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.

[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-

[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

[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)

[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,

[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

[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).

[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

[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.

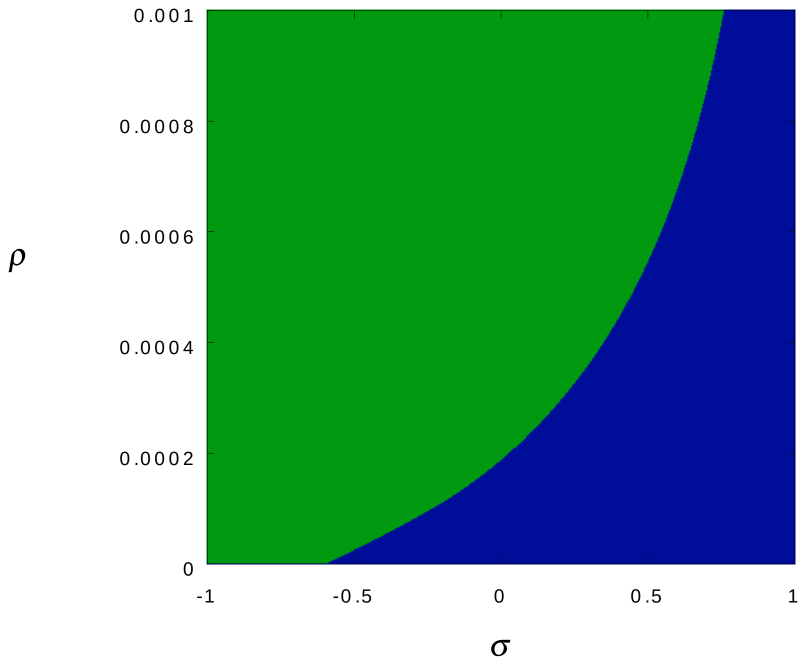

Figure 1: Parameter combinations that yield interior solutions (blue), a boundary solution at $e^* = 1$ (green)

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.

[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.

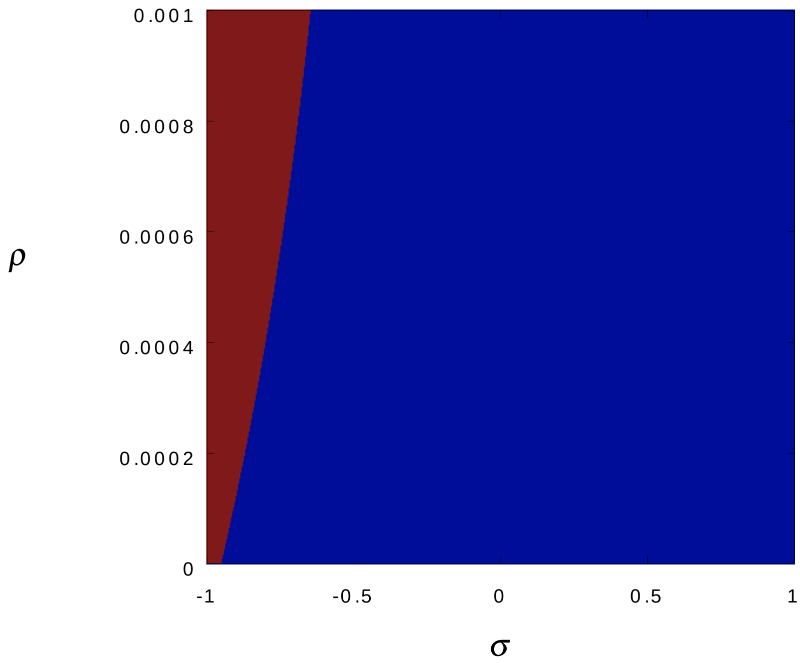

Figure 2: Parameter combinations that yield interior solutions (blue), a boundary solution at $e^{*} = 0$ (red)

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.

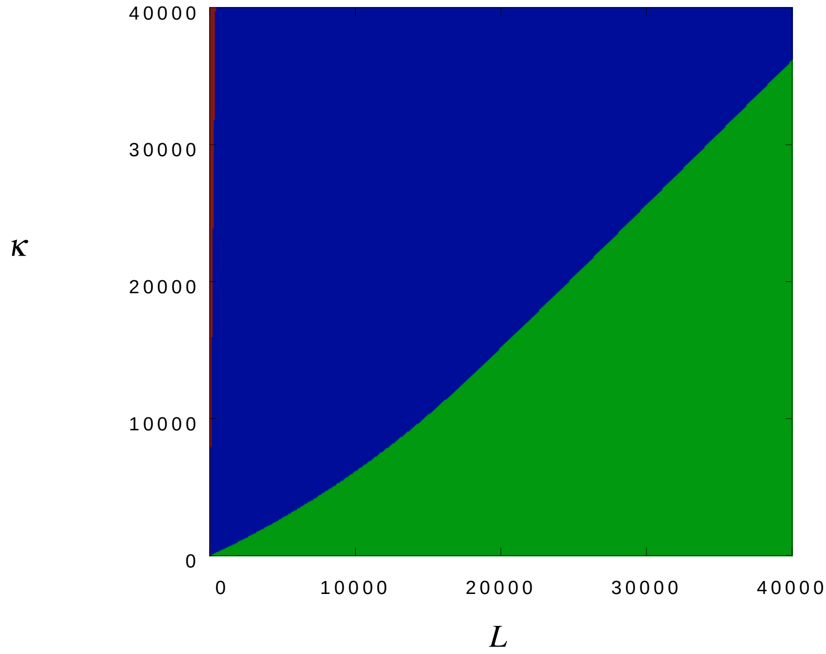

Figure 3: Parameter combinations that yield interior solutions (blue), a boundary solution at $e^* = 1$ (green), a boundary solution at $e^* = 0$ (red)

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.

[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.

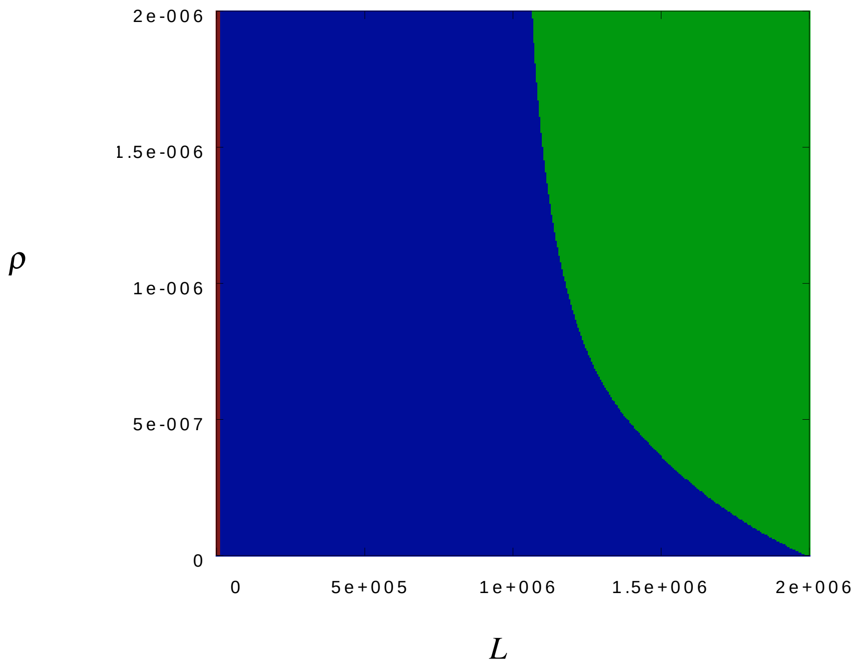

Figure 4: Parameter combinations that yield interior solutions (blue), a boundary solution at $e^* = 1$ (green), a boundary solution at $e^* = 0$ (red)

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.

[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.

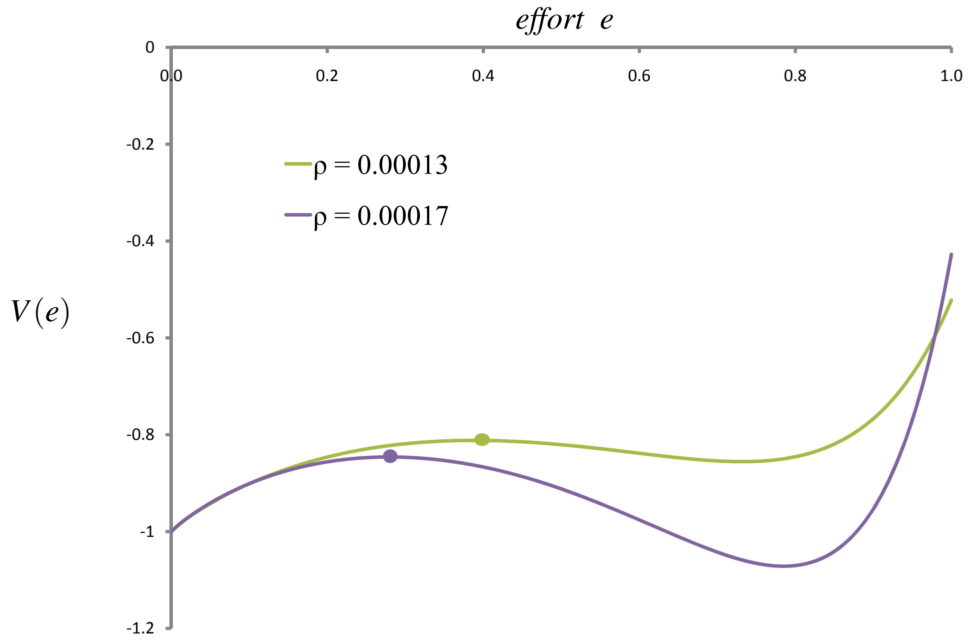

Figure 5: Parameter values: $L = 20,000,\ \kappa = 15,000,\ \sigma = 0.1,$

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 $\kappa \to \infty$. Thus, condition (12) is not satisfied $\forall \; e \in (0,1]$ and hence result (15) holds.

- κ

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

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

- σ

  For $\sigma \to 1$ 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 $\sigma \to 1$ 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 $L \to 0$ or $\kappa \to \infty$.

  For $\sigma \to -\infty$ 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 $\sigma \to -\infty$ 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, $\sigma \to -\infty$

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

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