Response to interactive comments on “Sustainable use of renewable resources in a stylized social-ecological network model under heterogeneous resource distribution” by W. Barfuss et al.

Review 1

General comments:

This manuscript satisfies your editorial criteria as described at http://www.earth-system-dynamics.net/peer_review/review_criteria.html.

The authors of this manuscript extend an existing model to explore the implications of resource heterogeneity, and social interactions, on the sustainable use of resources.

This manuscript makes substantial contributions to methodological developments that are required to advance science, however some of its fundamental definitions and arguments need to be reconsidered or reinforced, and some of the results have to be clarified and put into context. Therefore I recommend inviting the authors to carry out a major revision. Since this paper seems to have a seminal intention, I would suggest the editors to be generous in terms of space.

We thank the referee for taking the time to review our manuscript.

In the revised manuscript we gladly followed the suggestions on extending fundamental definitions necessary to comprehend the purpose of the reported modeling framework. We also discussed in more detail the implications of the obtained results to make the results more accessible to a broader audience.

We are confident that, together with handling the issues raised below, it has greatly improved the presentation of our work.

Specific comments:

The manuscript make substantial innovations, explaining the potential to extend the ideas presented into integrated models, although the latter do not have their main focus on private renewable resources, as described here, so a cautionary note should be added in the discussion or conclusions.

We are thankful for being pointed at this possibly misleading issue. In fact, our main focus is not to present a model that aligns with concepts from integrated (assessment) models, but rather to illustrate possible conceptual alternatives. One core ingredient of integrated models is the observation of averaged quantities under equilibrium conditions which is a standard way to study established macroeconomic processes. Our main intention here is to highlight the importance of understanding (i) the possible ways to reach the above mentioned equilibrium conditions and (ii) to assess the role of individual actors on the formation of such an equilibrium state. Our approach is neither comprehensive nor quantitatively applicable to real-world processes yet, but it serves to illustrate that individual actions, which are usually suppressed in integrated models, may allow to drive a system into different equilibrium states. We clarified our intentions in the revised manuscript.

> The theoretical example to which this model is applied has been chosen with certain misfortune, there are very few examples that follow the description of the resource. I can only think of a fisher's club who own the right of fishing in a river, with different amounts of fish in different portions to which the club members have restricted access, and even in this case the fish would migrate. Can you think of more examples? They should be mentioned to make this exercise sensible, and to add sense to the potential knowledge transfer towards integrated models, which seems to be a side goal because it is mentioned a number of times.

Our intention is not to model a real-world process in detail. The idea behind the model design results from the fact that on a conceptual level, human-environment interactions are either happening in a common-pool setting (e.g. climate change) or a private setting (e.g. some forms of land-use such as agriculture). On the one hand common-pool dilemmas have been extensively studied in the recent past. On the other hand agents can exchange harvesting information over the common pool itself, i.e. interactions between the agents happen via the ecological submodel. This is why on the contrary, we chose agents interacting with private resources. This was done to emphasize that these interactions between the agents are purely social-cultural, to make the case that this is an important domain of processes for further investigation.

The logistic resource function was chosen as the simplest and well established resource function, that may represent fish stock, but is also used in the context of forest growth.

> The manuscript makes a very well detailed description of methods; however, in the definition of the resources, I would like to suggest clarifying a number of points:
>
> is it a common pool resource?
>
> Does it have private access to its sections as accessed by agents?

The resources exemplary and stereotypically studied in this work are not of a common-pool type but individually assigned to each of the agents. With that respect no discrimination has to be made whether parts of the resource are accessible only by certain agents or whether there exists some distinct partitioning as each agent thus harvest its own resource exclusively in private. We clarified this point in the revised manuscript.

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> Would not it be more appropriate, in the context of a socio-ecological interaction, to talk about heterogeneity in the access to the resource?

Since we model private resource harvesting (see above), the size of the resource capacity denotes the amount of resource an agent has access to. Thus, heterogeneous capacities can be interpreted as one operationalization of heterogeneous access to resources. We pointed this out in the revised manuscript.

> More on confusions on the resources: you say “maximum stock (commonly referred to as carrying capacity)”. You here likely refer to the “maximum sustainable yield” or to the maximum stock that “can be extracted” per unit of time without compromising the future of the resource (commonly referred as sustainable use, but not always). If used alone, maximum stock could be understood as being the resource base.

Exactly, “maximum stock” was supposed to denote the carrying capacity. We clarified the respective terms in the manuscript's text.

> You mention a “preference formation process” in a “social preference network”, can you provide an extended rational for the process? Why preferences are formed in the way you describe and implement in the model, is there a theoretical paradigm you follow, and which is the evidence for it? This should be detailed and crystal clear because it is a fundamental basement of the whole contribution, from the current 5 lines at the beginning of section 2.1 is not possible for the broad climate community to see whether there is a rationale for your model. For instance, one of the questions to be considered in such suggested extended rationale is “how this model follows Traulsen’s results on strategy updates”, but not only mentioning it as in sentence 13th of page 4.

We made the motivation of the chosen social process more clear in the respective sections. We do not speak of “preferences” anymore, since it are rather the harvesting strategies that are formed and made the theoretical paradigms our social process is based upon more explicit. We are very thankful for the opportunity to clarify our intention with the model.

> In Figure 3, the homophily parameter is referred as “rewiring”, but that term exist only after section 3 starts. Why to use such term without mentioning it before, please be consistent over the terms and definitions used all along the paper.

We are thankful for being pointed towards this inconsistency in our manuscript. In the revised manuscript, “rewiring” is introduced already in Section 2.

> Section 3 (Results) is not accessible to the broader climate research community. This section should be rewritten, with a focus on making the results accessible to climate researchers with diverse backgrounds, from impact to pure circulation modellers. This comment alone justifies the need for a major review.

In fact, in its submitted state the manuscript may seemed more tailored to an audience with a background primarily from (socio-economic) physics or social-ecological modeling. Furthermore, the model does not exhibit any climatic component, but focuses primarily on dynamics related to social interactions in conjunction with local ecological dynamics. We therefore acknowledge that in its submitted state a solid knowledge of the related terminologies from physics and social-ecological modeling is required to comprehend the results put forward in the manuscript.

To satisfy the interdisciplinary self-understanding of “Earth System Dynamics” we first thoroughly revised all definitions of model components and gave appropriate real-world examples wherever possible in order to put the model setup itself into a comprehensive perspective. Secondly, we added more vivid and illustrative explanations to the technical discussion of the results that put our work into relation with observed real world systems. We are convinced that these two steps made the results more accessible also to a broader audience by reducing the need for prior technical knowledge to a bare minimum.

> Page 8, line 4: “In this setting” helps little to understand where to refer, to some of the displays in Figure 3? To the entire set of results

Originally, this phrase was intended to refer to the specific set of parameters that was used to obtain the results that are discussed in the respective section. We clarified this reference in the revised manuscript.

> Page 8, line 4: it can be argued that the fact that in the model “here, social interactions and thereby the comparison of harvest rates typically happen when the logistic resource has been harvested for a sufficiently long time” is an unrealistic assumption with no basis that conditions too much the results and therefore makes them invalid and its interpretation worthless. Can you explain such assumption as incorporated in the model and why the results are valid?

We compare the social interaction rate (tau) from faster to slower rates with respect to the resource growth rate. This was done to gain a system's understanding of the interaction processes. We do not intend to make claims how these two timescales relate to each other realistically. We clarified our intentions in the revised manuscript.

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> Page 9: "Non-sustainably harvesting agents exploit their resources exponentially". I wonder if you got confused here by the definition of the distributions used: exponentially means in this sentence that each time considered for the extraction the agents extract more resource according to a (large?) exponent, which seems far even from unsustainable behaviours (e.g. if acting as described, any country would finish its natural stocks in very few years).

Exponentially here refers to the time period the resource gets extracted, not a distribution among the agents. We clarified this misleading formulation.

> Figure 4 and comments about it seem to be overvaluing the differences, which are visible but not portentous; can you provide a statistical measure showing the significance of the differences observed?

Thank you for pointing this out. We certainly see the need to strengthen the evidence our discussion is based on. Each point in the 4 parameter space sections shown Figure 4 summarizes 250 ensemble runs. It therefore constitutes a statistical measure. Nevertheless, in the revised manuscript we updated Figure 4 to emphasize more on the differences between the log-normal and the normal based distributions.

> The results are seemingly contradictory to reasonable expectations on the following point, I suggest justifying why. Interactions faster than resource growth lead to unsustainable outcomes; this can be learnt from each of the graphs you present: shorter social interaction time scale brings the average fraction of sustainable nodes below 0.5. Overall these results imply that higher exchange of knowledge between resource users is bad(!). Why is that reasonable? The paper does not make a strong case on this item and I am left wondering whether this is just the result of the assumptions made while constructing the model.

We too find this an interesting result. Yet it is explainable since it is rather a myopic imitation of successful behavior than an exchange of knowledge. Our agent are not capable of estimating the consequence of their actions, they are myopic. We do not intend to recover a specific real-world case. Instead we constructed this model of social-cultural with biophysical interaction and examined this systematically. We understand the fact that unintuitive results emerge as evidence for the value of a thorough system's understanding and clarified our motivation in the revised manuscript.

> Furthermore there is no discussion in Section 3. No logic or context is provided

> for it beyond a purely mathematical interpretation of the results. I would suggest making this section meaningful and functional by including a discussion of the results in the light of the existing literature. I perceive this could make the paper more impactful and meaningful to the broad community working on similar issues.

We gratefully acknowledge the observation that Section 3 would greatly benefit of a deeper embedding into the relevant literature. We extended Section 3 towards this regard.

> **Technical corrections:**
>
> Overall, well presented and written.
>
> Page 3, the references for homophily do not need internal round brackets, a “,” suffices.
>
> You use these terms often: strategy update and social update, if referring to the same, use only one (strategy), otherwise clarify.

We thank the reviewer again for taking the time to revise our manuscript. All technical corrections proposed in the last paragraph have been implemented in the revised manuscript. We are confident that after revising our work with respect to all above issues (and the issues raised and the second review) our manuscript is now suitable for publication in “Earth System Dynamics”.

Review 2

We thank the referee for taking the time and effort in completing the review of our manuscript. It resulted in additional clarification, especially in terms of methods and notions that greatly benefit the presentation of our work.

> **General comments:**
>
> I think this manuscript presents a very important step forward in the analysis of social-ecological networks by considering explicitly resource heterogeneity. I endorse all comments made by Referee #1, and will provide observations on topics not covered in said previous review. In general the paper is very well written and results are clearly presented. Finally, I also will recommend inviting the authors to carry out a major revision.

Response to interactive comments on “Sustainable use of renewable resources in a stylized social-ecological network model under heterogeneous resource distribution” by W. Barfuss et al.

Specific comments:

In page 3 the idea of a Poisson process driving the social update times is presented, with parameter tau being the mean and std. dev. of the associated exponential distribution of said times. According to this distribution, tau can get values in the positive real line. This means that network rewirings can happen on a continuous time line. Meanwhile, rewirings can imply an update in the strategy such that a harvest rate for a given agent can change immediately. This implies suddenly updating the -Ei*si term in the differential equation for stocks (Eq. 3, pg. 4). While nothing is said about the numerical method used for solving these equations (and that needs to be provided) I will assume you are using some form of Runge-Kutta method (perhaps simply 1st. Order Euler). Depending on the software package utilized, you need to set the desired accuracy to the method and the algorithm should adapt the Time Step accordingly, or you set the Time Step by hand according to some criteria (which should be made explicit). In any discrete-time numerical approximation method, interrupting an integration step

with a sudden update to the equation (as discussed above) can be tricky. If you didn’t develop the integration method yourselves, many out-of-the-box numerical packages will silently update your equation only at the beginning of the next integration step (and NOT exactly at ti) when the update is required to happen at a social update time ti that is not an exact multiple of the method’s selected Time Step (with the latter coincidence bearing a theoretical probability of zero !). This is a common phenomena (an error) that might or might not alter your numerical results. What is for granted is that this could become a numerical artifact that artificially synchronizes your emergent system’s behavior to the solver’s Time Step, and that could be a problem, because sometimes you are not in control of this TIme Step, or simply did not pay attention to it. E.g. if the Time Step is in the order of magnitude of the average tau value, you can get noticeably biased behaviors. Please provide all required information to understand how your simulation code deals with these equation updates (called "time-event detection and handling" in the domain of continuous systems simulation). Also provide details for the numerical method adopted, its parameters (e.g. accuracy and/or Time Step), software used, etc.

Thank you for this careful analysis. We clarified this methodological issue in the revised manuscript.

In fact, between two social updates (and thus at constant effort per agent) the growth or decline of each individual resource stock is analytically integrable. This makes the corresponding following update processes easily solvable and circumvents the need to integrate any differential equation numerically.

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> In page 6, you state that the model will always converge to a consensus for the given set up. It is well known (see the bibliography on e.g. agent-based opinion dynamics http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0139572) that the initial configuration of states can dramatically change the final state of the system (e.g. full consensus vs. full polarization) Your inital conditions for si are drawn from an uniform distribution between 0 and si_max. This is one very particular case where the overall system’s average si(0) equals si_max/2. I believe that it is necessary to rule out the possibility that your conclusions are only applicable to this case. I.e. I suggest to test your system by sweeping a reasonable range of values for the overall system’s mean si(0) other than si_max/2.

We thank the referee for pointing out that our notion of “consensus” was chosen under a certain misfortune. What was actually meant with “consensus state” is a *subgraph consensus state*. To make things more clear we changed the term “consensus state” to “steady state” in the revised manuscript.

The article that is referred to above presents a very interesting model examining the steady state in an opinion formation model under the initial fraction of undecided agents. Certainly one could also move forward in this direction with the model presented in our manuscript. However, we think, that this is beyond the scope of this work, also because in the mentioned paper no social network effects are considered. The focus of our article is the model dynamics under resource heterogeneity. Other model parameters (the initial social network structure, initial conditions of harvesting strategy, initial stock values, harvesting rates) were chosen to be either constant or uniformly at random (Erdös-Renyi network, initial conditions). Furthermore, by this randomization we explicitly did not impose any correlations between different states variables or between state variables and network structure which in turn could alter the results significantly.

> In page 7, the name of 2.3 should be "Model parameterization and simulation protocol" as the system is not modeled here but is only parameterized, together with making experimentation decisions like the number of runs.

We changed the respective section name accordingly.

> In page 8, when talking about critical values for phi and tau, it gives the impression that the observations made apply for all possible cases, regardless of the heterogeneity sigma (lines 5 to 15). It is obvious that this is not the case, as you elaborate on the impact of sigma in 3.2 Please make it more explicit what scenario lines 5 to 15 apply to (perhaps for sigma=0.01 in Fig. 3 ?)

Indeed, you are right. We clarified the respective section by making it more accessibly.

Response to interactive comments on “Sustainable use of renewable resources in a stylized social-ecological network model under heterogeneous resource distribution” by W. Barfuss et al.

We are grateful for the time the reviewer put in to revise our manuscript in much detail. We are confident that our revised manuscript benefited greatly in terms of clarity from this review, such that it is eventually suitable for publication in “Earth System Dynamics”.

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

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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~~ private resource use and ~~preference formation~~ social learning 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~~ strategies 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)~~.~~, depending on the scope of the the research question. ~~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.~~ However, both approaches do not take into account social dynamics beyond macroeconomic paradigms.

We here conceptually explore avenues for a third strand of global modeling, next to the biophysical and biophysical-economic one, incorporating also social-cultural dynamics. Founded on a genuinely social-ecological perspective, we term these *World-Earth system* models to emphasize the free coevolution of the social and ecological components (Schellnhuber, 1998, 1999). ~~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., 2016) 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~~ imitation and homophily may have a profound influence on the environmental state, such as determining whether a collection of private ~~regional~~ renewable resources 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 global system models, supplementing already established 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~~ learning network process the model converges to a sustainable regime for different degrees of resource access heterogeneity. Parameters governing social~~preference~~ learning 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~~. We purposely do not model any form of individual learning of the agents with regard to the best harvesting strategy to emphasize the effects of the described social learning process. Already ~~in the homogeneous case~~ for homogeneous resource access (Wiedermann et al., 2015) one observes a ~~tipping~~ threshold 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

The intention behind our model design is not to closely follow any specific real-word setting, but to explore the coevolution of social-cultural with ecological dynamics. On a conceptual level, human-environment interaction happening either in a common-pool or private-pools setting. Common-pool dilemmas have been studied extensively in the past (Hardin, 1968; Tavoni et al., 2012; Ostrom, 2015). Here, agents can retrieve information on other agent's harvesting strategy either via the ecological subsystem, i.e., the common-pool, itself or via purely social interactions. In order to specifically focus on the latter of the two as an important domain of processes we eliminate any transfer of information via the ecological system and discard a common-pool setting in favor of individual and private resource stocks per agent. Wiedermann et al. (2015) introduced a model for for such a setting for the special case of homogeneously distributed private resources, revealed transitions and distinct regimes in its parameter space, and provided analytical approximations of its dynamics. Here, we adjust this setting for the more general case of an inhomogeneous resource distribution. 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 maximization. The resulting harvest rates h_i are used to update the node's strategies S_i (for $i=1\ldots N$) 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). Wiederman 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.~~

2.1 A stylized anthroposphere

The social learning (Bandura, 1977) process takes place in a network initialized as a random graph G (Erdös and Rényi, 1960) with nodes labeled by integer number $i=1,\ldots,N$ that are representing social agents. It is based on two theoretical paradigms: ~~The social module is guided by two principles of interaction in a social network.~~ (i) ~~Nodes~~ Agents either change their strategy through boundedly rational *imitation* (Traulsen et al., 2010; Bahar et al., 2014) or ~~homophilic adaptation, i.e. the nodes~~ (ii) adapt their local network structure by ~~connecting~~ rewiring 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 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~~ agent v_i with the lowest update time in the queue performs the social update process according to:

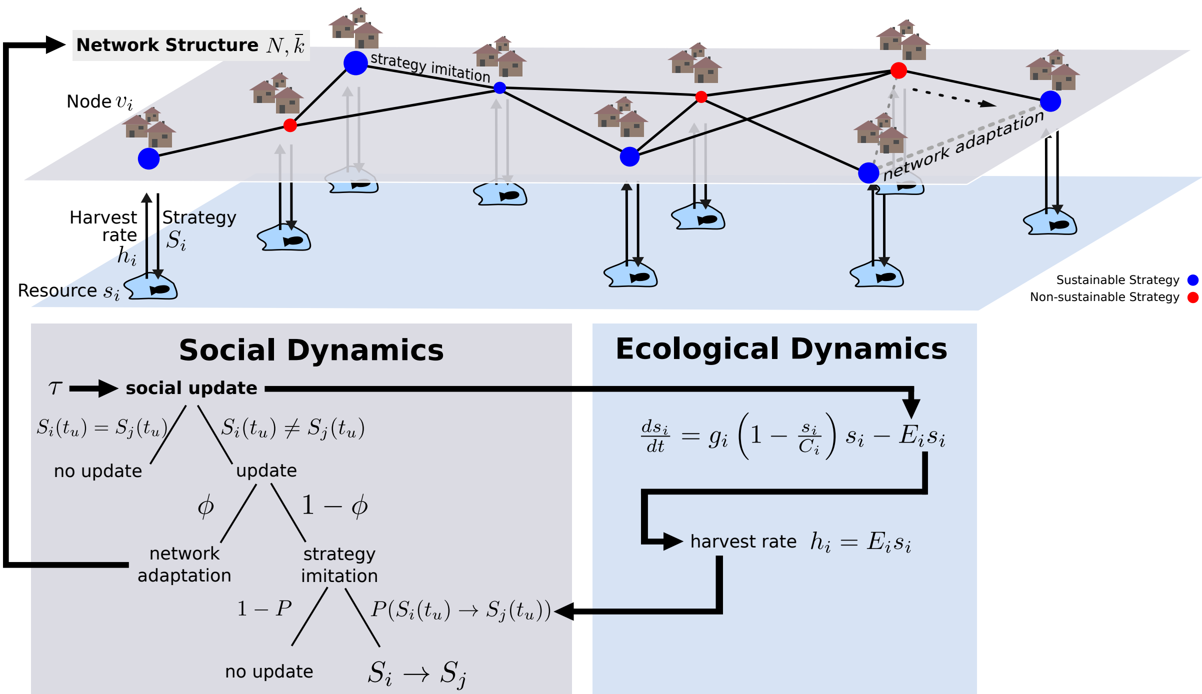

Figure 1. Illustration of our stylized social-ecological model. As the ecological sub-process the ~~nodes~~ agents harvest their private logistically growing renewable resource with either a sustainable (blue) or non-sustainable (red) strategy. The social sub-process follows the logics of strategy imitation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

- (1) if the degree of ~~node~~ agent 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, see below), do nothing. Otherwise,

- (2.1) with rewiring probability ϕ disconnect v_j from v_i and connect v_i to a randomly chosen ~~node~~ agent 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

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

~~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~~ agent v_i is to change its strategy to the one of ~~node~~ agent v_j. Agents ~~Nodes~~ only consider their current yields when formulating their next harvesting strategy. This assumption reflects boundedly rational ~~agent~~ behaviour in the form of the agent's 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~~ agent 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. In fact, Traulsen et al. (2010) found this sigmoidal shape of imitation probability in a behavioral experiment.

– (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~~ Private 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 stock~~s~~ s_i. E_i denotes the *effort* of agent ~~node~~ v_i. Thus, the dynamics of the *i*th resource is given by

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

Here, g_i denotes the growth rate, ~~$s_{i,\max}$ the maximum stock (also commonly referred to as *carrying capacity*)~~ C_i the 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~~ agent 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~~ coincides with the maximum sustainable yield, 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. When in interplay with the social update process, Equation 3 is used as its analytically derived definite integral, which circumvents the need of any numerical integration methods.

2.2.2 Resource heterogeneity

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

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

with parameters μ and σ (not to be confused with the standard deviation of C). 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 logarithmic variable ~~$\ln s_{max}$~~ $\ln C$, respectively. The log-normal distribution ~~is present~~ occurs in variables from many fields, including biological and economic attributes (Sachs, 1984).

Fig. 2 shows ~~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.

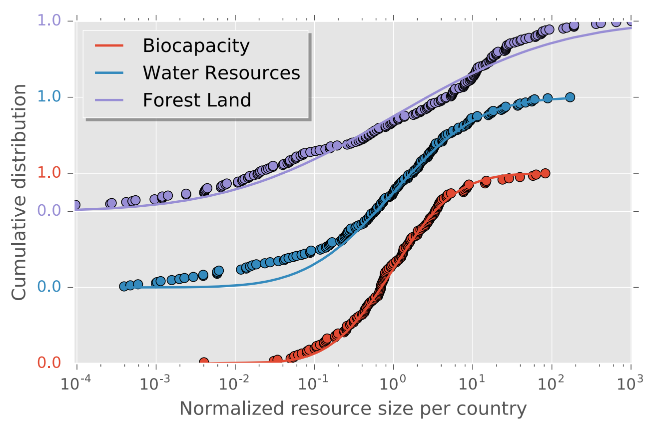

Figure 2. Empirical resource data per country normalized to the respective average (dots) together with least-square fitted log-normal distributions (lines): The biocapacity ($\sigma = 1.42$) computed from the Ecological Footprint Network (Ewing et al., 2008) represents the capacity of ecosystems to 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.

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~~

[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

~~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}~~ C 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}~~ C. Hence, we only ask for the effect of different resource distributions and keep the total amount of available resource stock constant.

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

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

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 ~~$s_{i,\max}$~~ C.

2.3 ~~Modeling protocol~~ Model parameterization and simulation protocol

A model run starts with an initial condition of stocks $s_i(0)$ uniformly distributed between 0 and ~~$s_{i,\max}$~~ C_i 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*~~ *steady state* at t_f, where no further ~~strategy updates will~~ updates of strategy can 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. We are interested in the fraction of sustainable harvesting nodes at the ~~consensus~~ steady 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 sustainable harvesting nodes at the ~~consensus~~ steady 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).

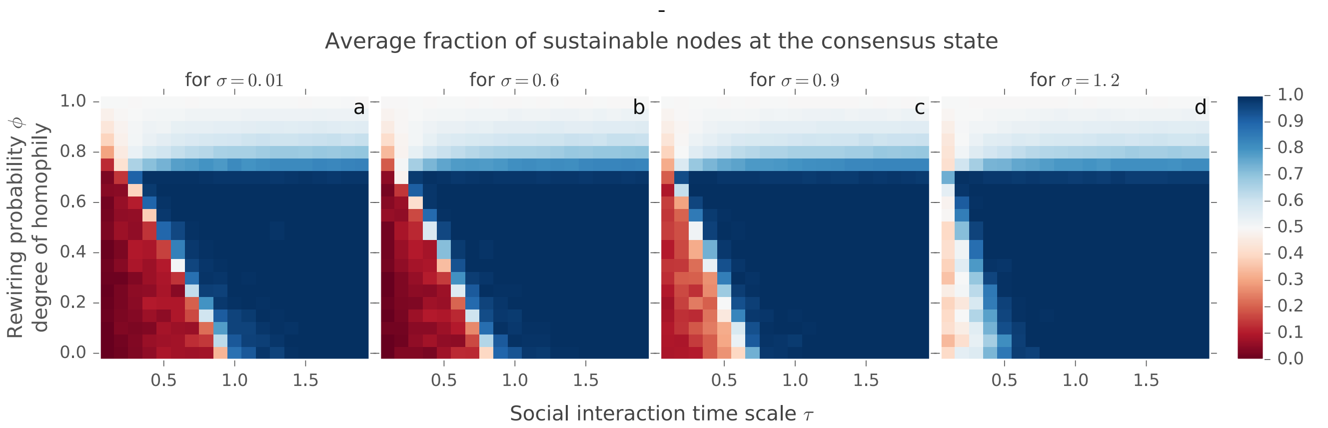

Figure 3. Social interaction time scale–homophily parameter space. Average fraction of sustainable harvesting agents in the ~~consensus~~ steady state depending on the social network rewiring probability ϕ (measuring the degree of homophily) and the social interaction time scale τ for four distinct levels 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 $\phi \gtrsim 0.8$~~ for sufficiently large ϕ the network fragmentation ~~transition~~ regime. The latter occurs since for large ϕ, social dynamics ~~is~~ are dominated by homophily and, hence, by the process of social network rewiring, and thus negligibly few changes in strategy occur. ~~In this setting,~~ The ~~consensus~~ steady 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 ~~$\phi \lesssim 0.8$,~~ smaller ϕ the effect of homophily is sufficiently weak such that most agents remain connected to a single component in the social network ~~and, hence,~~. The ~~a consensus~~ steady state is reached with a big connected network component ~~while connecting between a large fraction of all agents is eventually found~~. ~~In this setting~~ Here, large interaction time scales τ lead to a sustainable regime. This is because ~~here, social interactions and thereby~~ the comparisons 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.

Our main focus lies on the emergent properties of our model from a complex system's perspective. Hence, we do not claim that any quantitative choice of parameters is based on real-world assumptions. We rather focus here on qualitative observations in terms of general parameter regimes which in correspondence with the arbitrarily chosen ecological time scale cause a certain differential outcome of the model. However, in order to qualitatively compare our model with some real-world observations, we first look at the timescale of social updates τ. It has been suggested than modern lifestyles are dominated by a *social acceleration* (Rosa, 2013). Simultaneously the pressure humanity is putting on the planet(Steffen et al., 2004) has experienced a *great acceleration* (Steffen et al., 2015a). This can be interpreted such that faster social timescales τ lead to a non-sustainable regime, as observed in our model (see Fig. 3). Viewed with caution, the mechanisms in our model might be a possible explanation of this phenomenon. In any case, it highlights the importance of well interacting social timescales with ecological ones. Since ecological timescales (e.g. the seasonal cycle) are difficult to influence, this suggests to take social timescales (e.g. election cycles, fashion trends, product launches) into account for possible policy interventions. As such it might be worthwhile to study the relationship between social and ecological timescales more intensively to identify suitable policy actions for the benefit of a sustainable system.

We furthermore observe a linear ~~inter~~relationship 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~~ the transition occurs at $1/\tau \approx 1$, 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.

In other words, the homophily process in our model is beneficial for reaching the sustainable regime, where all agents harvest their resource gaining the maximum sustainable yield. All stochasticity and inherent shocks towards this sustainable steady state are absorbed and not affecting the final outcome. In this sense the sustainable regime can be described as resilient. This aligns with findings Newig et al. (2010), who (although from a different perspective) hypothesize that homophily has a beneficial effect on the resilience of a social-ecological network. Furthermore, one can interpret a large homophily parameter ϕ as the agent's means to protect themselves against the fast and free exchange of harvesting strategies. Along similar lines, it has been found that individuals with more environmental concerns hold also more protectionist policy preferences (Bechtel et al., 2012). Our model suggests one possible mechanism how these relationships might come into place. However, it remains to remark that a too high rewiring probability leads to a fragmentation of the social network into smaller groups of disjoint strategies, preventing the opportunity of a completely sustainable outcome. Thus, network adaptation at very high rates should be avoided for the sake of knowledge exchange and consensus formation.

Overall, t~~T~~hese 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~~ steady 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 sustainable 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.

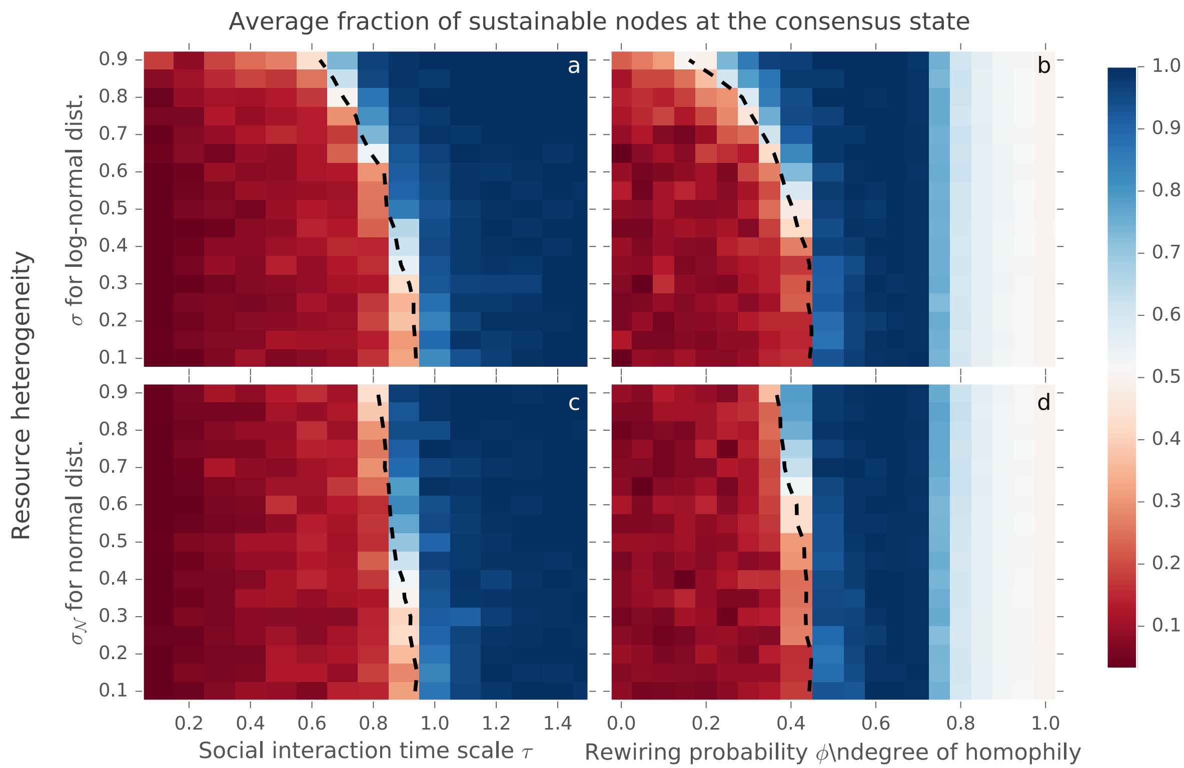

Figure 4. Effects of resource heterogeneity. Average fraction of sustainable harvesting nodes at the ~~consensus~~ steady state for several segments of parameter space: (a,b) for (heavy-tailed) log-normally distributed capacities, and (c,d) for (non-heavy-tailed) normally distributed capacities. Parameter 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. The dashed black lines indicate the linearly interpolated 50% average fraction of sustainable nodes. 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.

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~~ steady 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 is a sufficiently high probability that some agents will be assigned a comparably large resource capacity. Non-sustainable harvesting agents exploit their resources exponentially fast in time, whereas sustainable harvesting agents with comparably large resource capacity can retain their resource stock at a level that is still sufficiently large to convince other ~~nodes~~ agents to become sustainable as well.

At first, the observation that heterogeneity in the access to the private resources is enlarging the sustainable regime might be contradictory to reasonable assumptions. However, it demonstrates the value of a thorough system's analysis and being critical about the own perception of what is reasonable. Cautiously comparing this phenomenon with the real-world one can interpret the size of the resource capacity as the effective economic power of international macro-agents, such as world-regions or nation states. This is justified, since we do not model any other economic processes but resource extraction; for example trade, innovation, labor, etc. The agents with comparably large economic power that employ a sustainable strategy have greater persuasive power than sustainable agents with smaller economic power. The German energy transition and its perceived impact on other countries regarding the transition towards a sustainable energy supply might be a real-world example where a comparably strong economic country exerts also comparable large persuasive power to other countries to move forward towards sustainable energy supply.

Overall, heterogeneity to resource access in our model demonstrates, how ~~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.

4 Conclusions

In this paper, we have studied how social-ecological ~~tipping points~~ thresholds 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~~ social learning 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~~ strategy formation by bounded 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 feedbacks ~~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 the ongoing debate on global change (Steffen et al., 2004) and the Anthropocene (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 intellectual, strategic and financial support from the Heinrich-Böll-Foundation. JFD thanks the Stordalen Foundation (via the Planetary Boundaries Research Network PB.net), the Earth League's EarthDoc program and the Leibniz Association (project DOMINOES) 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). The authors gratefully acknowledge the European Regional Development Fund (ERDF), the German Federal Ministry of Education and Research and the Land Brandenburg for supporting this project by providing resources on the high performance computer system at the Potsdam Institute for Climate Impact Research. Last but not least we thank ~~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.

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