consider logical statements as tautological, their main interest consists in providing a criterion for empirical significance. That criterion is found in the possibility of verification: either a statement is verifiable in principle or it refers only to a pseudo-problem.[3] Schlick (1936) radicalizes this reasoning by equalizing *meaning* and *possibility of verification*. He contends that the only appropriate answer to the question "What does statement X mean?" is to indicate a procedure by which X could be empirically tested. Hence, verifiability distinguishes relevant statements from meaningless statements:

> "The dividing line between logical possibility and impossibility of verification is absolutely sharp and distinct; there is no gradual transition between meaning and nonsense. For either you have given the grammatical rules for verification, or you have not; *tertium non datur*." (Schlick 1936: 352, emphasis in original)

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[3] The point is not that a statement has to be positively confirmed to bear meaning but that you have to be able to denote a procedure by which it could be empirically verified.

As no gray area exists between verifiable and meaningless statements, conceptual precision is crucial. Only sharp propositions can be empirically tested. If all pseudo-problems are dismissed, empirical science can do its job:

> "Neatness and clarity are striven for, and dark distances and unfathomable depths rejected. [...] Clarification of the traditional philosophical problems leads us partly to unmask them as pseudo-problems, and partly to transform them into empirical problems and thereby subject them to the judgment of experimental science." (Carnap et al. [1929] 1973: 306)

Whereas Popper rejects verification as criterion of meaning, he agrees with the Vienna Circle on a very fundamental level – science strives for empirical validation which implies conceptual precision as a precondition. Empirical validation, for Popper, is not positively possible. Hypotheses can never be logically verified, only refuted by empirical tests. Hence, Popper substitutes falsifiability for verifiability. The degree of falsifiability indicates a theory's quality: "Every "good" scientific theory is a prohibition: it forbids certain things to happen. The more a theory forbids, the better it is" (Popper 1963: 36). Falsifiability, in turn, increases in the degree of clarity and precision of a theory (Popper 1959). Vague theories are more difficult to falsify than clearly stated ones because vague concepts and hypotheses are easily reconciled with whatever may eventuate. Precise statements, in contrast, exhibit a higher probability of being refuted since they yield a much higher set of events that are prohibited. Thus, vagueness in concepts is bad science – as it accommodates reality more easily, vagueness impedes the scientific progress which relies on the trial-and-error mechanism of repeated formulation and refutation of hypotheses.

3.2 Arguments pro conceptual vagueness and versus precision

In contrast to the traditional view of science presented in the last Section, other authors hold that precision is not a precondition for good science and that conceptual vagueness is an asset. The arguments to support that claim can be summarized as follows: (V 1) Creativity relies on open, vague language. (V 2) Inter- and transdisciplinary communication may profit from blurred concepts. (V 3) Problem-solving requires participative processes rather than precise, abstract conceptualization. I first introduce argument (V 1) which figures most prominently in Feyerabend's attack on traditional philosophy of science. Then, I set out argument (V 2) by presenting Wittgenstein's discussion of blurred concepts and argument (V 3) by presenting the emerging perspective of post-normal science.

First, in a famous attack against traditional philosophy of science, Feyerabend (1975, 1998) rejects the latter's emphasis on precision, clarity and abstraction and highlights vagueness as a source of creativity (cf. Hodges 2008a for a similar argument in the ecological discussion). Feyerabend dismisses the traditional assumption of a superiority of science and argues that there cannot be a decisive argument against other forms of knowledge (possibly vague and inconsistent) that are incommensurable with science. Just as the choice between competing scientific theories always includes a subjective value-judgement, the choice between scientific knowledge and other forms cannot be grounded on purely objective arguments. Hence, traditionally precise scientific concepts and definitions are not a priori superior to others. On this reasoning builds Feyerabend's (1998) case for vagueness as source of creativity. Every-day language is mostly vague, in contrast to the traditional requirements for scientific language which Feyerabend dismisses in the first place. He insists that there is no decisive, objective argument in favor of "scientific standards" of precision and abstraction. To the contrary, science loses its creative potential when it gets too obsessed with precise language and conceptual rigor.[4] Every attempt to dispose of ambiguities is detrimental because open-minded, creative thinking thrives on vagueness. The traditional quest for scientific rigor and absolutely precise concepts, in Feyerabend's view, may yield a deadlock instead of the desired progress. The capacity to find genuine research questions and inventive solutions is dependent on some degree of blurredness. While inconsistencies and ambiguities traditionally are seen as flaws to be eliminated, they are fuel for constructive, open-ended science. A perfectly precise and closed conceptual scheme would rather terminate creativity and epistemic motivation than promote new research. Feyerabend (1998: 131, own translation) concludes: "Thus, I would say that it is better to remain vague."

Second, Wittgenstein [1953] (2009) insists that some concepts cannot be pinned down to a single, concise definition but rather have a "family of meanings". While all members of the family show "family resemblances", they do not share one specific trait. Also, it is not possible to indicate an exact boundary that separates members from non-members. Wittgenstein's example is the question of how to explain to someone what a *game* is. It is not advisable,

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[4] Some of the logical empiricists already warned that the emphasis on clear and careful language should not lead the way to dogmatism (e.g., Neurath 1941).

he argues, to try to give an exact definition. Rather, some paradigmatic examples of games give a better idea of the concept. For some special purpose, a precise definition may be useful, but the concept *game* as a whole refers to a "family of meanings" and thus cannot be squeezed into a single definition. Family resemblances and vague concepts have the same root: the use of terms is not explicitly regulated. Thus, a vague concept is applicable to a wide range of cases and more adaptable to hitherto unknown examples. While employing a narrow definition justifies the use of a term in a particular way, it sharply restricts the concept's applicability. By refusing to draw exact boundaries, i.e., avoiding precise definitions, the set of possible examples for a concept remains open. Hence, it is easier to accommodate new members to the family of meanings. While Wittgenstein makes his argument in a very general way, the point easily transfers to philosophy of science. Precise definitions are appropriate for the respective specific research purposes. Yet they are less adaptable to other cases and purposes. This problem will be magnified when a concept is used across disciplines and outside the scientific discourse. Following this reasoning, a vague concept makes inter- and transdisciplinary communication easier since it allows for integration of different meanings; there is no boundary that precludes any perspective beforehand. For example, resilience as a vague "boundary object" (Brand and Jax 2007) with less specific content and more openness to usage in other contexts, facilitates inter- and transdisciplinary communication.

Third, while traditional views of science call for abstraction and rigor in order to achieve scientific certainty, the idea of post-normal science (Funtowicz and Ravetz 1993, 2003) challenges the picture of science as an unbiased endeavor. Post-normal science does not claim to provide objective, value-free knowledge. It admits that purported neutral scientific input may make controversies even worse (Sarewitz 2004) and acknowledges that decision stakes and uncertainty are high. Under these circumstances the traditional aim of research, truth, "...may be a luxury or indeed an irrelevance"; it is thus replaced by "maintenance and enhancement of quality" (Funtowicz and Ravetz 2003: 653) as the appropriate aim. Consequently, post-normal knowledge "does not conform to the ideal of scientific knowledge as universal, explanatory and proven" (Hirsch Hadorn et al. 2006: 125). The authority of science to provide hard inputs that guide soft policy decisions is gone. Rather, post-normal science engages in a mutually respectful dialogue with stakeholders, where everyone who desires has a say and no one is morally or epistemically superior (Luks 1999, Frame and Brown 2008). This public discourse aims at maintaining and enhancing quality by tackling pressing problems. Conceptual rigor and abstract, theoretical knowledge do not necessarily contribute to that aim. This particularly holds for “wicked” problems (Rittel and Webber 1973). “Wicked” indicates that the definition or formulation of the problem is contested, so it is not clear at which point it can be considered as solved (or whether a solution is possible at all). As different perspectives struggle for the dominant interpretation of a problem, language becomes an important issue. Therefore, Pohl et al. (2008) suggest to deliberately use everyday language instead of scientific terms in order to achieve common understanding among researchers and stakeholders. In other words, conceptual vagueness may be more helpful than conceptual precision for advancing post-normal problem-solving.

4 Assessment of arguments pro and contra precision and vagueness respectively

Resilience comes in a wide spectrum, ranging from very concise concepts on the one hand, to the vague concept of “resilience thinking” on the other hand (cf. Section 2). Both ways can draw on arguments from philosophy of science (cf. Section 3). Does one side prevail? First, I argue that there is not a generally appropriate level of vagueness. Rather, a trade-off between vagueness and precision exists, which might be solved differently depending on the specific research context. Second, I suggest that “resilience thinking” might benefit from a less vague conceptual framework and sketch a restructuring proposal.

4.1 The vagueness-precision trade-off

I assume that extreme philosophical positions are untenable. Neither must all research comply with the logical empiricists’ standards, nor is all research interdisciplinary, transdisciplinary and embedded in post-normal contexts. As Wittgenstein’s reasoning about the benefits and drawbacks of precise definitions indicates, a trade-off between vagueness and precision exists. Vague definitions do accommodate a variety of cases but this comes at the cost of reduced usefulness in particular cases. The arguments from Section 3 that add to this trade-off are summarized in Table 1. Whereas Hodges (2008b: 179) recognizes a “dangerous trade-off between quantifiable operational definitions and meanings understood in natural language”, I propose that this trade-off is mainly harmful if its existence is not acknowledged and one side inadvertently dominates. A universal balance between vagueness and precision is prob-

precision	vagueness
(P 1) scientific method	(V 1) creativity
(P 2) establishing the validity of concepts	(V 2) inter- and transdisciplinary communication
(P 3) empirical testability	(V 3) problem-solving instead of puzzle-solving

Table 1: Summary of arguments from philosophy of science in favor of precision and vagueness, respectively

ably not achievable: careful use of concepts distinguishes between situations where general concepts are appropriate and those where precise concepts fit better (Jax 2008). Furthermore, some of the methodological arguments draw on fundamental issues that are not objectively reconcilable. Different philosophical points of view may lead to diverging appraisals of the same research context. However, I conjecture that consciously approaching the trade-off and giving explicit justification for a particular solution should prevent excessive precision where vague delimitations would be more appropriate and vice versa.

Some research contexts favor the arguments of traditional philosophy of science, others favor the arguments attacking this traditional view. Especially the weights of the traditional argument (P 3), requiring precision to ensure empirical testability, as well as the counter-arguments (V 2), promoting vagueness to facilitate inter- and transdisciplinay communication and (V 3), focussing on problem-solving instead of puzzle-solving, are context-dependent. The research contexts may be distinguished with respect to their degree of "normalcy". In normal circumstances research takes place in a well-defined area, under a paradigm which includes the relevant problems ("puzzles") as well as the methods that are regarded as adequate to their solution (Kuhn 1970). Here, the traditional call for empirical testability (P 3) is highly relevant. In contrast, contexts that deviate from the normal situation of science as puzzle-solving favor post-normal arguments. The argument for vagueness to promote transdisciplinary communication (V 2) is more relevant when research is directly in touch with societal stakeholders. Yet it is debatable wether conceptual precision itself inhibits communication or wether it is the apologetic defense of a particular definition that poses an obstacle to common understanding. Precision should not hinder communication across disciplinary boundaries as long as researchers are aware of other, equally legitimate meanings of concepts. Conceptual vagueness, on the contrary, may also be a hindrance for successfully communicating with practitioners (Fischer et al. 2009: 550). Finally, post-normal situations, where decision stakes and uncertainty are high, favor pragmatic problem-solving (V 3). To achieve that aim, conceptual precision may be of less outstanding importance than for normal puzzle-solving. Furthermore, conceptual vagueness may be a sign that research in that particular area is just beginning and has not yet reached the normal state (Hodges 2008a).

While some part of the vagueness-precision trade-off can be solved according to the particular research context, another part of it concerns more general questions. The traditional argument for strictly delimited concepts as precondition for establishing their validity (P 2) and Feyerabend's argument for vagueness as a source of creativity (V 1) must be traded off. Both are relevant for all contexts of resilience research. Creativity may be a main concern in other-than-normal circumstances, where no paradigm is in place, yet scientific progress generally is not conceivable without creativity. Then again, generalization and validation of concepts is not only important to traditional science contexts but also to transdisciplinary research if the latter does not content itself with "counseling" (Hirsch Hadorn et al. 2006: 125). That is, some compromise must be struck between the calls for validity and creativity. Furthermore, the question of whether and how to distinguish descriptive knowledge from normative knowledge is a crucial issue and cannot be answered solely by reference to the research context. While traditional philosophy of science emphasizes the "hair-line which separates science from faith" (Weber [1904] 1949: 110), post-normal science disposes of the fact-value dichotomy (Funtowicz and Ravetz 2003). This is a fundamental issue. Arguably, our epistemic interests and our values are related; so are our descriptive and evaluative statements. If, therefore, Weber's "hair-line" is a construct, should we completely dismiss it? I would still side with Weber and argue that this is all the more reason for us to state our value-judgements as explicitly as possible.

4.2 Resilience research and "resilience thinking"

What does the preceding discussion imply for the wide spectrum of resilience concepts set out in Section 2? The contexts of resilience research are certainly diverse. Sometimes, resilience research aims at solving fundamental questions, like understanding ecological interactions in a specified setting, and sometimes it has transdisciplinary, non-epistemic targets, such as improving outreach to societal actors. For instance, the Resilience Alliance's project to assemble a database of thresholds and regime shifts in ecological and social-ecological systems (Walker and Meyers 2004) fundamentally depends on the falsifiability of key concepts in empirical settings. Here, conceptual precision is a *conditio sine qua non*. In contrast, some approaches are explicitly directed at practitioners who are not bound to any scientific standard. In delivering this transdisciplinary message, the traditional focus on rigor and precision may be dispensable. Furthermore, the initially metaphorical concepts adaptive cycle and panarchy should never have entered the academic discourse following the logical empiricists' standards. Yet these metaphors are useful in that they generate new research questions (Holling et al. 2002b). This might indicate that some areas of resilience research have not yet reached a normal phase of puzzle-solving but still constitute a situation that rewards creativity and fuzzyness more than precision and rigor.

In the following, I discuss the example of "resilience thinking" in more detail. First, I argue that the implicit mix of normative and descriptive aspects is problematic. Second, I propose to address this problem by explicitly distinguishing normative and descriptive aspects along the lines of the conception of transdisciplinary research (Hirsch Hadorn et al. 2006).

First, it has been suggested that due to an unduly amalgamation of evaluative and descriptive content, resilience runs the risk of becoming too much like sustainability (Brand and Jax 2007). Sustainability is a contested buzzword (Jacobs 1999) whose "plethora of meanings" and "definitional chaos" draw heavy criticism (Marshall and Toffel 2005: 1). Indeed, its positive connotation and the variety of meanings make sustainability prone to inflationary use in dubious contexts. For instance, Shell advertises the extraction of oil from Canada's tar sands as a "sustainable" operation (The Economist 2008). Contrariwise, the influence of the notion of sustainability within "resilience thinking" is fading. While sustainability exhibits a long tradition as a guiding principle for resilience research (e.g., Common and Perrings 1992, Holling et al. 2002b), "resilience thinking" by now substitutes this function of sustainability. Folke et al. (2010) present "resilience thinking" without referring to sustainability at all. Instead, "Earth system resilience" (keeping our planet on a desirable trajectory) implicitly figures as a normative anchor. This implicit mix of description and evaluation is problematic because it may lead to confusion over the type of knowledge that resilience refers to.

Second, and following these arguments, I suggest that "resilience thinking" should explicitly distinguish between normative and descriptive aspects. Specifically, I propose (i) an emphasis on the descriptive side of resilience, (ii) a return to sustainability as the normative meta-goal of resilience research and (iii) the use of adaptability and transformability as concepts that represent human capabilities to manage resilience following the sustainability target. To that end, established frameworks could be used (Walker et al. 2004, Derissen et al. 2011, Hirsch Hadorn et al. 2006).

(i),(ii) Derissen et al. (2011) employ resilience as a purely descriptive and sustainability as a normative concept. They argue that sustainability comprises a society's basic normative orientation, thereby providing a "sustainability set". This set circumscribes those future states which satisfy a society's norms of intra- and intergenerational justice. Wether a resilient system is also sustainable cannot be determined a priori. It depends on the system's location on the stability landscape with respect to the sustainability set. Derissen et al.'s (2011) analysis implies that a social-ecological system is on a sustainable path if and only if human actors are able to shape the stability landscape so as to keep the system within the normatively given target set. Hence, (iii) adaptability and transformability, defined as the capabilities to influence resilience and devise new system configurations (Walker et al. 2004) are preconditions for sustainability. In short, my suggestion boils down to the following relation. *Sustainability implies that social-ecological resilience can be successfully managed through adaption and transformation.*

By relating and distinguishing descriptive, transformative and evaluative aspects, I follow the categories of knowledge in transdisciplinary research (Hirsch Hadorn et al. 2006: 127), as developed within the Swiss system approach (ProClim 1997):

i) Systems knowledge – Why and how do processes occur and where is change needed: empirical level?

ii) Target knowledge – What are better practices (targets): purposive level?

iii) Transformation knowledge – How can existing practices be transformed: pragmatic and normative level?

The correspondence, as summarized in Table 2, should be clear. Resilience refers to empirical knowledge about social-ecological systems (category i). Sustainability embodies the normative considerations which system states are desirable and where change is necessary (category ii). Adaptability and transformability refer to practical knowledge about how to manage resilience and initiate transformations (category iii). While my proposal slightly differs from the systems understanding of Hirsch Hadorn et al. (2006) in that the second category (target knowledge) instead of the third category (transformation knowledge) includes normative considerations, the crucial point and main similarity is the distinction of description and target (P

concept in resilience thinking	category in transdisciplinary research	type of knowledge
resilience	systems knowledge	empirical
sustainability	target knowledge	purposive, normative
adaptability, transformability	transformation knowledge	pragmatic

Table 2: Correspondence of categories between resilience thinking and transdisciplinary research

1).

In sum, I suggest to advance the vagueness-precision trade-off in “resilience thinking” by being explicit about normative aspects. I advocate a polysemous concept of resilience by clearly distinguishing the three related aspects of description, evaluation and transformation. Yet I do not eradicate all vagueness. My proposal is compatible with multiple resilience definitions and keeps the blurred boundary between adaptive capacity and transformability. Thus, it provides scope for creativity (V 1). Depending on the specific research context, empirical testability (P 3) or pragmatic problem-solving (V 2,3) could be emphasized. In this way I try to account for the arguments of both vagueness and precision.

5 Conclusion

Philosophy of science provides conflicting arguments pro and contra precision and vagueness respectively. These arguments must be traded off with respect to the aims and purposes of research. Sound empirical knowledge requires conceptual precision but pragmatic and creative problem-solving may benefit from conceptual vagueness. That said, a universal solution to the trade-off does probably not exist. First, fundamental methodological points of view cannot objectively be reconciled and second, different research contexts may call for individual degrees of vagueness. Thus, every particular research approach should explicitly justify its balance of vagueness/precision in order to avoid inadvertent and excessive domination of one side.

Assessing the example of “resilience thinking”, I conclude that its implicit mix of descriptive and normative aspects is problematic. By relating resilience, sustainability and adaptability/transfomability according to the approach of transdisciplinary research (Hirsch Hadorn et al. 2006), I indicate how “resilience thinking” could explicitly distinguish between descriptive and normative content. Thus, I propose a polysemous conceptual structure of "resilience thinking" where individual aspects may be similar yet different levels of knowledge are clearly distinguishable. On the one hand, this leaves ample room for extension and application to different contexts; on the other hand, this avoids confusion over the type of knowledge that is generated.

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Chapter 2: (Non-)convexity of the self-protection problem

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Abstract: Commonly, we assume that the optimization problem within a simple self-protection problem (spp) is convex. We show, however, that the condition given in the literature to legitimate this assumption may have implausible consequences. Via a simple functional specification we investigate the (non-)convexity of the spp more thoroughly and find that for reasonable parameter values strict convexity may not be justified. In particular, we demonstrate numerically that full self-protection is often optimal. Neglecting these boundary solutions and analyzing only the comparative statics of interior maxima may entail misleading policy implications such as underinvestment in self-protection. Thus, we highlight the relevance of full self-protection as a policy option even for non-extreme losses.

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1 Introduction

Self-protection refers to a real action that reduces the probability by which an unfavorable event occurs (Ehrlich and Becker 1972). For instance, individuals may apply sunscreen to reduce the probability of skin cancer or live on healthy diets to avoid cardiovascular disease. Local communities may invest in resilience of ecosystems (e.g., semi-arid rangelands, coral reefs) to reduce the probability of welfare losses from adverse regime shifts, also termed “catastrophic shifts” (Scheffer et al. 2001). The global community may adopt mitigation policies (e.g., reducing carbon emissions) to diminish the probability of exceeding global climate tipping points with potentially disastrous consequences such as substantial see level rise, widespread droughts or marine mass extinction (Kane and Shogren 2000, Lenton et al. 2008).

When effort is costly, what is the optimal level of self-protection and on which parameters does it depend? By now, comparative statics of the self-protection problem (spp) is well-documented. Emphasizing high generality, the established literature on the spp (see Meyer and Meyer (2011) for an overview) analyzes how the optimal level of self-protection varies with the subjective risk preferences of the individual (risk-aversion, prudence, ambiguity-aversion) and the objective parameters of the decision problem (potential income loss, initial wealth). To ensure that the standard methods of comparative statics can be applied, convexity of the spp is assumed. This guarantees that the objective function is “well-behaved” and interior solutions are obtained. Often a second-order condition is provided as justification, sometimes convexity is just supposed to hold. For instance, Jullien et al. (1999: 23), focussing on the effect of increasing risk-aversion, write a second-order condition and add: “For the problem to be meaningful, we also assume that the optimal level of effort for U is interior ...”. Eeckhoudt and Gollier (2005: 990) investigate the effect of increasing prudence and state: “We assume that V [expected utility] is concave in e [effort]”. Snow (2011: 35) analyzes the effect of ambiguity aversion. After establishing a necessary and sufficient condition for global concavity of the objective function, he states that “[h]enceforth, the required concavity of ... [expected utility] will be assumed to hold...”. Meyer and Meyer (2011: 51) confirm and generalize previous results, noting: “It is assumed that the second order condition for this maximization is satisfied.”

We extend this established research on the spp by analyzing the hitherto neglected non-convexity aspect. To that end, we investigate a simple specification of the spp with common functional forms and plausible parameter values. In particular, we explicitly address the question how self-protection e translates into a reduction of the probability of a loss p. In contrast, the literature on the spp employs this relation $p(e)$ only to justify convexity of the spp: all second-order requirements are placed on $p(e)$ while no restrictions are placed on the individual's utility function. We show that restricting only $p(e)$ to assure convexity is questionable because it may place implausible burdens on $p(e)$. Without some restriction on the individual's utility function, in the sense that it should not be "too curved", strict convexity of the spp is a very strong assumption. Thus, we complement the literature's emphasis on comparative statics by showing how non-convexity of the spp may come about.

Furthermore, we demonstrate numerically that non-convexities are not exceptional and may have important consequences for the correct interpretation of comparative statics. Most saliently, we find that full self-protection is often optimal: even for non-extreme losses full elimination of their occurrence probability may be warranted. Also, we show that underinvestment in self-protection may result from ignoring such boundary solutions. If full self-protection is optimal and an interior local maximum exists, analyzing only the comparative statics of the local maximum may lead to a further decrease in the level of self-protection.

The remainder of this paper is organized as follows. In Section 2, we introduce our specification of the spp. We parameterize the individual's degree of risk aversion, the cost of self-protection, the elasticity of the probability function and the size of the loss. In Section 3, we first show that the condition for a strictly convex spp given in the literature may have implausible consequences. Subsequently, we provide analytical conditions for boundary solutions and show which parameter changes likely satisfy these conditions. In Section 4, we devise four numerical scenarios. In each case, we scan the parameter space and determine the share of parameter combinations that entail boundary solutions. Furthermore, we provide an example where neglecting boundary solutions misleads the comparative statics of interior maxima. Finally, we discuss our findings and draw conclusions in Section 5.

2 A simple specification of the spp

We follow the standard spp where an individual seeks the appropriate level of self-protection effort e to avoid the unfavorable event of losing amount L. The rational individual chooses the optimal effort e^* that maximizes her expected utility $V(e)$:

$$V(e) = p\,(e)\,u(w\ -L\ -c\,(e)) + (1-p\,(e))\,u(w\ -c\,(e)) \tag{1}$$

In words, the individual is endowed with some initial wealth w, which she may invest in self-protection e at a cost $c\ (e)$ in order to decrease the probability $p\ (e)$ that the loss occurs. Yet every unit of wealth not spent on self-protection raises the wealth still available if the loss occurs. So the individual faces a trade-off between decreasing the probability p of incurring the loss L and saving in order to prepare for the occurrence of the loss. The optimal effort level e^* then depends on the specifics of p, L, w, c and the individual's subjective valuation via the utility function u on final wealth W.

Commonly, the literature places no restrictions on the different functions and parameters other than $p' < 0$, $L > 0$, $c'' > 0$ and $u'' \leq 0$. To ensure high generality, no functional forms are specified beforehand. This generality, however, masks a very restrictive assumption on p (cf. Section 3), which is necessary to satisfy second-order requirements. In order to demonstrate the implausible consequences of this assumption, we now provide the spp with a more explicit structure. We rely on common functional forms for p, c and u that satisfy the usual assumptions mentioned above.

First, we model self-protection as a continuous state variable $e \in [0,1]$ that determines the probability of a loss:

$$p = p(e) \qquad \text{with} \qquad p'(e) \leq 0 \text{ for all } e \ \text{ and } \ p'(e) < 0 \text{ for all } e \in (0,1) \tag{2}$$

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

Thus, with zero effort, the loss occurs for sure; and with a maximum effort of one there will certainly be no loss. Specifically, we assume the following model about the relationship between the level of effort e and the probability of a loss p:

$$p(e) = 1 - e^{1-\sigma} \quad \text{with} \quad -\infty < \sigma < 1\,. \tag{4}$$

This specification has the fundamental properties (2) and (3). In addition, it has the analytically handsome property that p' is a constant-elasticity function of e, where the parameter σ is the (constant) elasticity of p',[1] i.e. σ specifies by how much (in percent) the loss probability's slope increases when the level of effort increases by 1 %. For short, we will refer to σ as

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[1] Note that (4) implies $-p''(e)e/p'(e) = \sigma$.

“elasticity”. As σ may be positive or negative, one has[2]

$$p''(e) \left\{ \begin{array}{c} > \\ = \\ < \end{array} \right\} 0 \; \forall \, e \in (0,1) \qquad \text{iff} \qquad \sigma \left\{ \begin{array}{c} > \\ = \\ < \end{array} \right\} 0 \, .$$

Thus, $\sigma > 0$ means decreasing returns from self-protection so that the first units of effort entail greater reduction in the probability of a loss than later units. Conversely, for $\sigma < 0$ the effect of self-protection on the probability increases in the level of effort. The case $\sigma = 0$ depicts a situation where all units of effort yield an equal reduction of the probability of a loss. While more complex specifications might be plausible as well, equation (4) represents a simple and fairly general functional relation between p and e.

Second, we assume that the costs of self-protection follow the quadratic form

$$c\,(e) = \kappa e^2 \quad \text{with} \quad \kappa > 0 \quad \text{so that} \quad c\,(0) = 0 \text{ and } c\,(1) = \kappa \, . \tag{5}$$

Thus, self-protection is increasingly expensive and incurs costs up to κ.

Third, the individual’s risk preferences are standardly represented by a continuous and differentiable Bernoulli utility function $u(W)$ with $u'(W) > 0$ and $u''(W) \leq 0$; that is, the individual is non-satiated and risk neutral or risk averse. Specifically, we assume that the individual is characterized by constant absolute risk aversion in the sense of Arrow (1965) and Pratt (1964), i.e. $-u''(W)/u'(W) \equiv$ const., so that the Bernoulli utility $u(W)$ function is

$$u(W) = -\underline{\mathrm{e}}^{-\rho W} \qquad \text{with} \qquad \rho > 0 \, , \tag{6}$$

where the parameter ρ measures the individual’s risk aversion. Observe that throughout this paper $\underline{\mathrm{e}}$ denotes the mathematical constant whereas e denotes self-protection effort.

3 Analytical results

In this section, we first demonstrate that the condition for strict convexity of the self-protection problem given in the literature is not plausible in the important case where iso-elastic functions such as (4) represent the relationship between self-protection and reduction in the probability of a loss (proposition 1). Second, we provide explicit conditions for boundary solutions and analyze how their occurrence depends on the parameters of the spp (proposition 2).

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[2] For $\sigma = 0$, $p''(e) = 0$ holds also for $e = 0$ and $e = 1$. Yet, for $\sigma < 0$, one has $p''(0) = 0$, and for $\sigma \to 1$, one has $p''(1) \to 0$.

Jullien et al. (1999: 23) and Snow (2011: 35) provide an explicit condition that, combined with standard restrictions on the utility function ($u'' \leq 0$) and the costs of self-protection ($c'' > 0$), assures strict convexity of the spp. Note that the condition relies solely on the relation between effort and reduction in the probability of a loss:

$$p''(e)\,p(e)\,-2\,(p'(e))^2\,\geq 0 \tag{7}$$

Interestingly, $p'' > 0$ is necessary but not sufficient to satisfy (7). If $e = 0$, (7) trivially holds. If self-protection occurs, we can use (4), the specification of p as an iso-elastic function, and the observation that $p'' > 0$ in our model implies $\sigma > 0$ to reformulate and solve condition (7) to:

$$e \leq (\frac{2-\sigma}{\sigma})^{\frac{1}{\sigma-1}} \tag{8}$$

The right hand side of equation (8) is smaller than one for all $\sigma \in [0,1]$. Thus, condition (7) does not hold for all $e \in (0;1]$. This leads to the following result.

Proposition 1

The condition the literature provides to assure that the expected utility of the spp is a strictly concave function of effort to self-protect is not plausible for the most simple specification of $p(e)$ as an iso-elastic function.

We conclude that, in the important case where iso-elastic functions such as (4) represent the relationship between effort to self-protect and reduction in the probability of a loss, the condition given by Jullien et al. (1999) and Snow (2011) is not convincing and is not a useful instrument to determine wether the maximization problem is strictly convex.

Proposition (1) shows that a seemingly high degree of generality may come at the cost of hidden restrictions. While the up front assumption $p' < 0$ seems to imply high generality, condition (7) may lead to a drastic reduction in generality. The problem is that (7) places the burden exclusively on p while making no restriction on the individual's risk preferences whatsoever: condition (7) holds for risk neutral as well as infinitely risk or ambiguity averse individuals. Yet as the following analysis shows, very strong aversion against risk greatly influences the structure of the spp and stronger assumptions on u than $u'' < 0$ are necessary to assure strict convexity. In short, assuring convexity of the spp only via p is questionable and some restrictions on the risk preferences should complement it.

It is difficult, however, to derive a general expression for the required "not too curved" assumption on u. We proceed by using the specifications of u and c as introduced in Section 2.

This enables us to provide analytical conditions for boundary solutions to the self-protection problem. Analyzing these boundary conditions with respect to the model's parameters shows how the individual's risk preferences affect the structure of the spp.

In general, full self-protection is optimal (i.e., $e^* = 1$) if the expected utility of full self-protection exceeds the expected utility of all other levels of self-protection, or

$$V(1) > V(e) \quad \forall \quad e \in [0,1). \tag{9}$$

The equivalent condition for an optimum at $e^* = 0$, implying no self-protection, is:

$$V(0) > V(e) \quad \forall \quad e \in (0,1]. \tag{10}$$

Explicating these conditions by using (1), (4), (5) and (6) leads, after rearranging, to the following proposition. It indicates explicit conditions for boundary solutions and shows how their likelihood depends on the parameters L, κ, σ and ρ.

Proposition 2

(i) A boundary solution at $e^* = 1$ occurs iff

$$1 < \underline{e}^{\rho\kappa(e^2-1)}[(1-e^{1-\sigma})\underline{e}^{\rho L}+e^{1-\sigma}] \quad \forall \quad e \in [0,1). \tag{11}$$

A boundary solution at $e^* = 0$ occurs iff

$$1 < \underline{e}^{\rho\kappa e^2}(1-e^{1-\sigma}+e^{1-\sigma}\underline{e}^{-\rho L}) \quad \forall \quad e \in (0,1]. \tag{12}$$

(ii) The likelihood of a boundary solution at $e^* = 1$

$$\text{increases in the potential income loss} \quad L, \tag{13}$$

$$\text{decreases in the costs} \quad \kappa. \tag{14}$$

The likelihood of a boundary solution at $e^* = 0$

$$\text{decreases in the potential income loss} \quad L, \tag{15}$$

$$\text{increases in the costs} \quad \kappa. \tag{16}$$

The likelihood of both boundary solutions

$$\text{decreases in elasticity} \quad \sigma, \tag{17}$$

$$\text{increases in risk aversion} \quad \rho. \tag{18}$$

Proof. See Appendix □

Without potential loss, there is no need for self-protection and full saving is optimal. The greater the potential loss, the more inclined the individual to fully self-protect, as stated in result (13). A complete renouncement of self-protection, on the other hand, becomes less attractive with increasing potential loss. This is indicated in result (15).

If self-protection did not incur any costs, the individual would naturally choose full self-protection. Results (14) demonstrates that with growing costs full self-protection gets less likely. In contrast, result (16) indicates that the option to renounce all self-protection becomes more attractive the higher the costs of self-protection.

Result (17) states that increasing elasticity diminishes the likelihood of boundary solutions. The intuition is as follows: for very low levels of σ only the last units of effort close to full self-protection do significantly reduce the probability of a loss whereas all other units have a negligible effect. Hence, it seems reasonable either not to self-protect at all or to opt for full self-protection. With increasing elasticity, this all-or-nothing intuition fades and eventually reverses. For $\sigma = 0$, all units of effort contribute equally to a reduction in the probability and without knowledge of the problem's other components no level of effort is to be preferred. For positive elasticity, the first units of effort do have a greater impact on the probability reduction than the following ones. In the extreme, it's at a very low level of effort that the bulk of the probability reduction occurs and all later units of self-protection only have a negligible impact. Thus, it is very attractive to spent some effort on self-protection while renouncing full self-protection.

Result (18) indicates that increasing aversion against risk raises the likelihood of extreme levels of self-protection, both of full self-protection and of no self-protection. This result follows intuitively from Jullien et al. (1999), although they do not consider boundary solutions. Their main result is that higher risk aversion entails higher (lower) levels of self-protection when the probability of a loss is close to 0 (1).[3] In other words, risk aversion has an ambiguous effect on the optimal amount of self-protection. The more risk-averse the decision maker, the less attractive are intermediate levels of self-protection compared to full (no) self-protection. It is straightforward to conclude that – unless you assume *a priori* that the solution

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[3] Chiu (2000) provides a detailed examination of the switching level that determines wether the probability of a loss is high or low.

will be an interior one, as Jullien et al. (1999) do – for a sufficiently high level of risk aversion, the optimal amount of self-protection lies at the boundary and either full self-protection is chosen or none at all.

Put another way, proposition 2 implies that without restrictions on the individual's degree of risk-aversion convexity of the spp is a very strong assumption and may place harsh restrictions on the remaining parameters. As shown in proposition 1, this leads to extreme consequences if the restrictions are borne by only one component of the spp.

4 Numerical results

In the following, we provide numerical results showing that boundary solutions to the spp are not exceptional (proposition 3) and may have important consequences for the comparative statics for local maxima (proposition 4).

Our approach is as follows: by scanning the parameter space we establish which combinations of risk-aversion ρ, elasticity σ, potential income loss L and costs of self-protection κ lead to interior solutions and which combinations yield boundary solutions. There is, however, no objective answer to the question which share of the parameter space entails boundary solutions because the exact share depends on the ranges of parameter values that are considered. Since boundary solutions do trivially arise for extreme parameter values, we need plausible restrictions: risk-aversion should be bounded from above, elasticity should be bounded from below and the potential loss should not be much smaller or greater than the costs of full self-protection.

To determine a reasonable range of values for risk-aversion ρ, we draw on empirical results and theoretical considerations. Abadi Ghadim et al. (2005) and Guiso and Paiella (2008) estimate coefficients of absolute risk-aversion for non-trivial investment opportunities. We use these empirical results and employ *lower* values of absolute risk-aversion for higher potential losses. Here, we follow Rabin's (2000) argument that risk-aversion coefficients elicited for modest-scale risks imply implausibly high levels of aversion against large-scale risks. Rabin concludes that aversion against modest risks seems to be different from aversion against large risks. Similarly, Babcock et al. (1993) argue that for larger risks *lower* values for risk-aversion coefficients are appropriate. Following this reasoning, we consider parameter values of absolute risk-aversion that decline with increasing scale of the potential income loss L.

scan	L	κ	ρ	σ	possible boundary solution
1	5 000	4 000	$\in (0, 0.001)$	$\in (-1, 1)$	$e^* = 1$
2	4 000	5 000	$\in (0, 0.001)$	$\in (-1, 1)$	$e^* = 0$
3	$\in (0, 40\,000)$	$\in (0, 40\,000)$	0.00004	0	$e^* = \{0; 1\}$
4	$\in (0, 2\,000\,000)$	1 000 000	$\in (0, 0.000002)$	0	$e^* = \{0; 1\}$

Table 1: Overview of parameter scans

With parameter σ for elasticity we introduce a new concept to the self-protection literature. We are not aware of any research that indicates plausible lower/upper bounds for values of σ. Therefore, we exclude strongly negative values of σ that would induce boundary solutions (cf. result 17) and consider only values of $\sigma > -1$.[4] Yet we do allow for extreme elasticity ($\sigma \to 1$). The latter guarantees interior solutions and is one subcase of the probability of a loss as a decreasing convex function of effort.

If the potential loss is much greater (smaller) than the costs, optimal self-protection implies full (no) effort. Only if both parameters are roughly of the same size, the spp is non-trivial from an economic point of view. $L \approx \kappa$ involves two possibilities. First, consider $L > \kappa$. This excludes the possibility of a boundary solution at $e^* = 0$ since a rational risk-averse individual will always exert *some* self-protection effort if the potential benefit of this action (prevention of a loss) exceeds the costs at all levels of self-protection. Second, consider $\kappa > L$. This excludes the possibility of a boundary solution at $e^* = 1$ since full self-protection cannot be optimal if it is more costly than the potential loss.

In accordance with the above reasoning, we devise four representative scans to give an accessible account of how the four model parameters interact. In each scenario we fix two of the parameters and scan the remaining ones. First, we choose a value (range of values) for the potential loss L and subsequently assign appropriate values (range of values) for risk-aversion ρ, the costs of full self-protection κ and elasticity σ. While many different scenarios are conceivable, these scans comprehensively reflect all scenarios that follow the restrictions outlined above. We summarize the four scans in table 1 and address them in turn.

---

[4] If $\sigma = -1$, an effort level of 0.5 corresponds to a flip probability of 0.75. Thus, for the lowest value of elasticity we consider, the first units of effort reduce the probability of a loss less than the later units of effort but the first units' impact is not negligible.

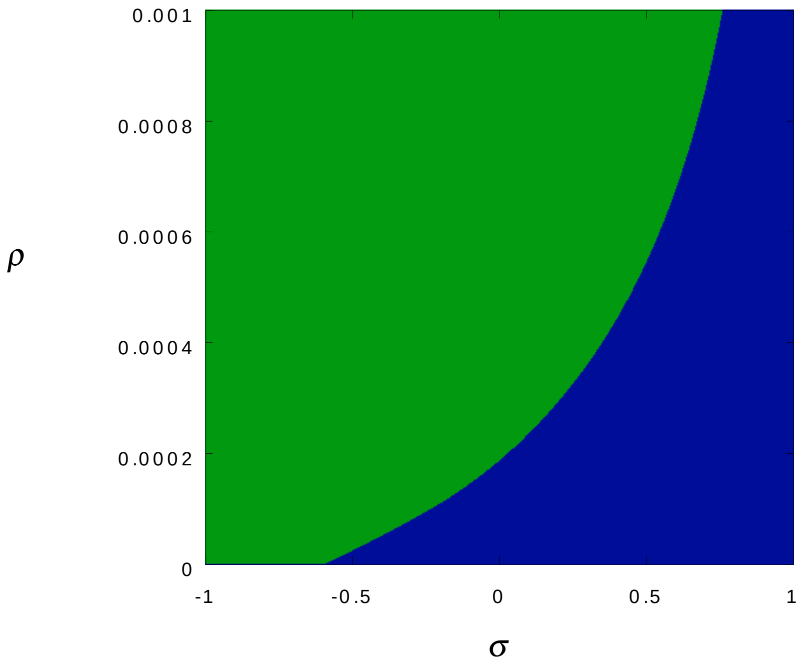

Figure 1: Parameter combinations that yield interior solutions (blue), a boundary solution at $e^* = 1$ (green)

Scan 1

This scan shows which combinations of risk-aversion ρ and elasticity σ lead to a boundary solution with full self-protection. We assume that the potential loss ($L = 5\ 000$) exceeds the costs of full self-protection ($\kappa = 4\ 000$) and assign an empirically plausible range of values for risk-aversion $\rho \in (0, 0.001)$ for lotteries in this order of magnitude.[5] We exclude strongly negative values of σ and consider elasticity in the range of $\sigma \in (-1, 1)$. Figure 1 shows which parameter combinations of ρ and σ satisfy condition (11). Combinations that entail a boundary solution are indicated in green, combinations that entail interior solutions in blue.

The parameter scan reveals that only a minority of parameter combinations implies a mix of saving and self-protection as optimal trade-off. In a majority of parameter combinations full self-protection is optimal. For moderately high risk-aversion and elasticity the spp has an interior solution but for high risk-aversion and in-elasticity, the boundary solution at $e^* = 1$ arises. Put another way, interior solutions arise for moderately risk-averse individuals and strongly decreasing returns to self-protection.

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[5] Guiso and Paiella (2008: 1114) estimate 0.0007 as the median value of absolute risk-aversion (the average value of 0.0198 is much higher) for an investment opportunity valued at 5 000 euros. Setting $\rho = 0.001$ as the highest considered level of risk-aversion thus excludes extreme levels of risk-aversion.

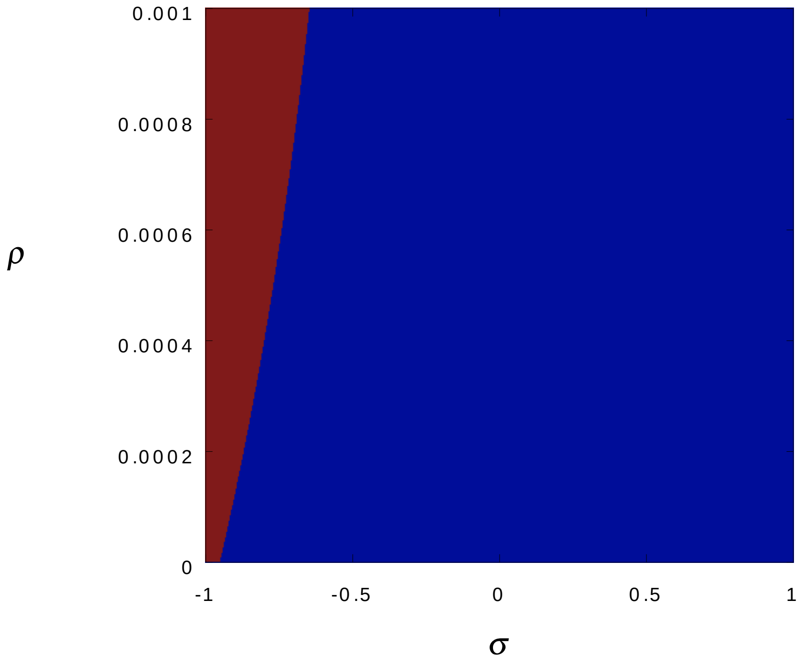

Figure 2: Parameter combinations that yield interior solutions (blue), a boundary solution at $e^{*} = 0$ (red)

Scan 2

This scan illustrates which combinations of risk-aversion ρ and elasticity σ yield a boundary solution with no self-protection so that all resources are saved. We assume that the potential loss ($L = 4\ 000$) is smaller than the costs of full self-protection ($\kappa = 5\ 000$). Again, we consider elasticity in the range of $\sigma \in (-1, 1)$ and risk-aversion in the range of $\rho \in (0, 0.001)$. Figure 2 displays which parameter combinations satisfy condition (12). Combinations that entail a boundary solution are indicated in red, combinations that entail interior solutions in blue.

The numerical analysis shows that the share of parameter combinations that yield a boundary solution is much smaller than in scan 1. Comparing Figures 1 and 2, the blue segment, representing interior solutions, is considerably larger in scan 2. In the latter, only for clear in-elasticity do boundary solutions arise.

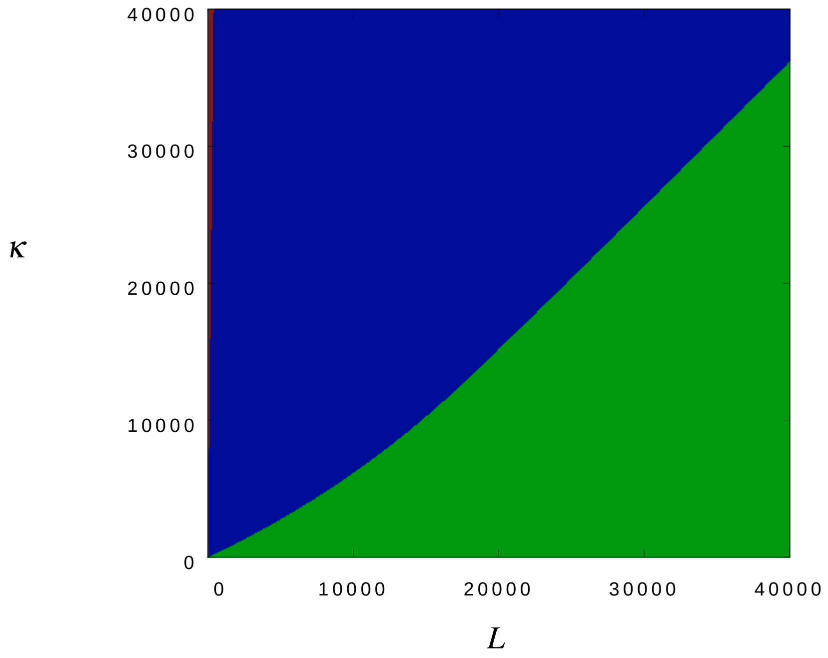

Figure 3: Parameter combinations that yield interior solutions (blue), a boundary solution at $e^* = 1$ (green), a boundary solution at $e^* = 0$ (red)

Scan 3

This scan illustrates how the relationship between the costs of full self-protection κ and the potential loss L affects the likelihood of boundary solutions. Both costs and the potential loss vary so that $\kappa, L \in (0, 40\,000)$. The parameter for risk-aversion is fixed at $\rho = 0.00004$[6] and the parameter for elasticity is held constant at 0, i.e., constant returns to self-protection.

Figure 3 shows an even greater asymmetry between the boundary solutions at $e^* = 0$ and $e^* = 1$ than the previous scans. Only a tiny fraction of all considered parameter combinations, where the potential loss is extremely small compared to the costs (left vertical axis), represents an optimum with no self-protection at $e^* = 0$. In contrast, full self-protection at $e^* = 1$ is optimal for a large part of parameter combinations. Note that the diagonal separates both possible boundary solutions: above the diagonal, the costs of full self-protection exceed the potential loss, so full self-protection cannot be optimal. Below the diagonal, the potential loss is bigger than the costs of full self-protection and a rational individual would exert some effort. Considered this, the share of parameter combinations representing a boundary solution at $R^* = 1$ is substantial.

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[6] Abadi et al. (2005) estimate $\rho = 0.000055$ as a coefficient of absolute risk-aversion for farmers who may engage in a risky investment with mean expected payoff of $37,779$ \$. Therefore, choosing $\rho = 0.00004$ for a potential loss of $40,000$ seems not extreme.

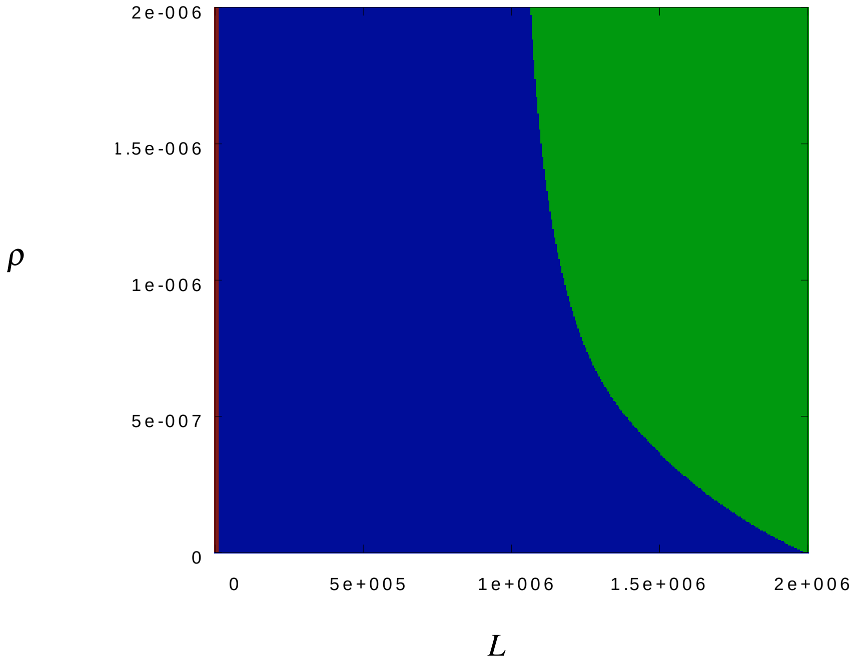

Figure 4: Parameter combinations that yield interior solutions (blue), a boundary solution at $e^* = 1$ (green), a boundary solution at $e^* = 0$ (red)

Scan 4

This scan shows how the likelihood of boundary solutions depends on combinations of potential loss L and risk-aversion ρ. Furthermore, it demonstrates that the patterns observed in the previous scans also appear in case of large-scale risks. The costs of full self-protection κ is fixed at a much higher level of 1 000 000 and L varies $\in (0, 2\,000\,000)$. Thus, we consider increasing losses, up to twice the amount of the costs of full self-protection. Elasticity is held constant at 0 and absolute risk-aversion ρ varies $\in (0, 0.000002)$.[7]

Figure 4 confirms the results of the previous scans. For a substantial part of all parameter combinations, full self-protection at $e^* = 1$ is optimal while no self-protection at $e^* = 0$ follows only from a negligible part of all parameter combinations. Note that the middle of the horizontal axis separates both possible boundary solutions: for $L > 1\ 000\ 000$ the boundary solution at $R^* = 1$ and for $L < 1\ 000\ 000$ the boundary solution at $R^* = 0$ is possible.

The following proposition condenses the results of our parameter scans.

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[7] Babcock et al. (1993: 22) argue that increasing the gamble size by a factor of 10 decreases the appropriate maximum value of risk-aversion by a factor of 10. Hence, for a potential income loss approximately 500 times the size of the income loss in scans 1 and 2, we consider a maximum value of ρ that equals $\frac{1}{500}$ of the maximum value in the first two scans.

Proposition 3

(i) Full self-protection is optimal if

- the potential loss exceeds the costs of full self-protection ($L > \kappa$)

  and either

  - risk-aversion ρ is high

    or

  - elasticity σ is low.

(ii) No self-protection is optimal if

- the costs of full self-protection exceed the potential loss ($L < \kappa$)

  and

- elasticity σ is very low.

Having shown that boundary solutions to the self-protection problem are not exceptional, we now demonstrate the relevance of this result for comparative statics. Do boundary solutions matter if the comparative statics of interior maxima is of main concern? Yes, because neglecting the existence of boundary solutions may mislead conclusions following from comparative statics analysis for maxima that are only local. The following proposition indicates such cases.

Proposition 4

If $e^* = 1$ and an interior local maximum exists, increasing risk-aversion and decreasing elasticity may decrease the level of effort for which the local interior maximum occurs while the global optimum persists at $e^* = 1$.

Proposition 4 shows that focusing on comparative statics of interior maxima may give rise to misleading policy conclusions. Ignoring boundary solutions may entail wrong implications about the effects of increasing risk-aversion and decreasing elasticity on the optimal level of effort. Figure 5 illustrates an example. It displays the individual's expected utility from equation (1) for two different levels of risk-aversion. While increasing risk-aversion shifts the local maximum to the left, thereby suggesting a lower level of self-protection to maintain optimality, the global optimum persists at $e^* = 1$. Hence, underinvestment in self-protection may result from neglecting boundary conditions.

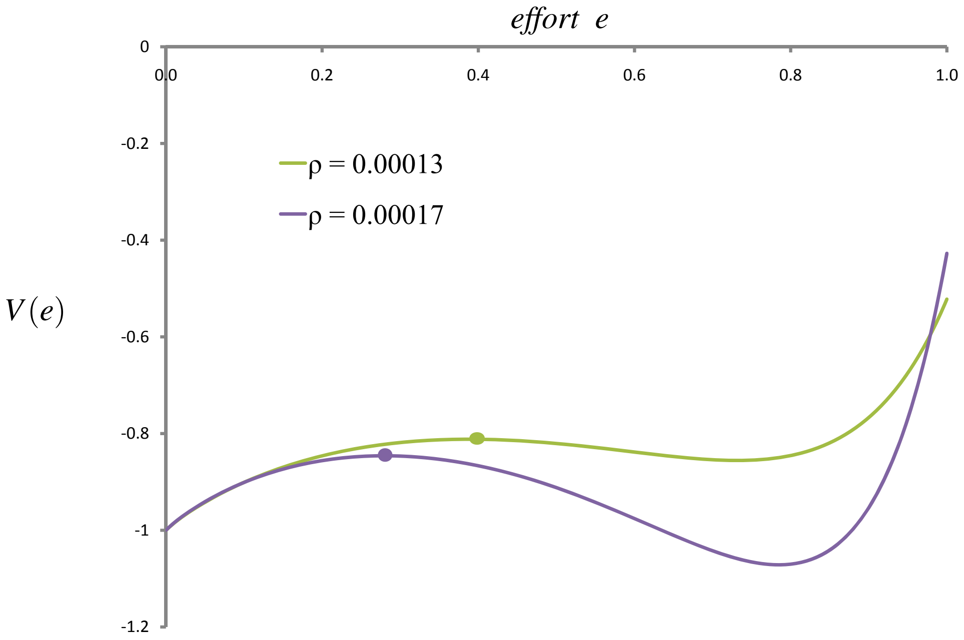

Figure 5: Parameter values: $L = 20{,}000$, $\kappa = 15{,}000$, $\sigma = 0.1$,

5 Discussion and conclusion

Our analysis built on a simple specification of the spp, with parameters for risk-aversion, elasticity, potential loss and costs of self-protection. We provided four salient results. First, we showed that the condition given in the literature to justify the convexity assumption may have implausible consequences because it places restrictions only on $p(e)$ but not on other components of the spp such as the individual's risk preferences. Second, we established explicit conditions for boundary solutions to the spp and analyzed these conditions with respect to the model parameters. Third, we numerically showed that reasonable assumptions on parameter values do not guarantee convexity of the spp. Instead, we found that full self-protection is often optimal. Fourth, we demonstrated that neglecting boundary solutions may lead to wrong interpretations of comparative statics for local maxima and hence underinvestment in self-protection.

These results are particularly relevant in two respects. First, our results have implications for the correct formulation of optimal self-protection policies. Consider again examples such as individual health care or global climate policy. Our analysis implies that welfare losses need not necessarily be catastrophic to warrant policies aiming at the highest possible level of self-protection. For rather risk-averse individuals and low elasticity, full self-protection is optimal if the potential loss exceeds the costs of full self-protection. The common wisdom that optimally trading off two possible strategies in a maximization problem always results in a mix of those policies does not apply here. In contrast, assuming interior solutions a priori and ignoring boundary solutions may entail misleading policy conclusions such as underinvestment in self-protection.

Second, our results contest the economic practice of assuming "well-behaved" objective functions in seemingly simple cases as the spp. It is well known that a convexity assumption is overly simplistic for management problems involving non-linear ecosystem behavior (e.g., Dasgupta and Mäler 2003, Tschirhart 2011) or multiple benefits (Swallow et al. 1990, Boscolo and Vincent 2003). Yet we showed that intricate ecologic processes and complex benefit structures are not necessary to invalidate the convexity assumption. The spp is an example where standard economic assumptions on risk preferences and objective characteristics of the decision problem are not sufficient to guarantee the desired properties of the objective function.

Appendix

Proof of Proposition 2

Differentiating the right hand sides of equations (11) and (12) with respect to L, κ and σ yields the tendencies stated in results (13) to (17). The derivatives of (11) and (12) with respect to ρ are not directly determined. Yet a raise in ρ again increases the likelihood that the derviatives are positive, which yields the tendency stated in result (18). We need to show, however, that conditions (11) and (12) are not vacuous and that there are parameter values for which they hold, respectively do not hold. Accordingly, we investigate (11) and (12) separately for L, κ, σ and ρ in their limits.

- L

  For $L \to 0$ equation (11) is violated since the term in brackets reduces to 1 but $\underline{e}^{\rho\kappa(e^2-1)}$ is < 1. For $L \to \infty$ equation (11) holds because $\underline{e}^{\rho L} \to \infty$ and all other terms are positive. This proofs result (13).

  For $L \to 0$ condition (12) holds since the term in brackets reduces to 1 and $\underline{e}^{\rho\kappa e^2}$ is > 1. For $L \to \infty$ the right hand side of condition (12) reduces to $(1 - e^{1-\sigma})\underline{e}^{\rho\kappa e^2}$ which is not

$> 1 \; \forall \; e \in (0,1]$ unless we make extreme additional assumptions such as $\kappa \longrightarrow \infty$. Thus, condition (12) is not satisfied $\forall \; e \in (0,1]$ and hence result (15) holds.

- κ

  For $\kappa \longrightarrow 0$ condition (11) holds because the first term on the right hand side collapses to 1 and the term in brackets is > 1. For $\kappa \longrightarrow \infty$ condition (11) is violated because the first term $\longrightarrow 0$ and thus the whole right hand side is < 1. Thus, result (14) holds.

  For $\kappa \longrightarrow 0$ condition (12) is violated since the term $\underline{e}^{\rho\kappa e^2}$ reduces to 1 but the term in brackets is smaller than 1. For $\kappa \longrightarrow \infty$ condition (12) holds because the term in brackets is positive and $\underline{e}^{\rho\kappa e^2} \longrightarrow \infty$ since $e \in (0,1]$. Thus, result (16) holds.

- σ

  For $\sigma \longrightarrow 1$ condition (11) is violated since the term in brackets on the right hand side reduces to 1 but $\underline{e}^{\rho\kappa(e^2-1)} < 1$. For $\sigma \longrightarrow 1$ condition (12) reduces to $1 < \underline{e}^{\rho(\kappa e^2 - L)}$, which is violated because $\kappa e^2 > L$ does not hold $\forall \; e \in (0,1]$ unless we make extreme additional assumptions such as $L \longrightarrow 0$ or $\kappa \longrightarrow \infty$.

  For $\sigma \longrightarrow -\infty$ the right hand side of condition (11) reduces to $\underline{e}^{\rho(L+\kappa(e^2-1))}$. This term is > 1 if $L > \kappa(1-e^2) \; \forall \; e \in [0,1)$; that is, for $e = 0$ the restriction becomes $L > \kappa$. Thus, condition (11) holds $\forall \; e \in [0,1)$ if $L > \kappa$. For $\sigma \longrightarrow -\infty$ condition (12) reduces to $1 < \underline{e}^{\rho\kappa e^2}$ if $e \in (0,1)$. For $e = 1$, however, it reduces to $1 < \underline{e}^{\rho(\kappa - L)}$. Thus, condition (12) holds $\forall \; e \in (0,1]$ if $\kappa > L$.

  In sum, $\sigma \longrightarrow -\infty$

  (i) leads to a boundary solution at $e^* = 0$ if $\kappa > \Delta y$

  (ii) leads to a boundary solution at $e^* = 1$ if $L > \kappa$.

  Hence, conditions (11) and (12) are not vacuous for decreases in σ and result (17) holds.

- ρ

  For $\rho \longrightarrow 0$ conditions (11) and (12) both collapse to $1 < 1$ and do not hold.

  For $\rho \longrightarrow \infty$ the right hand side of condition (11) reduces to $\underline{e}^{\rho(L+\kappa(e^2-1))}(1-e^{1-\sigma})$ because $\underline{e}^{\rho(\kappa(e^2-1))}(e^{1-\sigma}) \longrightarrow 0$. If $L > \kappa(1-e^2)$, the right hand side $\longrightarrow \infty$. Observe that $e \in [0,1)$. Thus, condition (11) is satisfied $\forall \; e \in [0,1)$ if $L > \kappa$. For $\rho \longrightarrow \infty$ condition (12) behaves as follows. If $e \in (0,1)$, the term in brackets reduces to $(1-e^{1-\sigma})$ and as

$\underline{e}^{\rho\kappa e^2} \to \infty$ the right hand side > 1. If $e = 1$, however, the whole right hand side reduces to $\underline{e}^{\rho(\kappa - L)}$. Thus, condition (12) holds $\forall\, e \in (0,1]$ if $\kappa > L$.

In sum, $\rho \to \infty$

(i) leads to a boundary solution at $e^* = 0$ if $\kappa > L$

(ii) leads to a boundary solution at $e^* = 1$ if $L > \kappa$.

Hence, conditions (11) and (12) are not vacuous for increases in ρ and result (18) holds.

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Chapter 3: The economic insurance value of ecosystem resilience

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

JEL-Classification: Q57, Q56, D81, G22

Keywords: ecosystem, economic value, insurance, resilience, risk, risk preferences

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1 Introduction

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

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

An ecosystem's resilience in a given stability domain can be measured by the probability that exogenous perturbations make the system flip into another stability domain. Therefore, enhancing the resilience of a particular (desired) domain reduces the likelihood of a flip into another (less desired) domain. It is for this reason that ecosystem resilience has been referred to as "insurance", e.g. in the following manner:

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

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

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

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

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

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

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

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

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

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

2 Model

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

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

is the potential income loss when the system flips from the high-production into the low-production stability domain.

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

In line with Holling's (1973) notion of resilience as the maximum amount of disturbance a system can absorb in a given stability domain while still remaining in that stability domain, we define and measure resilience as a continuous state variable $R \in [0,1]$ that determines the probability of the system flipping from the high-production into the low-production stability domain as follows:

$$p = p(R) \qquad \text{with} \qquad p'(R) \leq 0 \text{ for all } R \ \text{ and } \ p'(R) < 0 \text{ for all } R \in (0,1) \tag{2}$$

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

In words, the higher the ecosystem's resilience in the high-production domain, the lower the probability that it flips into the low-production domain due to exogenous disturbance; with zero resilience, it flips for sure; and with maximum resilience it will certainly not flip. For future reference, we define $\underline{R}$ through $p(\underline{R}) = 1/2$ as the level of resilience at which the probability of a system flip exactly equals the probability of the system not flipping. This is the level of resilience at which the future state of nature is maximally uncertain.

In order to give more ecological structure to our ecosystem model (2)–(3), in some parts of our analysis we assume the following more specific model about the relationship between the level of resilience R and the flip probability p:

$$p(R) = 1 - R^{1-\sigma} \quad \text{with} \quad -\infty < \sigma < 1\ . \tag{4}$$

This model has the fundamental resilience-defining properties (2) and (3). In addition, it has the analytically handsome property that $p'(\cdot)$ is a constant-elasticity function of R, where the parameter σ is the (constant) elasticity of $p'(\cdot)$,[2] i.e. σ specifies by how much (in percent) the flip probability's slope increases when the level of resilience increases by 1 %. For short, we will refer to σ as "the ecosystem's elasticity". As σ may be positive or negative, one has[3]

$$p''(R) \left\{ \begin{array}{c} > \\ = \\ < \end{array} \right\} 0 \text{ for all } R \in (0,1) \qquad \text{if and only if} \qquad \sigma \left\{ \begin{array}{c} > \\ = \\ < \end{array} \right\} 0 \, .$$

Lacking ecological evidence or a plausible guess on the value of σ, we will study the full range of theoretically possible values of σ. Notwithstanding this generality, the case of $\sigma = 0$ has an epistemically outstanding importance. For, one may argue that one can meaningfully define and measure the system's state variable "resilience" only through, and not independently of, the observable variable "flip probability".[4] Such an epistemic equivalence between the state variable R and the observable p is exactly what is expressed by $\sigma = 0$. In this case, (4) reduces to a linear negative relationship, $p(R) = 1 - R$, so that resilience is measured directly in units of reduced flip-probability. As this case has an epistemically outstanding importance, we will treat the case of $\sigma = 0$ as the preeminent case, and discuss the cases of $\sigma < 0$ and $\sigma > 0$ against it.

Given the ecosystem model (2), (3) – or, more specifically, model (4) – the ecosystem user thus faces a binary income lottery $\{y_L, y_H; p(R), (1 - p(R))\}$. That is, given that the system is initially in the high-production stability domain and is characterized by a level R of resilience, the system will provide net income y_L with probability $p(R)$ and net income y_H with probability $1 - p(R)$. Obviously, with changing level of resilience R the statistical distribution of income will also change. As in our simple analytical framework only the level of resilience R may vary, R uniquely characterizes the income lottery. One may thus speak of "the income lottery R".

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[2] Note that (4) implies $-p''(R)R/p'(R) = \sigma$.

[3] For $\sigma = 0$, $p''(R) = 0$ holds also for $R = 0$ and $R = 1$. Yet, for $\sigma < 0$, one has $p''(0) = 0$, and for $\sigma \rightarrow 1$, one has $p''(1) \rightarrow 0$.

[4] If the system's state space was one-dimensional, one could indeed meaningfully define and measure the system's resilience (sensu Holling 1973) independently of the system's flip probability, namely as the "distance" in state space – measured in units of the single state variable – between the current system state and the threshold between stability domains. However, if the system is characterized by more than one state variable, the "distance" in state space is not uniquely defined but requires some metric which is not naturally given. Then, the system's resilience in a given stability domain cannot be measured through some distance in state space, but only through the observable consequence in terms of flip probability.

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

$$U = \mathscr{E}_R[u(y)] \qquad \text{with} \qquad u'(y) > 0 \text{ and } u''(y) < 0 \text{ for all } y\,, \tag{5}$$

where $\mathscr{E}_R$ is the expectancy operator based on the probabilities of lottery R, y is net income,[5] and $u(y)$ is a continuous and differentiable Bernoulli utility function which is assumed to be increasing and strictly concave, i.e. the ecosystem user is non-satiated and risk averse.[6] In order to study in the most simple way how the insurance value of resilience depends on the ecosystem user's degree of risk aversion, we assume that the ecosystem user is characterized by constant absolute risk aversion in the sense of Arrow (1965) and Pratt (1964), i.e. $-u''(y)/u'(y) \equiv$ const., so that the Bernoulli utility $u(y)$ function is

$$u(y) = -e^{-\rho y} \qquad \text{with} \qquad \rho > 0\,, \tag{6}$$

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

3 Conceptual clarification: insurance and insurance value

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

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

In the concrete setting described in the previous section, the term "insurance" takes on a more concrete meaning. As a person's (here: the ecosystem user's) *well-being* is determined

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

[6] 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).

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

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

In order to precisely define and measure the economic insurance value of some act of self-protection (here: an increase in the ecosystem's resilience), we follow Baumgärtner (2007: 103–104). One standard method of how to value the riskiness of an income lottery to a decision maker in monetary terms is to calculate the *risk premium* Π of the lottery, which is defined by (e.g. Kreps 1990, Varian 1992: 181)[7]

$$u\left(\mathscr{E}_R[y]-\Pi\right)=\mathscr{E}_R\left[u(y)\right] \ . \tag{7}$$

In words, the risk premium Π is the amount of money that leaves a decision maker equally well-off, in terms of utility, between the two situations of (i) receiving for sure the expected pay-off from the income lottery R, $\mathscr{E}_R[y]$, minus the risk premium Π, and (ii) playing the risky income lottery R with random pay-off y.[8] In the model employed here, the risk premium as

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[7] By Equation (7), $\mathscr{E}_R[y]-\Pi$ is the *certainty equivalent* of lottery R, as it yields exactly the same expected utility as playing the risky lottery, $\mathscr{E}_R\left[u(y)\right]$.

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

defined by Equation (7) uniquely exists because, by assumption (cf. Section 2), $y \in Y$ with Y as an interval of $\mathbb{R}$, and u is continuous and strictly increasing (Kreps 1990: 84). In general, if the Bernoulli utility function u characterizes a risk averse decision maker, i.e. if $\rho > 0$ in Equation (6), the risk premium Π is strictly positive.

The economic insurance value of resilience can now be defined based on the risk premium of the income lottery R as follows.

Definition 2

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

$$I(R) := -\frac{d\Pi(R)}{dR} \ . \tag{8}$$

Thus, the economic insurance value of ecosystem resilience is the marginal value of its function to reduce the risk premium of the ecosystem user's income risk from using ecosystem services under uncertainty. Being a marginal value, it depends on the existing level of resilience R. The minus sign in the defining Equation (8) serves to express a *reduction* of the risk premium as a *positive* value.

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

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

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with random pay-off y.

Definition 3

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

$$V(R) := \lim_{\Delta R \to 0} \frac{WTP(\Delta R)}{\Delta R} , \tag{9}$$

where WTP is defined through

$$\mathscr{E}_R \left[u(y) \right] = \mathscr{E}_{R+\Delta R} \left[u(y - WTP(\Delta R)) \right] . \tag{10}$$

In words, we measure the total economic value of a change ΔR in resilience as the maximum willingness to pay (WTP) for that change, more exactly as the WTP per marginal unit of resilience. The maximum willingness to pay for the increase ΔR in resilience is the amount of money that leaves an individual indifferent, in terms of expected utility, between the two situations of (i) resting in the original position with resilience R and (ii) paying the amount WTP and getting into a situation with resilience $R + \Delta R$.[9] As value is typically expressed as a per-unit quantity characterizing a marginal change, we divide WTP by ΔR and let $\Delta R \to 0$ to obtain the marginal value of resilience. Being a marginal value, it depends on the existing level of resilience R.

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

4 Results

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

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[9] In the language of welfare measurement, WTP is the Hicksian compensating surplus for a finite change of ΔR in the level of resilience (Hicks 1943, Freeman 2003: Chap. 3). Alternatively, one could also use the Hicksian equivalent surplus to measure the monetary value of the welfare change associated with a finite change of ΔR in the level of resilience, that is, the minimum amount of monetary compensation to the individual ("willingness to accept", WTA) that leaves the individual indifferent between the two situations of (i) resting in the original position with resilience R and receiving a monetary payment of WTA and (ii) getting into a situation with resilience $R + \Delta R$. In general, WTP and WTA will differ for finite changes of ΔR. However, for the marginal changes studied here, i.e. for $\Delta R \to 0$, WTP and WTA coincide, so that the value of $V(R)$ does not depend upon whether WTP or WTA is used in the defining Equation (9).

with, we discuss the risk premium associated with different levels of resilience.

Lemma 1

The risk premium $\Pi(R)$ of the income lottery R is given by

$$\Pi(R) = -p(R)\Delta y + \frac{1}{\rho} \ln \left[1 + p(R) \left(e^{\rho \Delta y} - 1 \right) \right] \,, \tag{11}$$

which has the following properties:

(i)

$$\Pi(0) = \Pi(1) = 0 \quad \text{and} \quad \Pi(R) > 0 \text{ for all } R \in (0,1) \,. \tag{12}$$

(ii) For all $R \in (0,1)$[10]

$$\Pi'(R) \left\{ \begin{matrix} > \\ = \\ < \end{matrix} \right\} 0 \qquad \text{for} \qquad R \left\{ \begin{matrix} < \\ = \\ > \end{matrix} \right\} \tilde{R} \,, \tag{13}$$

$$\text{where} \quad \tilde{R} := p^{-1} \left(\frac{1}{\rho \Delta y} - \frac{1}{e^{\rho \Delta y} - 1} \right) \,, \tag{14}$$

$$\text{so that} \quad \underline{R} < \tilde{R} < 1 \quad \text{and} \quad \frac{d\tilde{R}}{d\rho}, \frac{d\tilde{R}}{d\Delta y} > 0, \frac{d\tilde{R}}{d\sigma} < 0 \tag{15}$$

(iii) There exists $\bar{\sigma}$ with $0 < \bar{\sigma} \leq 1$ and

$$\frac{d\bar{\sigma}}{d(\rho \Delta y)} > 0 \,, \quad \lim_{\rho \Delta y \to +\infty} \bar{\sigma} = 1 \,, \quad \lim_{\rho \Delta y \to 0} \bar{\sigma} = 0 \,, \tag{16}$$

so that

$$\Pi''(R) < 0 \quad \begin{cases} \text{for } R > \tilde{\tilde{R}} & \text{if} \quad \sigma < 0 \\ \text{for all } R \in (0,1) & \text{if and only if} \quad 0 \leq \sigma \leq \bar{\sigma} \\ \text{for } R < \tilde{\tilde{R}} & \text{if} \quad \sigma > \bar{\sigma} \end{cases} \,, \tag{17}$$

where $\tilde{\tilde{R}}$ is defined through $\Pi''(\tilde{\tilde{R}}) = 0$ for $\sigma < 0$, and through $\tilde{\tilde{R}} = \min\{R \mid \Pi''(R) = 0\}$ for $\sigma > \bar{\sigma}$, so that $\tilde{\tilde{R}} \gtrless \tilde{R}$ for $\sigma \gtrless 0$.

(iv) For all $R \in (0,1)$

$$\frac{d\Pi(R)}{d\rho} > 0 \quad \text{and} \quad \lim_{\rho \to 0} \Pi(R) = 0 \,, \tag{18}$$

$$\frac{d\Pi(R)}{d\Delta y} > 0 \quad \text{and} \quad \lim_{\Delta y \to 0} \Pi(R) = 0 \,, \tag{19}$$

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[10] For $\sigma = 0$, the statement about the sign of $\Pi'(R)$ holds also for $R = 0$ and $R = 1$. Yet, for $\sigma < 0$, one has $\Pi'(0) = 0$; for $\sigma \to 1$, one has $\Pi'(1) \to 0$.

$$\frac{d\Pi(R)}{d\sigma}\left\{\begin{array}{c} > \\ = \\ < \end{array}\right\}0 \quad \text{for} \quad R\left\{\begin{array}{c} < \\ = \\ > \end{array}\right\}\tilde{R}\,, \tag{20}$$

$$\text{and} \quad \lim_{\sigma\to 1}\Pi(R) = \lim_{\sigma\to -\infty}\Pi(R) = 0\,. \tag{21}$$

Proof. See Appendix A.1. □

Result (12) states that the risk premium of income lottery R is strictly positive at all levels of resilience in between 0 and the maximum level of 1, and is zero at the extreme levels of 0 and 1. That is, income is risky at all levels of resilience in between 0 and 1; and only at the extreme levels of 0 and 1 does the income risk vanish, as in the case $R = 0$ the system will flip into the low-productivity domain with income y_L for certain, and at $R = 1$ the system will remain in the high-productivity domain with income y_L for certain.

As a consequence of Result (12), the risk premium varies with the level of resilience in a non-monotonic way (Figures 1 and 2, orange line). Result (13) states that there uniquely exists a level $\tilde{R}$ of the domain's resilience at which the risk premium is maximal, that is, the income lottery is most risky ($\tilde{R} = 0.647$ in Figure 1, $\tilde{R} = 0.794$ in Figure 2 left, $\tilde{R} = 0.004$ in Figure 2 right). For $R > \tilde{R}$ a marginal increase in resilience reduces the risk premium, and for $R < \tilde{R}$ a marginal increase in resilience raises the risk premium. This maximum-income-risk level of resilience, $\tilde{R}$ (Equation 14), is strictly in between $\underline{R}$ and 1, where $\underline{R} > 0$ denotes the level of resilience at which the probability of a system flip exactly equals the probability of the system not flipping (Result 15a).[11] So, the maximum-income-risk level of resilience $\tilde{R}$ is always strictly larger than the level of resilience $\underline{R}$, at which the future state of nature is maximally uncertain. Also, the range $(0, \tilde{R}]$ of low levels of resilience, for which the risk premium is strictly increasing with resilience, is non-empty.

Furthermore, the maximum-income-risk level of resilience $\tilde{R}$ increases with the degree of risk aversion ρ and the potential income loss Δy, it decreases with the ecosystem's elasticity σ (Result 15b).

The statement about the second derivative of the risk premium (Result 17) is rather technical, and will be needed for the proof of an important property of the insurance value in Proposition 1 below. Essentially, it states that there exists a domain of (positive) values of ecosystem elasticity, $0 \leq \sigma \leq \bar{\sigma}$, including the preeminent case of $\sigma = 0$, for which the risk premium is strictly concave over the entire range of resilience (Figure 1, orange line). This

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[11] Note that $\underline{R}$, which is defined through $p(\underline{R}) = 1/2$, will be greater than (equal to, smaller than) $1/2$ for $\sigma < 0$ $(= 0, > 0)$.

domain of ecosystem elasticities is bounded from below by zero, and from above by some maximal value $\bar{\sigma}$, which has the properties stated in Result (16): it increases with the risk-aversion-weighted potential income loss, $\rho\Delta y$, and for $\rho\Delta y$ going to infinity (zero) approaches the maximal ecosystem elasticity of one (zero).

The more risk-averse the ecosystem user is, the larger the perceived riskiness of the income lottery R and the larger the associated risk premium (Result 18). For a risk-neutral individual, on the other hand, the risk premium would be 0 for all R. Similarly, for the potential income loss Δy (Result 19): the risk premium raises with an increasing potential income loss Δy. For equal income levels in both stability domains, which means no income loss in case of a system flip ($\Delta y = 0$), the risk premium would be zero over the whole range of R.

Result (20) states that the risk premium increases (decreases) with the ecosystem's elasticity for levels of resilience below (above) the maximum-income-risk level of resilience, $\tilde{R}$. That is, in the range of resilience where the riskiness of income increases (decreases) with resilience, i.e. for $R < (>)\tilde{R}$ (cf. Result 13), an increase in ecosystem elasticity increases (decreases) the riskiness of income. This can be seen from comparing the orange lines in Figures 2 (left), 1 and 2 (right), as σ increases in this order. Ecosystem elasticity thus has the very same ambivalent role as ecosystem resilience for the riskiness of income. Result (21) states that the risk premium vanishes as the ecosystem's elasticity approaches either its maximum or its minimum value. The reason is that in either limiting case, according to model (4), the flip probability $p(R)$ does not depend on the level of resilience any more, except for the extreme levels of $R = 0$ (for $\sigma \to 1$) or $R = 1$ (for $\sigma \to -\infty$) where it jumps from one to zero or from zero to one, respectively. As a result, the risk premium is non-vanishing only at $R = 0$ (for $\sigma \to 1$) or $R = 1$ (for $\sigma \to -\infty$), but vanishes for all other levels of resilience.[12]

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

Proposition 1

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

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

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[12] Note that an overall vanshing risk premium, except for either $R = 0$ (for $\sigma \to 1$) or $R = 1$ (for $\sigma \to -\infty$) is compatible with Result (20)'s statement that the risk premium increases with σ for $R < \tilde{R}$, because $\tilde{R}$ decreases with σ (Result 15).

which has the following properties:

(i) For all $R \in (0,1)$[13]

$$I(R)\left\{\begin{matrix}<\\=\\>\end{matrix}\right\}0 \quad \text{for} \quad R\left\{\begin{matrix}<\\=\\>\end{matrix}\right\}\tilde{R}\text{ , where } \tilde{R} \text{ is given by Equation (14) .} \tag{23}$$

(ii) The insurance value is globally increasing with resilience,

$$I(0) < I(1) , \tag{24}$$

in particular, it is strictly monotonically increasing depending on ecosystem elasticity:

$$I'(R) > 0 \quad \begin{cases} \text{for } R > \tilde{\tilde{R}} & \text{if} \quad \sigma < 0 \\ \text{for all } R \in (0,1) & \text{if and only if} \quad 0 \leq \sigma \leq \bar{\sigma} \\ \text{for } R < \tilde{\tilde{R}} & \text{if} \quad \sigma > \bar{\sigma} \end{cases} , \tag{25}$$

where $\bar{\sigma}$ and $\tilde{\tilde{R}}$ are as defined in Lemma 1(iii).

(iii) For all $R \in (0,1)$

$$\frac{dI(R)}{d\rho}\left\{\begin{matrix}<\\=\\>\end{matrix}\right\}0 \quad \text{for} \quad R\left\{\begin{matrix}<\\=\\>\end{matrix}\right\}\tilde{R} \quad \text{and} \quad \lim_{\rho\to 0} I(R) = 0 , \tag{26}$$

$$\frac{dI(R)}{d\Delta y}\left\{\begin{matrix}<\\=\\>\end{matrix}\right\}0 \quad \text{for} \quad R\left\{\begin{matrix}<\\=\\>\end{matrix}\right\}\tilde{R} \quad \text{and} \quad \lim_{\Delta y\to 0} I(R) = 0 , \tag{27}$$

$$\frac{dI(R)}{d\sigma}\left\{\begin{matrix}<\\=\\>\\=\\<\end{matrix}\right\}0 \quad \text{for} \quad \left\{\begin{matrix}R < {}'R\\ R = {}'R\\ {}'R < R < R'\\ R = R'\\ R > R'\end{matrix}\right. \tag{28}$$

$$\text{and} \quad \lim_{\sigma\to 1} I(R) = \lim_{\sigma\to -\infty} I(R) = 0 , \tag{29}$$

where $\tilde{R}$ is as defined in Lemma 1(iii) and ${}'R < \tilde{R} < R'$.

Proof. See Appendix A.2. ☐

Result (23) states that the insurance value of resilience may be negative or positive, depending on the level of resilience R. If resilience is below the maximum-income-risk level $\tilde{R}$, an increases in resilience raises the risk premium (Result 13) and therefore, as the insurance value is defined as the reduction in the risk premium (Definition 2), resilience has a negative insurance value for all $R < \tilde{R}$. Only if $R > \tilde{R}$, an increase in resilience reduces the risk premium and the insurance value is positive (Figures 1 and 2, green line).

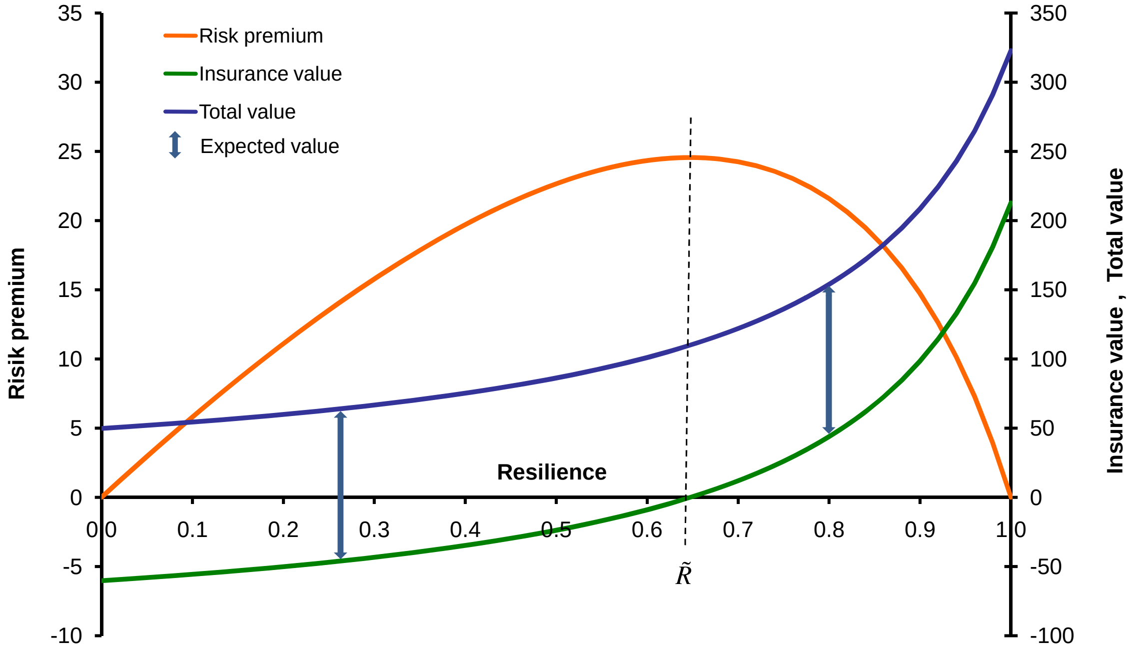

Figure 1: Risk premium (orange curve), insurance value (green curve), expected value (vertical distance between green and blue curves) and total value (blue curve) as a function of resilience for the case of intermediate ecosystem elasticity $0 \leq \sigma \leq \bar{\sigma}$. The dashed line marks the maximum-income-risk level of resilience $R = \tilde{R}$. (Parameter values: $\sigma = 0$, $\Delta y = 110$, $\rho = 0.017$)

Result (24) states that the insurance value of ecosystem resilience globally increases with the level of resilience: it is strictly higher for the maximum level of resilience than for zero resilience. Result (25) states that for a domain of (positive) values of ecosystem elasticity, $0 \leq \sigma \leq \bar{\sigma}$ (including the preeminent case of $\sigma = 0$), the insurance value of ecosystem resilience increases even strictly monotonically with the level of resilience (Figure 1, green line). Only as ecosystem elasticity σ turns negative or exceeds the threshold value $\bar{\sigma}$, it may happen that the insurance value locally decreases.[14] For negative ecosystem elasticity, $\sigma < 0$, it may

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[13] For $\sigma = 0$, the statement about the sign of $I(R)$ holds also for $R = 0$ and $R = 1$. Yet, for $\sigma < 0$, one has $I(0) = 0$; for $\sigma \rightarrow 1$, one has $I(1) \rightarrow 0$.

[14] A parameter value of $\sigma < 0$ in Function (4) implies a relationship between p and R such that the first marginal units of resilience starting from $R = 0$ do not have any significant impact on the reduction of the flip probability p. Only increases in resilience close to the maximum level of $R = 1$ do significantly lower the flip probability p. For such ecosystems, the insurance value of resilience decreases for small levels of resilience and

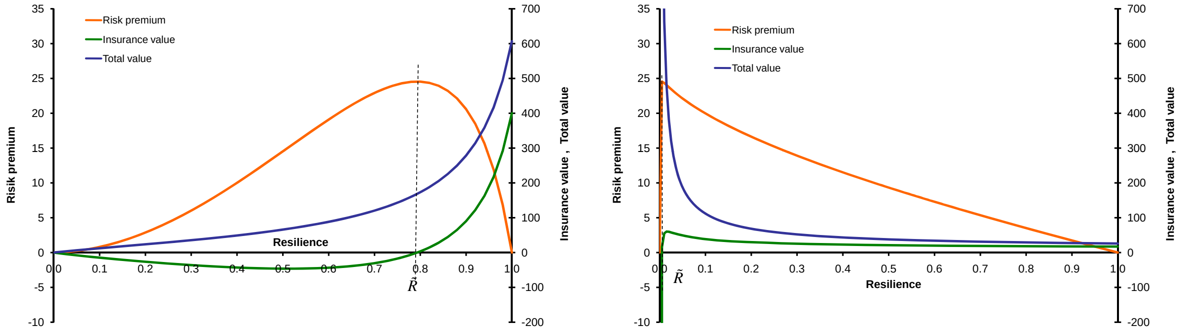

Figure 2: Risk premium (orange curve), insurance value (green curve), expected value (vertical distance between green and blue curves) and total value (blue curve) as a function of resilience for the two extreme cases of negative ecosystem elasticity ($\sigma < 0$, left) and very large positive ecosystem elasticity ($\sigma > \bar{\sigma}$, right). The dashed line marks the maximum-income-risk level of resilience $R = \tilde{R}$. (Parameter values, left: $\sigma = -0.88$; right: $\sigma = 0.92$; both: $\Delta y = 110$, $\rho = 0.017$)

be that the (negative) insurance value locally decreases at levels of resilience smaller than $\tilde{\tilde{R}}$ (Figure 2 left, green line); and for very large positive ecosystem elasticity, $\sigma > \bar{\sigma}$, it may be that the (positive) insurance value locally decreases at levels of resilience greater than $\tilde{\tilde{R}}$ (Figure 2 right, green line).

In economic terms, an increasing insurance value means that the higher the level of resilience, the more valuable – as an insurance – is a marginal increase in resilience. This is unusual and in contrast to normal economic goods, the marginal value of which decreases with their amount: normally, the more abundant a good, the less valuable the next marginal unit. Technically, the increasing marginal value of resilience comes about as the objective function, expected utility (5), when expressed as a function of the level of resilience, is non-concave in R.

Result (26) states how the ecosystem user's degree of risk-aversion affects the insurance value. If the ecosystem user was risk neutral ($\rho = 0$), the insurance value would vanish for

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increases for high levels of resilience close to $R = 1$ (Figure 2 left, green line). Conversely, a parameter value of σ close to its maximum value of 1 means that the first marginal unit of resilience has a huge impact on the reduction of the flip probability p, whereas all later units of resilience only have a negligible effect. Under such circumstances, the insurance value of resilience steeply increases in the vicinity of $R = 0$ from a negative value to its maximum (positive) value and then decreases with R (Figure 2 right, green line).

all levels of resilience R. With increasing risk-aversion, the insurance value increases for high levels of $R > \tilde{R}$, where it is positive, and decreases for low levels of $R < \tilde{R}$, where it is negative. Thus, the more risk-averse the ecosystem user is, the steeper the curve for I (Figure 1, green line). The same goes for the potential income loss Δy (Result 27). For equal income levels in both stability domains, which means no income loss in case of a system flip ($\Delta y = 0$), the insurance value would vanish for all levels of resilience R. With increasing potential income loss Δy, the I-curve gets steeper, as the insurance value decreases for $R < \tilde{R}$ and raises for $R > \tilde{R}$.

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

Result (28) states that the insurance value decreases with increasing ecosystem elasticity for low and high levels of resilience, $R < {}'R < \tilde{R}$ and $R > R' > \tilde{R}$, and increases with increasing ecosystem elasticity in between, ${}'R < R < R'$. This can be seen from comparing the green lines in Figures 2 (left), 1 and 2 (right), as σ increases in this order. Result (29) states that the insurance value vanishes as the ecosystem's elasticity approaches either its maximum or its minimum value, which becomes plausible from the underlying property of the risk premium (Result 21). This can also be seen from comparing the green lines in Figures 2 (left and right) and 1.

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

Proposition 2

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

$$V(R) = -p'(R)\frac{1}{\rho}\frac{e^{\rho\Delta y} - 1}{1 + p(R)\left(e^{\rho\Delta y} - 1\right)} \, , \tag{30}$$

which has the following properties:

(i)

$$V(R) \equiv -p'(R)\Delta y + I(R). \tag{31}$$

(ii)

$$V(R) \geq 0 \quad \text{for all } R. \tag{32}$$

Proof. See Appendix A.3. □

From Equation (31) it becomes obvious that the total economic value of resilience is the sum of two components: the expected increase in income due to a marginal increase in resilience, $-p'(R)\Delta y$, which is always positive,[15] and the insurance value of increased resilience, which may be negative or positive (cf. Proposition 1). This reflects the fact that an increase in ecosystem resilience has two effects on the ecosystem user's income: (i) it raises the expected income; (ii) it may raise or lower the riskiness of income, i.e. deviations from expected income. Thus, the total value of resilience is more than its insurance value, or, put the other way round, the insurance value is a value component over and above the expected value of resilience.

Figures 1 and 2 show the total economic value as a function of resilience (blue line). In the figures, the expected value of resilience, $-p'(R)\Delta y$, is just the vertical difference between the curves for I (green) and V (blue). Whereas the insurance value $I(R)$ of resilience may be positive or negative, depending on the level of resilience R, the expected value of resilience, $-p'(R)\Delta y$, is positive at all levels of resilience R.[16] As a consequence, for $R < \tilde{R}$ where the insurance value is negative, the total economic value of resilience is smaller than its expected value. Yet, at all levels of resilience the total value is positive (Result 32). That means, even if the insurance value should be negative, the mean-increasing value of resilience is large enough to offset this negative effect on the total value.

5 Discussion and conclusion

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

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[15] By Assumption (2), $p'(R) < 0$ for all $R \in (0,1)$.

[16] Note that for $\sigma = 0$, one has $p'(R) = -1 =$ const., so that the expected value of resilience does not depend on the level of resilience. That is, the vertical difference between the curves for I (green) and V (blue) in Figure 1 is constant.

mitigation"), from other components of its total economic value, which are due to resilience's function to raise the *expected* income from ecosystem services.

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

Second, the (marginal) insurance value as well as the (marginal) total value of resilience increase globally with the level of resilience – for some ecosystem types (namely those with moderately positive elasticity) even monotonically: the higher the level of resilience, the more valuable is another unit of resilience. This is in contrast to normal economic goods, the (marginal) value of which *de*creases with their quantity. As unusual as this increasing-returns property may be for normal economic goods, it is not implausible and also known from other goods which are of systemic importance and thus give rise to a non-concavity in the social objective function, such as e.g. information (Radner and Stiglitz 1984) or biodiversity conservation (Hunter 2009). The management consequences for such non-convex ecological-economic systems are discussed e.g. by Dasgupta and Mäler (2003).

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

While we have made one specific assumption about risk preferences, i.e. constant absolute risk aversion, actually all of our results qualitatively hold more generally for all risk preferences satisfying the von-Neumann-Morgenstern axioms. These axioms, including continuity and context-independence, appear plausible for standard small-risk situations. But one may doubt that they adequately describe people's risk preferences when it comes to catastrophic (i.e. discontinuous) risk that irreversibly threatens the subsistence level of income, as it is the case for many threats to the resilience of life-supporting ecosystems. For such risks, it may be interesting to study how resilience provides insurance under, e.g., safety-first preferences (Roy 1952, Telser 1955, Kataoka 1963).

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

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Appendix

Throughout the appendix, we denote the risk-aversion-weighted income loss by $\lambda \equiv \rho \Delta y$.

A.1 Proof of Lemma 1

Explicating the general definition of the risk premium (Equation 7) by the CARA-utility function (6) yields

$$-e^{-\rho[(1-p(R))y_H+p(R)y_L-\Pi(R)]} = -(1-p(R))e^{-\rho y_H} - p(R)e^{-\rho y_L} \,, \tag{A.33}$$

which can be rearranged into

$$e^{\rho\Pi(R)} = \frac{(1-p(R))e^{-\rho y_H} + p(R)e^{-\rho y_L}}{e^{-\rho[(1-p(R))y_H+p(R)y_L]}} \,. \tag{A.34}$$

Using $\Delta y = y_H - y_L$, (A.34) can be solved for $\Pi(R)$, which leads to Result (11).

ad (i). Inserting $p(0) = 1$ or $p(1) = 0$ into (11) immediately yields $\Pi = 0$ (Result 12a). Strict positivity of $\Pi(R)$ for all $R \in (0,1)$ (Result 12b) can be demonstrated as follows. Note that

$$1 - p(R) > e^{p(R)\lambda} - p(R)e^{\lambda} \tag{A.35}$$

because the right hand side of this inequality approaches $1 - p(R)$ as $\lambda \to 0$ and strictly monotonically decreases with λ,

$$\frac{d}{d\lambda}\left[e^{p(R)\lambda} - p(R)e^{\lambda}\right] = p(R)\left(e^{p(R)\lambda} - e^{\lambda}\right) < 0\ ,$$

since $\lambda > 0$ and $R \in (0,1)$, i.e. $0 < p(R) < 1$. Inequality (A.35) can be rearranged

$$\begin{aligned} 1 - p(R) &> e^{p(R)\lambda} - p(R)e^{\lambda} && \text{(A.36)}\\ 1 + p(R)\left(e^{\lambda} - 1\right) &> e^{p(R)\lambda} && \text{(A.37)}\\ \ln\left[1 + p(R)\left(e^{\lambda} - 1\right)\right] &> p(R)\lambda && \text{(A.38)}\\ -p(R)\lambda + \ln\left[1 + p(R)\left(e^{\lambda} - 1\right)\right] &> 0\ , && \text{(A.39)} \end{aligned}$$

which yields, after dividing by $\rho > 0$, Result (12)b.

ad (ii). Differentiating Result (11) with respect to R yields

$$\Pi'(R) = -\frac{p'(R)}{\rho}\left\{\lambda - \frac{e^{\lambda} - 1}{1 + p(R)\left(e^{\lambda} - 1\right)}\right\}\ . \tag{A.40}$$

By Assumption (2), $p'(R)$ is strictly negative for all $R \in (0,1)$. Hence, the sign of $\Pi'(R)$ is determined by the sign of the term in braces. For $R \to 0$, using $e^x > 1 + x$ for all $x \neq 0$, one has

$$\begin{aligned} \lim_{R\to 0} \lambda - \frac{e^{\lambda} - 1}{1 + p(R)\left(e^{\lambda} - 1\right)} &= \lambda - \frac{e^{\lambda} - 1}{1 + \left(e^{\lambda} - 1\right)} = \lambda - 1 + e^{-\lambda}\\ &> \lambda - 1 + 1 - \lambda = 0 && \text{(A.41)} \end{aligned}$$

For $R \to 1$, and again using $e^x > 1 + x$ for all $x \neq 0$, one has

$$\begin{aligned} \lim_{R\to 1} \lambda - \frac{e^{\lambda} - 1}{1 + p(R)\left(e^{\lambda} - 1\right)} &= \lambda - \frac{e^{\lambda} - 1}{1 + 0} = \lambda - e^{\lambda} + 1\\ &< \lambda - 1 - \lambda + 1 = 0 && \text{(A.42)} \end{aligned}$$

And $\Pi'(R) = 0$ for

$$\lambda - \frac{e^{\lambda} - 1}{1 + p(\tilde{R})\left(e^{\lambda} - 1\right)} = 0\ . \tag{A.43}$$

This can be uniquely solved for $R = \tilde{R}$ where $\tilde{R}$ is defined through

$$p(\tilde{R}) = \frac{1}{\lambda} - \frac{1}{e^{\lambda} - 1} \ , \tag{A.44}$$

which is equivalent to Result (14), since $p'(R) \neq 0$ for all $R \in (0,1)$. Pulling all this information together, from $\Pi'(0) > 0$ (A.41), $\Pi'(1) < 0$ (A.42), and $\Pi'(R) = 0$ if and only if $R = \tilde{R}$ (A.44), it follows that Result (13) holds.

In order to study the properties of $\tilde{R}$ (Equation 14) introduce

$$F(\lambda) = \frac{1}{\lambda} - \frac{1}{e^{\lambda} - 1} \ , \tag{A.45}$$

so that (A.44) and (14) can be rewritten as

$$p(\tilde{R}) \equiv F(\lambda) \quad \text{and} \quad \tilde{R} \equiv p^{-1}(F(\lambda)) \ . \tag{A.46}$$

Note that

$$\begin{aligned}
\lim_{\lambda \to 0} F(\lambda) &= \lim_{\lambda \to 0} \frac{e^{\lambda} - 1 - \lambda}{\lambda(e^{\lambda} - 1)} = \lim_{\lambda \to 0} \frac{e^{\lambda} - 1}{(1+\lambda)e^{\lambda} - 1} = \lim_{\lambda \to 0} \frac{1}{2+\lambda} = \frac{1}{2} \ , && \text{(A.47)} \\
& \text{(apply l'Hôpital's rule twice)} \\
\lim_{\lambda \to +\infty} F(\lambda) &= \lim_{\lambda \to +\infty} \frac{1}{\lambda} - \lim_{\lambda \to +\infty} \frac{1}{e^{\lambda} - 1} = 0 \ , && \text{(A.48)} \\
F'(\lambda) &= -\frac{1}{\lambda^2} + \frac{e^{\lambda}}{(e^{\lambda} - 1)^2} = \frac{1}{e^{\lambda} + e^{-\lambda} - 2} - \frac{1}{\lambda^2} < 0 \quad \text{for all } \lambda \ , && \text{(A.49)} \\
& \text{(as, through Taylor expansion, } e^{\lambda} = \sum_{n=0}^{\infty} \frac{\lambda^n}{n!} \quad \text{and therefore} \\
& e^{\lambda} + e^{-\lambda} - 2 = \lambda^2 + \sum_{n=1}^{\infty} \frac{2\lambda^{2n}}{(2n)!} > \lambda^2 \text{ for all } \lambda) \\
F(\lambda) &> 0 \quad \text{for all } \lambda \ . && \text{(A.50)} \\
& \text{(follows immediately from A.47–A.49)}
\end{aligned}$$

From (A.50) it follows immediately that $p(\tilde{R}) = F(\lambda) > 0$ for all λ, which implies, with $p'(R) < 0$ for all R, that $\tilde{R} < 1$ for all λ. On the other hand, from (A.47) and (A.49) one has that $F(\lambda) < 1/2$ for all $\lambda > 0$. Hence, $p(\tilde{R}) = F(\lambda) < 1/2$ for all λ, which implies, with $p'(R) < 0$ for all $R \in (0,1)$, that $\tilde{R} > \underline{R}$ for all λ. This establishes Result (15a).

With (A.46), Assumption 2 ($p'(R) < 0$ for all $R \in (0,1)$) and Property (A.49), it follows that

$$\frac{d\tilde{R}}{d\lambda} = \frac{1}{p'(\tilde{R})} F'(\lambda) > 0 \ . \tag{A.51}$$

From that, with $\lambda \equiv \rho \Delta y$ it follows immediately that $d\tilde{R}/d\rho > 0$ and $d\tilde{R}/d\Delta y > 0$ (Result 15b). Using (4) and (A.46), $\tilde{R}$ can be rewritten as

$$\tilde{R} = p^{-1}\left(F(\lambda)\right) = \left[1 - F(\lambda)\right]^{\frac{1}{1-\sigma}} \;, \tag{A.52}$$

from which it it follows that

$$\frac{d\tilde{R}}{d\sigma} = \left[1 - F(\lambda)\right]^{\frac{1}{1-\sigma}} \ln\left[1 - F(\lambda)\right] \frac{1}{(1-\sigma)^2} < 0 \,, \tag{A.53}$$

since $0 < F(\lambda) < 1/2$ (from A.47–A.50) and $\sigma < 1$ (by Assumption 4) imply that the first and third factors are strictly positive and the second is strictly negative.

ad (iii). Differentiate (A.40) again with respect to R:

$$\Pi''(R) = -\frac{1}{\rho}\left\{ p''(R)\left[\lambda - \frac{e^{\lambda}-1}{1+p(R)(e^{\lambda}-1)}\right] + \left[p'(R)\frac{e^{\lambda}-1}{1+p(R)(e^{\lambda}-1)}\right]^2 \right\} \,. \tag{A.54}$$

Under Assumption (4) one has

$$\begin{aligned} p(R) &= 1 - R^{1-\sigma} && \text{(A.55)} \\ p'(R) &= -(1-\sigma)R^{-\sigma} && \text{(A.56)} \\ p''(R) &= \sigma(1-\sigma)R^{-\sigma-1} && \text{(A.57)} \end{aligned}$$

Inserting (A.55)–(A.57) into (A.54) yields an explicit equation for $\Pi''(R)$ in the elementary parameters of the model, σ, ρ and Δy. Systematic numerical simulation of this equation for all $-\infty < \sigma < 1$ and for various $\rho, \Delta y > 0$ yields Results (16) and (17).

ad (iv). By definition, the risk premium is zero for a risk-neutral decision-maker ($\rho = 0$), and is known to increase with her degree of risk-aversion ρ (e.g. Gravelle and Rees 2004: 463), which yields Result (18).

Setting $\Delta y = 0$ in Expression (11) for $\Pi(R)$ obviously yields $\Pi(R) \equiv 0$. That the risk premium increases with Δy can be seen from the first derivative of $\Pi(R)$ with respect to Δy:

$$\begin{aligned} \frac{d\Pi(R)}{d\Delta y} &= p(R)\left[\frac{e^{\lambda}}{1+p(R)\left(e^{\lambda}-1\right)} - 1\right] \\ &= p(R)\left[\frac{1}{p(R)+(1-p(R))e^{-\lambda}} - 1\right] \,. && \text{(A.58)} \end{aligned}$$

As $e^{-\lambda} < 1$ for $\lambda > 0$, and $0 < p(R) < 1$ for $R \in (0,1)$, the denominator in the fraction is strictly smaller than 1, so that the term in brackets is strictly positive and the whole expression is strictly positive, which yields Result (19).

From Result (11) it follows that

$$\frac{d\Pi(R)}{d\sigma} = -\frac{1}{\rho}\left\{\lambda - \frac{e^{\lambda}-1}{1+p(R)\left(e^{\lambda}-1\right)}\right\}\frac{dp(R)}{d\sigma} \ . \tag{A.59}$$

From (A.40) it is apparent that

$$\left\{\lambda - \frac{e^{\lambda}-1}{1+p(R)\left(e^{\lambda}-1\right)}\right\} = -\rho\frac{\Pi'(R)}{p'(R)} \ , \tag{A.60}$$

so that (A.59) becomes

$$\frac{d\Pi(R)}{d\sigma} = \frac{\Pi'(R)}{p'(R)}\frac{dp(R)}{d\sigma} \ . \tag{A.61}$$

As $p'(R) < 0$ for all $R \in (0,1)$, and, with Assumption (4), $dp(R)/d\sigma < 0$ for all $R \in (0,1)$, the sign of $d\Pi(R)/d\sigma$ is determined by the sign of $\Pi'(R)$. With Result (13), Result (20) then follows immediately.

Result (21) follows from Result (11) and noting that model (4) implies

$$\lim_{\sigma\to 1} p(R) = 0 \quad \text{as well as} \quad \lim_{\sigma\to -\infty} p(R) = 1 \quad \text{for all } R \in (0,1) \ . \tag{A.62}$$

A.2 Proof of Proposition 1

Differentiating $-\Pi(R)$ with respect to R immediately yields Result (22).

ad (i). Result (23) follows immediately from Definition (8) and Result (13).

ad (ii). Result (24) can be demonstrated by noting that Result (22) implies

$$I(0) = p'(0)\frac{1}{\rho}\left(\lambda - 1 + e^{-\lambda}\right) \quad \text{and} \quad I(1) = p'(1)\frac{1}{\rho}\left(\lambda - e^{\lambda} + 1\right) \ , \tag{A.63}$$

where

$$\lambda - 1 + e^{-\lambda} > 0 \quad \text{and} \quad \lambda - e^{\lambda} + 1 < 0 \ , \tag{A.64}$$

since $e^x > 1 + x$ for all $x > 0$. Under Assumption (4), one has (A.56), so that

$$\left\{\begin{array}{l} p'(0) = 0 \ \text{ and } \ p'(1) < 0 \\ p'(0) < 0 \ \text{ and } \ p'(1) < 0 \\ p'(0) < 0 \ \text{ and } \ p'(1) \leq 0^{17} \end{array}\right\} \quad \text{if} \quad \left\{\begin{array}{c} \sigma < 0 \\ \sigma = 0 \\ \sigma > 0 \end{array}\right\} . \tag{A.65}$$

Combining (A.63)–(A.65), one has

$$\left\{\begin{array}{l} I(0) = 0 \ \text{ and } \ I(1) > 0 \\ I(0) < 0 \ \text{ and } \ I(1) > 0 \\ I(0) < 0 \ \text{ and } \ I(1) \geq 0^{18} \end{array}\right\} \quad \text{if} \quad \left\{\begin{array}{c} \sigma < 0 \\ \sigma = 0 \\ \sigma > 0 \end{array}\right\} , \tag{A.66}$$

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[17] $p'(1) < 0$ for $\sigma < 1$, and $p'(1) \to 0$ as $\sigma \to 1$.

which means that, in any case, $I(0) < I(1)$, which is Result (24). Result (25) follows immediately from Definition (8) and Result (17).

ad (iii). Results (26), (27), (28) follow from Definition (8), the fact that the function $\Pi(R)$ is continuous and differentiable, and Results (12), (18), (19), (20). In, addition, systematic numerical simulations of Equation (23), using model (4), for all $-\infty < \sigma < 1$ and for various $\rho, \Delta y > 0$ have been employed to demonstrate Result (28). Result (29) follows from Definition (8), the fact that the function $\Pi(R)$ is continuous and differentiable, and Result (21).

A.3 Proof of Proposition 2

Explicating the general Definition of the ecosystem user's WTP (Equation 10) by the CARA-utility function (6) yields

$$\begin{aligned} & -(1-p(R))e^{-\rho y_H} - p(R)e^{-\rho y_L} && \text{(A.67)} \\ = & -\Big[p(R+\Delta R)e^{-\rho(y_L - WTP(\Delta R))} + (1-p(R+\Delta R))e^{-\rho(y_H - WTP(\Delta R))}\Big] && \text{(A.68)} \\ = & -e^{\rho WTP(\Delta R)}\left[p(R+\Delta R)e^{-\rho y_L} + (1-p(R+\Delta R))e^{-\rho y_H}\right] . && \text{(A.69)} \end{aligned}$$

Rearranging leads to

$$-e^{\rho WTP(\Delta R)} = \frac{-(1-p(R))e^{-\rho y_H} - p(R)e^{-\rho y_L}}{\left[p(R+\Delta R)e^{-\rho y_L} + (1-p(R+\Delta R))e^{-\rho y_H}\right]} . \qquad \text{(A.70)}$$

Solving for $WTP(\Delta R)$, using $\Delta y = y_H - y_L$ and $\lambda \equiv \rho \Delta y$, yields

$$WTP(\Delta R) = \frac{1}{\rho} \ln \frac{(1-p(R)) + p(R)e^{\lambda}}{(1-p(R+\Delta R)) + p(R+\Delta R)e^{\lambda}} . \qquad \text{(A.71)}$$

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[18] $I(1) > 0$ for $\sigma < 1$, and $I(1) \to 0$ as $\sigma \to 1$.

Using (A.71) in Definition 3 and applying l’Hôpital’s rule, one has

$$V(R) = \frac{1}{\rho}\lim_{\Delta R\to 0} \frac{\ln \frac{(1-p(R))+p(R)e^{\lambda}}{(1-p(R+\Delta R))+p(R+\Delta R)e^{\lambda}}}{\Delta R} \tag{A.72}$$

$$\begin{aligned} &= \frac{1}{\rho}\lim_{\Delta R\to 0} \frac{(1-p(R+\Delta R))+p(R+\Delta R)e^{\lambda}}{(1-p(R))+p(R)e^{\lambda}} \\ &\qquad \times \frac{d}{d\Delta R}\left[\frac{1-p(R)+p(R)e^{\rho\Delta y}}{1-p(R+\Delta R)+p(R+\Delta R)e^{\lambda}}\right] \end{aligned} \tag{A.73}$$

$$= \frac{1}{\rho}\lim_{\Delta R\to 0} \frac{d}{d\Delta R}\left[\frac{1-p(R)+p(R)e^{\lambda}}{1-p(R+\Delta R)+p(R+\Delta R)e^{\lambda}}\right] \tag{A.74}$$

$$= -\frac{1}{\rho}\lim_{\Delta R\to 0} \frac{\left[1-p(R)+p(R)e^{\lambda}\right]\left[-p'(R+\Delta R)+p'(R+\Delta R)e^{\lambda}\right]}{\left[1-p(R+\Delta R)+p(R+\Delta R)e^{\lambda}\right]^2} \tag{A.75}$$

$$= -\frac{p'(R)}{\rho}\frac{e^{\lambda}-1}{1+p(R)\left(e^{\lambda}-1\right)}\,. \tag{A.76}$$

ad (i). Rearranging Result (30), and using Result (22), immediately yields Result (31).

ad (ii). Expression (A.76) for V is non-negative for all R, since $-p'(R)$ is non-negative and the term $(e^{\lambda}-1)$ is strictly positive for all R. Hence, Result (32) holds.

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Chapter 4: Consumer preferences determine resilience of ecological-economic systems

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Abstract: We perform a model analysis to study the origins of limited resilience in coupled ecological-economic systems. We demonstrate that under open access to ecosystems for profit-maximizing harvesting forms, the resilience properties of the system are essentially determined by consumer preferences for ecosystem services. In particular, we show that complementarity and relative importance of ecosystem services in consumption may significantly decrease the resilience of (almost) any given state of the system. We conclude that the role of consumer preferences and management institutions is not just to facilitate adaptation to, or transformation of, some natural dynamics of ecosystems. Rather, consumer preferences and management institutions are themselves important determinants of the fundamental dynamic characteristics of coupled ecological-economic systems, such as limited resilience.

JEL-Classification: Q01, Q20, Q57

Keywords: consumption, ecological-economic systems, ecosystem services, natural resource management, preferences, resilience

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1 Introduction

Natural systems that are used and managed by humans for the ecosystem services they provide may exhibit non-trivial dynamics. This makes the long-term conservation and sustainable use of such systems a huge challenge.

In particular, a coupled ecological-economic system may be characterized by limited resilience (Holling 1973). That is, it exhibits multiple stability domains ("basins of attraction") that differ in fundamental system structure and controls as well as in the level and quality of ecosystem services provided to humans. These stability domains are separated by thresholds in the system's state variables. Theoretically, the resilience of the system in some state can be measured by the stability basin's width – also known as its "latitude" (Walker et al. 2004). As a result of exogenous natural disturbances or ill-adapted human interference with the system, the system may flip from one stability domain into another one with different basic functions and controls (Holling 1973, Levin et al. 1998, Carpenter et al. 2001, Scheffer et al. 2001). Examples encompass a diverse set of ecosystem types that are highly relevant for economic use, such as boreal forests, semi-arid rangelands, wetlands, shallow lakes, coral reefs, or high-seas fisheries (Gunderson and Pritchard 2002).

As the system undergoes a regime shift and flips from one basin of attraction with more desirable ecosystem service provision (from the anthropocentric point of view based on valuation of ecosystem services) to a basin of attraction with less desirable ecosystem service provision, humans will assess this change as a deterioration in ecosystem service provision, or even as a "catastrophic" shift (Scheffer et al. 2001). Such system flips may threaten the intertemporal efficiency of resource management and the intergenerational equity of ecosystem services use from this system, and may thus impair a sustainable development (Arrow et al. 1995, Perrings 2001, Perrings 2006, Mäler 2008, Derissen et al. 2011).

Many studies analyzing the role of resilience for the long-term development of coupled ecological-economic systems explain limits to resilience, i.e. the existence of multiple and limited basins of attraction in a dynamic system, by *natural* characteristics of the system which exist prior to any human interference with the system, such as e.g. ecological properties of shallow lakes or the interaction between grass and shrub species in semi-arid rangelands. Human management of the system then has to be adapted to this natural characteristic, or transform the dynamic characteristics of the natural system, so as to achieve sustainability (e.g. Berkes and Folke 1998, Gunderson et al. 2001, Berkes et al. 2002). How the stability landscape of a coupled ecological-economic system is determined by, and may be changed through, institutional arrangements has been analyzed by e.g. Horan et al. (2011).

In this paper, we point out that under open access to ecosystems for profit-maximizing harvesting firms – which describes many exploited ecosystems – consumer preferences may induce similar characteristics into a dynamic system. Here, the term "consumer preferences" denotes the preferences that consumers hold over the different commodities that are directly consumed, including ecosystem services, based on the individual utility conferred by such consumption – in contrast to preferences for particular ecosystem states or properties that may indirectly result from consumers' behaviour ("green consumerism").

A decrease in the resilience of some desired state in a coupled ecological-economic system, i.e. a decrease in the corresponding stability basin's width or an increase in the number of alternative basins of attraction, may arise due to particular consumer preferences for ecosystem services, even if the underlying ecological processes are rather simple and management institutions are stable. To demonstrate this, we present a model of a simple multi-species ecosystem that may be harvested for economic purposes by profit-maximizing resource-extracting firms. We model biological interactions as competition between the species. We show that multiple basins of attraction may be introduced into the system's dynamics, and, thus, the width of some desired state's basin of attraction may decrease, solely as a consequence of changes in consumer preferences. We also analyze how the resilience properties of the coupled ecological-economic system depend on the consumers' preferences for ecosystem services and on the degree of biological interaction between species. Thus, we clearly distinguish the effects of economic use and consumer preferences from the effect of ecological interactions on the system's resilience properties.

2 Model

Consider the following model, which gives a highly stylized description of dynamic ecological-economic systems. Society consists of *n* identical individuals whose well-being derives from the consumption of manufactured goods (*y*) and two different ecosystem services, say fish (*c*) and timber (*h*). Assume that all three goods are essential for individual well-being and that the two ecosystem services are complementary in human well-being. Then, a representative household's well-being can be described by the utility function

$$u(y,c,h) = y^{1-\alpha}\left[c^{\frac{\sigma-1}{\sigma}} + h^{\frac{\sigma-1}{\sigma}}\right]^{\alpha\frac{\sigma}{\sigma-1}} \quad (1)$$

.

Parameter α (with $0<\alpha<1$) expresses the representative household's dependence on ecosystem services, where a higher value of α describes a higher relative importance of ecosystem services for the household's utility. Parameter σ (with $\sigma>0$) represents the elasticity of substitution between the consumption of fish and timber: a smaller value of σ implies a higher degree of complementarity of fish and timber. In the limit $\sigma\to 0$, fish and timber would be perfect complements and utility would be determined by the relatively scarcer ecosystem service only. In the opposite limit $\sigma\to\infty$, fish and timber would be perfect substitutes and utility would be determined only by the sum of both ecosystem services.

The dynamics of the stocks of fish (*x*) and wood (*w*) is described by the following system of differential equations

$$\frac{dx}{dt} = f(x,w) - C \quad (2)$$

,

$$\frac{dw}{dt} = g(w,x) - H \quad (3)$$

,

where the functions $f(x,w)$ and $g(w,x)$ describe the intrinsic growth of the stocks of fish and wood, and C and H denote the aggregate amounts of fish and timber harvested. For expositional simplicity, we specify $f(x,w)$ and $g(w,x)$ in a standard manner as logistic growth functions with competitive interaction between species (e.g. Scheffer 2009: Appendix A4):

$$f(x,w) = \rho_x \left(1 - \frac{x + \gamma_x w}{\kappa_x}\right) x \quad , \tag{4}$$

$$g(w,x) = \rho_w \left(1 - \frac{w + \gamma_w x}{\kappa_w}\right) w \quad , \tag{5}$$

where ρ_i denotes the intrinsic growth rate and κ_i the carrying capacity of the stocks of fish ($i=x$) and wood ($i=w$), respectively, and γ_i denotes the impact of competition on species i ($i=x,w$) from the other species. The specification of logistic growth functions and this particular form of biological interaction is by no means essential for the results derived below. But using a well-known functional form of the biological growth functions $f(x,w)$ and $g(w,x)$ helps to clarify the argument and to highlight the role of consumer preferences for the dynamics of the ecological-economic system.

The consumption of ecosystem services relies on the harvest of fish and timber. There are m_x identical fish-harvesting firms and m_w identical timber-harvesting firms, where the exact numbers are endogenously determined according to market conditions in these two sectors. Let e_x and e_w denote the effort, measured in units of labor, spent by some representative fish-harvesting-firm and some representative timber-harvesting-firm. The maximum amounts of fish and timber that can be harvested from the respective stocks by individual firms are described by Gordon-Schaefer production functions

$$c^{\text{prod}} = \nu_x \, x \, e_x \quad , \tag{6}$$

$$h^{\text{prod}} = \nu_w \, w \, e_w \, , \tag{7}$$

where v_x and v_w denote the productivity of harvesting fish and timber, respectively. Then, the aggregate amounts of fish and timber harvested are simply

$$C = m_x \, c^{\text{prod}} \quad , \tag{8}$$

$$H = m_w \, h^{\text{prod}} \quad . \tag{9}$$

Assume that each household inelastically supplies one unit of labor, so that total labor supply of the economy is equal to human population size *n*. Households work either in one of the resource harvesting sectors or in the manufactured-goods sector. Assuming that labor is the only factor input for the production of manufactured goods, and that production is through a constant-returns-to-scale technology, i.e. each unit of labor produces $\omega > 0$ units of output, aggregate output of manufactured goods is

$$Y = \omega \, (n - m_x \, e_x - m_w \, e_w) \, . \tag{10}$$

3 Analysis

In order to show that under open access to ecosystems for profit-maximizing harvesting firms consumer preferences about ecosystem services essentially matter, we analyze the resilience properties of the coupled ecological-economic system for different scenarios in terms of resource-management and consumer preferences. To this end we employ local and global stability analysis based on graphical representation of the system's dynamics in state space. The analytics behind the graphical representation are derived in the Appendix.

3.1 Natural dynamics

In the absence of any resource harvesting by society, the system's dynamics is completely determined by the natural dynamics of the two resources stocks of fish and wood, described by Equations (2)–(5) with $C=H=0$. This scenario goes back to Lotka

(1932) and Volterra (1926) and sets the benchmark against which we then study the influence of harvesting and consumer preferences on resilience.

If the dynamics of the two resource stocks are independent of each other, i.e. if there is no inter-species competition ($\gamma_x=\gamma_w=0$), both stocks converge to their respective carrying capacities. The isoclines $dx/dt=0$ and $\dot{w} = 0$ thus are the straight lines with $w = \kappa_w$ and $x = \kappa_x$, respectively. This dynamics is represented by the upper phase diagram in Figure 1 for parameter values $\rho_x=\rho_w=0.5$ and $\kappa_x=\kappa_w=1$. The green line is the isocline for $dx/dt=0$, the red line is the isocline for $dw/dt=0$. Below (above) the $dx/dt= 0$-isocline the dynamics is characterized by $dx/dt>0$ (<0). Likewise, left (right) of the $dw/dt= 0$-isocline the dynamics is characterized by $dw/dt> 0$ (<0). In each segment of state space, the green and red arrows indicate this direction of dynamics. At the intersection of the isoclines (point D: $x=1$, $w=1$), one has $dx/dt=dw/dt=0$ and the arrows indicate that this is a stable equilibrium.

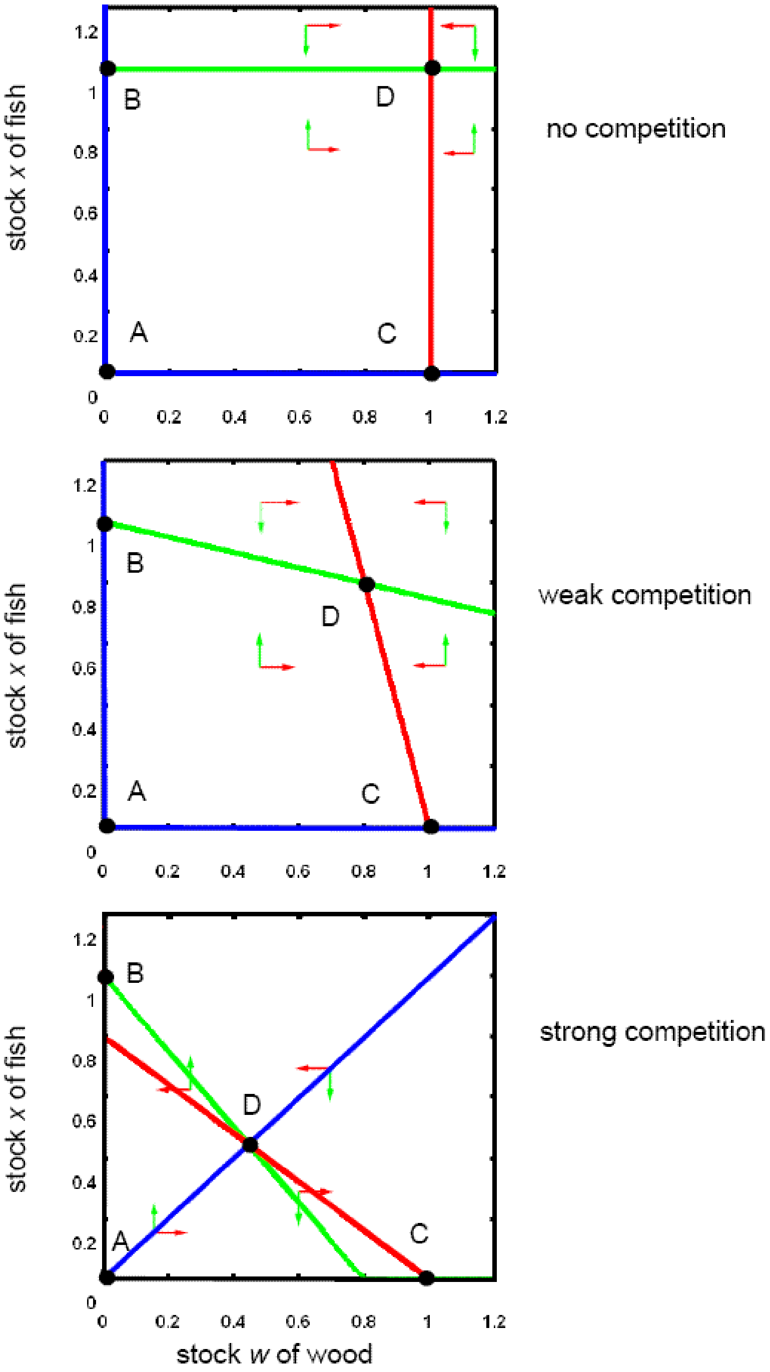

Figure 1: Phase diagrams in state space for the ecosystem's natural dynamics without any harvesting ($C=H=0$). Dynamics is characterized by $dx/dt>0$ (<0) below (above) the green line, and $dw/dt>0$ (<0) left (right) of the red line. Blue lines indicate saddlepaths. The upper diagram displays the case of independent species ($\gamma_x=\gamma_w=0$). In the middle diagram inter-species competition is weaker than intra-species competition ($\gamma_x=\gamma_w=0.25$), and in the lower diagram, inter-species competition is stronger than intra-species competition ($\gamma_x=\gamma_w=1.25$). Parameter values for all diagrams: $\rho_x=\rho_w=0.5$, $\kappa_x=\kappa_w=1$.

Other than D, the system has three more equilibria: A (x=w=0), B (x=1, w=0) and C (x=0, w=1). In the absence of inter-species competition (γ_x=γ_w=0), it is obvious from the state-space representation (Figure 1, upper diagram) that A is an unstable equilibrium, while B and C are locally saddlepoint-stable equilibria. The basin of attraction corresponding to the only stable equilibrium, D, comprises the entire state space with the exception of the axes (x=0, w≥0) and (x≥0, w=0). >From any system state in this domain will the system automatically converge towards equilibrium D. So, equilibrium D is (almost) globally stable – where the "almost" refers to the exception of the axes. In terms of resilience, (almost) every state of the natural system is therefore characterized by (almost) unlimited resilience.

If the system exhibits inter-species competition, neither stock reaches its full carrying capacity due to competition from the other species (Figure 1, middle and lower diagrams). As long as inter-species competition is weaker than intra-species competition (γ_i<1), however, the ecosystem still exhibits one almost globally stable equilibrium at point D (Figure 1, middle diagram). In terms of resilience, (almost) every state of the natural system with moderate ecological interaction (0≤γ_i<1) is therefore characterized by (almost) unlimited resilience.

If inter-species competition is stronger than intra-species competition (γ_i>1, Figure 1, lower diagram), this changes fundamentally as point D no longer represents an almost globally stable equilibrium. D is now only saddlepoint-stable, but B and C are locally stable. Hence, the system exhibits two corresponding basins of attraction: the area northwest of the saddlepath is the basin of attraction for equilibrium B, the area southwest of the saddlepath is the basin of attraction of equilibrium C. Due to an exogenous disturbance, the system may flip from one basin of attraction to another. This means, ecological interaction in the form of strong inter-species competition has a destabilizing effect on the ecosystem.

3.2 Profit-maximizing harvesting under open access to ecosystems significantly weakens resilience

We now include the impact of economic resource use. That is, we no longer study an isolated natural system (as in the last section), but a coupled ecological-economic system with profoundly different resilience properties. In this section, we study this impact for one given level of mild complementarity between ecosystem services in consumption, and without inter-species competition. In the next section, we then systematically study variations in these two parameters – complementarity and inter-species competition.

We suppose for the economic part that profit-maximizing firms can harvest the resource species from their natural stocks under open-access and competitively sell these ecosystem services as market products to consumers. This is the currently dominant economic institution for the use of ecosystem services. Compared to the scenario without resource harvesting and with not-too-strong inter-species competition (cf. Figure 1, upper and middle phase diagrams), the stability properties of the ecosystem are now fundamentally altered (for the mathematical derivation, see Appendix). This dynamics is represented by the state-space diagram shown in Figure 2 for parameter values $\rho_x=\rho_w=0.5$, $\kappa_x=\kappa_w=1$, $\gamma_x=\gamma_w=0$, $v_x= v_w=1$, $\alpha=0.6$, $\sigma=0.4$ and $n=1$.

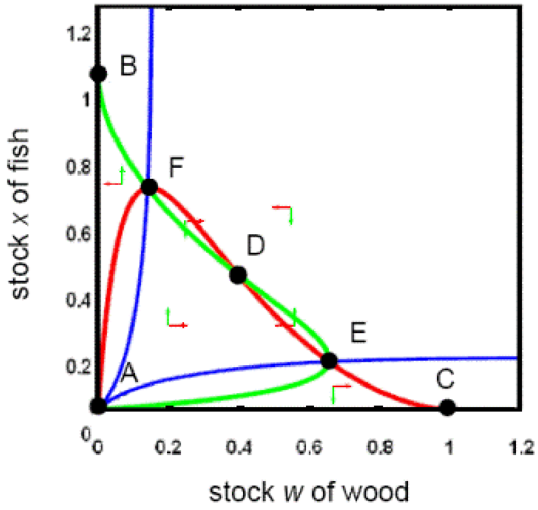

Figure 2: Phase diagram for the ecosystem's dynamics under open access and profit-maximizing harvesting. Dynamics is characterized by $dx/dt>0$ (<0) left (right) of the green line, and $dw/dt>0$ (<0) below (above) the red line. A is an unstable equilibrium; E and F are locally saddlepoint-stable equilibria; B, C and D are locally stable equilibria; the corresponding basins of attraction are the area northeast of the upper saddlepath (for B), the upper saddlepath (for F), the area in between the two saddlepaths (for D), the lower saddlepath (for E), and the area southwest of the lower saddlepath (for C). Parameter values: $\rho_x=\rho_w=0.5$, $\kappa_x=\kappa_w=1$, $\gamma_x=\gamma_w=0$, $v_x= v_w=1$, $\alpha=0.6$, $\sigma=0.4$, $n=1$.

Again, the green line is the isocline for $dx/dt=0$, the red line is the isocline for $dw/dt=0$. Left (right) of the $dx/dt=0$-isocline the dynamics is characterized by $dx/dt>0$ (<0). Likewise, below (above) the $dw/dt=0$-isocline the dynamics is characterized by

$dw/dt>0$ (<0). In each segment of state space, the green and red arrows indicate this direction of dynamics. While A ($x=w=0$) is still an unstable equilibrium, B ($x=1,\ w=0$) and C ($x=0,\ w=1$) are now locally stable equilibria. D is still a stable equilibrium, but it is now only locally stable. In addition, there are two new equilibria, E and F, which are locally saddlepoint-stable. The basins of attraction associated with the stable equilibria are as follows: the area northwest of the upper saddlepath (for B), the upper saddlepath (for F), the area in between the two saddlepaths (for D), the lower saddlepath (for E), and the area southeast of the lower saddlepath (for C).

It is obvious that the particular resource management institution considered here – open access to ecosystems of profit-maximizing harvesting firms – has fundamentally altered the resilience properties of the ecosystem. While in the absence of resource harvesting and not too-strong inter-species competition there exists only one (almost) globally stable equilibrium, so that (almost) every state of the system is characterized by (almost) unlimited resilience, under open access to ecosystems of profit-maximizing harvesting firms the system has three locally stable equilibria. Each of those has an associated basin of attraction which comprises only a limited part of the state space, so that the system may flip from one basin of attraction to another one as a result of exogenous disturbance. In particular, equilibrium D (with both resource species in existence) and any state in its basin of attraction have only limited resilience, and any of those states may be disturbed in a way that the system flips into another basin of attraction with another locally stable equilibrium characterized by extinction of one or the other species.

3.3 Complementarity and relative importance of ecosystem services in consumption decrease resilience

Consumer preferences about ecosystem services and manufactured goods are a significant determinant of an ecosystem's resilience properties. This is demonstrated here by illustrating for the institutional setting considered previously – open access to ecosystems of profit-maximizing harvesting firms – how a change in the elasticity of substitution σ between the consumption of fish and timber, and how a change in the relative importance of ecosystem services α, affect the resilience properties of the ecosystem.

In the previous section, the analysis of that setting was carried out for an elasticity of substitution between the consumption of fish and timber of σ=0.4, which reflects a mild complementarity (cf. Figure 2). Figure 3 illustrates the resilience properties of the ecosystem when – everything else being equal – the elasticity of substitution changes to σ=0.95 (low complementarity) and σ=0.05 (high complementarity).

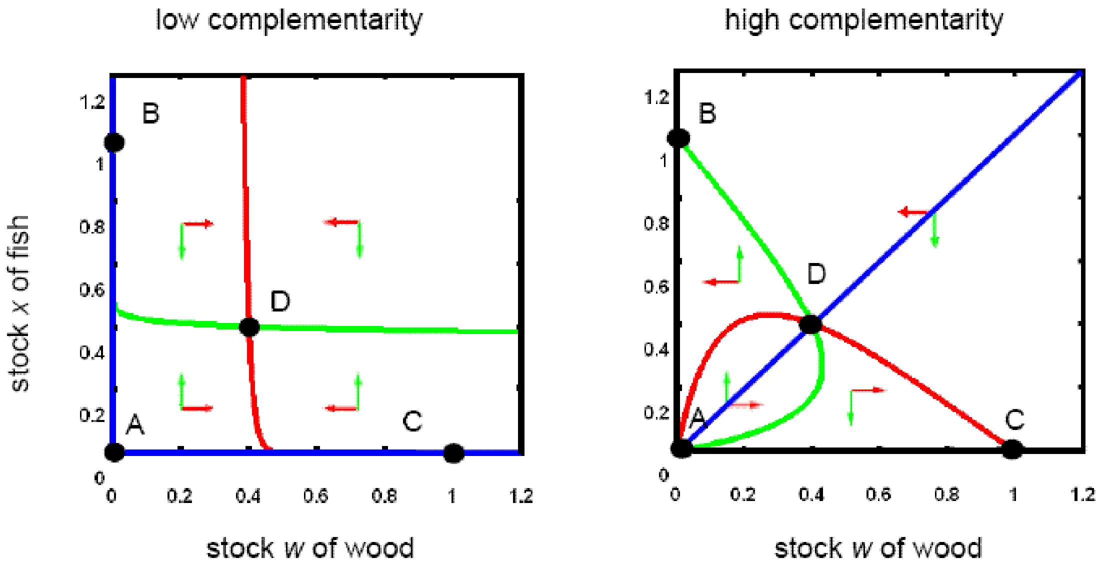

Figure 3: Phase diagrams for the ecosystem's dynamics under open access and profit-maximizing harvesting for low complementarity (σ=0.95, left diagram) and high complementarity (σ=0.05, right diagram) between ecosystem services in consumption. Dynamics is characterized by dx/dt>0 (<0) below (above) the green line, and dw/dt>0 (<0) left (right) of the red line. In the left phase diagram, A is an unstable equilibrium, B and C are locally saddlepoint-stable equilibria, D is the only and (almost) globally stable equilibrium; the corresponding basin of attraction comprises the entire state space with the exception of the axes (x=0, $w \geq 0$) and ($x \geq 0$, w=0). In the right phase diagram, A is an unstable equilibrium, B and C are locally stable equilibria; the corresponding basins of attraction consisting of the areas northeast (B) and southwest (C) of the saddlepath; D is a saddlepoint-stable equilibrium whose basin of attraction is just a one-dimensional line. Parameter values for both diagrams: $\rho_x=\rho_w=0.5$, $\kappa_x=\kappa_w=1$, $\gamma_x=\gamma_w=0$, $v_x=v_w=1$, $\alpha=0.6$, $n=1$.

From Figure 3 (left diagram) it is apparent that even for open access and profit-maximizing resource harvesting, with low complementarity between ecosystem services in consumption the resilience properties of the system are very similar as in the natural dynamics without human resource management and with moderate inter-species competition. That is, with low complementarity between ecosystem services in consumption, and a low relative importance of ecosystem services, resource harvesting only lowers the species' abundances at the stable equilibrium D (cf. Figure 1), but this equilibrium and every state of the system in its basin of attraction are characterized by (almost) unlimited resilience.

With increasing complementarity between the two ecosystem services in consumption, i.e. a decreasing value of σ, the resilience of this equilibrium reduces. The reason for this decrease in resilience is a vicious circle brought about by the complementarity between ecosystem services. Since the benefits from ecosystem services use are limited by the scarcer service, more effort is spent on harvesting this resource. The increased harvesting effort, in turn, reduces the abundance of that resource even further, thus leading to self-re-enforcing dynamics. At a certain threshold value of σ ($\sigma = 1/3$ for the parameter values used to compute the figures) the locally stable equilibrium D in Figure 3 (left diagram) loses its stability and turns into an only saddlepoint-stable equilibrium (Figure 3, right diagram). The basin of attraction for this equilibrium is just a one-dimensional line. This means, its resilience is extremely reduced and the state of the system is very brittle and sensitive to exogenous disturbance.

Consumer preferences influence the ecological-economic system's resilience properties also via the relative importance of ecosystem services in the consumer's utility function, α. If ecosystem services are relatively unimportant in the utility function, as compared to the manufactured good, the system shows almost unlimited resilience. In contrast, increasing the relative importance of ecosystem services destabilizes the system. If the relative importance of ecosystem services is very large, the ecosystem's resilience sharply declines and small exogenous perturbations may lead to extinction of one of the species.

Figure 4 illustrates this result. Taking Figure 2 again as a reference point, the phase diagrams of Figure 4 show how changes in the relative importance of ecosystem services in the consumer's utility-function alter the resilience properties of the system. Everything else being equal, decreasing the value of α from 0.4 to 0.25 stabilizes the system in that interior equilibrium D is now almost globally stable (Figure 4, left diagram). Conversely, increasing the relative importance of ecosystem services in the consumer's utility function by raising α from 0.4 to 0.75 entails destabilization of the system: the interior equilibrium's basin of attraction now consists only of the saddlepath, so its resilience is sharply reduced and the system is very sensitive to exogenous disturbance (Figure 4, right diagram).

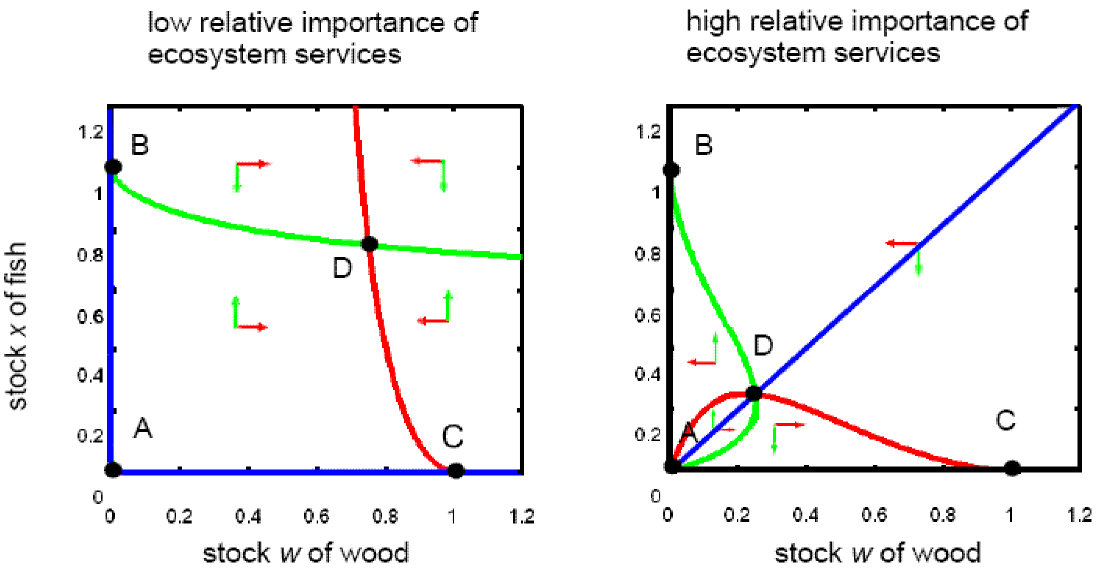

Figure 4: Phase diagrams for the ecosystem's dynamics under open access and profit-maximizing harvesting for different levels of relative importance of ecosystem services, α. Dynamics is characterized by $dx/dt>0$ (<0) left (right) of the green line, and $dw/dt>0$ (<0) below (above) the red line. Blue lines indicate saddlepaths. In both diagrams, A is an unstable equilibrium. In the left diagram, relative importance of ecosystem services is low ($\alpha=0.25$) and D is an (almost) globally stable equilibrium, while B and C are only saddlepoint-stable. In the right diagram, relative importance of ecosystem services is high ($\alpha=0.75$) and D is only saddlepoint-stable while B and C are locally stable, the corresponding basins of attraction consisting of the areas northeast (B) and southwest (C) of the saddlepath. Parameter values for both diagrams: $\rho_x=\rho_w=0.5$, $\kappa_x=\kappa_w=1$, $\gamma_x=\gamma_w=0$, $v_x= v_w=1$, $\sigma=0.4$, $n=1$.

In passing we note that increasing the productivity of the harvest technology, v_x and v_w, has qualitatively exactly the same effect as increasing the relative importance of ecosystem services in the consumer’s utility function, α: in a market economy and under open access to ecosystems, both changes lead to an increase in harvesting pressure, which reduces the potential for sustainable resource use. Similarly, decreasing the resources’ intrinsic growth rates, ρ_x and ρ_w, lowers their ability to recover from harvesting and destabilizes the system in qualitatively the same way.

The general insight from the analysis so far is that resilience of the interior equilibrium with both resource species in existence (point D) tends to decrease (i) with increasing complementarity, i.e. decreasing elasticity of substitution, between the two ecosystem services in consumption and (ii) with increasing relative importance of ecosystem services for the consumer's well-being. In other words, while complementarity and relative importance of ecosystem services in consumption reduce the resilience of the interior equilibrium with both resource species in existence, substitutability and relative unimportance of ecosystem services in consumption tend to make this equilibrium and all system states in its basin of attraction more resilient. This general insight continues to hold with inter-species competition. This is shown in the remainder of the section.

Whereas in Figures 2 to 4 there was no inter-species competition, in the analogously constructed phase diagrams of Figure 5 there is weak inter-species competition (γ_i=0.25). Figure 5 shows that the destabilizing effect of complementarity in consumption also occurs under inter-species competition. The same holds for the destabilizing effect of relative importance of ecosystem services (not shown).

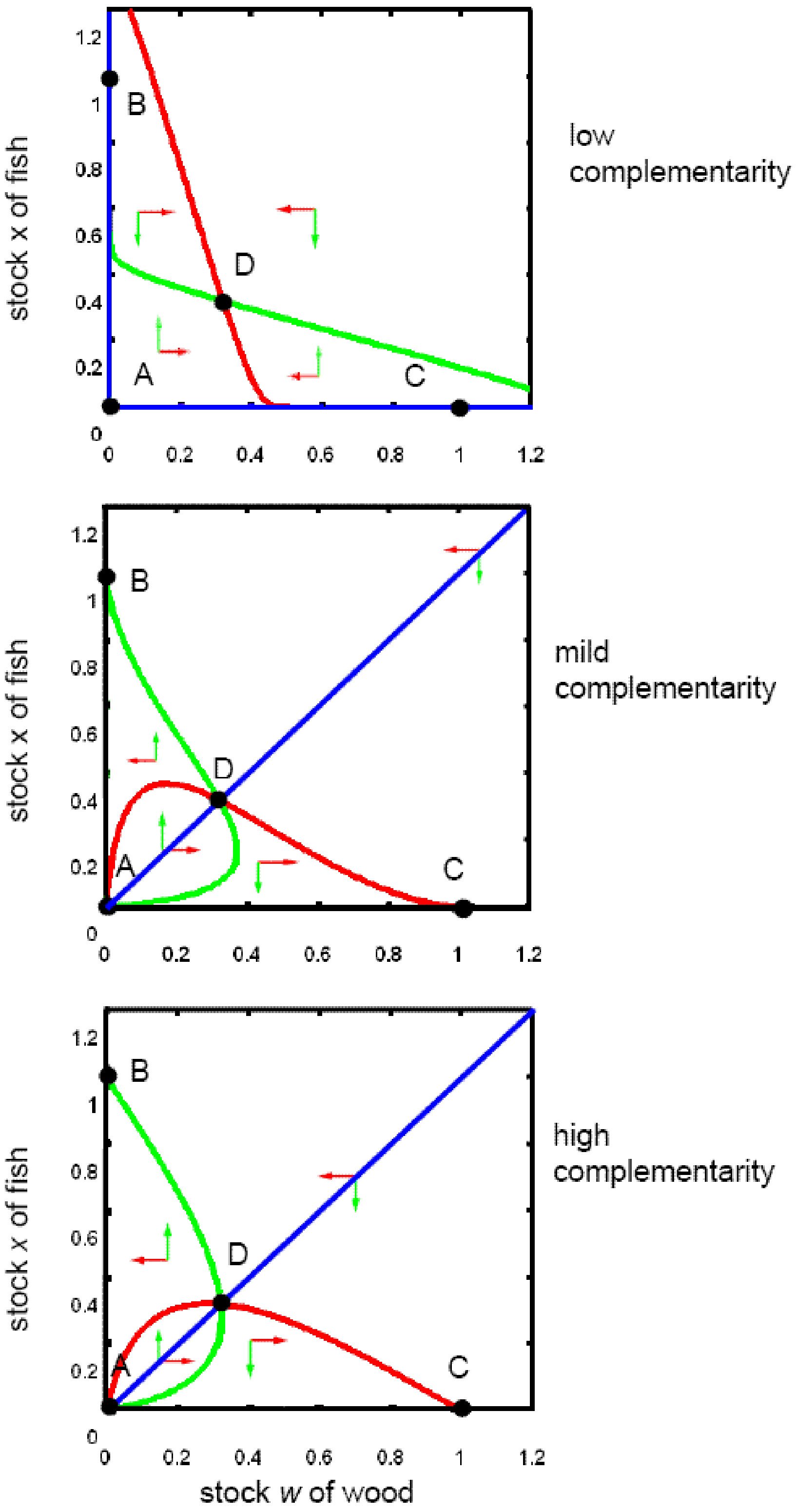

Figure 5: Phase diagrams for the ecosystem's dynamics with inter-species competition for different levels of complementarity between ecosystem services in consumption, σ. Dynamics in each diagram is characterized by $dx/dt>0$ (<0) left (right) of the green line, and $dw/dt>0$ (<0) below (above) the red line. Blue lines indicate saddlepaths. The upper diagram shows the case of low complementarity ($\sigma=0.95$), the middle diagram displays mild complementarity ($\sigma=0.4$) and the lower diagram high complementarity ($\sigma=0.05$).

Parameter values for all diagrams: $\rho_x=\rho_w=0.5$, $\kappa_x=\kappa_w=1$, $\gamma_x=\gamma_w=0.25$, $v_x= v_w=1$, $\alpha=0.6$, $n=1$.

In all three phase diagrams of Figure 5, equilibrium A, where both species are extinct, is unstable. In the case of low complementarity ($\sigma=0.95$, upper diagram, Figure 5), D is an almost globally stable equilibrium, whereas B and C are only saddle-point stable. Thus, there is only one basin of attraction and co-existence of both species is likely. At a certain threshold value of σ (about $\sigma=0.62$ for the parameter values used to compute the figures) the locally stable equilibrium D loses its stability and turns into a saddlepoint-stable equilibrium: D lies on a saddle-path and B and C are locally stable equilibria. In other words, if complementarity is high enough, there are two basins of attraction and the interior equilibrium D exhibits very limited resilience ($\sigma=0.4$, middle and $\sigma=0.05$, lower diagram, Figure 5). Note that compared to Figures 2–4, the threshold value of σ in Figure 5 is higher (i.e. threshold-complementarity is lower) due to the additional destabilizing effect of species competition.

The destabilizing effect of increasing inter-species competition also occurs under resource harvesting. This is shown in Figure 6 for a given level of resource complementarity. Without inter-species competition ($\gamma_x=\gamma_w=0$, upper diagram, Figure 6), the interior equilibrium D with both resource species in existence is locally stable, but exhibits limited resilience due to open-access resource harvesting. The resilience of this interior equilibrium sharply decreases with the introduction of species competition ($\gamma_x=\gamma_w=0.25$, middle diagram, Figure 6): equilibrium D's basin of attraction shrinks to a one-dimensional-line. Thus the system is very brittle and sensitive to exogenous disturbances. Once dislodged from point D, the system will converge to either point B or C, where only one of the species exists. Both B and C remain locally stable equilibria. Further increasing the strength of inter-species competition ($\gamma_x=\gamma_w=1.25$, lower diagram, Figure 6) entails lower abundances of both species at the saddlepoint-equilibrium D.

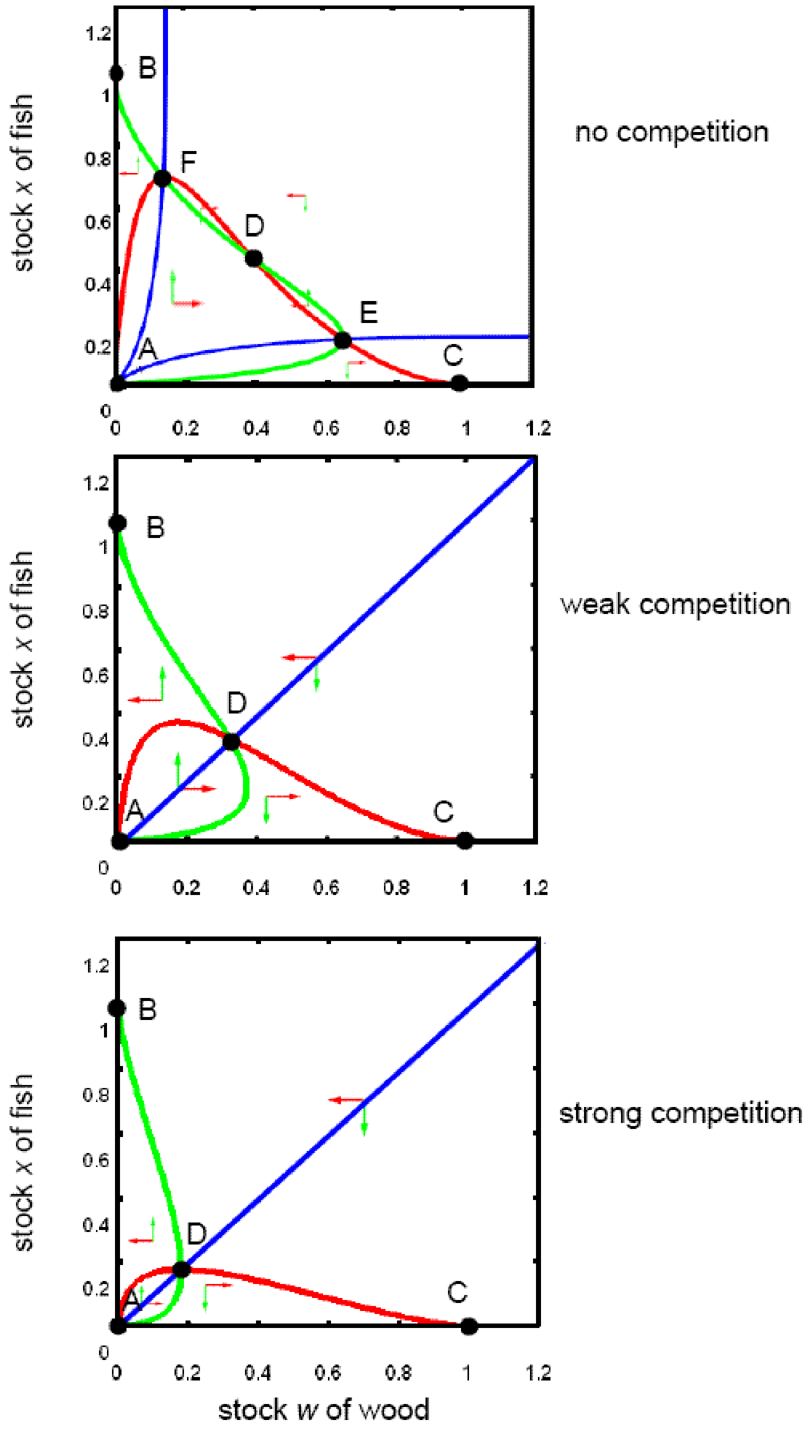

Figure 6: Phase diagrams for the ecosystem's dynamics at a given level of resource complementarity and increasing inter-species competition, γ_i. Dynamics in each diagram is characterized by $dx/dt>0$ (<0) left (right) of the green line, and $dw/dt>0$ (<0) below (above) the red line. Blue lines indicate saddlepaths. The upper diagram displays the case of independent species ($\gamma_x=\gamma_w=0$). Competition occurs in the middle ($\gamma_x=\gamma_w=0.25$) and increases in the lower ($\gamma_x=\gamma_w=1.25$) diagram. Parameter values for all diagrams: $\rho_x=\rho_w=0.5$, $\kappa_x=\kappa_w=1$, $\nu_x=\nu_w=1$, $\alpha=0.6$, $\sigma=0.4$, $n=1$.

Comparing Figure 6 to Figure 1 shows that the effects on resilience of increasing inter-species competition are also present under economic resource use. In Figure 6 however, as equilibrium D's resilience is already decreased by resource harvesting and consumer preferences, low levels of species competition are sufficient to significantly further decrease the resilience of state of the system. Put another way, open-access economic resource use, relative importance of ecosystem services and complementarity in consumption entail a decrease of resilience which may be even larger with stronger species competition.

4 Discussion and conclusion

Our analysis has demonstrated that consumer preferences are an important determinant of the dynamic characteristics of coupled ecological-economic systems, such as limited resilience. In particular, we have clearly distinguished the effects of economic use and consumer preferences from the effect of ecological interactions on the system's resilience properties.

We have identified three destabilizing effects that genuinely stem from consumer preferences in an ecological system used for economic purposes: First, we have shown that profit-maximizing harvesting by competitive firms under open access to the ecosystem considerably weakens the resilience of the interior equilibrium of the coupled ecological-economic system as compared to the natural dynamics. Second, we have shown that complementarity of ecosystem services in consumption significantly reduces the resilience of the system's interior equilibrium where both species are in existence. The economic logic behind this result is the following: out of two complementary ecosystem services, the scarcer one is limiting the benefits from ecosystem service use. Hence, under an institutional setting of open access, this ecosystem service is the one to which harvesting is directed primarily. The increased harvesting effort, in turn, reduces the abundance of that resource even further, thus leading to self-re-enforcing dynamics. Third, we have shown that an increased relative importance of ecosystem services for the consumer's well-being destabilizes the system. The economic logic behind this result is the following: if consumers' well-being derives to a larger degree from ecosystem services, the share of their budget spent on ecosystem services increases. In a market economy and under open access to resource, this leads to an increase in harvesting pressure, which reduces the potential for sustainable resource use. Conversely, if the consumer's well-being does not, or only to a small degree, derive from consuming ecosystem services, harvesting pressure on the ecosystem is very low and it displays an almost globally resilient interior equilibrium. These three preference-effects act in addition to the ecological mechanisms that are well-known to destabilize an ecological-economic system and to give rise to multiple basins of attraction and limited resilience: increased competition between species and low intrinsic growth rates (e.g. Scheffer 2009).

While our model analysis was based on specific functional forms and certain properties of the particular functions used, of course, determine the results obtained, our results would qualitatively survive a fair amount of generalization. As for the utility function (1), the crucial property, upon which our results critically depend, is the complementarity between the two ecosystem services and the substitutability of aggregate ecosystem services by manufactured goods. As for the logistic growth functions (4) and (5) for both biological resources, the crucial property, upon which our results critically depend, is that the intrinsic growth rate is bounded as the stock declines to zero. Other models with this property, such as e.g. the Beverton-Holt (1957) or the Ricker (1954) models used to describe the dynamics of fish stocks, would yield qualitatively the same results. In contrast, if the intrinsic growth rate increased to infinity as the stock level declines to zero one would obtain qualitatively very different results. Assuming the existence of a minimum viable population level for one or both biological resources would make the whole system even more instable, as we have demonstrated elsewhere (Derissen et al. 2011), and would therefore reinforce our results. As for the Gordon-Schaefer-harvest functions (6) and (7), the crucial property, upon which our results critically depend, is that harvest positively depends on the stock level. Any other harvest function with this property would yield qualitatively the same results. As for the institutional setting, strong complementarity between ecosystem services reduces the resilience of the ecological-economic system also when resources are optimally managed, provided the discount rate applied is relatively large (Quaas et al. 2011).

In the joint endeavor of natural and social scientists as well as practitioners of resource management to understand and manage coupled ecological-economic systems for sustainability, our results call for truly interdisciplinary and integrated analysis of such systems and their management.

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Appendix

Taking manufactured goods as the numeraire, the representative household's utility maximization problem is

$$\max_{y,c,h} u(y,c,h) \quad \text{subject to} \quad \omega = y + p_x c + p_w h \ , \tag{A.1}$$

where p_x and p_w are the market prices of fish and timber, respectively. With utility function (1), this leads to Marshallian demand functions for fish and timber:

$$c(p_x, p_w, \omega) = \alpha\, \omega \frac{p_x^{-\sigma}}{p_x^{1-\sigma} + p_w^{1-\sigma}} \quad \text{and} \tag{A.2}$$

$$h(p_x, p_w, \omega) = \alpha\, \omega \frac{p_w^{-\sigma}}{p_x^{1-\sigma} + p_w^{1-\sigma}} \ . \tag{A.3}$$

Profits of representative firms harvesting fish and timber are given by

$$\pi_x = p_x c^{\text{prod}} - \omega\, e_x = (p_x \nu_x x - \omega)\, e_x \qquad \text{and} \tag{A.4}$$

$$\pi_w = p_w h^{\text{prod}} - \omega\, e_w = (p_w \nu_w w - \omega)\, e_w \ , \tag{A.5}$$

where production functions (6) and (7) have been employed in the second equality. In open-access equilibrium, which is characterized by zero profits, i.e. $\pi_x = 0$ and $\pi_w = 0$ for all firms, we thus have the following relationships between equilibrium market prices and resource stocks of fish and wood:

$$p_x = \frac{\omega}{\nu_x} x^{-1} \quad \text{and} \tag{A.6}$$

$$p_w = \frac{\omega}{\nu_w} w^{-1} \ . \tag{A.7}$$

Inserting these expressions into demand functions (A.2) and (A.3), we obtain open-access per-capita resource demands of fish and timber as functions of the respective resource stocks:

$$c(x,w) = \alpha \frac{(\nu_x x)^{\sigma}}{(\nu_x x)^{\sigma-1} + (\nu_w w)^{\sigma-1}} \quad \text{and} \tag{A.8}$$

$$h(x,w) = \alpha \frac{(\nu_w w)^{\sigma}}{(\nu_x x)^{\sigma-1} + (\nu_w w)^{\sigma-1}} \ . \tag{A.9}$$

General market equilibrium, when aggregate supply equals aggregate demand on the markets for both ecosystem services, is characterized by the conditions

$$C = m_x c^{\text{prod}} = nc(x,w) \;\; \text{and} \tag{A.10}$$

$$H = m_w h^{\text{prod}} = nh(x,w) \; . \tag{A.11}$$

Inserting these market-clearing-conditions into equations (2) and (3) yields the following system of coupled differential equations that characterize the dynamics of the ecological-economic system in the general market equilibrium:

$$\frac{dx}{dt} = f(x,w) - nc(x,w) \;\; \text{and} \tag{A.12}$$

$$\frac{dw}{dt} = g(w,x) - nh(x,w) \; , \tag{A.13}$$

where $f(x,w)$ and $g(w,x)$ are given by Equations (4) and (5), and $c(x,w)$ and $h(x,w)$ are given by Equations (A.8) and (A.9). The phase diagrams in the main text graphically display the dynamics in state space determined by the system of Equations (A.12) and (A.13).

Chapter 5: How real options and ecological resilience thinking can assist in environmental risk management

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Abstract: In this paper, we describe how real option techniques and resilience thinking can be integrated to better understand and inform decision making around environmental risks within complex systems. Resilience thinking offers a promising framework for framing environmental risks posed through the non-linear responses of complex systems to natural and human-induced disturbance pressures. Real options techniques offer the potential to directly model such systems including consideration of the prospect that the passage of time opens new options while closing others. The implications (cost) of risk can be described by option prices that describe the net present values generated by alternative regimes in the resilience construct, and the shadow prices of particular attributes of resilience such as the speed of return from a shock and the distance or time to transition. Examples are provided which illustrate the potential for integrated resilience and real options approaches to contribute to understanding and managing environmental risk.

Keywords: Resilience thinking, real options, risk, uncertainty, thresholds, transitions

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1 Introduction

Environmental risks are no less a feature of modern society than of times past, and the exposure of society is growing due to population growth and climate change in particular. The pertinence of questions about risk is illustrated by the debate on climate change action: what are the risks? And, what are the consequences of these risks? Alternatively, how much and when should we invest in avoiding or abating the consequences? Our focus in this paper is to describe the potential to integrate resilience theory and real options approaches to inform the cost and management options of complex environmental risks in ecological systems (such as via pre-emptive and responsive investments in protection, restoration, or adaptation).

Resilience thinking offers a way of framing the responses of complex social and ecological systems to human and other interventions (Walker and Salt 2006). The concept of resilience as set out by Holling (1973) comprises two key elements for the purposes of risk research. First, resilience relates to the capacity of the system to absorb shocks or continuous disturbances while maintaining stability (remaining within a single basin of attraction) – generally represented as the reliable delivery of a set of ecosystem or other services. The second element relates to the consequences of disturbance which results in transition of the system to a different state (or basin of attraction). These transitions may be irreversible and non-desirable in the sense that they may lead to a less preferred state (a state which delivers a less valued mix of services). Resilience is directly linked to the concept of risk via an interpretation of transition potential as a probability; albeit often non-measurable (uncertain).

Real options are the application of the methods of finance to a wider range of real world problems to understand the implications of decisions (i.e., to make, abandon, or adjust investments, policies or other interventions) and the passage of time in creating new options and foreclosing others. These features of real options approaches can accommodate resilience thinking by considering the uncertainty of transition, time, and the concepts of irreversibility and path dependent transitions between states. Real option approaches offer a tool for ‘valuing’ the consequences of transitions from one state to another as an option price relating to the difference in net present values between two different states of a system. Real options approaches also estimate shadow prices of particular attributes of resilience that can be characterised as environmental risks including the speed of return following disturbance, the distance to a threshold, and the expected time to system transition.

For policy purposes there are three useful interpretations of the real options approach to understanding and dealing with risk and resilience. First, the approach can inform questions about whether and when investment in avoiding or mitigating risk is worthwhile by reference to the option price. Second, real options shadow prices can help inform what types of risk reducing investment are most likely to be useful. Third, the approach can be used to inform how we respond to system resilience and the consequent risk to ecosystem service provision in terms of switching decisions about management or investment. A simple ecological example relating to system transition caused by eutrophication of a freshwater lake illustrates these three interpretations. First, option prices can help inform investments in avoiding the risk of eutrophication, such as whether it is worthwhile investing and when to invest. Second, shadow prices can help identify the marginal value of investment in protecting or enhancing particular aspects of resilience and the consequent risk. Finally, the difference in values derived from each system and shadow prices can help inform adaptation decisions to eutrophication where it is not worthwhile or possible to manage environmental risk.

The paper is set out as follows. In the next section we use the concept of resilience thinking to frame and conceptualise how systems respond to disturbances and how to operationalise the concept to aid in evaluating risk. In section three we focus on the information for managing complex systems using a real options approach and we provide a simplified illustration of the approach and the outputs that would result. In section four we use examples of real options applications to describe how these approaches can be used to inform resilience thinking. We conclude with a brief summary of the potential for integrated resilience thinking and real options models to inform environmental risk management, noting the difficulties in practical applications.

2 Resilience as a construct for evaluating risk

2.1 The concept of resilience in social and ecological systems

The “Resilience Alliance” defines resilience as “the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks” (Walker et al. 2004: 2). It is an ecological construct originally used to frame non-linear ecological responses to disturbance. This concept of resilience is rooted in Holling’s (1973) seminal article on stability and non-linear changes in ecosystems. Resilience is measured by the duration and magnitude of disturbance a system can absorb before it switches into another, qualitatively different stable state with a different functional structure and which provides a different, potentially less valued, set of goods and services. A resilient system can absorb exogenous shocks without changing its basic processes. However, a loss of resilience makes the system prone to disturbances and small changes in exogenous conditions may trigger a fundamental change in the system’s functional structure (the notion of a non-linear response to disturbance).

The best-known example of alternating stable states in ecosystems is probably found in eutrophication of shallow lakes. Initially, a shallow lake’s pristine stable state is characterized by clear water and rich submerged vegetation. Human farming activities often increase the nutrient concentration in shallow lakes. This nutrient loading has no perceivable impact on the water clarity until a critical threshold is reached and the lake undergoes an abrupt transition to the turbid water stable state. In this system configuration, submerged vegetation is almost completely absent and different feedback cycles keep the lake in the new stable state (see for example Carpenter et al. 1999). Other examples include switches between a coral-dominated and an algae-dominated stable state in coral reefs, and switches between a grassy stable state and one dominated by shrubs in semi-arid savannahs (see also Scheffer et al. 2001 for an overview).[1]

2.2 Implications of resilience thinking for system analysis

“Resilience thinking” provides a framework for understanding and evaluating the risk of a system change, and in particular the potential for a non-linear response to disturbances and transitions between potential system states. The transitions between stable states may be evaluated along the two dimensions of desirability and reversibility. First, stable states may be favourable or unfavourable. Hence, transitions are either beneficial or detrimental and system management will either aim at inducing or preventing transitions. An example for a stable state that is highly resilient yet not beneficial from a human point of view is the Sahara desert. Until around 6000 years ago, the North African climate was much wetter than today and large areas were covered with vegetation including wetlands and lakes. Since the abrupt transition to the desert state (a “catastrophic shift” in the terminology of Scheffer et al. 2001), a strong albedo-related vegetation feedback keeps the system in this stable state (see for example Knorr and Schnitzler 2006).

Second, not all transitions are reversible in any practical sense. The forward and backward transitions may occur at different values of the system variables; termed “hysteresis” (Dixit

1989, 1992 albeit an equivalent economic interpretation). Whereas the forward transition might have been triggered by an incremental variable change, the backward transition will *not* be induced by an equivalent incremental change and indeed may require a much larger variable change. Thus, the system exhibits path dependence. An irreversible transition implies a system so hysteretic that a backward shift cannot be effectuated. Clearly, the costs of reversing a transition increase with the system's hysteresis. That is, although a backward shift might be theoretically possible, it could be too costly to achieve.

Although common in a variety of ecosystems, non-linear transitions between multiple stable states may also arise from human management of the ecosystem (see Quaas et al. 2008 for example). In a simple system without complex ecological interactions, limited resilience may be induced into a dynamic state by particular human preferences and resource management institutions. Thus, resilience thinking is ideal to frame the dynamics of coupled social-ecological systems – and these dynamics do not only concern the interactions *within* a single system but also *across* different systems. Following Gunderson and Holling (2002), human and natural systems form clumped, interdependent structures on different scales in time and space. This in turn suggests that the concept of resilience is also relevant for purely man-made systems. Understood as a general concept indicating the risk of a transition occurring, the "resilience perspective" (Walker and Salt 2006) might be applied to any economic or social system that exhibits different stable states. Evidence for non-linear transitions in societies exists throughout human history (see for example Tainter 1988; Diamond 2005; Scheffer 2010) and in economic systems (Dixit 1989, 1992).

2.3 Can resilience be considered as risk?

At this point it is worth defining how we term risk and related terms in this paper. Common parlance tends to refer to risk as the likelihood (not specified as a probability) of an event with adverse consequences and for which there are opportunities to manage the risk in some way. Economists typically apply a more formal definition dividing risk and uncertainty along the lines proposed by Knight (1921) whereby risk is described as having known outcomes with known probabilities and uncertainty implies unknown probabilities and also unknown outcomes. However, Knight's definition is difficult to apply. If there is true uncertainty, decisions are impossible. Instead, people tend to think of systems in transition as uncertain and systems near equilibrium as risky. Kolmogorov (1931) showed how to derive probabilities for such stochastic dynamic systems. Systems in transition have transition probabilities and systems near equilibrium have the more familiar probabilities of Knight's definition. In this paper we regard risk as also incorporating uncertainty for systems in transition as well as near an equilibrium. Where uncertainty is mentioned we are specifically precluding the possibility that either all outcomes or their probabilities are knowable.[2]

Risk can also be scale related in which case systemic risk relates to an entire system rather than a component of that system (and similarly must be managed at the whole of system scale). The preceding discussion implies that the concept of resilience relates to systemic risk explicitly relating to a switch of the system from one state to another (Scheffer et al. 2002). If a system is currently located in a favourable stable state, the risk of a non-linear transition to a less favourable stable state decreases with its resilience. Accordingly, resilience is inversely related to the degree of threat a system is prone to (Brand 2009). That is, resilience may be interpreted as an indicator of the degree of systemic risk: the higher the resilience of a given system configuration, the lower the risk of system transition.

Resilience thinking can be applied to systemic risk either via the probability of a transition from one state to another or to the time that elapses until the system switches to another stable state. First, consider the probability interpretation. Perrings (1998) defines transition probabilities between different states and relates this to the system's resilience. The transition probabilities are conceptualized as a direct measure of resilience: "By this interpretation, the greater the probability that the system in one state will change to some other state, the less resilient is the system in the first state" (Perrings 1998: 8). Hence, resilience is defined as the dependent variable, relying on information about transition probabilities. Baumgärtner and Strunz (2009) and Walker et al. (2010) take another approach and conceptualize resilience as a measurable state variable which determines the probability of a system transition.[3] In this view, resilience is the independent variable and the transition probability results as a function of the current level of resilience. This rests on the assumption that resilience, albeit not a directly observable system property, can be measured by means of surrogates (Bennett et al. 2005).

Second, consider the time interpretation. Pimm (1991) defined resilience as the time the system needs to reach its equilibrium after a disturbance. Since this concept of resilience concentrates on predictability and stability, it has been termed "engineering resilience" (Holling 1996). By focussing on system dynamics close to a single equilibrium steady state, this approach is not adequate to analyse transitions between multiple stable states. Hertzler and Harris (2010) connect resilience to the expected time that elapses until a system subject to disturbance undergoes a transition to another state. They use a real options approach in which probabilities result from stochastic dynamic systems. Unlike the Knightian distinction between measurable risk and uncertainty, time separates risk in the near term and uncertainty in the distant future. As time passes and information is collected uncertainty can usually be resolved. However, many real options studies do not even mention probabilities for three reasons. First, they may not exist. Second, even if they exist, transition probabilities have to be solved for numerically. And third, instead of using probabilities, stochastic dynamic systems are usually modelled directly based on the underlying processes that drive variability (see McDonald and Siegel 1985; Dixit and Pindyck 1994 as examples).

3 Real Options techniques for evaluating the benefits from resilience

3.1 Resilience and the real options approach

Since the social and economic systems to which resilience thinking is applied often provide valued services, the question arises as to the value of resilience. In particular, there may be alternative investment options that would enhance (or reduce) resilience, or in managing the consequences of system transition for the services generated. That is, from the perspective of an environmental manager the usefulness of resilience thinking lies in informing investment decisions about avoiding or preparing for (or promoting) environmental risks posed by system thresholds. It is in thinking about these investment choices, or options, that the real options approach is useful.

Real options are often defined as the application of techniques developed in finance to non financial problems. In the real world, as in finance, every decision (i.e., to make, abandon, or adjust investments, policies or other interventions) and the passage of time creates new options and forecloses others. Real options techniques can be used to model the time dimension of resilience as well as risk in the absence of directly measurable probabilities in a tractable form to inform policy and investment decisions. The ‘option’ which is the focus of the technique is the value of an abstract concept: the flexibility to keep options open while uncertainty is resolved (Dixit 1989). This reveals the notion that options can be sequential and can involve switches between different forms of intervention such as investment, policy, or management. An option represents the opportunity to undertake a specific action but it is not an obligation.

The link to resilience is the value of retaining flexibility by avoiding or reducing the risk of undesirable system transitions. Nevertheless the application of resilience thinking within real options approaches is not necessarily straightforward. Resilience concepts usually refer to systems that remain in a particular state (basin of attraction) in the absence of further disturbances. In a stochastic world, this is called stationarity. Real options approaches do not require stationarity. In fact most real options models assume geometric Brownian motion which is non-stationary. The famous Black-Scholes formula (Black and Scholes 1973) and the investment analysis by Dixit and Pindyck (1994) are two examples. Nor do stochastic systems need to change continuously. Real options can also be analysed in discrete time using discrete probability distributions (see Copeland and Tufano 2004; Luehrman 1998; and Trigeorgis 1996 as examples).

Careful consideration also needs to be given to how risk concepts relating to resilience are best quantified within a real options approach. Resilience is an abstract concept, but could it be valued in the same way that options are valued within the real options approach? The option price describes the net difference in values with and without the management intervention, and can be interpreted as the benefit (cost) from reducing the adverse consequence of risk. Similarly, the resilience related risk constructs (speed of return to equilibrium, distance from a threshold, probability of crossing a threshold, and expected time to cross a threshold) can be described by the relevant shadow price within an appropriately constructed stochastic real option model (though each shadow price is likely to require a different model formulation). The relevant shadow price represents the benefit (or cost) of an additional unit of the particular attribute which can be compared against the cost (or benefit) of changing management to deliver the desired outcome. For example, if we are interested in the risk of a continuous disturbance (such as represented by Brownian motion) causing system transition, we might be particularly interested in whether the speed of return is exceeded by the degree and frequency of disturbance, and if so on the expected time until a threshold is crossed. Alternatively, we may be interested in the price of an option that provides for enhanced flexibility in transitioning a threshold in the face of discrete events (such as represented by a Poisson process).

There are two analytical ways of applying these real options concepts to understanding the consequences and opportunities of environmental risks. The first is a simple diagrammatic approach without any mathematics (Hertzler 2007). Hertzler’s approach involves the use of decision diagrams (similar to decision trees) to set out the available options and consequences and map how these may change with the passing of time or as different options are taken or refused. Anyone can use this approach as a framework for thinking about systems over time and under risk. The second is highly mathematical. It involves modelling nonlinear stochastic dynamic systems, subject to thresholds and irreversibilities. The mathematics is challenging, but the biggest challenge and the potential benefits from the approach, are in understanding how real options approaches model risk and uncertainty. In the remainder of this paper we focus on illustrating the potential of combining resilience thinking with real options to understand and manage environmental risks rather than on the mathematical technicalities.

3.2 Applying the real options approach to resilience thinking

The easiest way to explain the real options approach to managing environmental risk in a resilience context is by way of an illustrative example, in our case using the classic resilience example of eutrophication of shallow lakes. The key conceptual relationships are illustrated in Figure 1 based on three biophysical assumptions (following Scheffer et al. 2002): turbidity increases with nutrient levels; vegetation reduces turbidity; and vegetation disappears at a critical nutrient concentration threshold.

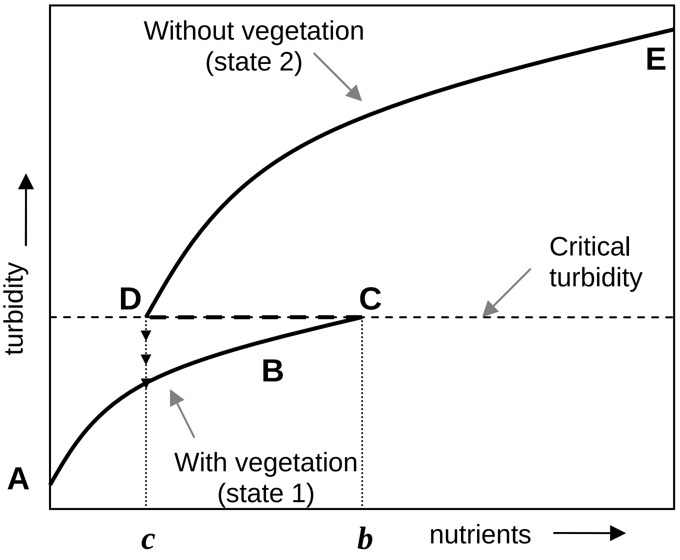

Figure 1: Two stable states in a shallow lake as a function of nutrients and turbidity

Source: Adapted from Scheffer et al. (2002)

The risk of the lake changing state is dependent on the initial state, the vegetation level and the nutrient level. In the vegetated state 1 (A-B-C), increased nutrients lead to increased turbidity until *b* is reached triggering a catastrophic collapse in vegetation and a shift to response curve D-E (the non-vegetated state 2). Return to the vegetated state is only possible if nutrients are reduced below *c*. The nutrient level may be driven by a chain of human decisions and environmental factors, but for simplicity it is assumed that the system is driven entirely by farmer decisions about fertilizer levels (the source of changes to nutrient levels) and stochastic rainfall events (which transport the nutrients to the lake). From two possible starting points in state 1 ('A' with low nutrients and low turbidity, and 'B' with low turbidity and a moderate nutrient concentration) a simple representation of a range of system outcomes can be shown using a decision tree like structure as shown in Figure 2. Attaching probabilities to the rainfall events for given fertiliser levels would estimate the environmental risk associated with eutrophication in this example. Attaching economic benefits to the different outcome states will allow consideration of the value of the 'option' to apply less fertiliser in the system which can then be compared against the costs to agricultural production.

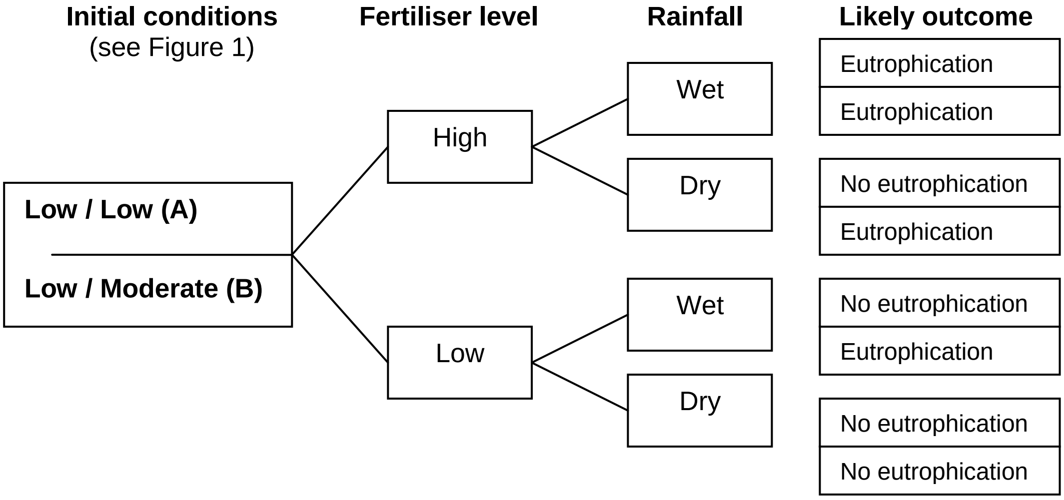

Figure 2: Illustrative decision diagram illustrating the environmental risks associated with different options

Decision diagrams such as shown in Figure 2 provide an excellent way to conceptualise the environmental risks associated with different states of nature. However, such diagrams may not represent the inherent complexity in the real world. In particular, decision diagrams quickly become complex when applied to a large number of options or across a larger number of events and always represent conceptual simplicity at the expense of knowledge about the gaps between defined options, events and outcomes. For example, the initial conditions may change over time depending on previous decisions; rainfall events will not just fall into high and low, but across some distribution from extreme wet to drought and so on.

One way of representing the ecosystem values from the system in different states is shown conceptually in Figure 3. Agricultural benefits increase with increased nutrients, albeit at a diminishing rate and are not state dependent. Community benefits (recreation, fishing, aesthetic, drinking water) sharply diminish with the eutrophic state 2. Total benefits are simply the sum of agricultural and community values. The community and total values derived in each state overlap between *c* and *b* representing the hysteresis effect shown in Figure 1.

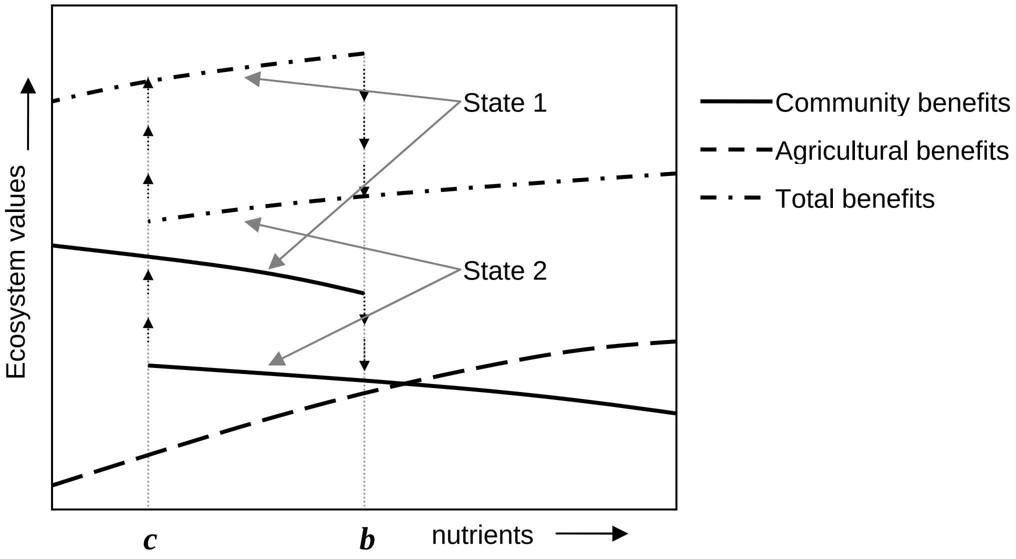

Figure 3: Conceptual model of economic values from shallow lake in two states

Managers and policy makers are most interested in maximising the net benefits that arise and comparing these against the cost of the management options available to maintain these benefits. The net benefits are described for each state by an option price associated with remaining in that regime and represents the value of ‘keeping your options open’ – the value of flexibility. Unfortunately these values may be difficult to estimate because they are dependent on both the current state of the system and the alternate states of the system. For example, if we are currently in state 1 in Figure 3, we would need to know the option price in state 2 in order to solve for the option price in state 1. In other words, the model must be solved backwards from some terminal value, calculating the option prices for all possible outcomes and using these to calculate the option prices at the present point in the system. Hence, as we will discuss later, option prices are time dependent unless the system is in a stable equilibrium. Option prices have the advantage of being expected values which avoids the need to directly calculate probabilities for each possible outcome. Decision makers can then use these option prices to inform their decisions.

3.3 Describing real options

The real options approach can be used to identify the price of the option of avoiding the state switch in Figure 1; that is the maximum we should be willing to pay to manage the environmental risk of state transition. Conceptually the price of an option also illustrates a fundamental but confusing aspect of real options: how to value an option separately from the value of an entire investment. The value of an option in the resilience construct is generally (but not always) time dependent and since it represents an opportunity (or a right in finance markets terms) rather than an obligation, it will be non-negative.[4]

An illustration of the option values that will result in the shallow lake example we have been following is shown in Figure 4 for avoiding a transition from state 1 to state 2 (non-eutrophic to eutrophic state) based on total benefits from the system. Option values for remaining in state 1 are shown as the heavy solid line in Figure 4. As the state transition is approached the likelihood of transition rises (the environmental risk is higher) and the option price (expected value of an investment ensuring we remain in state 1) becomes larger, eventually reaching the expected value of the future difference in benefits between state 1 and state 2. Once the threshold is breached the option value is bounded by zero (the option only relates to remaining in state 1 and has no value in state 2). Figure 4 also illustrates the value of resolving or reducing uncertainty in a real options framework as time progresses. The lighter lines in Figure 4 represent option values at previous points in time. As we learn more about the system and the environmental risks posed by differing activities, the option value of remaining in state 1 is resolved.

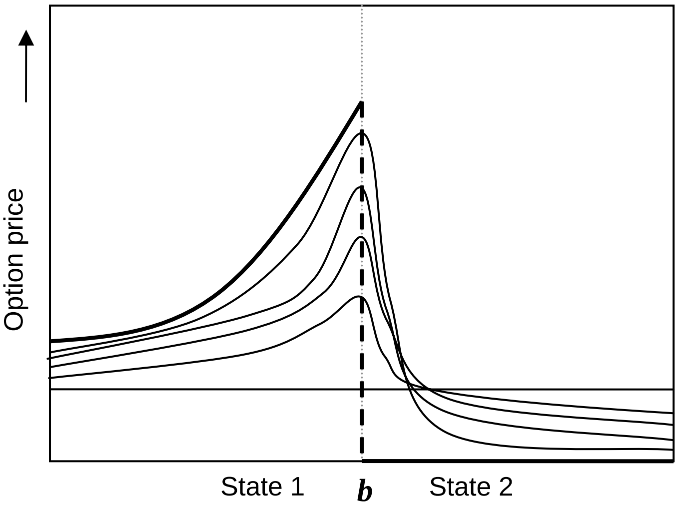

Figure 4: Option price to avoid transition from state 1 to state 2.

A similar exercise can be constructed for the price of an option in state 2 that would return the system to state 1 as shown in Figure 5 (without option prices at previous points in time). As previously, the option price increases close to the threshold due to the expected benefits that would result from transition. At points further from the threshold the agricultural losses would be greater. Note that the transition point changes from *b* to *c* as a result of the hysteresis in the system response to management. The interpretation of the option price differs however in this instance as it no longer represents a maximum willingness to pay to manage environmental risk, and instead represents the maximum price of an investment with benefits defined by the difference between state 1 and state 2.

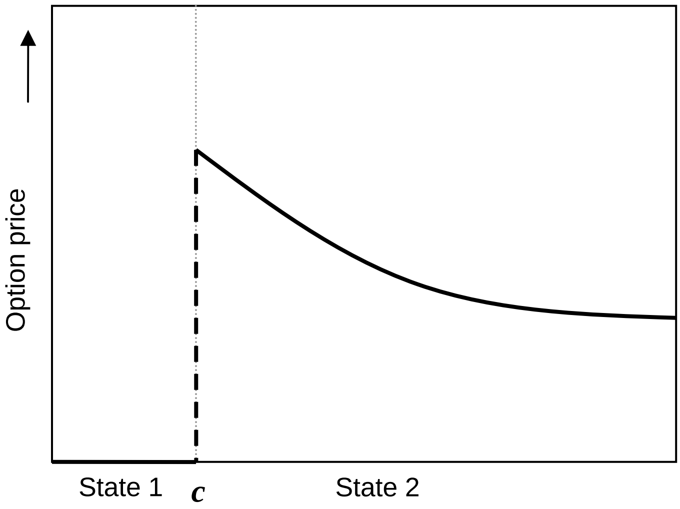

Figure 5: Option price to promote transition from state 2 to state 1.

In the (unlikely) event that both options are available (avoiding transition from 1 to 2, and promoting transition from state 2 to 1) the option value in the zone of hysteresis will be the lesser of the two as illustrated in Figure 6. This would be the equivalent of having the option to invest in make-good insurance rather than further investments in managing environmental risk and avoiding system transition.

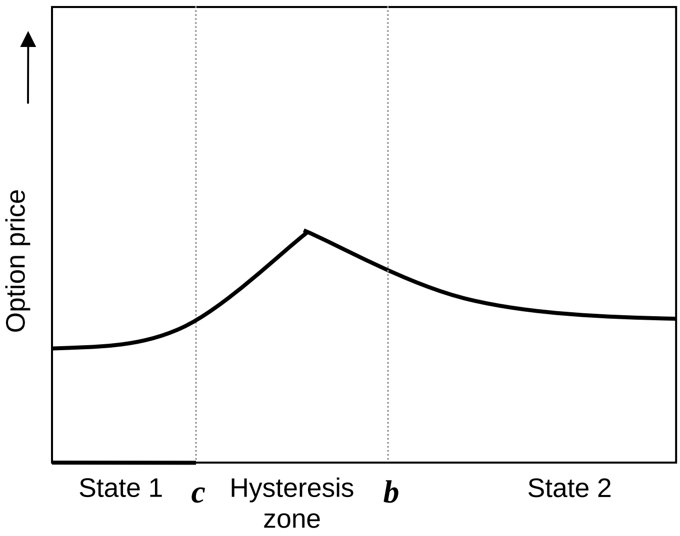

Figure 6: Option prices in the presence of options to avoid transition state 1 to 2 and promote transition state 2 to 1

If the relative benefits from agriculture rise over time, the option value of remaining in state 1 will decline and eventually, the system will be allowed to switch. Conversely if the relative community benefits from the lake rise over time, the option value of remaining in state 1 will increase and the option value of investments to make state 1 more resilient will rise correspondingly.

4 Discussion

The previous discussion has characterised environmental risk management through real options models via an illustration of option prices to avoid or promote transition across regimes. As previously noted, real options models also allow the estimation of shadow prices which represent the marginal value of a specific attribute of resilience, such as the distance from a threshold, the probability of transition, and the expected time to transition. These shadow prices also represent option values in the sense that the cost of an investment (an option) can be compared against the marginal benefit that would result. In this section we describe the ways in which the outputs generated from real options models can influence management of environmental risk and illustrate our points with examples from a sample of the real options literature.

4.1 Option prices as an indicator of the value of resilience

Real options can help us choose appropriate indicators of the dynamics of a system (and of environmental risk) because it is important that we know the resilience of the system to perturbations and the value of this resilience. Just as an option value is the amount we are willing to pay to avoid risk, the option value of system resilience is the maximum amount we are willing to pay to avoid the risk of an adverse transition. If we are willing to pay a large amount it means that the services provided by the system in its current state are valuable to us and we are willing to invest in additional resilience to ensure their continued provision

The real options model illustrated previously was constructed to explicitly provide an option price reflecting the difference in values between two different basins of attraction. The option price is effectively the difference in the net present values of the two alternate regions: the value of resilience in the preferred region. The investment or policy conclusions are as follows. If there is a risk management investment or policy option that would cost less than the option price and which would ensure the system remains in the preferred region, it would be advisable to make that investment. If the only available investments or policies would cost more than the option price, it is preferable (and indeed beneficial from a net present value perspective) to allow transition.

Since real options has rarely been applied in a context that explicitly uses resilience thinking, it is difficult to identify examples which calculate a true option price of a transition between stable states that may be used as a proxy for the value of resilience. Leroux et al. (2009), for example, estimate a price similar to an option price for the value of irreversibly converting land from conservation to agriculture in Costa Rica. In this example, Leroux et al. parameterise their model to generate estimates of a quasi-option value relating to the impact of the ecological concept of an extinction debt (the delayed impact of landuse conversion on biodiversity). If one were to cast Leroux et al.'s study within the framework of resilience thinking the quasi-option value of the extinction debt might be considered as an option price relating to managing the extinction risk resulting from conversion of habitat to agriculture.

Most other real options approaches which could be conceptualised in resilience thinking are focused on aspects of optimal switching points, most commonly in terms of when to commence or discontinue a particular action or policy. Morgan et al. (2007) for example, consider the question of when to discontinue forest harvesting activities with the objective of protecting a population of Caribou under conditions of uncertainty about other impacts on the forest such as wildfire. The decision to stop harvesting is taken at the point just before the probability of extinction exceeds a specified target probability. In a similar way Bakshi and Saphores (2004) consider the (option) value of reintroductions in analysing wolf management decisions.

Possibly the most important optimal switching models in this class (though it is difficult to consider these in terms of shifts between stable states in resilience thinking except in the very long run) consider the implications of uncertainty and climate change policy. Pindyck (2000) considers the implications of uncertainties over future costs and ecosystem responses along with the irreversibilities associated with sunk benefits and costs of environmental regulation. Baranzini et al. (2003) extend the application of real options to include consideration of climate catastrophes. In both cases uncertainty leads to delays in the adoption of climate adaptation policy. The inclusion of increased risk of climate catastrophes by Baranzini et al. (via a Poisson jump process) has the opposite effect by increasing the return from the adoption of adaptation policy. The use of discrete transition probabilities offers significant promise in considering problems of resilience where an extreme event (flood, fire, storm etc.) may trigger a shift in the system from one stable state to another.

4.2 Shadow prices as marginal values for resilience attributes

A key contribution of real options is that it facilitates estimation of marginal values representing the shadow price of resilience (whatever indicator is used for resilience). For example, we could choose speed of return from a disturbance as the indicator of resilience, the distance from a transition, the probability of a transition, or the expected time to cross the threshold. Pimm (1991) for example, proposed the speed at which a system returns to equilibrium as an indicator of resilience. A faster system would be deemed more resilient. It is an ambiguous indicator which leaves out the distance the system may have to travel to push it over the threshold (Holling’s 1973 theory) and the frequency and magnitude of the disturbances. Perrings (1998) proposed the probability that a system will cross a threshold as an indicator of resilience. This is an unambiguous indicator but would require solving for transition probabilities at all possible times and states of the system. Hertzler and Harris (2010) proposed the expected time until a system crosses a threshold, given the current state of the system. This is also an unambiguous indicator but requires solving option pricing equations.

Parameters describing speed of return, distance, transition probabilities or time to transition form important aspects of many of the papers described in the previous section, though again we are faced with the consideration that none of these papers explicitly described the problem using resilience thinking. Morgan et al. (2007) incorporate a mean reversion process, while Bakshi and Saphores (2004) incorporate a population growth parameter. In both cases the first derivative of these parameters would provide a marginal value associated with speed of return from a disturbance as an indicator of resilience. Bakshi and Saphores (2004) note that the inclusion of a mean reverting process would provide for limits to predator carrying capacity in the case of wolves, which can also be interpreted as a maximum resilience in a specific ecological state.

Published papers seldom calculate the marginal value of additional information though many of the papers discussed note the implications of uncertainty about ecological or other processes. Leroux et al. (2009) is an exception in that their model can be interpreted as estimating the value that additional information would provide to decisions about optimal conservation subject to environmental risk.

5 Concluding remarks

In this paper, we have described the way in which real option techniques can be applied to resilience concepts to identify the consequences of environmental risk and the management options available to decision makers. Resilience thinking offers a promising framework for considering environmental risk in the context of the non-linear responses to disturbance of complex systems such as ecological and socio-economic systems. In particular, it offers a framework for describing the dynamics of such systems and the existence of thresholds between states or regions of a system, each with different functions, structures, and feedbacks. As transitions from one state or region to another may involve substantive shifts in the values generated from the system, resilience thinking provides a consistent and robust framework for managers and policy makers to better identify and understand the risks and consequences of regime change.

Real options techniques offer the potential to directly model the benefits that result from whole or parts of complex systems. They present managers and policy makers with improved information about the costs (and benefits) of environmental risks and of delaying risk management activities. Investment and disinvestment decisions about whether to manage environmental risks subject to thresholds, hysteresis and irreversibilities can be rigorously analysed.

The formulation and outputs from the real options approach depends critically on the nature of the problem being considered and on the potential intervention opportunities available. Where opportunities to directly influence transition probabilities are available, option prices relating to the difference in net present values generated by alternate regimes may present the most useful output. Targeted information can be obtained from shadow prices, or the marginal values, of particular attributes of resilience such as the speed of return from a shock, the distance to transition or the time to transition. The examples presented in the paper detail the potential for real options analysis to contribute to policy and investment questions in these areas.

Despite the positive assessment presented in this paper, we note the difficulty in applying resilience thinking and real options models to practical problems. These include limited data, analytical complexity, and difficulty in adequately describing the consequences of threshold transition. As an illustration of these difficulties many of the examples identified in the literature incorporate sensitivity and scenario analyses to account for the uncertainty associated with key parameters. In conclusion, there seems to be a rich opportunity to researchers to integrate the fields of resilience thinking and real options models with substantive potential to improve investment and policy decisions under risk and uncertainty.

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Notes:

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[1] The "Resilience Alliance" is assembling a database of examples of alternating stable states in ecosystems (Walker and Meyers 2004).

[2] This definition remains rather limited and does not address the notion of subjective risk compared to objective risk and other debates in risk literature.

[3] Note that we have used 'state' in two ways in this paper: the first in resilience thinking to describe the basin of attraction in which the system lies; and the second to refer to the more detailed 'state of a dynamical system' which also contains sufficient information to describe its future behaviour (i.e. its future basin of attraction).

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[4] We also note that American options (that may be activated at any point in time prior to state transition) are the type most likely to be of interest rather than European options (that can only be exercised at a terminal time).

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