Quantifying the Economic Insurance Value of Ecosystem Resilience – The Walker et al. (2010) Case Study from South East Australia

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Nov 10$^{\text{th}}$ 2011

Abstract: Ecosystem resilience, i.e. an ecosystem's ability to maintain its basic functions and controls under disturbances (Holling, 1973), draws attention to the problems of complex ecosystem dynamics and represents a system attribute that has not been adequately appreciated by economic valuation of the environment (see, e.g., Mäler (2008)). Resilience is seen as a core question of sustainability science (Kates et al., 2001) and has lately received increasing attention in the environmental economist community (see Bateman et al., 2011), yet only a few studies exist that scrutinize the applicability of this innovative approach. This paper builds on the works of Walker et al. (2010), who are the first to provide a measurement of the total economic value of resilience for a case study from South East Australia, and Baumgärtner and Strunz (2010), who derive the economic insurance value of ecosystem resilience in a simple ecological-economic model, and makes a first attempt at valuing the economic insurance value of ecosystem resilience for the system described in Walker et al. (2010). It develops a (quasi-)dynamic ecological-economic model that combines the approaches of Walker et al. (2010) and Baumgärtner and Strunz (2010), provides a first estimate of the insurance value, and discusses the potential for further economic evaluation of ecosystem resilience.

JEL-Classification: D81, G22, Q24, Q51, Q54, Q56, Q57

Keywords: Resilience, Economic Valuation of Ecosystem Services, Insurance, Sustainable Development

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1 Introduction

Without a resilient provision of important ecosystem services, human life on Earth would not be possible (Arrow et al., 1995, p. 521). Yet, the loss of life supporting ecosystem services is occurring at an ever-increasing pace (Millennium Ecosystem Assessment, 2005). The ethical norm of (strong) sustainable development requires that all capital stocks are used in an efficient way that accords with a general perception of intra- and intergenerational justice, while stocks of critical natural capital that may lack man-made substitutes are preserved.[1] Besides the delicate ethical argument and required democratic decision making on the balance between various spheres of intra- and intergenerational justice, it is not clear which ecosystem components are to be considered as critical natural capital. As Brand (2009) argues, a resilience approach may be helpful for deciding which forms of natural capital can be regarded as 'critical'. Furthermore, Kates et al. (2001) see the analysis of resilience as one of the core question of sustainability science and Bateman et al. (2011, p. 205) as an "innovative approach to assessing sustainability" of ecosystem service provisioning.

A resilience approach draws attention to non-linear dynamics and in particular to tipping points in the provision of ecosystem services, occurring on various temporal and spatial scales (see, e.g., Scheffer et al. (2001) for an overview, Scheffer et al. (1993) for a discussion of resilience dynamics in a shallow lake setting and Lenton et al. (2008) or Rockström et al. (2009) for coverage of tipping points on a global scale). One common definition of resilience has been provided by Walker et al. (2004), who define resilience as the ability of a system to remain in a given state while undergoing change and experiencing shocks.

In view of the fact that this function of life-supporting systems is evidently of key importance for a sustainable development, as a possible irreversible shift in ecosystem service provision may have devastating effects, economists (see, e.g., Brock et al. (2002), Mäler (2008) or Perrings (2006)) have pondered over how to account for it in order to devise efficient policies and to guarantee a sufficient investment in resilience.

As a higher level of resilience reduces the probability of the occurrence of an unwelcome regime shift (i.e. crossing a threshold), resilience has often been interpreted as insurance, though, only a part of the function of resilience actually serves as an economic insurance

[1] For a discussion on the idea and various conceptions of sustainable development see, e.g., Baumgärtner and Quaas (2010) and Neumayer (2010).

(Baumgärtner and Strunz, 2010). Knowing the size of the insurance value of resilience is e.g. important for knowing whether resilience actually functions as an insurance and for deciding on whether one should insure oneself via providing real action to increase resilience or by buying substitutive insurance contracts (ibid., p. 23).

The aim of this paper is to scrutinize the prospect and feasibility of quantifying the economic insurance value of ecosystem resilience. Building in particular on Walker et al. (2010) and Baumgärtner and Strunz (2010), it makes a first attempt at quantifying the economic insurance value of ecosystem resilience for the system described in Walker et al. (2010) – the Goulburn-Broken Catchment (GBC) case study from South East Australia. The GBC is a highly productive agricultural region that is threatened by salinization due to rising groundwater tables – a danger many farmers face all around the world (Walker and Pearson, 2007, p. 711). To account for the insurance value of ecosystem resilience, I develop an ecological-economic model that combines the approaches of Walker et al. (2010) and Baumgärtner and Strunz (2010), provide an estimate of the insurance value for the GBC case study, and discuss the potential for further economic evaluation of ecosystem resilience.

The remainder of this paper is structured as follows: Section 2 will introduce the concept of resilience in more detail while Section 3 depicts the system of the GBC. In Section 4, the models of Walker et al. (2010) and Baumgärtner and Strunz (2010) are recapitulated before the combined quantification model is developed. Section 5 describes the evaluation of the economic insurance value of resilience, while Section 6 discusses the results and Section 7 concludes.

2 Resilience

Resilience, like sustainable development, is a contested concept that comes in various representations (see, e.g., Brand and Jax (2007), who compile and categorize ten classes of resilience definitions varying in their degree of normativity). In the remainder of this text, I will refer to the notion of 'ecosystem resilience', which has its roots in the seminal work of Holling (1973) and has been defined, e.g., by Walker et al. (2004) as the "capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks".[2] Such a resilience

[2]Note that there also exists a conception of resilience very different from the Holling definition of 'ecosystem resilience', which is concerned with the speed with which a system returns to its equilibrium

approach rests on the view that ecosystems can have multiple stability domains ('regimes') and non-linear system dynamics, in particular threshold effects (Folke et al., 2004).[3]

A fundamental attribute of ecological systems is their complexity – it may thus be difficult to meaningfully define the 'state' of an ecosystem and changes in it, as the system will be described by an abundance of factors. Resilience researchers therefore differentiate between specified and general resilience (Carpenter et al., 2001). A general resilience perspective (ibid.; Walker and Salt, 2006) approaches complexity without trying to simplify systems for model building and emphasizes the importance of modularity, i.e. the loose connectedness between different components of a system, and diversity, in particular functional and response diversity.[4]

Specified resilience, in contrast, abstracts from the general complexity of ecosystems and tries to bring resilience into a setting where the alternate regimes, important stressors and possible thresholds can be specified by clarifying the question "resilience of what to what" (Carpenter et al. 2001). Many studies analyse the simplest form of specified resilience, i.e. a system that has two alternate regimes (also referred to as 'basins of attraction' or simply 'stable states'), which are separated by a threshold (see Fig. 1).

Fig. 1 illustrates the specified resilience case in two different representations. The elevated 'ball-in-the-basin' diagram depicts the stability landscape at five different stages, with the ball describing the state of the system and the basins representing the alternate regimes. Changes in key variables or conditions alter the stability landscape, while external shocks may contribute to this and may eventually lead to a regime shift (stage four counted

state following a perturbation (this has been termed 'engineering resilience' after Pimm (1984; 1991)). Other conceptions that have been developed from the Holling notion have broadened the focus to be applicable to social-ecological systems. Although the insights these newer approaches have generated – in particular with the focus on adaptive capacity and experimental management of ecosystems – are very relevant also for the management if the GBC (see Walker et al. 2009), they cannot be further explored in this text and the interested reader is referred to Folke et al. (2002) for a brief overview and Walker et al. (2006) for a more detailed coverage.

[3]The existence of multiple (usually bi-stable) regimes and corresponding thresholds has been confirmed by empirical evidence for a growing number of systems, see, e.g., Resilience Alliance and SFI (2004) and Walker and Meyers (2004).

[4]While functional diversity refers to the range of functional groups a system depends on, response diversity alludes to the diversity in how different elements or species within a functional group, which are redundant from a functional diversity view, react to shocks (Walker and Salt, 2006, pp. 69–73).

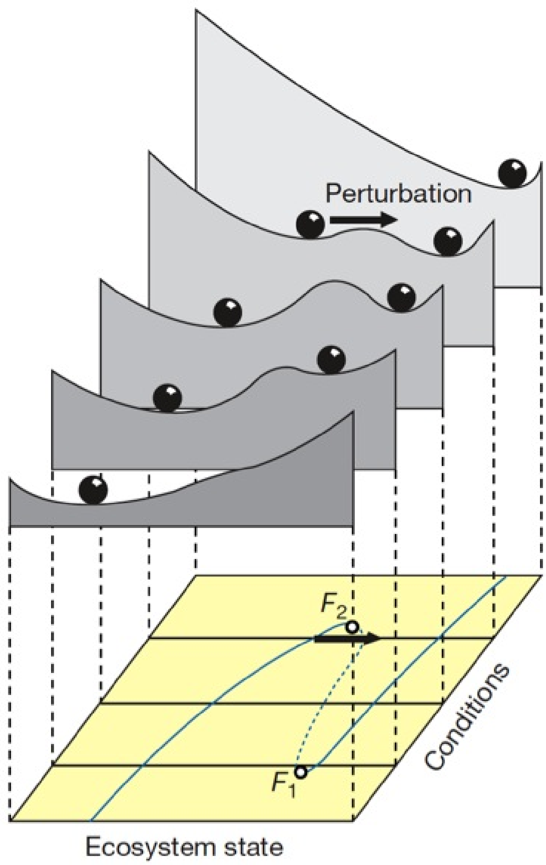

Figure 1: *Illustration of the specified resilience dynamics in a bi-stable ecosystem.*

This Fig. illustrates the simple specified resilience dynamics in a bi-stable ecosystem as a bifurcation diagram (on the floor) and a ball-in-the-basin diagram (at the top). See the text for a description. Taken from Scheffer et al. (2001, p. 593).

from the front). The floor of Fig. 1 highlights the 'equilibrium' curve or 'bifurcation diagram', where again the state of the ecosystem is influenced by the changes in the driving condition(s). This representation highlights a hysteresis effect, as a shift of the system from an ecosystem state left on the axis (e.g. a clear water lake as in the example provided in Fig. 4 of Scheffer et al. (2001, p. 594)) to the alternative state (a lake with turbid water) can only be undone if the driving variable (phosphorus concentration) is reduced substantially below the level where the system has flipped initially (i.e. not at F_2 but F_1.).

While this simple diagram has illustrated a bi-stable system with a hysteretic regime shift, it must be emphasized that regime flips can also be irreversible (at least on a time scale relevant for the ecosystem users). This relates to a further point: a specified 'resilience of what to what' poses very high demands on data availability, as the system, its alternate regimes, the relevant driving forces and thresholds need to be specified both temporally and spatially.

As most economic approaches to account for (ecosystem) resilience rely on a notion of specified resilience, this challenge of data availability will be picked up again in the concluding section. The major body of literature on accounting for resilience in economics – the capital pricing approach of Mäler, Arrow, Dasgupta and others – is addressed in the remainder of this paper. For further economic approaches to resilience, the reader is referred to, e.g., Baumärtner et al. (2011), Derissen et al. (2009), Gren (2010), Strunz and Baumgärtner (2010) and Vergano and Nunes (2006).

3 Case Study: The Goulburn-Broken Catchment

In the following, I will describe the system of the Goulburn-Broken Catchment (GBC) in South East Australia drawing in particular on Walker and Salt (2006, pp. 39-52), Walker et al. (2009) and Walker et al. (2010, pp. 191-193). First, I will present more general information about the GBC and afterwards turn to the more specific resilience dynamics, which shall be analysed in the remainder of this paper.

The GBC is located in South East Australia in the State of Victoria (see Fig. 2), covering 2.1 million hectares. The GBC is one of Australia's most important agricultural regions, with the 'dairy processing' sector being the largest contributor to the regions marketed output (Walker et al., 2009). Most of the agricultural production takes place in the lower (to the sea level) parts of the GBC – an area of 300,000ha that is only covered by 2% of native vegetation and is predominantly used for irrigated dairy- (80%) as well as fruit production (ibid.; Walker et al., 2010, p. 191). Additional to marketed output, studies indicate that non-marketed goods such as ecosystem services constitute a substantial part of regional welfare (ibid.).

Walker et al. (2009) provide an extensive assessment of resilience in the GBC region. First, they identify major problems in the region (such as rising saline water tables threatening crop production or insufficient native dryland vegetation connectivity leading to biodiversity loss) and discuss specified and general resilience in this setting. A range of specified resilience cases are presented, grouped into the three subsystems of the social-ecological-economic system. For every specified resilience case, Walker et al. (2009) also provide a three-step assessment of the degree of uncertainty in the knowledge of the specific

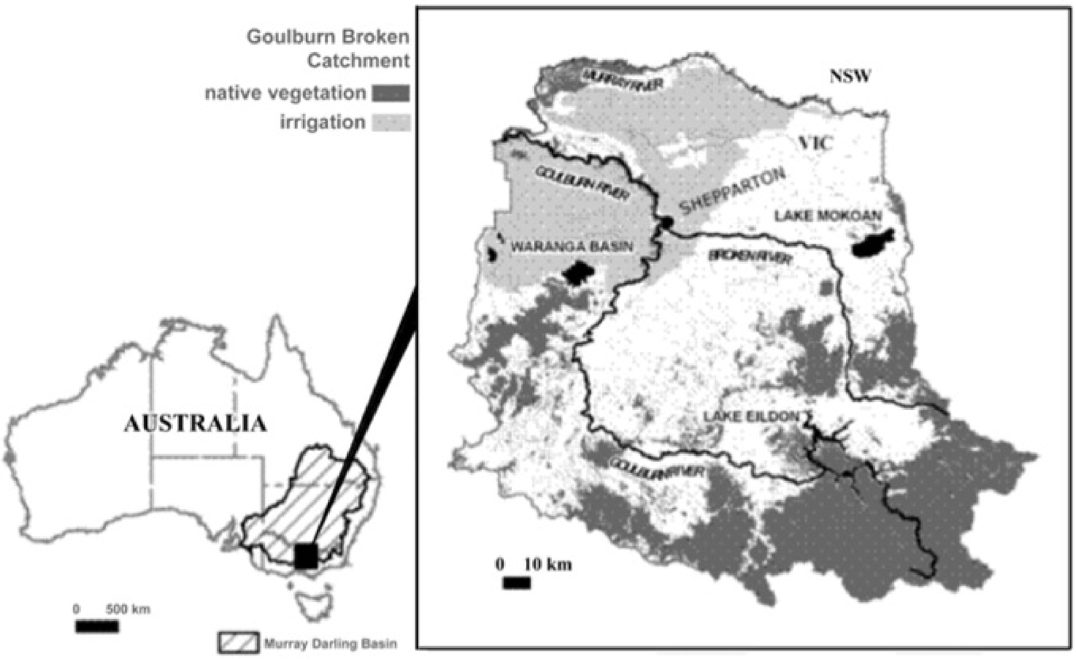

Figure 2: *Functional map of the Goulburn-Broken Catchment.*

This Fig. depicts the location and the functional use (notably the later analysed irrigation area) of the GBC. Taken from Walker et al. (2009).

threshold (known, strongly suspected and unknown).

In their resilience evaluation of the GBC, Walker et al. (2010) have included three of these specified resilience cases – (i) rising groundwater tables leading to a salinization of the soils, (ii) native dryland vegetation connectivity determining nature conservation and (iii) the condition of the irrigation infrastructure. However, only the first case constitutes the focus of their remainder of the study, while the other two are considered in the discussion part (Walker et al., 2010, p. 200).

The case of groundwater table dynamics and the resulting threat of salinized soils shall now be discussed in more detail. According to Walker and Salt (2006, p. 43), the groundwater table was between 20 and 50 meters below the surface before European settlers arrived and occupied the land of the Aboriginal people. To create space for the new settlements and, in particular, for cultivation and agricultural production, natural vegetation has been largely cleared. This, together with the later installed irrigation infrastructure, has led to a successive rise of the water table. Because of salt deposits in the soil profile, a rising water table constitutes a major threat to the productivity of the soil, as the salinized water will be drawn to the surface by capillary action if it reaches a critical threshold of approximately 2m below the surface (Walker et al., 2010, p. 191). Half of the GBC irrigation region is threatened by salinity and as a response to the past crossing of the critical threshold in the 1950ies and 1970ies, which led to widespread crop losses, pumps have been installed that are supposed to keep the water level below 2m under the soil (ibid.).

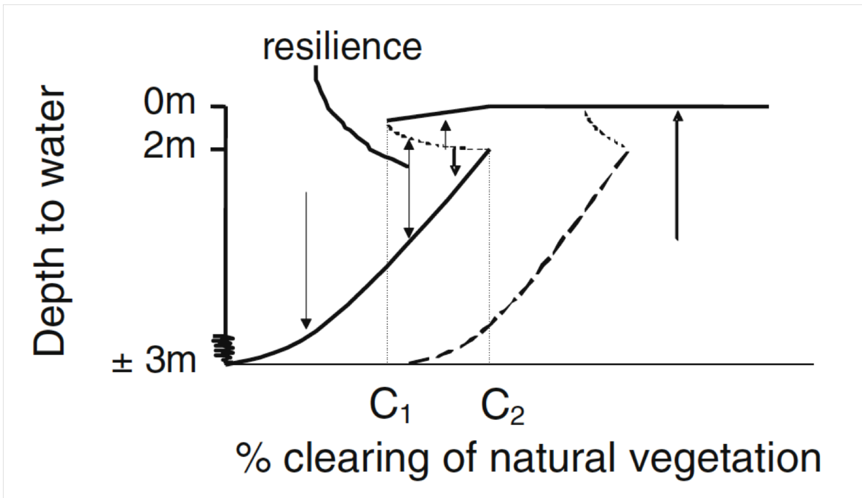

Figure 3: *Bifurcation diagram of the relationship between the level of the groundwater and the clearing of natural vegetation.*

This bifurcation diagram highlights the equilibrium levels of the groundwater in relation to the clearing of natural vegetation. For the regime with a lower water table, a scenario with (solid line) and without (dashed line) pumping activity is depicted. Pumps may therefore be regarded as "mechanical trees", as they can to some degree fulfil the function of the native vegetation cover (Walker et al., 2010, p. 192). Taken from ibid.

Thus, the GBC is now in a very complicated situation, where the threshold to a new equilibrium with salinized soils may have already been crossed, with only the installed pumping machinery keeping it in the desired high productivity regime (Walker and Salt, 2006, p. 49). This situation is illustrated in Fig. 3, which describes the relationship between (natural) vegetation cover and the depth of the water table. Fig. 3 also highlights a hysteresis effect, as vegetation would need to be restored not only up to point C_2, where the regime flipped, but up to point C_1.

Fig. 4 shows these resilience dynamics from a different angle. It tries to explain soil fertility with the depth of the water table relative to the topsoil, also exhibiting a hysteresis

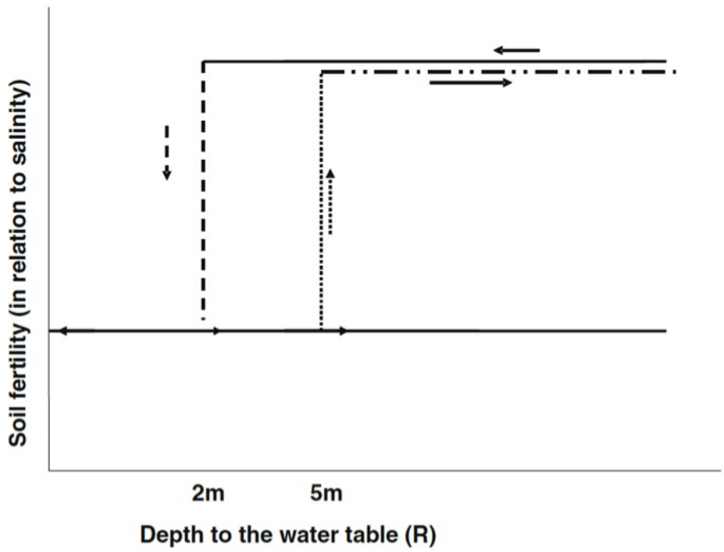

Figure 4: *Bifurcation diagram for the relationship between soil fertility and water table depth*

This bifurcation diagram shows the relationship between soil fertility and water table depth. Taken from Walker et al. (2010, p. 192).

effect. Over time, the water table may rise due to higher irrigation input or rain fall but the system remains in the high soil fertility regime (solid line). If further inputs occur and pumping cannot reduce the water table, it may cross the critical threshold at 2m below the surface, thus leading to a salinized soil – the land will loose its productivity almost entirely.[5] For a small decadal scale, this regime shift can be regarded as irreversible, but the high productivity soil may be revitalized if the salt is flushed away and tree planting and increased pumping activity can insure that the water table is sufficiently distant from the critical threshold – in Fig. 4, this is assumed to happen at a water table 5m below the surface (see Walker et al., 2010, p. 192f.).

[5]It must be noted that the two major land management regimes – horticultural and dairy production – are affected differently by a possible salinization, as horticultural crops are more sensitive to salinity (due to their longer roots) as pastures (Walker et al., 2010, p. 192; see also Section 4.1.2).

4 Model Analysis

In this section, I will first introduce the model of Walker et al. (2010) that describes the above presented resilience dynamics in the Goulburn-Broken Catchment and evaluates the economic value of resilience. Second, I present the model of Baumgärtner and Strunz (2010), who derive the economic insurance value of ecosystem resilience in a simple ecological-economic setting. Third, I will proceed to combine features of these two models to construct a model, with which the economic insurance value of ecosystem resilience for the system described in Walker et al. (2010) can be quantified.

4.1 The model of Walker et al. (2010)

Building on the works of Mäler et al. (2007), Mäler (2008) and Mäler and Li (2010), Walker et al. (2010) employ a capital-pricing model, with which the economic value of resilience may be calculated using shadow prices for the purpose of an inclusion into the calculation of an Inclusive Wealth indicator for the GBC.[6] Before presenting their analytical model, I will briefly recapitulate the system components and specified resilience definition of Walker et al. (2010) for the GBC case.

To make resilience measurable in one form or another, one has to specify "resilience of what to what" (Carpenter et al., 2001) both temporally and spatially. Walker et al. (2010, p. 189) use the "resilience of crop production in the [GBC] to variations in the [ground-]water table" as their specification, which is defined temporally for a 40-year time span starting in the year 1991 and spatially located at the farm level.[7] This specified system has two alternate regimes, where the current regime is described through productive soil and the alternate regime exhibits degraded, salinized soil, i.e. the current regime is thus regarded to be the desirable one. In the following, the resilience of the desirable regime will

[6]Since the Inclusive Wealth indicator is not the focus of this study, I will not cover it in more detail. The reader is referred to Arrow et al. (2003), Arrow et al. (2010) or Walker et al. (2010).

[7]Walker et al. (2010) also discuss other potential resilience stocks, however, without trying to incorporate them into the model. This limitation may be justified by e.g. arguing that the resilience of crop production in the GBC at the farm level for the next 40 years (a common time horizon for long-term infrastructure and development projects in the GBC) is predominantly in danger due to fluctuations in the groundwater table; so even though other variables might also lead to a regime shift, such an event is far less likely than a flip due to a rise in the groundwater table.

be analysed. It is furthermore assumed that the level of groundwater is the sole key variable for analysing the resilience of this system and, based on empirical evidence, that there exists a threshold in the groundwater table of approximately two meters under ground, due to capillary actions that carry deposited salt to the surface and lead to the salinization of the soil. The possible regime shift is assumed to be irreversible for the time span analysed.

4.1.1 Theory

Walker et al. (2010) define resilience more specifically as a stock variable R that equals the distance from the current water table to the threshold level of 2m under ground.[8] Furthermore, $F(R_0, t)$ represents the cumulative probability distribution of a regime shift up to time t for an initial resilience stock R_0 (also referred to as 'flip probability' in the following) and the cumulative probability that the system has not flipped before time t is the 'survival probability' $S(R_0, t) = 1 - F(R_0, t)$. With $U_1(t)$ as the net benefit at time t if the system has not flipped and $U_2(t)$ as the net benefit if the system has flipped before or at t as well as δ as the discount rate, Walker et al. (2010, p. 189) derive present expected welfare depending on the resilience stock:

$$E(W(R_0)) = \int_0^\infty [S(R_0, t)U_1(t) + F(R_0, t)U_2(t)]e^{-\delta t} dt, \tag{1}$$

as has already been shown by Mäler et al. (2007, p. 7).

The shadow price of resilience at time 0 is then equal to the change in present expected welfare due to a marginal increase in the initial resilience stock R_0:

$$q_{\mathrm{R}}(0) = \frac{\partial\, E(W(R_0))}{\partial\, R_0} = \int_0^\infty \left[\frac{\partial\, S(R_0, t)}{\partial\, R_0} U_1 + \frac{\partial\, (1 - S(R_0, t))}{\partial\, R_0} U_2\right] e^{-\delta t} dt, \tag{2}$$

where the net benefits in both regimes U_1 and U_2 are assumed to be constant over time Walker et al. (2010, p. 191).[9]

With discrete time and a time horizon m, this becomes:

$$q_{\mathrm{R}}(0) = (U_1 - U_2) \sum_{t=0}^{m} \left(\frac{\Delta S(R_0, t)}{\Delta R_0} \frac{1}{(1+\delta)^t}\right). \tag{3}$$

[8]In order to insure notational consistency with the model of Baumgärtner and Strunz (2010), I will use R as the resilience stock instead of X as done by Walker et al. (2010).

[9]This ceteris paribus formulation of the shadow price assumes amongst others that the land area of a farmer or the whole GBC remains constant during the 40-year time horizon and that the survival probability is not influenced e.g. through different management practices.

In order to allow for an estimation of this shadow price, more information is needed about the net benefit streams in the two regimes and in particular detailed knowledge is required about the cumulative flip probability $F(R_0, t)$. Walker et al. (2010) estimate U_1 and U_2 as the net present revenues of farmers in the two regimes, which necessitates the assumptions that there are no (forecasted) future changes in prices and technology and no externalities (see Walker et al. (2010, p. 191) and ibid. (p. 199) for a discussion on this).[10]

Furthermore, Walker et al. (2010) specify the cumulative survival probability function as follows:

$$S(R_0, t) = \prod_{t=1}^{m} \left(1 - \theta e^{-\eta R_t}\right), \tag{4}$$

where m is again the time horizon, θ is a hypothetical benchmark probability for a flip if the initial resilience stock would be zero and η is a parameter measuring how fast the flip probability decreases as the resilience stock increases.[11]

4.1.2 Evaluation

For an evaluation of the economic value of resilience (i.e. the shadow price at time 0 multiplied by the total initial resilience stock), empirical estimates or forecasts are needed for (i) the development of the resilience stock over time, (ii) the cumulative flip probability and (iii) the net benefit streams.

Walker et al. (2010, p. 193f.) define two forecasts for the development of the resilience stock for the years 2001 to 2030 (the groundwater table has decreased from 3m in 1991 to approximately 3.5m in 2001, i.e. the resilience stock has increased by 0.5m). The *normal* forecast predicts that the groundwater table will rise again to 3m below the surface in 2030 whereas the *dry* forecast predicts that the water table will fall to 5m below the surface. It is further assumed that the changes in climate conditions that lead to variations in the water table do not alter other conditions of the system, which need to stay constant in this ceteris paribus analysis. It should also be noted that these forecasts only rely on projections based on historical developments and do not take future projected changes e.g. due to anthropogenic climatic change into account (ibid., p. 194). Walker et al. (2010,

[10] Note also that this linear-in-income utility implies risk-neutral farmers.

[11] Note that R_t represents the expected value of the resilience stock at time t depending on R_0 according to a certain, later specified process; it would thus be consistent to denote R_t as $R_t(R_0)$, which is not pursued here for simplicity reasons.

p. 195) further state that R_t depends on R_0 "according to a certain stochastic process", which may allude to the work of Mäler et al. (2007, p. 11f.), who specify such a stochastic process. However, it seems that the development of R_t over time is rather governed by a linear, deterministic process.[12]

The parameters θ and η of the cumulative survival probability were estimated from monthly observations and assumed to be stable for the time horizon of the analysis (Walker et al., 2010, p. 195). It must be emphasized here that these past observations have only been collected from the bore of one central site and thus carry with them the assumption that water table dynamics are identical across the whole GBC.[13] Based on these calculations, the cumulative survival probability is specified as follows

$$S(R_0, t) = \prod_{t=1}^{m} \left(1 - 0.4583e^{-2.75R_t}\right), \tag{5}$$

while a sensitivity analysis for the resilience prices with respect to these two crucial parameters is also conducted with alternate parameter pairs (θ,η) equal to (0.25, 2.15) and (0.125, 1.45) respectively (ibid., p. 198f.).[14]

With this specification of the survival probability function and a not clearly specified development path of the resilience stock, Walker et al. (2010) calculate the cumulative survival probability for each month, as is depicted in Fig. 5 for the *normal* climate forecast.

The net benefit streams U_1 and U_2 have been calculated based on net present value calculations of land rents serving as a proxy for the unavailable shadow prices. According to these calculations, the prices of land per hectare are \$448.29 for dairy- and \$723.00 for horticultural land in the initial high production regime.[15] The estimated 'shadow' prices for dairy (horticultural) land in the alternate, salinized regime is assumed to be 10% (1%)

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[12]This impression has arisen during the correspondence with the authors and by trying to replicate their results, see Section 5.1.3.

[13]This has been clarified in an e-mail exchange with T.Baynes.

[14]It may be argued that such a sensitivity analysis should also include parameter sets that differ to both sides of the initially used values in size, i.e. also a parameter pair of e.g. (0.59, 3.00; own calculation). See Walker et al. (2010, p. 198) for a description of how these parameter pairs can be generated.

[15]Walker et al. (2010) do not further specify the currency – whether they deal with Australian- or US-Dollar. I therefore assume that they use Australian dollars as they would have otherwise needed to convert land prices (presumably in Australian dollars) to US-Dollars and should have specified the mode of currency conversion. I furthermore assume that Australian dollars are given in 1991 values in the remainder of this paper.

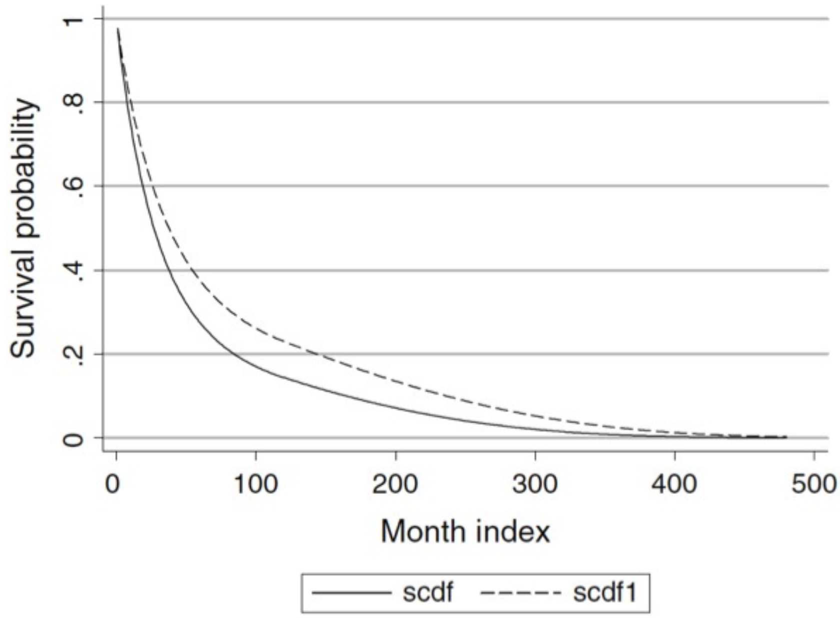

Figure 5: *Cumulative survival probability for the* normal *climate forecast of Walker et al. (2010).*

This Fig. shows the cumulative survival probability curves conditional on different initial resilience levels of 10dm (scdf) and 11dm (scdf1); For each month, the vertical difference between the two curves is $\frac{\Delta S(R_0,t)}{\Delta R_0}$. This Fig. has been taken from Walker et al. (2010, p. 196).

of their respective initial regime prices. The net present benefit streams are then calculated by multiplying the total land area of dairy- and horticultural land with their respective proxy 'shadow' prices.

Assuming an annual discount rate of 4% and thus a monthly discount rate δ of approximately 0.33%, Walker et al. (2010, p. 196f.) calculate the shadow price of the resilience stock per dm according to equation (3) for the 40-year time horizon. The 1991 resilience price per dm for the *normal* climate forecast is \$4,570,530 and the one for the *dry* forecast is \$5,711,672.

4.2 The model of Baumgärtner and Strunz (2010)

While Mäler et al. (2007) and Mäler and Li (2010) have provided a model for the assessment of the (total) economic value of resilience using a capital-pricing approach and Walker et al. (2010) a first evaluation of resilience for the GBC using this modelling framework, Baumgärtner and Strunz (2010) have developed a simple ecological-economic model to derive the economic insurance value of ecosystem resilience.

As Baumgärtner and Strunz (2010, p. 4) argue, ecosystem resilience has often been interpreted metaphorically as insurance without referring to a rigorous economic definition of insurance. Such a definition should include three components: (i) objective risk characteristics, i.e. different states of nature that may occur with certain probabilities, (ii) subjective risk preferences of the decision maker, and (iii) a mechanism that allows for a mitigation of the perceived risk. Baumgärtner and Strunz (2010) adopt the classic insurance definition of McCall (1987), whereby insurance is an "institution that mitigates the influence of uncertainty" on a person's well-being. The insurance value of ecosystem resilience can then be defined as the function of a resilience stock to reduce an ecosystem user's (income) risk from using ecosystem services, whose provision may be subject to regime shifts, under uncertainty.

The fundamental change to the model of Walker et al. (2010) is that ecosystem users are now assumed to be risk averse. Baumgärtner and Strunz (2010, p. 5ff.) further consider an ecological-economic system with two regimes, where the initial regime is characterized by a high level of ecosystem service provision and corresponding high income y_H and the alternate regime is associated with a low level of ecosystem service provision and a low income y_L, with $\Delta y := y_H - y_L > 0$ being the income loss in case of a regime shift. Such a regime shift may be triggered by exogenous stochastic disturbances and occurs with a probability p, with $0 \leq p \leq 1$.[16] The flip probability depends on the resilience stock – modelled as a continuous state variable $R \in [0, 1]$ – and a parameter σ termed the "ecosystem elasticity", measuring in percentage terms by how much the flip probability's slope increases if the level of resilience increases by 1%:

$$p(R) = 1 - R^{1-\sigma} \quad \text{with} \quad -\infty < \sigma < 1. \tag{6}$$

The flip probability has the following characteristics:

$p'(R) \leq 0$ for all R, $p'(R) < 0$ for all $R \in (0, 1)$ as well as $p(0) = 1$, $p(1) = 0$, i.e. the

[16]Note that p corresponds to the cumulative flip probability $F(R_0, t)$ in the model of Walker et al. (2010) and that uncertainty in this model is *Knightian risk* (see, e.g., Faber et al. (1992) for a typology of different representations of uncertainty), as the states of nature are known and it will be also assumed that the probabilities are known as well. As a further contrast to the model of Walker et al. (2010), the model of Baumgärtner and Strunz (2010) is static.

flip probability decreases with an increase in the level of resilience.

Given this set-up, the ecosystem user, who is assumed to only care about income and not about other characteristics of the two regimes, faces a binary income lottery $\{y_L, y_H;\ p(R), (1 - p(R))\}$ that only varies with the level of resilience R. Her preferences over the income lottery R are then described by a von Neumann-Morgenstern expected utility function

$$U = E_R[u(y)] \quad \text{with} \quad u'(y) > 0 \text{ and } u''(y) < 0 \text{ for all } y, \tag{7}$$

where E_R is the expectancy operator based on the probabilities of the income lottery R, y is net income, here given as a random variable that has the two realizations y_H and y_L, and $u(y)$ is a continuous and differentiable Bernoulli utility function, assumed to be increasing and strictly concave (ibid., p. 8). More specifically, Baumgärtner and Strunz (2010) assume constant absolute risk aversion (CARA) so that the utility function of the ecosystem user is

$$u(y) = -e^{-\rho y}, \quad \text{with} \quad \rho > 0, \tag{8}$$

where the CARA coefficient ρ measures the degree of risk aversion. Insurance of the ecosystem user's well-being is thus the mitigation (condition iii) of uncertainty – here *Knightian risk* – in the binary income lottery R (condition i) according to her subjective risk preferences (condition ii; Equation (8)). Baumgärtner and Strunz (2010, p. 9f.) understand mitigation not in the sense of a classic insurance contract but as "self-protection" in the sense of Ehrlich and Becker (1972), meaning a real action that leads to the reduction of perceived risk via a reduced likelihood of the occurrence of an unfavourable event. Some real action that increases the ecosystem's resilience – e.g. vegetation management, installing pumps etc. – may thus be interpreted as insurance, as it reduces the probability of an income loss.

Baumgärtner and Strunz (2010) specify the riskiness of the income lottery as its risk premium Π, i.e. the (maximum) amount of money that the ecosystem user would be willing to pay to receive the expected income for sure instead of having to play the risky income lottery:

$$u(\mathrm{E}_R[y] - \Pi) = \mathrm{E}_R[u(y)]. \tag{9}$$

The *economic insurance value* of ecosystem resilience is then defined as the "change of the risk premium Π of the income lottery R due to a marginal change in the level of resilience R" (ibid., p. 11):

$$I(R) := -\frac{d\Pi(R)}{dR}, \tag{10}$$

where the minus sign is included to express a reduction in the risk premium as a positive value.

The insurance value of ecosystem resilience is, however, only a part of the total economic value of resilience (ibid., p. 12), which is given by the maximum willingness to pay (WTP) per unit for a marginal increase of the level of resilience R, i.e.

$$V(R) := \lim_{\Delta R \to 0} \frac{WTP(\Delta R)}{\Delta R}, \tag{11}$$

where $WTP(\Delta R)$ is defined by $\mathrm{E}_R[u(y)] = \mathrm{E}_{R+\Delta R}[u(y - WTP(\Delta R))]$.

By explicating the general definition of the risk premium given in Equation (9) with the CARA-utility function given in Equation (8), Baumgärtner and Strunz (2010) derive the risk premium $\Pi(R)$ as

$$\Pi(R) = -p(R)\Delta y + \frac{1}{\rho}\ln\left[1 + p(R)(e^{\rho\Delta y} - 1)\right]. \tag{12}$$

The insurance value of resilience $I(R)$ can then be easily derived using Equations (10) and (12). It is given by

$$I(R) = p'(R)\left\{\Delta y - \frac{1}{\rho}\frac{e^{\rho\Delta y} - 1}{1 + p(R)(e^{\rho\Delta y} - 1)}\right\} \tag{13}$$

and has the following properties (see Baumgärtner and Strunz (2010, p. 13f.)):

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

$$I(R) \left\{\begin{matrix} < \\ = \\ > \end{matrix}\right\} 0 \quad \text{for} \quad R \left\{\begin{matrix} < \\ = \\ > \end{matrix}\right\} \tilde{R}, \tag{14}$$

where $\tilde{R}$ is defined by $\tilde{R} := p^{-1}\left(\frac{1}{\rho\Delta y} - \frac{1}{e^{\rho\Delta y}-1}\right)$, with $\frac{d\tilde{R}}{d\rho}, \frac{d\tilde{R}}{d\Delta y} > 0, \frac{d\tilde{R}}{d\sigma} < 0$.

(ii) The insurance value increases globally with resilience:

$$I(0) < I(1), \tag{15}$$

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

$$\frac{dI(R)}{d\rho} \begin{Bmatrix} < \\ = \\ > \end{Bmatrix} 0 \quad \text{for} \quad R \begin{Bmatrix} < \\ = \\ > \end{Bmatrix} \tilde{R} \quad \text{and} \quad \lim_{\rho \to 0} I(R) = 0, \tag{16}$$

$$\frac{dI(R)}{d\Delta y} \begin{Bmatrix} < \\ = \\ > \end{Bmatrix} 0 \quad \text{for} \quad R \begin{Bmatrix} < \\ = \\ > \end{Bmatrix} \tilde{R} \quad \text{and} \quad \lim_{\Delta y \to 0} I(R) = 0, \tag{17}$$

$$\frac{dI(R)}{d\sigma} \begin{Bmatrix} < \\ = \\ > \\ = \\ < \end{Bmatrix} 0 \quad \text{for} \quad R \begin{Bmatrix} R < \underline{R} \\ R = \underline{R} \\ \underline{R} < R < \overline{R} \\ R = \overline{R} \\ R > \overline{R} \end{Bmatrix} \tilde{R}, \tag{18}$$

with $\underline{R} < R < \overline{R}$. See Appendices A.1 and A.2 in Baumgärtner and Strunz (2010) for proofs.

From these theoretical derivations, it is evident that the insurance value $I(R)$ of resilience depends (i) on objective risk characteristics, i.e. the level of resilience R as well as the corresponding flip probability $p(R)$, (ii) the income loss due to a flip from the high to the low productivity regime Δy, and (iii) the ecosystem user's risk preferences, here defined by the the coefficient of CARA ρ (cf. Equation (13)). Furthermore, the insurance value of resilience increases globally with the level of resilience (cf. Equation (15)), while the insurance value can be both negative and positive, depending on the level of resilience (cf. Equation (14)) – being negative for low levels and positive for high levels of resilience. Moreover, the effects of changes in the subjective risk preferences (cf. Equation (16)), in the size of the income loss (cf. Equation (17)), as well as in the ecosystem elasticity (cf. Equation (18)), on the insurance value of resilience depend on the level of resilience and a certain, variable threshold value of resilience ($\tilde{R}$), which represents the level of resilience for which the income lottery is most risky (Baumgärtner and Strunz, 2010, p. 15; p. 18ff.).

Baumgärtner and Strunz (2010, p. 21; Appendix A.3) furthermore show that the total economic value of resilience is given by

$$V(R) = -p(R)\frac{1}{\rho}\frac{e^{\rho\Delta y} - 1}{1 + p(R)(e^{\rho\Delta y} - 1)}\,, \tag{19}$$

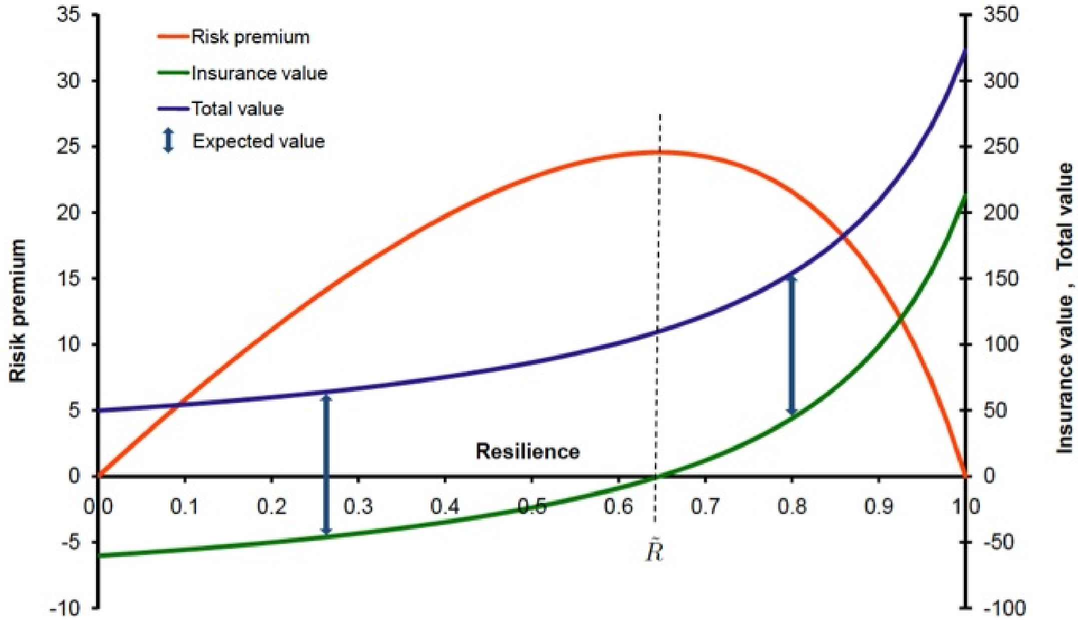

Figure 6: *Overview of the different components of resilience from Baumgärtner and Strunz (2010) I.*

This Fig. provides an overview of the different components of resilience. The risk premium (orange-), insurance value (green-), total value of resilience (blue curve) and expected value (double-headed arrow) have been calculated for the whole interval of possible levels of resilience with the following parameter values: $\sigma = 0$, $\Delta y = 110$, $\rho = 0.017$. Taken from Baumgärtner and Strunz (2010, p. 18).

and has the following properties

(i)

$$V(R) \equiv -p'(R)\Delta y + I(R) \tag{20}$$

(ii)

$$V(R) \geq 0 \quad \text{for all} \quad R. \tag{21}$$

The total economic value of resilience is thus positive irrespective of the level of resilience (cf. Equation (21)), while the insurance value of resilience is one additive component of its total value, together with the expected increase in income due to a marginal increase in the level of resilience (cf. Equation (20)). This reflects the fact that an increase in resilience has two effects: First, it will raise expected income and, second, it may raise or lower the (perceived) riskiness of income.

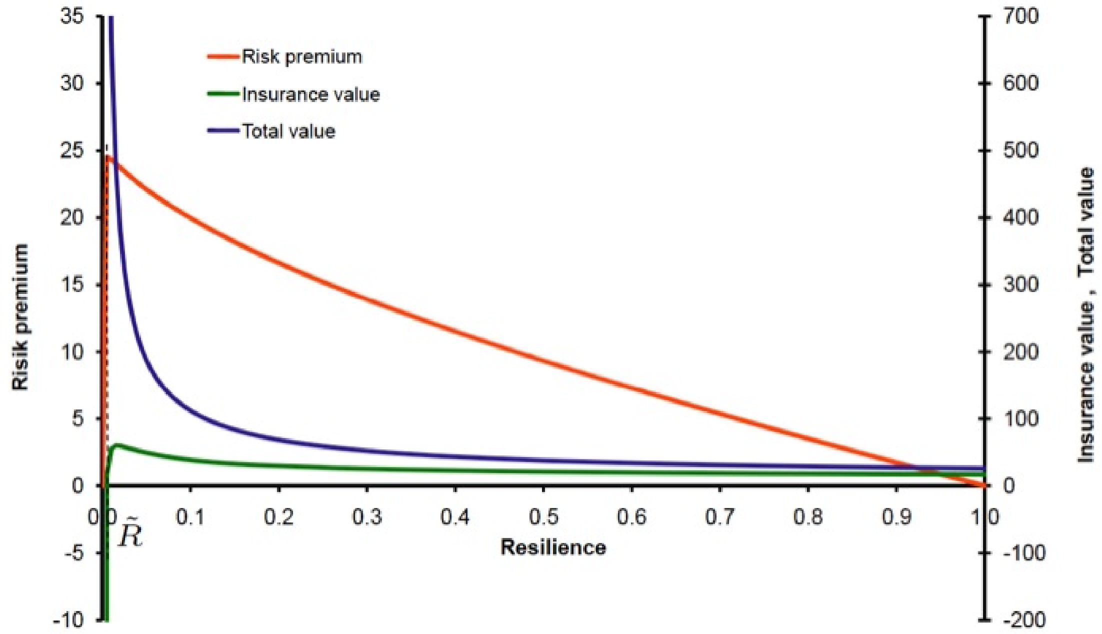

Figure 7: *Overview of the different components of resilience from Baumgärtner and Strunz (2010) II.*

This Fig. again provides an overview of the different components of resilience for different parameter values: $\sigma = 0.92$, $\Delta y = 110$, $\rho = 0.017$; The only difference to Fig. 6 is the very large and positive ecosystem elasticity, i.e. the flip probability decreases more than proportionally as the level of resilience increases (cf. Baumgärtner and Strunz (2010, p. 7)). Taken from Baumgärtner and Strunz (2010, p. 19).

These findings are further illustrated in Figs. 6 and 7, whose main purpose here is to emphasize how strongly the magnitude of the insurance value of ecosystem resilience depends on the ecosystem elasticity σ.

4.3 The quantification model

In the following, the models of Walker et al. (2010) and Baumgärtner and Strunz (2010) are combined and extended in order to facilitate an evaluation of the insurance value of ecosystem resilience in the GBC case. This shall be achieved by integrating the dynamic flip probability of Walker et al. (2010) for different discrete time horizons into the static model of Baumgärtner and Strunz (2010). Furthermore, the ecosystem user – here an Australian farmer – is assumed to exhibit constant relative risk aversion (CRRA), judged to be a more realistic assumption than CARA (see, e.g., Kingwell (1994)).

Following Walker et al. (2010, p. 189), resilience at the farm level is specified as the "resilience of crop production in the [GBC] to variations in the [ground-]water table" for a 40-year time horizon. Walker et al. (2010), however, have not analysed single specific farms but provided an estimate of the economic value of resilience for the whole system, implicitly assuming that the water table dynamics are similar on all farms. Since it is beyond the scope of this study to analyse the insurance value of resilience for all heterogeneous farms in the GBC, it will be assumed that all individual farms are assumed to be symmetric.

The representative farmer faces a binary (net present) income lottery that only varies with the level of resilience R_0 for a given time horizon m and, following Baumgärtner and Strunz (2010), is assumed to only care about income and not about other characteristics of the two regimes (e.g. about other use- or non-use values that are connected to certain ecosystem services). It is further assumed that net present income (assessed as the net present value of land rents) is only a part of the farmer's total wealth. Since the net present value of land rents obviously depends on the time horizon, I will denote net present income in the salinized regime as $y_L(m)$, net present income in the current, productive regime as $y_H(m)$ and $\Delta y(m)$ as the net income loss, i.e. $y_H(m) - y_L(m) > 0$.[17]

The flip probability is taken from the model of Walker et al. (2010), where the cumulative flip probability f is given by one minus the cumulative survival probability (cf. Equations (4) and (5)), depending on the time horizon m and the (initial) level of resilience R_0:

$$f(R_0; m) = 1 - \prod_{t=1}^{m} \left(1 - 0.4583e^{-2.75R_t}\right), \tag{22}$$

with R_t following a certain, later specified process depending on the initial level of resilience R_0. The flip probability decreases with an increasing resilience level and is, ceteris paribus, higher for longer time horizons.[18]

The binary income lottery for a discrete time horizon m is thus:

[17]Note that y_L, and y_H respectively, also depend on the time horizon m in the following evaluation, with e.g. $y_L(m) = \sum_{t=1}^{m} y_{L,t} \frac{1}{(1+\psi)^t}$, where $y_L(m)$ is the net present value of land rents in the salinized regime for time horizon m, ψ the yearly discount rate and $y_{L,t}$ the yearly land rents.

[18]That the flip probability is c.p. higher for longer time horizons is intuitively clear but impossible to verify via derivation. The derivation of p$(\cdot)$ with respect to R_0, however, can be shown to be negative: $\frac{dp(R_0;m)}{dR_0} = \sum_{k=1}^{m} (\underbrace{-\theta e^{-\eta R_i}}_{<0} \eta \underbrace{\frac{\partial R_i}{\partial R_0}}_{>0}) \underbrace{\prod_{t=1;t\neq i}^{m} \left(1 - \theta e^{-\eta R_t}\right)}_{>0} < 0.$

$\{y_L(m), y_H(m);\ f(R_0;m), (1-f(R_0;m))\}$.

Using the von Neumann-Morgenstern expected utility function described in Equation (7) and assuming a CRRA utility function specification in the form of

$$u(y) = \frac{1}{1-\rho} y^{1-\rho}, \quad \text{with} \quad \rho \equiv \text{coefficient of CRRA} \quad \text{and} \quad \rho \neq 1;^{19}\ \rho > 0,^{20} \tag{23}$$

the general definition of a risk premium (cf. Equation (9)) can be explicated as follows:

$$\begin{aligned} &\frac{1}{1-\rho}\left[f(R_0;m)y_L(m) + (1-f(R_0;m))y_H(m) - \Pi(R_0;m)\right]^{1-\rho} = \\ &\quad f(R_0;m)\frac{1}{1-\rho}(y_L(m))^{1-\rho} + (1-f(R_0;m))\frac{1}{1-\rho}(y_H(m))^{1-\rho}, \end{aligned} \tag{24}$$

which can be rearranged by crossing out $\frac{1}{1-\rho}$ to

$$\begin{aligned} &\left[f(R_0;m)y_L(m) + (1-f(R_0;m))y_H(m) - \Pi(R_0;m)\right]^{1-\rho} = \\ &\quad f(R_0;m)(y_L(m))^{1-\rho} + (1-f(R_0;m))(y_H(m))^{1-\rho} \end{aligned} \tag{25}$$

and solved for the risk premium $\Pi(R_0;m)$:

$$\begin{aligned} \Pi(R_0;m) =& f(R_0;m)y_L(m) + (1-f(R_0;m))y_H(m) - \\ & \left[f(R_0;m)(y_L(m))^{1-\rho} + (1-f(R_0;m))(y_H(m))^{1-\rho}\right]^{\frac{1}{1-\rho}}. \end{aligned} \tag{26}$$

The risk premium thus depends on the (initial) level of resilience R_0, the time horizon m, the degree of risk aversion ρ as well as the relation between the net benefits in the two regimes $\Delta y(m)$.

The insurance value of resilience, i.e. the marginal value of resilience's function to reduce the risk premium of the Australian farmer by operating in this risky environment, can now be calculated according to Equations (10) and (26). Note in particular the minus sign included in Equation (10) to express a reduction in the risk premium as a positive value.

[19]Note that $\rho = 1$ leads to $u(y) = ln(y)$; calculating the insurance value for this special case is not pursued here as it is extremely unlikely that ρ is exactly equal to unity empirically.

[20]Note that $\rho > 0$ implies risk-averse behaviour ($\rho = 0$ would describe a risk neutral and $\rho < 0$ a risk-seeking individual. Assuming a risk-averse behaviour by our representative farmer in the GBC seems to be the most plausible case and is also confirmed by the literature review on risk version in Section 5.1.1. All theoretic results derived hereafter, however, also hold for $\rho < 0$.

The insurance value of resilience is given by

$$I(R_0;m) = -\frac{d\Pi(R_0;m)}{dR_0} = -f'(\cdot)\left[y_L(m) - .y_H(m)\right] + \\ \frac{1}{1-\rho} f'(\cdot)\left[y_L(m) - .y_H(m)\right]^{1-\rho}\left[f(\cdot)y_L(m)^{1-\rho} + (1-f(\cdot))y_H(m)^{1-\rho}\right]^{\frac{\rho}{1-\rho}} \tag{27}$$

and can be rearranged to

$$I(R_0;m) = f'(\cdot)\Delta y(m) - \\ \frac{1}{1-\rho} f'(\cdot)(\Delta y(m))^{1-\rho}\left[f(\cdot)y_L(m)^{1-\rho} + (1-f(\cdot))y_H(m)^{1-\rho}\right]^{\frac{\rho}{1-\rho}} \tag{28}$$

and further simplified to

$$I(R_0;m) = f'(R_0;m) \times \\ \left\{\Delta y(m) - \frac{1}{1-\rho}(\Delta y(m))^{1-\rho}\left[f(R_0;m)y_L(m)^{1-\rho} + (1-f(R_0;m))y_H(m)^{1-\rho}\right]^{\frac{\rho}{1-\rho}}\right\}. \tag{29}$$

The effects of an increase in the level of resilience R_0, in the degree of risk aversion ρ, and the income loss in case of a regime shift $\Delta y(m)$ on the insurance value will again depend on some specific initial level of resilience and its development path over time (corresponding to $\tilde{R}$ in the model of Baumgärtner and Strunz (2010)). An analytical verification of this is, however, beyond the scope of this study, as in particular the dynamic flip probability function leads to results that are not easily interpretable. Nonetheless, the elaboration of the model has served its purpose, as it will now be possible to present a first attempt of quantifying the insuance value of resilience in the next section building on this modelling framework.

5 Evaluation

In this section, I provide a first estimate of the insurance value of ecosystem resilience (cf. Equation (29)) for the presented GBC case study for the *normal* climate forecast from Walker et al. (2010). Before the insurance value itself is calculated in Section 5.2, I will discuss the necessary inputs – the degree of risk aversion ρ, present net income in the two regimes $y_H(m)$ and $y_L(m)$, as well as the specification of the cumulative flip probability $f(R_0;m)$ – in separate subsections.

5.1 Preliminaries

5.1.1 Risk aversion

One of the most important inputs to the model is the assumed degree of risk aversion of the farmers in the GBC. The aim of this subsection is to clarify what types of risk aversion empirical studies have found to be prevalent and, in particular, to determine a suitable value for the coefficient of relative risk aversion for the latter evaluation of the insurance value of resilience in the GBC. To this end, a literature review on the type and degree of risk aversion among Australian farmers has been conducted.

Bond and Wonder (1980) conduct a survey of 201 farmers throughout Australia and find that these are mostly risk-averse, while the type of risk-aversion is not specified. Due to shortcomings in the interview process, only tentative conclusions can be drawn from this study. Bardsley and Harris (1987) estimate the risk attitude of Australian farmers with an econometric method using a combination of cross-sectional and time-series data from broadacre agriculture concerning the comparison of a farmer's financing and production decision. They find Australian broadacre farmers to be risk averse and estimate a partial coefficient of risk aversion that decreases with wealth and increases with income and ranges from 0.072 to 0.696. Quiggin (1981) estimate a coefficient of absolute risk aversion, roughly similar to Bond and Wonder's (1980) estimate in size (i.e. very small) but also only of an indicative nature as only a very small number of farmers have been interviewed. Abadi Ghadim et al. (2005) examine risk attitude of 114 West-Australian chickpea farmers and estimate a CARA coefficient of 0,000055. Kingwell (1994) builds a model to describe dryland farming in Western Australia and assumes CARA risk aversion in the range of 0.000003 to 0.000005, where the 0.000003 CARA measure re-expressed as a coefficient of relative risk aversion (CRRA) is equal to 0.78 (ibid., p. 194). Kingwell (1994, p. 195) furthermore acknowledges that a CRRA specification may be more suitable.

Besides concluding that Australian famers can be assumed to be risk averse, there is support for the argument that a CRRA specification may be a better description of the farmer's real risk preferences as a CARA specification, which is nonetheless more often estimated in the presented studies. It may also be stated that the evidence is rather sparse and partly outdated, while many studies are of a rather indicative nature. It therefore seems most suitable to rely on an estimate of CRRA that is close to 0.78 (cf. Kingwell, 1994) and to perform a sensitivity analysis with respect to this coefficient, as uncertainty about its size is high and the impact on the insurance value of resilience may be substantial.

5.1.2 Income loss due to a regime shift

For calculating the insurance value of resilience, we need to know the net present benefits (income) in the two alternate regimes, while present means that we need to discount future net benefits up to the time horizon m with the discount rate per month provided in Walker et al. (2010, p. 196): $\sigma = 0.04/12$.[21] As referred to above, Walker et al. (2010) have calculated the net benefit streams based on net present value calculations of land rents. These present values of the land per hectare were estimated to be \$448.29 for dairy- and \$723.00 for horticultural land in the initial high production regime, while these values diminish by 90% (99%) in the case of dairy (horticultural) land if the system flips to the alternate, salinized regime (see Table 1 in Walker et al. (2010, p. 194)). Our income values $y_H(m)$ and $y_L(m)$ have thus (assumably) been calculated according to the following Equation

$$y_{L/H}(m) = \sum_{t=1}^{m} y_{L/H,t} \frac{1}{(1+\psi)^t}, \tag{30}$$

where $y_{L/H,t}$ represents the annual land rent (in \$/ha) for dairy and horticultural land multiplied by the respective total land area in the salinized (L) and productive (H) regime, and ψ represents the annual discount rate. Since it is not further explained in Walker et al. (2010) how the land rents were forecasted for the time period under scrutiny, I can only rely on the estimates provided for the terminal 480-month time horizon. For my calculations below, m thus equal 480 and I will use the present values of land rents provided in Table 1 in Walker et al. (2010, p. 194). It should also be noted with respect to Table 1, that the analysis conducted here only concerns those parts of the GBC that may be subject to salinization.

[21] By simply using the discount rate provided in Walker et al. (2010), the complex ethical argument on which discount rate would be appropriate shall not be masked and it would be most suitable to also perform a sensitivity analysis with respect to the discount rate. However, since the focus of this paper is the insurance value, which is more substantially influenced by the degree of risk aversion, a sensitivity analysis with respect to this parameter may suffice.

The necessary input to our quantification model can thus be specified as:

$$\begin{aligned}
y_H(480) &= 192,000(ha) \times 448.29(\$/ha) + 19,200(ha) \times 723.00(\$/ha) && = 99,953,280\$ \\
y_L(480) &= 192,000(ha) \times 44.83(\$/ha) + 19,200(ha) \times 7.23(\$/ha) && = 8,746,176\$ \\
\Delta y(480) &= y_H(480) - y_L(480) && = 91,207,104\$
\end{aligned}$$

5.1.3 Flip probability

Estimating the flip probability is the most challenging part of resilience assessment. As has been explained in Section 4.1.2, the parameters of Walker et al. (2010)'s cumulative survival probability function have been estimated from a single bore in the GBC and rely on projections that e.g. do not take future changes due to (anthropogenic) climatic change into account. As referred to above, it is not possible to clearly verify or replicate the results derived by Walker et al. (2010) with the information and data provided in their paper. Furthermore, information provided via personal communication with the authors was contradictory to the statements made in the paper and also did not allow for a replication of the results.[22] I thus cannot rely on their original data of the *normal* climate forecast that underlies Fig. 5 for the following quantification. It was, however, possible to reach a result of the shadow price of resilience that is very close to the one provided in Walker et al. (2010) in an iterative assumption-based process, which shall be briefly described: In view of the lack of detailed knowledge, I made various assumptions about how the development of R_t may depend on the initial level of resilience R_0, given the information provided in the two scenarios in Walker et al. (2010). I used the fixed points about the development of the resilience stock provided in Walker et al. (2010, p.194) for the *normal* climate forecast: the resilience stock is 1m in the year 1991, rises to 1.5m in the year 2001 and falls again to 1m in the year 2030. The best fit to these fixed points and the shadow price of resilience (\$4,570,530) provided in Walker et al. (2010) is a linear interpolation in between the following data points: 1st month of 1991 (1m), 1st month of 2001 (1,5m) and last month of 2030 (1m). This linear interpolation leads to a reconstruction of the shadow price that is, with \$4,566,640, very close to the original value (in fact it is 99.92% of it). It must be noted that even though the shadow price of resilience is given per dm, the resilience stock that is included in the calculation of the cumulative survival and thus the cumulative

[22] The corresponding author, B. Walker, did not have access to the dataset and T. Baynes provided data that was not in accord with the description in the paper itself.

flip probability is measured in meters. Unfortunately, a good fit to the results provided in Walker et al. (2010) for the *dry* climate forecast could not be obtained.

Using this linearly interpolated development path of R_t, the cumulative flip probability $f(R_0; m)$ has been calculated using EXCEL according to Equation (22) for the terminal time horizon $m = 480$ to be 0.999559032554912 and the marginal change in the flip probability due to a 0.1m or 1dm rise in the resilience stock $f'(R_0; m)$ to be -0.00242259625439152.

5.2 Quantification of the insurance value of resilience

5.2.1 Calculation of the insurance value of resilience

Since all necessary inputs to the quantification of the insurance value have been gathered and discussed, we can proceed to the actual calculation. In order to do so, we may recapitulate Equation (29):

$$I(R_0; m) = f'(R_0; m) \times$$
$$\left\{ \Delta y(m) - \frac{1}{1-\rho} (\Delta y(m))^{1-\rho} \left[f(R_0; m) y_L(m)^{1-\rho} + (1 - f(R_0; m)) y_H(m)^{1-\rho} \right]^{\frac{\rho}{1-\rho}} \right\}.$$

With our inputs gathered in the previous section, the insurance value of resilience (in 1991 Australian dollars) in the year 1991 is calculated as:[23]

$$I(1; 480) = -0.0024 \times$$
$$\left\{ 91207104 - 4.5455 \times (91207104)^{0.22} \left[0.0004 \times 99953280^{0.22} + 0.9996 \times 8746176^{0.22} \right]^{3.5455} \right\}$$
$$= -59,461.$$

According to this quantification, the (estimated) economic insurance value of resilience (i.e. the reduction in the risk premium due to a 1dm increase in the initial level of resilience) in the year 1991 for a 40-year time horizon in the GBC case for the *normal* climate forecast is -59,461\$. In this case, resilience does not function as insurance, as the riskiness of the income lottery is not reduced but increased by a marginal investment in resilience. As the magnitude of the insurance value is influenced by many different variables and parameters, in particular those of the cumulative flip probability, it can only be hypothesized about the driving factors for this result. In an attempt to shed some light on this issue, i.e. to scrutinize the robustness of this incidence, a sensitivity analysis with respect to the degree

[23] Note that only the fourth decimal place is represented here for succinctness.

of risk aversion is conducted in the following subsection. The finding will also be discussed more generally in the discussion and conclusion sections.

5.2.2 Sensitivity analysis

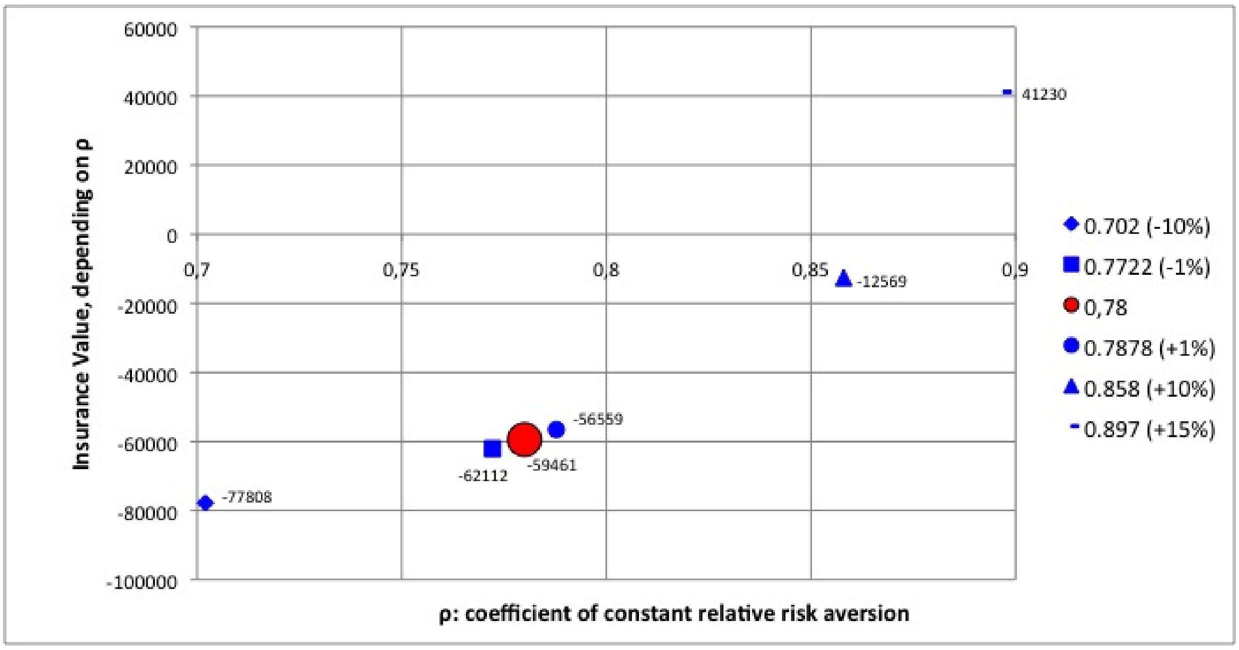

Figure 8: *Sensitivity analysis of the insurance value of resilience with respect to the degree of risk aversion.*

This Fig. depicts the sensitivity analysis of the insurance value of resilience (vertical axis) with respect to the CRRA coefficient ρ (horizontal axis). The thicker red point highlights the original assumption for ρ equalling 0.78, the changes in the CRRA coefficient are provided in percentage terms in brackets in the legend and the values of the insurance value for the alternative degrees of risk aversion next to the data points are given in 1991 Australian dollars. Source: Own calculation.

Since the degree of risk aversion, here in the form of the CRRA coefficient ρ, is the most important novel input to the model and a high degree of uncertainty exists with respect to its actual magnitude, a sensitivity analysis of the insurance value of resilience with respect to the CRRA coefficient is conducted using EXCEL – depicted in Fig. 8. The sensitivity analysis shows that the insurance value of resilience is indeed highly sensitive to the degree of risk aversion, as an increase in the initially assumed value of 0.78 by 1% leads to an increase in the insurance value of 4.8% and an increase in ρ of approximately 12% already leads to a positive insurance value. This underlines the importance of acquiring an estimate of the CRRA coefficient that is more thoroughly grounded in robust empirical evidence than could be done in this study.

Furthermore, the sensitivity analysis shows, in combination with Figs. 6 and 7 and the sensitivity analysis conducted in Walker et al. (2010, p. 199), how strongly the magnitude and sign of the insurance value depend on the system components whose magnitude is very difficult to verify with a sufficient degree of exactness.

6 Discussion

This paper is concerned with the quantification of the economic insurance value of resilience for the Goulburn-Broken Catchment (GBC) case study from South East Australia (see Walker et al. (2010)). Resilience – i.e. the ability of a system to withstand shocks and undergo change while keeping its basic function and properties in working order – has been identified as a key system property for the assessment of a sustainable development (see, e.g., Arrow et al. (1995), Bateman et al. (2011) and Kates et al. (2001)), but only few studies exist that scrutinize the economic assessment of resilience. Furthermore, most approaches have interpreted resilience as insurance in a rather metaphorical way (Baumgärtner and Strunz, 2010, p. 3) while it has been shown that the economic insurance value of resilience is only one part of the total economic value of resilience (ibid.). Analyzing the insurance value and the other component(s) of the total economic value of resilience separately is important as they might have different man-made substitutes – the insurance value of resilience may e.g. be substituted by ordinary financial insurance contracts while other functions of resilience may not (ibid., p. 23).

In order to quantify the economic insurance value of resilience for the GBC case study, this paper has presented and discussed the concept of resilience and described the relevant system components of the GBC. Furthermore, the approaches of Walker et al. (2010), who provide an estimate of the economic value of resilience for the GBC case study, and Baumgärtner and Strunz (2010), who develop a simple ecological-economic model to derive the economic insurance value of ecosystem resilience, have been briefly recapitulated.

Building on these two studies, a stylized (quasi-)dynamic, ecological-economic model has been elaborated, with which a first attempt at valuing the insurance value of resilience for the GBC case study can be made.

The quantification of the economic insurance value of resilience in the year 1991 for a 40-year time horizon has produced a value of -59,461 Australian dollars for the *normal* climate forecast of the GBC case study. This means that resilience does not function as insurance in this case, as a marginal investment in resilience increases the riskiness of the income lottery instead of lowering it. A sensitivity analysis, however, reveals that this incidence highly depends on the assumed degree of risk aversion of farmers in the GBC, who are assumed to exhibit constant relative risk aversion with a coefficient value of 0.78. The analysis has shown that already increasing the coefficient of risk aversion by not more than 12% leads to a positive insurance value. Together with the theoretical results derived by Baumgärtner and Strunz (2010) – in particular the dependency of the insurance value on the "ecosystem elasticity" presented in Figs. 6 and 7 – this highlights how little such results about the magnitude of the insurance value are generalizable as they are dependent on so many factors for which detailed knowledge is often sparse.

In particular because of some very crude assumptions that had to be made for the quantification and the high uncertainty about the actual degree of risk aversion of farmers in the GBC, the result provided here is only of a very tentative nature. Some of the major assumptions that limit the explanatory power of the quantification result shall be briefly recapitulated:

1. Market prices of land rents have been used to calculate the shadow price of land in the two regimes, which were assumed to be constant throughout the 40-year time horizon (this is a caveat that Walker et al. (2010, p. 199) discuss in more detail);

2. Analysing this specified resilience necessitates the ceteris paribus assumption that all other relevant variables, some of which are most certainly not independent of water table dynamics, remain constant throughout the time frame of the analysis;

3. Although the analysis of water table dynamics as the key variable influencing the resilience of crop production in the GBC has been chosen with a focus on the situation of a single farmer, both Walker et al. (2010) and this study have assessed resilience for the GBC system as a whole. I have made the explicit assumption that all farmers in the GBC have the same risk preferences and are equally affected by changes in the water table (the data presented in Walker et al. (2010) are only based on historical water table changes from one bore in a central location in the GBC). Furthermore, it

must be noted that the cumulative survival probability function used in this study is only an imperfect fit to the original data from Walker et al. (2010), which were not sufficiently obtainable.

This discussion of the strong assumptions that had to be made for the resilience assessment in this study and that of Walker et al. (2010) represents a good starting point for a more general discussion on problems associated with the economic assessment of specified resilience. Since the capital pricing approach to resilience assessment developed by Mäler and others (see in particular Mäler and Li (2010)) analyses specified resilience in a *Knightian risk* setting, detailed knowledge is in particular required about the location of the threshold and the cumulative probability that the system flips to the alternate regime. The fact that even economic resilience assessment for the GBC case analysed in this paper, which is deemed to be one of the best-studied ecosystems in the world (Walker and Salt, 2006, p. 40), still has to rely on these very crude assumptions presented above, strongly calls into question the universal applicability of this approach. Besides data availability seeming to be the most important limiting factor for elevating resilience assessment to a broader scale, the 'dimensional' reductionism of analysing one key variable only, on whose changes a possible regime shift depends, also represents a problem for more realistic resilience assessments (this challenge has been noted by Walker et al. (2010) but deferred for further research). The major problem with this reductionism is that if we focus too much on a specified resilience relationship that is driven by one key variable only, we might let other variables of the system degrade that will in turn threaten the resilience of the system from a very different angle (i.e. a narrow focus on specified resilience may lead to a lower general resilience of a system (cf. Walker and Salt (2006, p. 121))). So even though most economic approaches to resilience assessment have focused on specified resilience up to this point, as this offers the opportunity of an assumption- and proxy-based quantification, the analysis of general resilience should always be pursued simultaneously to account for the various interactions that might threaten the sustainable development of a given system (this is what Walker et al. (2009; 2010) have done, albeit in two separate papers and different groups of authors).

In terms of making recommendations for further research, I will concentrate on the work conducted in this paper before I will turn to presenting a more general concluding outlook in section 7. As discussed above and also noted by Walker et al. (2010, p. 199), acquiring better knowledge on the flip probability is crucial (see their sensitivity analysis in Table 3 (ibid.) for an indication on how the magnitude of the 1991 resilience price per dm changes if other values of the parameters of the cumulative survival probability function had been used). However, obtaining this would necessitate to also rely on more bore observations, which is beyond the scope of this study.

One task for further research clearly is to refine the quantification model. It might in particular be enquired whether the results obtained by Baumgärtner and Strunz (2010) on how the insurance value depends on its properties and on how the components of the total economic value of resilience relate to one another with a CRRA utility specification.

Furthermore, it would be interesting to calculate the insurance value of resilience not only for the 480-month time horizon but also for shorter ones. This was not possible in the present study, as Walker et al. (2010) only provided the net present value for the 40-year time horizon and not the data on land rents in the year 1991. Furthermore, it would be an illuminating exercise to also quantify the economic insurance value of resilience for the *dry* climate forecast – which was impossible to include in this study as the development of the resilience stock for this forecast proved to be not replicable and the data was not obtainable from Walker et al. (2010).

A clear imperative for further research has also resulted from the literature review on empirical estimates of the degree of risk aversion of Australian farmers (cf. Section 5.1.1) and the sensitivity analysis of the insurance value with respect to the degree of risk aversion (cf. Section 5.2.2), as meaningful estimates of the economic insurance value of resilience can only be obtained if they are rooted in more robust empirical evidence on risk aversion. Although the most relevant literature for Australia has been searched, it might be worthwhile to acquire estimates from other world regions that have socio-economic-environmental comparable characteristics, i.e. where highly professionalized farmers also face the threat of salinization or other threats to soil fertility such as desertification.

7 Conclusion

To sum up, this paper has provided a modelling and assessment approach with which the economic insurance value of ecosystem resilience can be quantified. It has found that the estimated insurance value is negative for the original specifications made for the evaluation – i.e. resilience does not seem to function as insurance in this case. Yet, a sensitivity analysis has revealed that the magnitude and also the sign of the insurance value are very sensitive to the (assumed) degree of risk aversion.

Furthermore, there are various problems with the underlying data and the presented approach of quantifying the insurance value had to rely on the use of proxies in the major stages of the evaluation process:

1. Market prices have been used instead of shadow prices for the calculation of the income loss due to a regime shift;

2. The flip probability has been estimated based on observations from one bore only and assumed to be similar all across the region;

3. Insufficient empirical evidence could be gathered for a reasonably robust estimate of the degree of risk aversion.

Because of these discussed shortcoming in the evaluation of the total economic value- as well as the insurance value of ecosystem resilience, it seems questionable that this specified resilience assessment can make major contributions to the practice of sustainability measurement and management, as the data requirements are very high.

Yet, such a specified resilience assessment would in particular be needed for creating really encompassing measures of progress such as the Inclusive Wealth Indicator (see Mäler (2008) and Walker et al. (2010)) and up to this date, the capital pricing approach, this paper has relied on, is the most advanced existing method for accounting for ecosystem resilience. As it is a necessary input to making efficient decisions that secure the livelihoods of people around the world who are threatened from the abrupt loss of critical ecosystem services, further research on this topic is certainly required.

Acknowledgments

I am deeply thankful to Stefan Baumgärtner for introducing me to resilience thinking and for (co-)hosting the working group on *Sustainability Economics* within the Social Sciences College 2009–2011 of the German National Academic Foundation, from which the idea for this thesis emerged. I have benefited from helpful discussions with Martin Quaas, Johannes Geibel, David Löw-Beer and Florian Baumann and am furthermore grateful to Tim Baynes and Brian Walker for their willingness to share (parts of their) data.

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