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Research

Consumer Preferences Determine Resilience of Ecological-Economic Systems

*Stefan Baumgärtner*¹, *Sandra Derissen*², *Martin F. Quaas*², and *Sebastian Strunz*¹

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

Key Words: *consumption; ecological-economic systems; ecosystem services; natural resource management; preferences; resilience*

INTRODUCTION

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

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

As the system undergoes a regime shift and flips from one basin of attraction with more desirable ecosystem service provision, from the anthropocentric point of view based on valuation of ecosystem services, to a basin of attraction with less desirable ecosystem service provision, humans will assess this change as a deterioration in ecosystem service provision, or even as a “catastrophic” shift (Scheffer et al. 2001). Such system flips may threaten the intertemporal efficiency of resource management and the intergenerational equity of

ecosystem services use from this system, and may thus impair a sustainable development (Arrow et al. 1995, Perrings 2001, 2006, Mäler 2008, Derissen et al. 2011).

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

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

A decrease in the resilience of some desired state in a coupled ecological-economic system, i.e., a decrease in the

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

MODEL

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

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

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

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

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

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

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

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

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

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

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

$$c^{\text{prod}} = \nu_x x e_x \quad (6)$$

$$h^{\text{prod}} = \nu_w w e_w \quad (7)$$

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

$$C = m_x c^{\text{prod}} \quad (8)$$

$$H = m_w h^{\text{prod}} \quad (9)$$

Assume that each household inelastically supplies one unit of labor, so that total labor supply of the economy is equal to

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

$$Y = \omega (n - m_x e_x - m_w e_w) \quad (10)$$

ANALYSIS

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

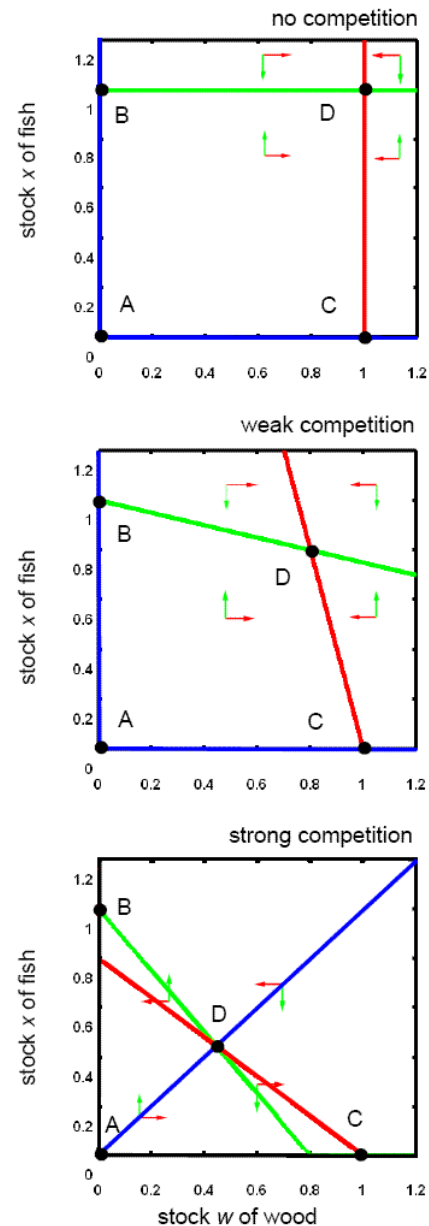
Natural dynamics

In the absence of any resource harvesting by society, the system's dynamics are completely determined by the natural dynamics of the two resource stocks of fish and wood, described by Equations (2) to (5) with $C = H = 0$. This scenario goes back to Lotka (1932) and Volterra (1926) and sets the benchmark against which we then study the influence of harvesting and consumer preferences on resilience.

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

Other than D, the system has three more equilibria: A ($x = w = 0$), B ($x = 1, w = 0$) and C ($x = 0, w = 1$). In the absence of interspecies competition ($\gamma_x = \gamma_w = 0$), it is obvious from the state-space representation (Fig. 1, upper diagram) that A is an unstable equilibrium, whereas B and C are locally saddlepoint-stable equilibria. The basin of attraction corresponding to the only stable equilibrium, D, comprises the entire state space

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



with the exception of the axes ($x = 0, w \geq 0$) and ($x \geq 0, w = 0$). From any system state in this domain the system will automatically converge toward equilibrium D. Therefore, equilibrium D is (almost) globally stable, where the “almost” refers to the exception of the axes. In terms of resilience, (almost) every state of the natural system is therefore characterized by (almost) unlimited resilience.

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

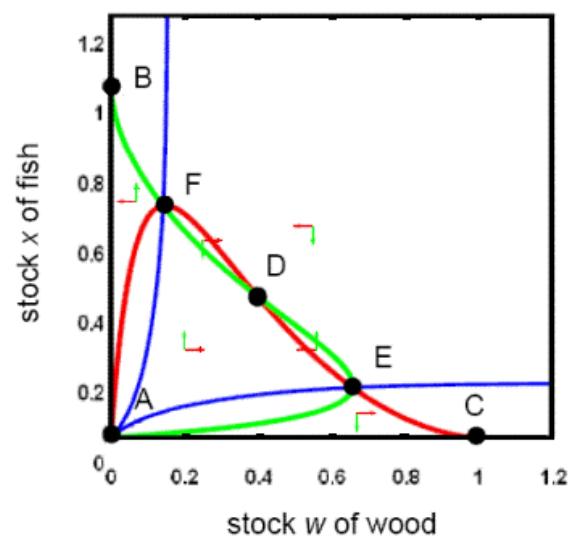
If interspecies competition is stronger than intra-species competition ($\gamma_i > 1$; Fig. 1, lower diagram), this changes fundamentally as point D no longer represents an (almost) globally stable equilibrium. D is now only saddlepoint-stable, but B and C are locally stable. Hence, the system exhibits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

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

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

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

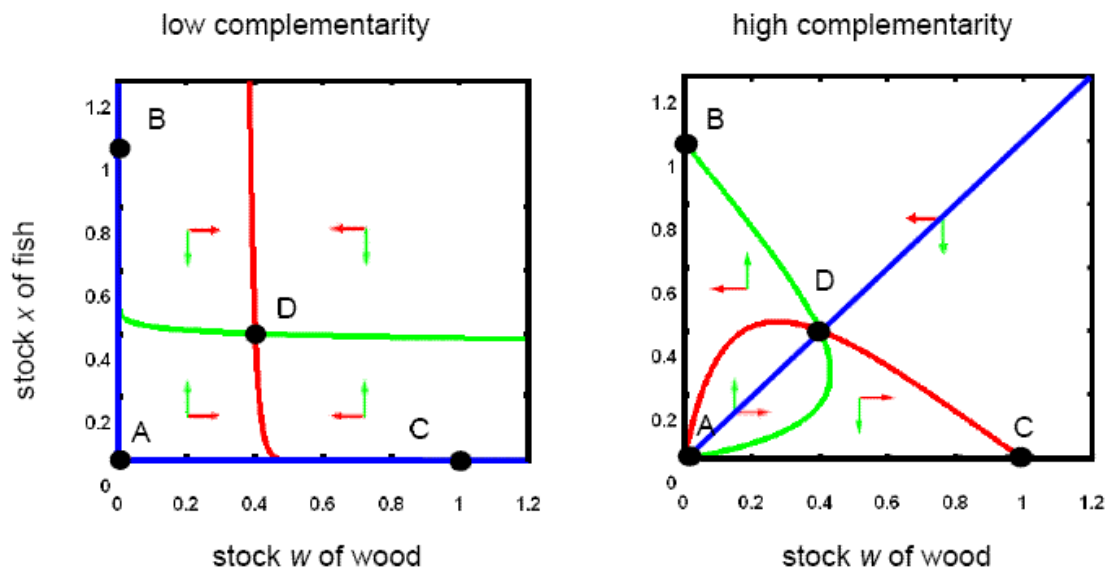
Fig. 2. Phase diagram for the ecosystem’s dynamics under open access and profit-maximizing harvesting. Dynamics are characterized by $dx/dt > 0$ (< 0) left (right) of the green line, and $dw/dt > 0$ (< 0) below (above) the red line. A is an unstable equilibrium; E and F are locally saddlepoint-stable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



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

It is obvious that the particular resource management institution considered here, i.e., open access to ecosystems of profit-maximizing harvesting firms, has fundamentally altered the resilience properties of the ecosystem. Although in the absence of resource harvesting and not-too-strong

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



interspecies competition there exists only one (almost) globally stable equilibrium, so that (almost) every state of the system is characterized by (almost) unlimited resilience, under open access to ecosystems of profit-maximizing harvesting firms the system has three locally stable equilibria. Each of those has an associated basin of attraction that comprises only a limited part of the state space, so that the system may flip from one basin of attraction to another one as a result of exogenous disturbance. In particular, equilibrium D (with both resource species in existence) and any state in its basin of attraction have only limited resilience, and any of those states may be disturbed in a way that the system flips into another basin of attraction with another locally stable equilibrium characterized by extinction of one or the other species.

Complementarity and relative importance of ecosystem services in consumption decrease resilience

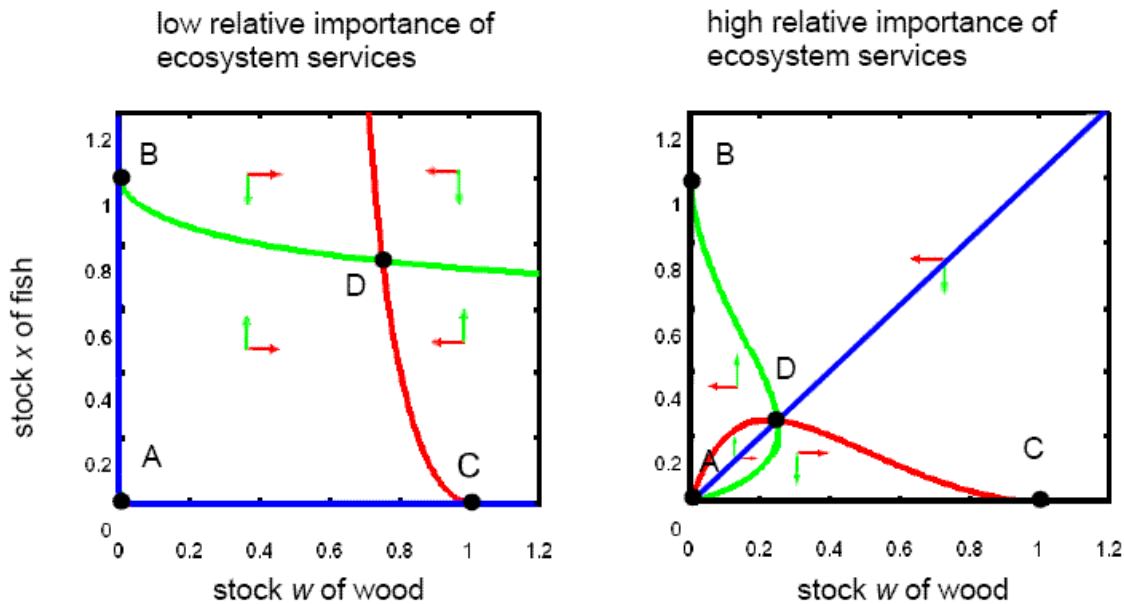
Consumer preferences about ecosystem services and manufactured goods are a significant determinant of an ecosystem's resilience properties. This is demonstrated here by illustrating for the institutional setting considered previously, i.e., open access to ecosystems of profit-

maximizing harvesting firms, how a change in the elasticity of substitution σ between the consumption of fish and timber, and how a change in the relative importance of ecosystem services α , affect the resilience properties of the ecosystem.

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

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

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



of the system in its basin of attraction are characterized by (almost) unlimited resilience.

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

Consumer preferences influence the ecological-economic system's resilience properties also via the relative importance of ecosystem services in the consumer's utility function, α . If

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

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

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

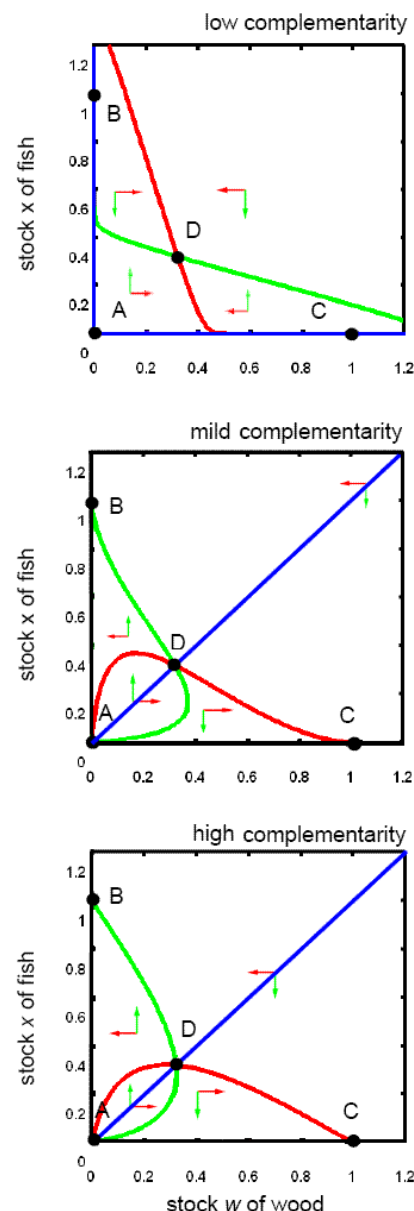
The general insight from the analysis so far is that resilience of the interior equilibrium with both resource species in existence (point D) tends to decrease (i) with increasing complementarity, i.e., decreasing elasticity of substitution, between the two ecosystem services in consumption and (ii)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

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

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

The destabilizing effect of increasing interspecies competition also occurs under resource harvesting. This is shown in Figure 6 for a given level of resource complementarity.

Fig. 5. Phase diagrams for the ecosystem's dynamics with interspecies competition for different levels of complementarity between ecosystem services in consumption, σ . Dynamics in each diagram are characterized by $dx/dt > 0$ (< 0) left (right) of the green line, and $dw/dt > 0$ (< 0) below (above) the red line. Blue lines indicate saddlepaths. The upper diagram shows the case of low complementarity ($\sigma = 0.95$), the middle diagram displays mild complementarity ($\sigma = 0.4$) and the lower diagram high complementarity ($\sigma = 0.05$). Parameter values for all diagrams: $\rho_x = \rho_w = 0.5$, $\kappa_x = \kappa_w = 1$, $\gamma_x = \gamma_w = 0.25$, $v_x = v_w = 1$, $\alpha = 0.6$, $n = 1$.



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

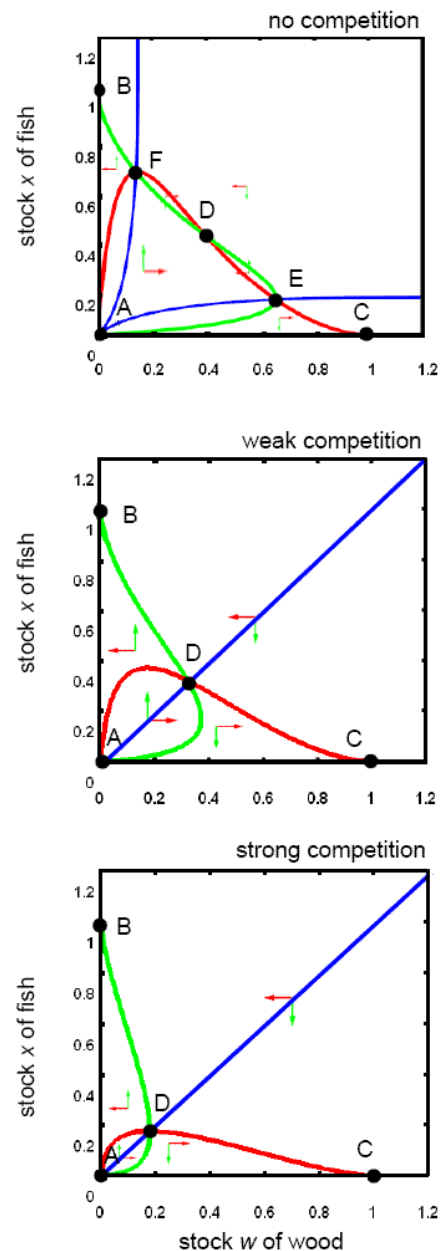
Comparing Figure 6 to Figure 1 shows that the effects on resilience of increasing interspecies competition are also present under economic resource use. In Figure 6 however, as equilibrium D's resilience is already decreased by resource harvesting and consumer preferences, low levels of species competition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

DISCUSSION AND CONCLUSION

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

We have identified three destabilizing effects that genuinely stem from consumer preferences in an ecological system used for economic purposes. First, we have shown that profit-maximizing harvesting by competitive firms under open access to the ecosystem considerably weakens the resilience of the interior equilibrium of the coupled ecological-economic system as compared to the natural dynamics. Second, we have shown that complementarity of ecosystem services in consumption significantly reduces the resilience of the system's interior equilibrium where both species are in existence. The economic logic behind this result is the following: out of two complementary ecosystem services, the scarcer one is limiting the benefits from ecosystem service use. Hence, under an institutional setting of open access, this ecosystem service is the one to which harvesting is directed primarily. The increased harvesting effort, in turn, reduces the abundance of that resource even further, thus leading to self-reinforcing dynamics.

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



Third, we have shown that an increased relative importance of ecosystem services for the consumer's well-being destabilizes the system. The economic logic behind this result is the following: if consumers' well-being derives to a larger degree from ecosystem services, the share of their budget spent on ecosystem services increases. In a market economy and under open access to resource, this leads to an increase in harvesting pressure, which reduces the potential for sustainable resource use. Conversely, if the consumer's well-being does not, or only to a small degree, derive from consuming ecosystem services, harvesting pressure on the ecosystem is very low and it displays an almost globally resilient interior equilibrium. These three preference-effects act in addition to the ecological mechanisms that are well-known to destabilize an ecological-economic system and to give rise to multiple basins of attraction and limited resilience: increased competition between species and low intrinsic growth rates (e.g., Scheffer 2009).

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

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

Responses to this article can be read online at:

<http://www.ecologyandsociety.org/vol16/iss4/art9/responses/>

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APPENDIX1. Analytical solution of the model.

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

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

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

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

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

Profits of representative firms harvesting fish and timber are given by

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

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

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

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

$$p_w = \frac{\omega}{\nu_w} w^{-1}. \quad (\text{A.7})$$

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

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

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

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

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

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

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

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

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

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