Earth Syst. Dynam. Discuss., doi:10.5194/esd-2016-15, 2016
Manuscript under review for journal Earth Syst. Dynam.
Published: 30 May 2016

Sustainable use of renewable resources in a stylized social-ecological network model under heterogeneous resource distribution

Wolfram Barfuss[1,2], Jonathan F. Donges[1,3], Marc Wiedermann[1,2], and Wolfgang Lucht[1,4]

[1]Potsdam Institute for Climate Impact Research, Telegrafenberg A31, 14473 Potsdam, Germany
[2]Department of Physics, Humboldt University, Newtonstraße 15, 12489 Berlin, Germany
[3]Stockholm Resilience Centre, Stockholm University, Kräftriket 2B, 114 19 Stockholm, Sweden
[4]Department of Geography, Humboldt University, Unter den Linden 6, 10099 Berlin, Germany

Correspondence to: Wolfram Barfuss (barfuss@pik-potsdam.de)

Abstract. Human societies depend on the resources ecosystems provide. Particularly since the last century, human activities have transformed the relationship between nature and society at a global scale. We study this coevolutionary relationship by utilizing a stylized model of regional resource use and preference formation on an adaptive social network. The latter process is based on two social key dynamics beyond economic paradigms: boundedly rational imitation of resource use preferences and homophily in the formation of social network ties. The private and logistically growing resources are harvested either with a sustainable (small) or non-sustainable (large) effort. We show that these social processes can have a profound influence on the environmental state, such as determining whether the private renewable resources collapse from overuse or not. Additionally, we demonstrate that heterogeneously distributed regional resource capacities shift the critical social parameters (social-ecological tipping points) where this resource extraction system collapses. We make these points to argue that, in more advanced coevolutionary models of the planetary social-ecological system, such socio-cultural phenomena as well as regional resource heterogeneities should receive attention in addition to the processes represented in established Earth system and integrated assessment models.

1 Introduction: resource use in social-ecological systems

Whether, when and how human usage of biophysical resources meets limits that produce feedbacks onto social functioning has a long history of controversial discussion (Malthus, 1872; Meadows et al., 1972; Rockström et al., 2009). Especially in the last century, human activities have changed the relationship between nature and society at the global scale (Crutzen, 2002; Steffen et al., 2007, 2015a), making them mutually interdependent in an unprecedented manner and the question of their joint dynamics urgent. Social and ecological systems should therefore be studied not only in isolation but also as interlinked social-ecological systems (SES) (Berkes and Folke, 1998). Here, we contribute to this debate by investigating properties of a stylized social system that cause the linked resource use system to either collapse or remain viable.

Such a perspective also has important implications for the mathematical modeling of interdependent, global human-environment interactions (Verburg et al., 2015; van Vuuren et al., 2015). Typically, in present-day analysis the Earth system is either modeled from a purely biophysical point of view (Claussen et al., 2002) or from a biophysical-economic one (van Vuuren et al., 2012).

However, both approaches largely lack a free coevolution of the social and ecological components (Schellnhuber, 1998, 1999) taking into account factors beyond macroeconomic optimization paradigms.

We here conceptually explore avenues for potential future World-Earth system modeling that are founded on a genuinely social-ecological perspective. While sophisticated models of this type are not yet available, the literature contains various modeling studies that incorporate potentially important features such as static interaction networks (Chung et al., 2013; Sugiarto et al., 2015) to depict stylized social dynamics (Holme and Newman, 2006; Auer et al., 2015), tele-coupling effects in a globalized society interacting through social networks (Janssen et al., 2006; Bodin and Tengö, 2012), social-ecological regime shifts (Scheffer et al., 2001; Lade et al., 2013) and (social) tipping elements (Schellnhuber, 2009; Bentley et al., 2014), structural re-organization occurring on adaptive social networks (Gross and Blasius, 2008; Snijders et al., 2010; Sayama et al., 2013; Schleussner et al., 2015) or structural transformations (Lade et al., in prep.) and cultural preference dynamics due to traits such as imitation (Traulsen et al., 2010) or homophily (McPherson et al., 2001; Centola et al., 2007).

We set out a simple model (see Sect. 2) to demonstrate that social network interactions, cultural preferences and homophily may have a profound influence on the environmental state, such as determining whether a private regional renewable resource collapses from overuse or not. We argue that more elaborate and sophisticated implementations of such social phenomena should receive attention in the future development of Earth system and integrated assessment models, neither of which at present include them.

As a particular case study for our model we examine the effect of heterogeneously distributed resources. This is important since in the real world agents do have access to different amounts of biophysical resources. Our study examines under which combinations of parameters characterizing a social preference network the model converges to a sustainable regime for different degrees of resource heterogeneity. Parameters governing social preference dynamics are on the one hand a homophily parameter ϕ, addressing the propensity of nodes to establish interactions with nodes of the same kind (see Sect. 2 for a detailed model description). On the other hand, the timescale of social interaction τ quantifies the average time for social updates on the network, expressed in relation to the growth timescale of the ecological resources. Already in the homogeneous case (Wiedermann et al., 2015) one observes a tipping in the parameter space of the model from non-sustainable to sustainable regimes at certain critical values ϕ_c and τ_c. Since the concrete heterogeneous resource distribution is often unknown, we show systematically how an increasing heterogeneity - starting from an almost homogeneous distribution - affects the critical transition parameters ϕ_c and τ_c. Additionally we show that in our stylized model a heavy-tailed resource distribution in comparison to a non-heavy-tailed distribution changes the model's behavior considerably. This is important as real-world resource data suggests that access to biophysical resources may indeed be distributed with heavy-tails.

2 Model Description

An overview of the model is provided in Fig. 1. It is based on an adaptive social network initialized as a random graph $G(V,E)$ (Erdös and Rényi, 1960) where the nodes $V = \{v_1, \ldots, v_N\}$ harvest their private renewable resource with either a sustainable or non-sustainable strategy. This represents two distinct social preferences: i) long-term sustainable yields and ii) short-term profit

Earth Syst. Dynam. Discuss., doi:10.5194/esd-2016-15, 2016
Manuscript under review for journal Earth Syst. Dynam.
Published: 30 May 2016

maximization. The resulting harvest rates h_i are used to update the node's strategies S_i (for $i = 1 \dots N$) through social preference interactions along the edges E of the network, which follow two key principles: *imitation* and *homophily*. The nodes are thought of as macro-agents that agree upon a resource use strategy, such as countries or international organizations. Note that interactions among the nodes are mediated solely over the social network and not through a widely examined common-pool resource (Ostrom, 2015). Wiedermann et al. (2015) introduced the model for homogeneously distributed resources, demonstrated transitions and distinct regimes in its parameter space and provided analytical approximations of its dynamics.

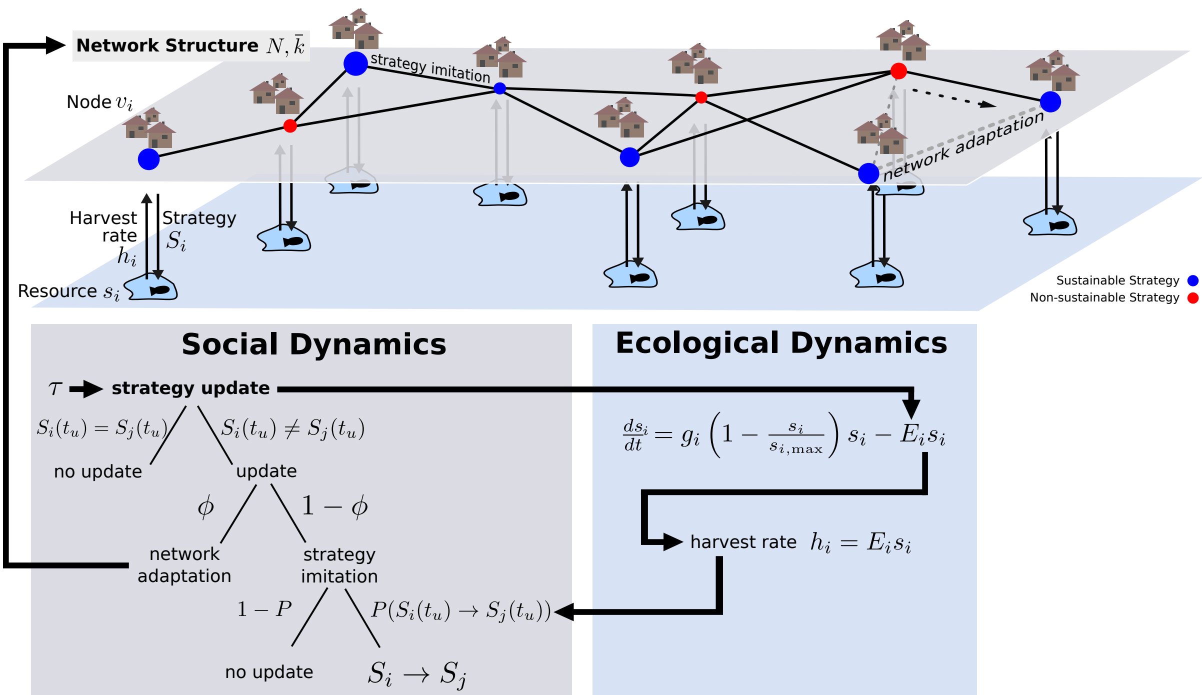

Figure 1. Illustration of our stylized social-ecological model. As the ecological sub-process the nodes harvest their private logistically growing renewable resource with either a sustainable (blue) or non-sustainable (red) strategy. The social sub-process follows the logics of strategy imitation due to comparisons of harvest rates and of social network adaptation due to homophily. The strategy update times are generated by a Poisson process with average inter-event time τ.

2.1 A stylized anthroposphere

The social module is guided by two principles of interaction in a social network. Nodes either change their strategy through boundedly rational *imitation* (Traulsen et al., 2010; Bahar et al., 2014) or homophilic adaptation, i.e. the nodes adapt their local network structure by connecting to other nodes with similar behavior (*homophily*, McPherson et al. (2001); Centola et al. (2007)). In order to integrate this discrete update process (Holme and Newman, 2006; Zanette and Gil, 2006) with the continuous evolution of the resource stocks, *social update times* t_i are assigned to the agents as generated by a Poisson process

Earth Syst. Dynam. Discuss., doi:10.5194/esd-2016-15, 2016
Manuscript under review for journal Earth Syst. Dynam.
Published: 30 May 2016

with an exponential distribution

$$p(\Delta t_i;\tau) = \frac{1}{\tau}\exp\left(\frac{-\Delta t_i}{\tau}\right) \tag{1}$$

of waiting times Δt_i, where the parameter τ gives the expected waiting time.

Thus, node v_i with the lowest update time in the queue performs the social update process according to:

- (1) if the degree of node v_i is zero (i.e. v_i has no neighbors), do nothing, otherwise choose a neighbor v_j of v_i at random.
- (2) If v_j and v_i employ the same harvesting strategy $S_i = S_j$ (either sustainable or non-sustainable), do nothing. Otherwise,
- (2.1) with probability ϕ disconnect v_j from v_i and connect v_i to a randomly chosen node v_k that employs the same strategy.
- (2.2) If (2.1) was not chosen, change the strategy of v_i to the one of v_j according to the sigmoidal imitation probability function

  $$P(S_i \to S_j) = \frac{1}{2}\left(\tanh\left(\gamma\left[h_j(t) - h_i(t)\right]\right) + 1\right) \tag{2}$$

  that is motivated by empirical studies of strategy updating in humans (Traulsen et al., 2010). Hence, the greater the harvest rate h_j (see below) of v_j with respect to the harvest rate h_i of v_i, the more likely node v_i is to change its strategy to the one of node v_j. Nodes only consider their current yields when formulating their next harvesting strategy. This assumption reflects boundedly rational agent behaviour in the form of limited knowledge of macro-agents of their own and their neighbors' ecosystems. The parameter γ controls the slope of the imitation probability function (Eq. (2)), i.e. for $\gamma \to \infty$ node v_i would always imitate node v_j's strategy if $h_j(t) > h_i(t)$, while for $\gamma \to 0$ the imitation probability tends to $1/2$ and is independent of the agents' harvest rates. Therefore, one can interpret γ as *imitation tendency* parameter.
- (3) For the next update, another waiting time is drawn from the exponential distribution (Eq. (1)) and added to the update time of node v_i.

2.2 A stylized ecosphere

2.2.1 Regional resource dynamics

The ecological module of our model consists of private regional renewable resources each following a logistic growth function, which is chosen as one of the simplest and most commonly used models of renewable resource dynamics in a constrained environment (Brander and Taylor, 1998; Keeling, 2000; Perman et al., 2003). Additionally, a harvest rate $h_i = E_i s_i$ is subtracted from the rate of change of the resource stocks s_i. E_i denotes the *effort* of node v_i. Thus, the dynamics of the ith resource is given by

$$\frac{ds_i}{dt} = g_i\left(1 - \frac{s_i}{s_{i,\max}}\right)s_i - E_i s_i. \tag{3}$$

Earth Syst. Dynam. Discuss., doi:10.5194/esd-2016-15, 2016
Manuscript under review for journal Earth Syst. Dynam.
Published: 30 May 2016

Here, g_i denotes the growth rate, $s_{i,\max}$ the maximum stock (also commonly referred to as *carrying capacity*) of the *i*th resource stock. For the sake of simplicity we allow the nodes to employ only one of two strategies S for harvesting their resources. The strategy S_i of node v_i can either be sustainable ($S_i = 1$), resulting in an effort $E_{i,s} = \frac{g_i}{2}$. Otherwise S_i is non-sustainable ($S_i = 0$) with an effort $E_{i,n} = \frac{3g_i}{2}$. These efforts have been chosen such that the sustainable strategy results in a continuously optimal harvest, whereas the non-sustainable strategy leads to the full depletion of the resource stock and, consequently, no harvest at all in the long term. Note that $E_{i,n}$ and $E_{i,s}$ are symmetrically separated from the critical effort $E_{i,c} = g_i$. The latter is defined such that for positive efforts below $E_{i,c}$ the resource stock converges to a non-zero stationary state, whereas for efforts above $E_{i,c}$ the resource stock collapses and converges to zero.

2.2.2 Resource heterogeneity

Resource heterogeneity is operationalized by randomly distributing the resource capacities $s_{i,\max}$ according to a prescribed probability density function. For this purpose, we examine the log-normal distribution

$$\ln\mathcal{N}(s_{\max};\mu,\sigma) = \frac{1}{s_{\max}\sigma\sqrt{2\pi}} \exp\left[-\frac{(\ln s_{\max}-\mu)^2}{2\sigma^2}\right], \quad s_{\max} > 0, \tag{4}$$

with parameters μ and σ. It is derived from the normal distribution: a positive random variable is log-normally distributed if its logarithm is normally distributed. The log-normal distribution is therefore applicable for positive valued quantities and has a heavy tail. σ and μ are the standard deviation and the mean of the logarithmized variable $\ln s_{max}$, respectively. The log-normal distribution is present in variables from many fields, including biological and economic attributes (Sachs, 1984).

We study exemplary empirical distributions of three different types of resources to illustrate that real-world resource data can be qualitatively described by a log-normal distribution (Fig. 2) with least square fits revealing different σ parameters: (i) forested land area[1] per country ($\sigma = 3.83$) for the year 1991, (ii) biocapacity[2] per country ($\sigma = 1.42$) computed from the Ecological Footprint Network (Ewing et al., 2008) representing the capacity of ecosystems to regenerate what people extract, and (iii) total renewable water resources data[3] ($\sigma = 1.98$) characterizing the maximum yearly amount of water available to each country for the year 2012. Although the agreement between the log-normal distribution and the data is far from perfect, Fig. 2 supports the use of a log-normal model for resource heterogeneity in modeling our stylized social-ecological system.

We utilize this distribution to investigate how resource heterogeneity affects the behavior of the model in comparison to the frequently studied homogeneous case. We systematically increase parameter σ of the log-normal distribution (not to be confused with the standard deviation of s_{max}) which can be interpreted as a *resource heterogeneity* parameter and study the resulting behavior of the model. This is done while keeping the mean of s_{max} and, consequently, the cumulative carrying capacity of all resource stocks constant, i.e. the parameter μ was adjusted according to $\mu(\sigma) = -\sigma^2/2$, resulting in a fixed value of one for the mean of s_{max}. Hence, we only ask for the effect of different resource distributions and keep the total amount of available resource stock constant.

[1] downloaded at http://faostat3.fao.org/download/R/RL/E on November 24, 2015
[2] downloaded at http://www.footprintnetwork.org/images/uploads/NFA_2010_Results.xls on October 14, 2014
[3] downloaded at http://www.fao.org/nr/water/aquastat/data/query/index.html?lang=en on November 25, 2015

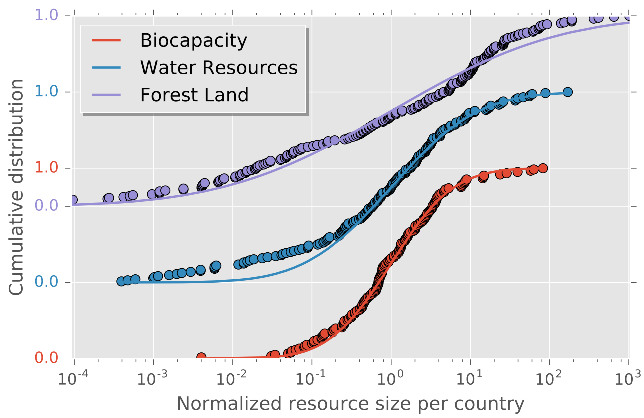

Figure 2. Empirical resource data per country normalized to the respective average (dots) together with least-square fitted log-normal distributions (lines): The Biocapacity ($\sigma = 1.42$) computed from the Ecological Footprint Network (Ewing et al., 2008) represents the capacity of ecosystems to regenerate what people demand from them for the year 2007; the Total Renewable Water Resources ($\sigma = 1.98$) corresponds to the maximum theoretical yearly amount of water actually available for a country for the year 2012; Forest land area per country ($\sigma = 3.83$) for the year 1991. The data are normalized to yield the same parameter $\mu = 0$ of the log-normal distribution and are shifted along the y-axis for the sake of visibility. Note that the data qualitatively fits the log-normal distribution and that they give different values for the σ parameters of the log-normal distribution.

For comparison we also present results for non-heavy tailed resource capacities

$$s_{\max} = |s_{\max}^{\mathrm{tmp}}| \quad \text{where} \quad s_{\max}^{\mathrm{tmp}} \sim \mathcal{N}(s_{\max}^{\mathrm{tmp}}; \mu_{\mathcal{N}}, \sigma_{\mathcal{N}}) = \frac{1}{\sigma_{\mathcal{N}}\sqrt{2\pi}} \exp\left[-\frac{(s_{\max}^{\mathrm{tmp}} - \mu_{\mathcal{N}})^2}{2\sigma_{\mathcal{N}}^2}\right] \tag{5}$$

where now $\mu_{\mathcal{N}}$ denotes the mean and $\sigma_{\mathcal{N}}$ the standard deviation of the underlying normal distribution. We also keep the mean fixed ($\mu_{\mathcal{N}} = 1$) and systematically increase the resource heterogeneity $\sigma_{\mathcal{N}}$ on comparable ranges of variances for both - normal and log-normal - distributions. Since the normal distribution is not bounded to positive values, we use the absolute value of the drawn random variable as the resource's carrying capacity $s_{i,\max}$.

2.3 Modeling protocol

A model run starts with an initial condition of stocks $s_i(0)$ uniformly distributed between 0 and $s_{i,\max}$ and harvesting strategies $S_i(0)$ drawn with a probability of 0.5 for a sustainable strategy $S_i = 1$ or a non-sustainable strategy $S_i = 0$. From the initial conditions, the model will converge to the *consensus state* at t_f, where no further strategy updates will occur. This is the case because the social network will consist solely of disconnected components with only one harvesting strategy (including the case of one single component) (Wiedermann et al., 2015). The remaining model parameters are the number of nodes $N = 500$, mean degree $\bar{k} = 20$, imitation tendency $\gamma = 1$ and ecological growth rate $g_i = 1$ for $i = 1, \ldots N$ which are kept fixed throughout the analysis. To account for the stochasticity inherent in the model, we perform $R = 250$ runs for each parameter setting of interest.

Earth Syst. Dynam. Discuss., doi:10.5194/esd-2016-15, 2016
Manuscript under review for journal Earth Syst. Dynam.
Published: 30 May 2016

Earth System Dynamics
Discussions
Open Access

We are interested in the fraction of sustainably harvesting nodes at the consensus state

$$\langle S(t_f)\rangle_{N,R} = \left\langle \frac{1}{N}\sum_{i=1}^{N} S_i(t_f) \right\rangle_R \tag{6}$$

averaged over all ensemble runs R. $\langle S(t_f)\rangle_{N,R}$ is bounded between one and zero where $\langle S(t_f)\rangle_{N,R} = 1(0)$ denotes a completely (non-)sustainable regime.

3 Results and discussion

3.1 Social interaction time scale–homophily parameter space

First, we study how the fraction of sustainably harvesting nodes at the consensus state $\langle S(t_f)\rangle_{N,R}$ (Eq. (6)) behaves in the parameter sub-space spanned by the rewiring probability ϕ (as a measure of the degree of homophily) and the average social interaction time scale τ for vanishing resource heterogeneity ($\sigma = 0.01$) (Fig. 3 a).

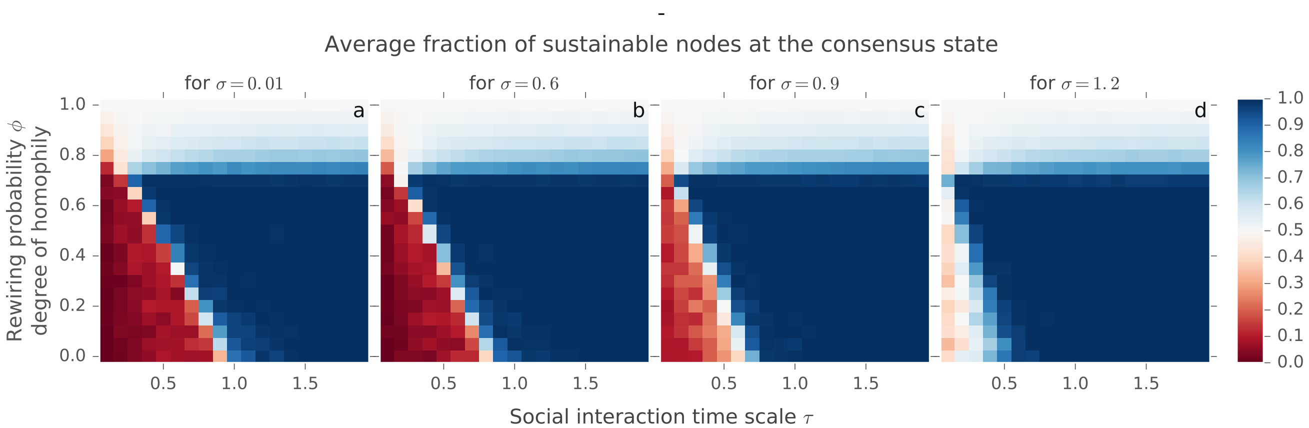

Figure 3. Social interaction time scale–homophily parameter space. Average fraction of sustainably harvesting agents in the consensus state depending on the social network rewiring probability ϕ (measuring the degree of homophily) and the social interaction time scale τ for four distinct levels of resource heterogeneity (a: $\sigma = 0.01$; b: $\sigma = 0.6$; c: $\sigma = 0.9$ d:$\sigma = 1.2$). One observes four qualitatively different regimes: (i) the sustainable regime for $\phi \lesssim 0.8$ and sufficiently large (slow) τ in blue, (ii) the non-sustainable or collapse regime for $\phi \lesssim 0.8$ and sufficiently small (fast) τ in red, (iii) in between both the transition regime in white as well as (iv) the network fragmentation regime for $\phi \gtrsim 0.8$.

Four qualitatively different regimes can be observed: the sustainable regime for $\phi \lesssim 0.8$ and sufficiently large τ (slow social interactions compared to resource growth rate) in blue, the non-sustainable or collapse regime for $\phi \lesssim 0.8$ and sufficiently small τ (fast social interactions compared to resource growth rate) in red, and the transition regime in white between these as well as above $\phi \gtrsim 0.8$ the network fragmentation transition. The latter occurs since for large ϕ, social dynamics is dominated by homophily and, hence, by the process of social network rewiring, and thus negligibly few changes in strategy occur. In this

Earth Syst. Dynam. Discuss., doi:10.5194/esd-2016-15, 2016
Manuscript under review for journal Earth Syst. Dynam.
Published: 30 May 2016

setting, the consensus state is reached by a fragmentation of the network into at least one purely sustainable and at least one purely non-sustainable component of comparable size. In turn, for $\phi \lesssim 0.8$, homophiliy is sufficiently weak such that most agents remain connected to a single component in the social network and, hence, a consensus between a large fraction of all agents is eventually found. In this setting, large interaction time scales τ lead to a sustainable regime because here, social interactions and thereby the comparison of harvest rates typically happen when the logistic resource has been harvested for a sufficiently long time to reveal that the harvest rate converges to a positive value for a sustainable strategy whereas for a non-sustainable strategy it converges to zero.

We furthermore observe a linear interrelationship between critical parameters ϕ_c and τ_c where the transition or social-ecological tipping point between collapse and sustainable regimes occurs (Fig. 3). This result can be explained by the rate at which strategy changes happen. For $\phi = 0$, these occur at $1/\tau = 1$, i.e. the ecological growth rate. For $\phi > 0$, imitation interactions happen at a rate $(1-\phi)/\tau$ (Wiedermann et al., 2015) since the network rewires with probability ϕ and, hence, imitation takes place with probability $1-\phi$. Hence, the effective imitation rate $(1-\phi)/\tau$ equals approx. 1 (the ecological growth rate) in the transition regime, which explains the linear dependence between the two social parameters.

These results demonstrate that immaterial processes distinct from macroeconomic optimization paradigms and residing exclusively in the social sphere, such as homophily and imitation, are capable of determining the eventual state of a material renewable resource. Thereby, these processes are able to govern a coupled social-ecological system such that full sustainability and total collapse are possible outcomes within the investigated social parameter space. Additionally, they show how the interaction of different social processes such as strategy imitation and homophily is able to shape the sustainable regime. This suggests that social-cultural processes should be considered as a potentially important part of feedback loops also in more elaborate models of the World-Earth system.

3.2 Systematic analysis of resource heterogeneity

We next investigate how the transition between sustainable and non-sustainable consensus states depends on the parameter σ governing resource heterogeneity. We observe a qualitatively similar structure of parameter space for varying degrees of resource heterogeneity, but observe a decreasing extent of the non-sustainable regime for increasing σ (Fig. 3a-d).

A more systematic analysis examines the average fraction of sustainably harvesting nodes at the consensus state $\langle S(t_f)\rangle_{N,R}$ for several segments of the parameter space spanned by τ, ϕ and the resource heterogeneity parameters σ ($\sigma_{\mathcal{N}}$), i.e. results are shown for both log-normally and normally distributed resource carrying capacities (Fig. 4). The ranges of σ for the log-normal and $\sigma_{\mathcal{N}}$ for the normal distribution are chosen such that they correspond to comparable standard deviations.

This analysis allows to explicitly show the effect of resource heterogeneity on the critical values τ_c (Fig. 4a,c) and ϕ_c (Fig. 4b,d), where the transition between the non-sustainable to the sustainable regime occurs. In general, the larger σ ($\sigma_{\mathcal{N}}$) the smaller τ_c and ϕ_c. In other words, a sustainable consensus state can be achieved for faster social interactions and smaller degrees of homophily, the larger resource heterogeneity is. The critical effective update time scale $\tau/(1-\phi) \stackrel{!}{=} \tau_{\text{eff,crit}}$ decreases to faster update times. This behavior is more pronounced for the log-normal distribution (Fig. 4a,b) than for the normal one (Fig. 4c,d) and can be explained by the heavy tails of the log-normal distribution. For a sufficiently large resource heterogeneity σ there

Earth Syst. Dynam. Discuss., doi:10.5194/esd-2016-15, 2016
Manuscript under review for journal Earth Syst. Dynam.
Published: 30 May 2016

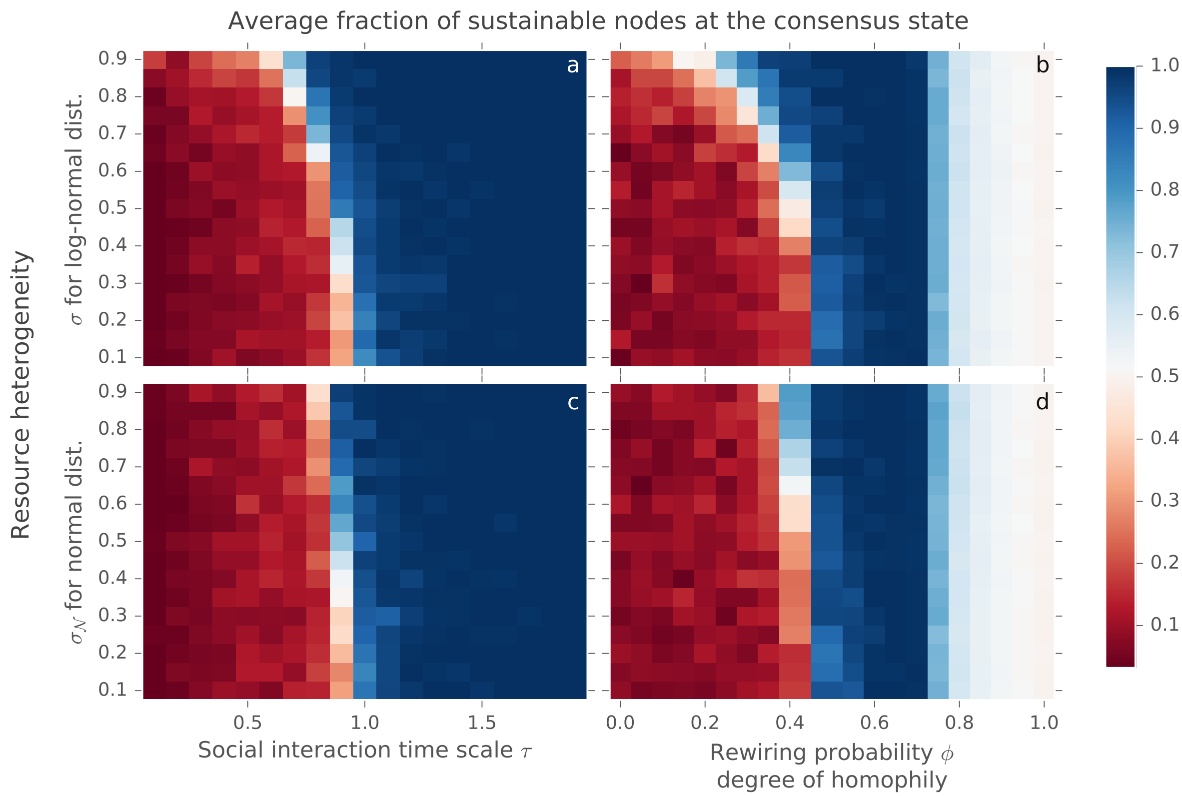

Figure 4. Effects of resource heterogeneity. Average fraction of sustainably harvesting nodes at the consensus state for several segments of parameter space: (a,b) for (heavy-tailed) log-normally distributed capacities, and (c,d) for (non-heavy-tailed) normally distributed capacities. Parameter spaces spanned by (a,c) social interaction time scale τ and resource heterogeneity σ ($\sigma_{\mathcal{N}}$) for rewiring probability $\phi = 0$, and (b,d) by ϕ and σ ($\sigma_{\mathcal{N}}$) for $\tau = 0.5$. The ranges of σ and $\sigma_{\mathcal{N}}$ were chosen such that the standard deviations of both distributions are comparable. For both distributions, the mean was fixed to 1. Note the considerable effect the log-normal resource capacity distribution (in comparison to the normal distribution) has on the critical values of τ and ϕ, where the transition between the sustainable and the non-sustainable regime occurs.

is a sufficiently high probability that some agents will be assigned a comparably large resource capacity. Non-sustainably harvesting agents exploit their resources exponentially, whereas sustainably harvesting agents with comparably large resource capacity can retain their resource stock at a level that is still sufficiently large to convince other nodes to become sustainable as well. In this way, comparably few sustainable first-movers with a large resource capacity are able to shift the overall system toward a sustainable state also at fast social interaction rates.

Earth Syst. Dynam. Discuss., doi:10.5194/esd-2016-15, 2016
Manuscript under review for journal Earth Syst. Dynam.
Published: 30 May 2016

Earth System Dynamics Discussions

4 Conclusions

In this paper, we have studied how social-ecological tipping points between sustainable and non-sustainable resource-use regimes depend on networked social interactions (related to imitation of harvesting strategies and homophily) under conditions of resource heterogeneity. We have employed a stylized model of networked agents harvesting private renewable resources with either a sustainable or non-sustainable strategy. The strategies employed by the agents are updated through a preference formation process on an adaptive social network reflecting an interconnected society. Resource heterogeneity is operationalized by log-normally and normally distributed carrying capacities of the resources.

We have shown that the properties of social processes such as preference formation by boundedly rational imitation and homophilic social network adaptation alone can precondition the long-term state of renewable resources with outcomes ranging from environmental collapse to sustainability. This observation is important because it highlights that following a purely economic rationale may lead to neglecting decisive processes when modeling coupled social-ecological systems and suggests that more sophisticated models of global coupled human-environment systems need to consider socio-cultural interactions and dynamics as well. Furthermore, we have shown that resource heterogeneities are important model ingredients that may not be neglected, especially when resource distributions possess heavy tails. This is relevant because our findings suggest that accessible biophysical resources may indeed follow heavy tailed distributions and, therefore, the resulting resource heterogeneities may have also have significant effects in more sophisticated modeling frameworks.

In the context of global change (Steffen et al., 2004) and the Anthropocene debate (Crutzen, 2002; Steffen et al., 2007, 2015a), such more advanced models of planetary social-ecological systems (World-Earth models) are needed for developing a deeper understanding of the dynamics and interrelations between planetary boundaries (Rockström et al., 2009; Steffen et al., 2015b) and social foundations (Raworth, 2012) for guiding humanity to a desirable safe and just operating space. Overall, our study highlights how socio-cultural (i.e. immaterial) dynamics and interactions can have a profound qualitative effect on physical (i.e. material) states of the environment and, consequently, that neither social processes nor resource heterogeneities should be neglected a priori in a more sophisticated modeling of the World-Earth system.

The code of our model (named `EXPLOIT`) in `Cython`, including a script to produce the results and related figures presented in this paper is available at github **https://github.com/wbarfuss/cyexploit**. For illustrative purposes, a `netlogo`-version can be downloaded as well: **https://github.com/wbarfuss/netlogo-exploit**

Acknowledgement. This work was developed in the context of the COPAN project on Coevolutionary Pathways in the Earth system at the Potsdam Institute for Climate Impact Research. WB is grateful for support from the Heinrich-Böll-Foundation. JFD thanks the Stordalen Foundation (via the Planetary Boundaries Research Network PB.net) and the Earth League's EarthDoc program for financial support. MW has been supported by the German Federal Ministry for Education and Research via the BMBF Young Investigators Group CoSy-CC^2 (grant no. 01LN1306A) We acknowledge Boyan Beronov for insightful discussions and his contributions to developing a high-performance software implementation of the `EXPLOIT` model as well as Vera Heck for her helpful comments on the manuscript.

References

Auer, S., Heitzig, J., Kornek, U., Schöll, E., and Kurths, J.: The Dynamics of Coalition Formation on Complex Networks, Scientific Reports, 5, 1–7, doi:10.1038/srep13386, 2015.

Bahar, D., Hausmann, R., and Hidalgo, C. A.: Neighbors and the evolution of the comparative advantage of nations: Evidence of international knowledge diffusion?, Journal of International Economics, 92, 111–123, 2014.

Bentley, R., Maddison, E. J., Ranner, P., Bissell, J., Caiado, C., Bhatanacharoen, P., Clark, T., Botha, M., Akinbami, F., Hollow, M., et al.: Social tipping points and Earth systems dynamics, Frontiers in Environmental Science, 2, 35, 2014.

Berkes, F. and Folke, C., eds.: Linking social and ecological systems: management practices and social mechanisms for building resilience, Cambridge University Press, 1998.

Bodin, Ö. and Tengö, M.: Disentangling intangible social–ecological systems, Global Environmental Change, 22, 430–439, 2012.

Brander, J. A. and Taylor, M. S.: The simple economics of Easter Island: A Ricardo-Malthus model of renewable resource use, American Economic Review, 88, 119–138, 1998.

Centola, D., Gonzalez-Avella, J. C., Eguiluz, V. M., and San Miguel, M.: Homophily, cultural drift, and the co-evolution of cultural groups, Journal of Conflict Resolution, 51, 905–929, 2007.

Chung, N. N., Chew, L. Y., and Lai, C. H.: Influence of network structure on cooperative dynamics in coupled socio-ecological systems, EPL (Europhysics Letters), 104, 28 003, 2013.

Claussen, M., Mysak, L., Weaver, A., Crucifix, M., Fichefet, T., Loutre, M.-F., Weber, S., Alcamo, J., Alexeev, V., Berger, A., et al.: Earth system models of intermediate complexity: closing the gap in the spectrum of climate system models, Climate Dynamics, 18, 579–586, 2002.

Crutzen, P. J.: Geology of mankind, Nature, 415, 23–23, 2002.

Erdös, P. and Rényi, A.: On the evolution of random graphs, Publ. Math. Inst. Hungar. Acad. Sci, 5, 17–61, 1960.

Ewing, B., Goldfinger, S., Wackernagel, M., Stechbart, M., Rizk, S. M., Reed, A., and Kitzes, J.: The Ecological Footprint Atlas 2008, Oakland: Global Footprint Network, 2008.

Gross, T. and Blasius, B.: Adaptive coevolutionary networks: a review, Journal of The Royal Society Interface, 5, 259–271, 2008.

Holme, P. and Newman, M. E.: Nonequilibrium phase transition in the coevolution of networks and opinions, Physical Review E, 74, 056 108, 2006.

Janssen, M. A., Bodin, Ö., Anderies, J. M., Elmqvist, T., Ernstson, H., McAllister, R. R., Olsson, P., and Ryan, P.: Toward a network perspective of the study of resilience in social-ecological systems, Ecology and Society, 11, 15, 2006.

Keeling, M. J.: Multiplicative moments and measures of persistence in ecology, Journal of Theoretical Biology, 205, 269–281, 2000.

Lade, S. J., Tavoni, A., Levin, S. A., and Schlüter, M.: Regime shifts in a social-ecological system, Theoretical Ecology, 6, 359–372, 2013.

Lade, S. J., Örjan, B., Donges, J. F., Enfors, E., Galafassi, D., Olsson, P., Österblom, H., and Schlüter, M.: Modelling social-ecological transformations: an adaptive network proposal, in prep.

Malthus, T. R.: An Essay on the Principle of Population Or a View of Its Past and Present Effects on Human Happiness, an Inquiry Into Our Prospects Respecting the Future Removal Or Mitigation of the Evils which it Occasions by Rev. TR Malthus, Reeves and Turner, 1872.

McPherson, M., Smith-Lovin, L., and Cook, J. M.: Birds of a feather: Homophily in social networks, Annual review of sociology, 27, 415–444, 2001.

Meadows, D. H., Goldsmith, E. I., and Meadows, P.: The limits to growth, vol. 381, Earth Island Limited London, 1972.

Ostrom, E.: Governing the commons, Cambridge university press, 2015.

Perman, R., Ma, Y., McGilvray, J., and Common, M.: Natural resource and environmental economics, Pearson Education, 2003.

Raworth, K.: A safe and just space for humanity: can we live within the doughnut, Oxfam Policy and Practice: Climate Change and Resilience, 8, 1–16, 2012.

Rockström, J., Steffen, W., Noone, K., et al.: A safe operating space for humanity, Nature, 461, 472–475, 2009.

Sachs, L.: Applied Statistics, Springer, 1984.

Sayama, H., Pestov, I., Schmidt, J., Bush, B. J., Wong, C., Yamanoi, J., and Gross, T.: Modeling complex systems with adaptive networks, Computers & Mathematics with Applications, 65, 1645–1664, 2013.

Scheffer, M., Carpenter, S., Foley, J. A., Folke, C., and Walker, B.: Catastrophic shifts in ecosystems, Nature, 413, 591–596, 2001.

Schellnhuber, H.-J.: Discourse: Earth System analysis—The scope of the challenge, in: Earth System Analysis, edited by Schellnhuber, H.-J. and Wenzel, V., pp. 3–195, Springer, 1998.

Schellnhuber, H.-J.: Earth system analysis and the second Copernican revolution, Nature, 402, C19–C23, 1999.

Schellnhuber, H. J.: Tipping elements in the Earth System, Proceedings of the National Academy of Sciences, 106, 20 561–20 563, 2009.

Schleussner, C.-F., Donges, J. F., Engemann, D. A., and Levermann, A.: Co-evolutionary behaviour selection in adaptive social networks predicts clustered marginalization of minorities, arXiv preprint arXiv:1512.05013, 2015.

Snijders, T. A., Van de Bunt, G. G., and Steglich, C. E.: Introduction to stochastic actor-based models for network dynamics, Social networks, 32, 44–60, 2010.

Steffen, W., Sanderson, R. A., Tyson, P. D., et al.: Global Change and the Earth System: A Planet Under Pressure, Springer, 2004.

Steffen, W., Crutzen, P. J., and McNeill, J. R.: The Anthropocene: are humans now overwhelming the great forces of nature, Ambio: A Journal of the Human Environment, 36, 614–621, 2007.

Steffen, W., Broadgate, W., Deutsch, L., Gaffney, O., and Ludwig, C.: The trajectory of the Anthropocene: The Great Acceleration, The Anthropocene Review, 2, 81–98, 2015a.

Steffen, W., Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M., Biggs, R., Carpenter, S. R., de Vries, W., de Wit, C. A., et al.: Planetary boundaries: Guiding human development on a changing planet, Science, 347, 1259 855, doi:10.1126/science.1259855, 2015b.

Sugiarto, H. S., Chung, N. N., Lai, C. H., and Chew, L. Y.: Socioecological regime shifts in the setting of complex social interactions, Phys. Rev. E, 91, 062 804, doi:10.1103/PhysRevE.91.062804, 2015.

Traulsen, A., Semmann, D., Sommerfeld, R. D., Krambeck, H.-J., and Milinski, M.: Human strategy updating in evolutionary games, Proceedings of the National Academy of Sciences, 107, 2962–2966, 2010.

van Vuuren, D. P., Bayer, L. B., Chuwah, C., Ganzeveld, L., Hazeleger, W., van den Hurk, B., van Noije, T., O'Neill, B., and Strengers, B. J.: A comprehensive view on climate change: coupling of earth system and integrated assessment models, Environmental Research Letters, 7, 024 012, 2012.

van Vuuren, D. P., Lucas, P. L., Häyhä, T., Cornell, S. E., and Stafford-Smith, M.: Horses for courses: analytical tools to explore planetary boundaries, Earth System Dynamics Discussions, 6, 1711–1741, doi:10.5194/esdd-6-1711-2015, 2015.

Verburg, P. H., Dearing, J. A., Dyke, J. G., van der Leeuw, S., Seitzinger, S., Steffen, W., and Syvitski, J.: Methods and approaches to modelling the Anthropocene, Global Environmental Change, doi:http://dx.doi.org/10.1016/j.gloenvcha.2015.08.007, 2015.

Wiedermann, M., Donges, J. F., Heitzig, J., Lucht, W., and Kurths, J.: Macroscopic description of complex adaptive networks coevolving with dynamic node states, Phys. Rev. E, 91, 052 801, doi:10.1103/PhysRevE.91.052801, 2015.

Earth Syst. Dynam. Discuss., doi:10.5194/esd-2016-15, 2016
Manuscript under review for journal Earth Syst. Dynam.
Published: 30 May 2016

Earth System Dynamics
Open Access
Discussions

Zanette, D. H. and Gil, S.: Opinion spreading and agent segregation on evolving networks, Physica D: Nonlinear Phenomena, 224, 156–165, 2006.