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Land-use and species tipping points in a coupled ecological-economic model

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ABSTRACT

Complex systems can have tipping points where the system behavior changes abruptly from one regime to another. We develop an ecological-economic model that simulates the spatio-temporal dynamics of the land-use induced by a tradable permit market and its consequences on the viability of a model species. The model analysis reveals that the land-use dynamics are subject to a tipping point with regard to changes in policy scheme design. One the level of species viability, this tipping point is amplified and a second tipping point emerges. The two tipping points interact and their location and sharpness depend on the characteristics of the species. We conclude that in the consideration of coupled ecological-economic systems tipping points can play an important role. The existence of tipping points considerably complicates the design of policy instruments for the sustainable management of ecological-economic systems because a small change in the policy design can have dramatic consequences on the system dynamics.

1. Introduction

Systems with heterogeneous and interacting agents often show complex behavior, such as feedback loops and discontinuous or abrupt changes. Such abrupt changes are often termed tipping points and can occur in many types of systems, including physical, economic and ecological ones (Polhill et al., 2016; Van Nes et al., 2016). They all have in common that they are difficult to predict and associated with irreversibility such that once a tipping point has been crossed it is difficult or even impossible to move the system back to the original state.

Tipping points, i.e. rapid transitions between different types of structure or behavior of a system, were first reported and analyzed in physical systems where they are termed phase-transitions (Reif, 1965). Popular examples are the transitions between the solid, liquid and gaseous phases of water and other substances, or between the magnetic and non-magnetic states of iron and various other metals. In the social sciences, tipping points have, e.g., been observed with regard to opinion dynamics on networks (e.g., Holme and Newman, 2006). The network structure describes which agents interact with each other. The variable of interest – the system state – is whether a certain opinion (e.g. a political preference) persists within the network. When certain model parameters describing the network topology (who interacts with whom) or the probability of an agent adopting a new opinion are varied, a discontinuous change in the system may occur. Another example is Schelling's famous model of social segregation where the spatial structure of neighborhoods abruptly changes when preferences of the residents are varied (Schelling, 1978).

An ecological phenomenon related to tipping points is extinction vortices that characterize the extinction of species (Gilpin and Soulé, 1986): Often, the extinction of species starts with habitat loss and fragmentation associated with land-use change, which reduces species populations to smaller numbers. These are more vulnerable to environmental influences including stochastic fluctuations. Environmental fluctuations can by chance further reduce population sizes where they become vulnerable to demographic stochasticity (caused, e.g., by adverse sex ratios and stochasticity in the sequence of birth and death events). Once a species is trapped in an extinction vortex it is difficult to save it.

To prevent species from extinction it is therefore necessary to stop threatening processes from the early beginning. This includes stopping habitat loss and fragmentation and improving the conditions of species in the remaining habitats. Habitat loss often results from the conversion of natural or extensively used land into settlements, industrial areas or intensive agriculture. The main reason for such conversions is that the new land-use types are more profitable than the original ones (MAE, 2005). Market-based conservation instruments (EC, 2005; OECD, 2012) try to counteract this economic pressure, e.g., by financially supporting biodiversity-friendly land use through payments for environmental services (PES: Engel et al., 2008), or by financially rewarding biodiversity-friendly land use and discouraging adverse land

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uses through tradable land-use permits (Panayatou, 1994; Hansjürgens et al., 2011).

In a tradable permit system a conservation agency, like an environmental ministry, sets a minimum level of an environmental good that has to be produced in a region (e.g., total amount of habitat for a target species). Here the agency does not prescribe at which particular locations in the landscape conservation measures must be carried out, but each land user can decide on whether to conserve habitat and sell the associated land-use permits on the market or buy land-use permits and use the land for economic purposes (e.g., agriculture). An advantage of this approach is that land users can adapt to changing conditions (e.g. changing economic costs of conservation).

Originally designed for emissions control, Drechsler and Wätzold (2009) applied the tradable permit approach to the field of biodiversity conservation, taking into account that spatially connected habitats generally are ecologically more valuable, i.e. have a stronger influence on population viability, than isolated ones. This required introducing some kind of neighborhood bonus, as it has been suggested by Parkhurst et al. (2002). The neighborhood bonus implies that the creation of a habitat next to other habitats earns more permits than the creation of an isolated habitat, and the destruction of a connected habitat requires more permits than the destruction of an isolated habitat. Drechsler and Wätzold (2009) showed that such a market is subject to a tipping point: if the neighborhood bonus is small compared to the spatial heterogeneity of conservation costs the emerging land use will lead to spatially dispersed habitats while for large neighborhood bonuses the habitats will be clustered. Between these two "phases" there is a discontinuous transition – a tipping point.

The number, size and spatial arrangement of habitats have a decisive influence on the survival of the species in a landscape (Hanski, 1999; Frank and Wissel, 2002; Hanski, 2015). Loss and fragmentation of habitat are major factors responsible for the decline of species worldwide (MEA, 2005; Haddad et al., 2015). To counteract these processes several strategies have been discussed such as habitat restoration and the establishment of dispersal corridors and stepping stones to increase the total amount and the spatial connectivity of habitats (Fischer et al., 2006; Ayram et al., 2015).

Habitat loss and fragmentation are interrelated and difficult to separate, since the former affects the latter (Fahrig, 2003; Hanski, 2015). The impact of habitat loss on habitat fragmentation has recently been observed in a global study of rainforest fragmentation (Taubert et al., 2018). The authors are able to explain the observed spatial patterns of rainforest remnants by a simple spatially random process of habitat loss and predict that if this process continues, a tipping point will be reached soon at which the proportion of small forest remnants and the isolation of these remnants abruptly increase. This type of tipping point can be observed in many spatial systems and is termed a percolation threshold (Staufer and Aharony, 1994).

The impact of such a habitat loss and fragmentation process on the viability of a species population has been analyzed by Oborny et al. (2007) who find that by crossing the percolation threshold the viability of the population abruptly declines.

Altogether, both the tradable permit market and the species dynamics on the resulting landscape are subject to tipping points and the question arises what happens if both components are coupled and the response of the species to the permit market is analyzed. Will the tipping points amplify or attenuate each other? Our main focus in the present study will be the effect of policy parameters (the amount of permits that have to be produced in the model region and the magnitude of the neighborhood bonus) and species parameters (the species colonization and local extinction rates) on species survival and possible tipping points. A similar coupled ecological-economic model has been analyzed by Hartig and Drechsler (2009). However, it focused on the cost-effectiveness of different market designs and ignored the issue of tipping points in the system.

2. Methods

The following section describes the economic module and the integration of the ecological module into the economic module. The two modules and their interaction as well the procedures for the model analysis (see below) were implemented and coded in C++. The section concludes with a description of the way in which the combined model is analyzed.

2.1. Economic module

The economic module simulates a market for tradable land-use permits where a conservation agency imposes on each land user the obligation to conserve some of his or her land. If a land user conserves more land than demanded by the agency the excess conservation effort can be sold to other land user in the region through land-use permits. In turn, a land user who wishes to conserve less land than required can buy some of these land-use permits on the market to compensate for his or her shortfall of conservation effort. The module has been described in detail by Drechsler and Wätzold (2009). Below we provide a brief outline.

We consider a region of land parcels arranged in a square grid. Each land parcel i is owned by a land user and can be managed in two ways: conservation (i.e. creation of habitat for some target species) or economic use, such as (intensive) agriculture or forestry. Conserving a land parcel i reduces agricultural or forestry profits on the land parcel, which reflects in conservation (opportunity) costs of magnitude z_i. The z_i are assumed to be uncorrelated uniform random numbers drawn from the interval $[1-\sigma,\ 1+\sigma]$, where σ denotes the cost variation. To model economic change the conservation costs z_i are randomly re-drawn in each time step (year). Economic use does not earn any land-use permits while conservation of a land parcel i generates land-use permits of an amount

$$v_i = 1 + wm_i$$

where m_i is the proportion of conserved land parcels in the Moore neighbourhood around land parcel i. The Moore neighbourhood consists of the eight land parcels adjacent to land parcel i. Parameter w is the weight attached to the presence of other habitats in the Moore neighbourhood. It is chosen by the policy maker and can take any non-negative value. If $w = 0$ conserving a land parcel adjacent to other conserved land parcels generates as many land-use permits as the conservation of an isolated land parcel. An isolated land parcel generates land-use permits of an amount $v_i = 1$. If $w > 0$ conserving a land parcel adjacent to other conserved land parcels increases the amount of generated land-use permits by wm_i. Therefore, by choosing a large (small) value of w the conservation agency can set a strong (weak) incentive to the land users to conserve land particularly next to other conserved land.

The conservation agency imposes an obligation on each land user i to generate a certain amount N of land-use permits. The maximum of land-use permits a single land user can ever generate from his or her land parcel is $1 + w$ which is obtained when the land parcel is conserved and completely surrounded by conserved land parcels ($m_i = 1$). Rather than demanding this maximum the agency demands from each land user to generate a certain proportion of it. The proportionality factor is denoted as $\lambda \in [0,1]$, so each land user has to generate an amount of $N = \lambda(1 + w)$ land-use permits. To interpret the two extreme values of λ, a value of $\lambda = 0$ implies that no land-use permits have to be produced and there is no conservation in the model region while $\lambda = 1$ implies that each land user has to generate the maximum possible amount of land-use permits and all land parcels need to conserved. For λ in between not all but some land will be conserved in the model region.

The land users are allowed to trade permits (meaningful only for $0 < \lambda < 1$). Assuming that each land user maximises his or her profit,