Ecological Economics 154 (2018) 272–281

Contents lists available at ScienceDirect

Ecological Economics

journal homepage: www.elsevier.com/locate/ecolecon

Analysis

Sustainable Land-use Management Under Biodiversity Lag Effects

A.-S. Lafuite*, G. Denise, M. Loreau

Centre for Biodiversity Theory and Modelling, Theoretical and Experimental Ecology Station, CNRS and Paul Sabatier University, Moulis, France

ARTICLE INFO

Keywords:
Biodiversity
Ecosystem services
Extinction debt
Social-ecological system
Sustainability
Land tax

ABSTRACT

The destruction of natural habitats for agricultural production results in local biodiversity loss. Biodiversity loss in turn affects agricultural production indirectly through a range of biodiversity-dependent ecosystem services. Land conversion thus results in a negative externality, mediated by changes in biodiversity. When the consequences of this externality are delayed in time, lack of internalization results in overshoot-and-collapse dynamics, which are undesirable from a sustainability perspective. Here, we emphasize the importance of forward-looking policies for the long-term sustainability of human–nature interactions. We show that the internalization of this externality through a land tax can result in several win-win effects in the long run. First, more biodiversity is preserved at equilibrium, which increases the carrying capacity and total well-being of the human population. Second, a taxation path that maximizes the discounted sum of human utilities prevents or greatly alleviates overshoot-and-collapse crises, thus increasing the sustainability of the system. In particular, this result holds in the case of imperfect information regarding the precise temporal dynamics of biodiversity loss, suggesting that the design of efficient land-use management policies is possible despite incomplete ecological data. This study highlights the need to internalize biodiversity-dependent externalities through economic incentives, especially under uncertainty regarding long-term ecological dynamics.

1. Introduction

Human use of land has transformed ecosystems across most of the terrestrial biosphere for millennia (Ellis et al., 2013). The conversion of natural lands to croplands, pastures and urban areas represents the most visible form of human impact on the environment (Meyer and Turner, 1992), with 40% of Earth's land surface being currently under agriculture (Sanderson et al., 2002), and 75% experiencing measurable human pressures (Venter et al., 2016). These pressures are rapidly intensifying in biodiversity-rich places, since most land conversion occurs in the tropics through forest conversion to agriculture (McGranahan et al., 2005; Hansen et al., 2013). As a consequence, land use and land cover changes are among major drivers of biodiversity loss, at both local (Newbold et al., 2015) and global scales (Foley et al., 2005).

In turn, biodiversity loss affects the provisioning of essential ecosystem services, such as pollination, pest control, nutrient cycling and erosion control (Cardinale et al., 2012), with consequences on many human activities, and especially for agricultural production (Foley et al., 2005). Biodiversity loss is thus a major and underestimated feedback that may affect human population growth in the long run (Motesharrei et al., 2016), and concerns about the potential of land-use changes to push terrestrial biodiversity beyond major planetary boundaries are rising (Newbold et al., 2016).

These impacts of land-use changes on biodiversity are poorly reflected in market prices, and hence have been mostly ignored by decision-makers, despite their large cost for human economies. The estimated value for global ecosystem services was $145 trillion in 2011, which represents up to $20 trillion loss per year between 1997 and 2011 (Costanza et al., 2014b). Loss of biodiversity-dependent ecosystem services thus constitutes a negative externality, which threatens intergenerational equity (Brundtland et al., 1987) along with the sustainability of coupled human–nature systems (Lafuite and Loreau, 2017). As a result, taking this loss into account is crucially needed to implement prudent and forward-looking policies that address biodiversity and natural habitat loss.

At the global scale, natural habitat loss is primarily driven by the growth of the human population (Dietz et al., 2007), and arable lands are rapidly shrinking (Lambin and Meyfroidt, 2011). Recent evidence suggests that land use efficiency has been rising at the global scale (Venter et al., 2016). However, such efficiency gains may not help save natural habitats and biodiversity in the long run, due to economic rebound effects, i.e., if lower prices stimulate demand and if higher yields raise profits, thus encouraging agricultural expansion (Lambin and Meyfroidt, 2011). By increasing the opportunity cost of conservation,

---

* Corresponding author.
E-mail address: lafuite.as@gmail.com (A.-S. Lafuite).

https://doi.org/10.1016/j.ecolecon.2018.08.003
Received 18 April 2018; Received in revised form 3 August 2018; Accepted 8 August 2018

these effects undermine the efficiency of regulatory environmental policies, such as government protected forests and natural habitats, in protecting biodiversity (Phalan et al., 2016).

Land-sparing mechanisms that could help overcome these rebound effects include land zoning, incentive-based economic instruments (e.g., land taxes, subsidies and payments), spatially strategic intensification and voluntary standards (Phalan et al., 2016). Especially, incentive-based mechanisms such as land taxes may allow internalizing the externality of land conversion on biodiversity-dependent ecosystems services and agricultural production (Cropper and Oates, 1992). Such mechanisms are based on economic efficiency concepts, so as to achieve the maximum amount of resource protection for a given production level.

During the past decade, the European Union has widely used incentive-based mechanisms to reduce gas emissions from motor fuels and vehicles, but also plastic bags, landfill waste, batteries, pesticides, and fertilizers. Mounting evidence shows that taxes have helped reducing pollution and the consumption of natural resources in many cases, with a higher efficiency and at lower costs than conventional regulatory approaches (Costanza et al., 2014a). However, use of such negative price signals for environmentally damaging activities has been less spread in the US, where tax credits and deductions are favored. More generally, interest group pressures, extensive data requirements (e.g., regarding the external costs of human activities) and scientific uncertainty tend to reduce the level of acceptance of taxes.

Indeed, the efficiency of conventional taxes is limited by available scientific knowledge. This is especially true for the relationship between biodiversity-dependent ecosystem service loss and land use changes, for which there is still a high uncertainty regarding the long-term temporal dynamics of ecosystems in the context of accumulating extinction and functioning debts (Tilman et al., 1994; Isbell et al., 2015; Haddad et al., 2015; Lafuite and Loreau, 2017; Lafuite et al., 2017), i.e., the time-delayed loss of species and services following a change in land use. Moreover, conventional taxes do not necessarily guarantee intergenerational equity and sustainability, i.e., they do not prevent the over-use of natural capital and reductions in human well-being over time (Brundtland et al., 1987; Pezzey, 1992).

As a result, some authors have proposed to define a broad natural capital depletion tax to ensure that resource inputs from the environment to the economy remain sustainable (Costanza, 1991; Costanza and Daly, 1992; Perrings, 1991). Implementation of such a tax would raise prices of natural resources, thus encouraging technological advances while slowing down the rate of environmental depletion (Costanza et al., 2014a). Other authors have proposed a corrected version of the net national product in order to account for the effect of agricultural land development on biodiversity, while ensuring a constant social welfare (Hartwick, 1995; Endres and Radke, 1999).

However, these developments have poorly accounted for the temporal dynamics of biodiversity-dependent ecosystem service loss, and have ignored its consequences for human demography. Biodiversity-dependent agricultural consumption affects human demography, resulting in a dynamic feedback loop between biodiversity loss and human population growth, mediated by land conversion (Lafuite and Loreau, 2017; Lafuite et al., 2017). Time delays between land conversion and biodiversity loss, i.e., extinction debts (Tilman et al., 1994), result in a lagged feedback on agricultural production (Pingali, 2012; Haddad et al., 2015; Isbell et al., 2015). Such lag effects can result in overshoot-and-collapse population cycles that transiently reduce human well-being, and undermine the sustainability of the system (Lafuite and Loreau, 2017; Lafuite et al., 2017).

In this paper, we propose to assess the efficiency of a natural land depletion tax in securing sustainability and preserving biodiversity, despite uncertainty about the temporal dynamics of biodiversity loss. The paper is organized as follows. In Section 1, we present a dynamical system model that couples human demography and technological change to biodiversity loss, through the effect of land conversion on the flow of biodiversity-dependent ecosystem services to agricultural production (Lafuite and Loreau, 2017; Lafuite et al., 2017). In Section 2, the externality of land conversion on biodiversity is internalized through a natural land depletion tax τ per unit of converted land. We show how this tax affects the consumption levels, the ratio of the production inputs, and the rate of land conversion. In Section 3, we analyze the effects of this tax on the long-term equilibrium and sustainability of the system, as captured by a criterion ensuring a non-decreasing human well-being over time. We show that a land tax can increase both biodiversity and total agricultural production at equilibrium, when the substitution of labor and ecosystem services for land has a net positive effect on total agricultural production. The land tax also reduces the vulnerability of the system to time delays, but its ability to prevent crises depends on its level at equilibrium, and thus on the land conversion policy. Section 4 derives the optimal land conversion policy designed by a foresighted planner, who aims to internalize the externality of land conversion on biodiversity under the assumption that the temporal dynamics of biodiversity is unknown. We illustrate the efficiency of such a policy in preserving biodiversity, increasing total production, and preventing the unsustainable consequences of time-delayed ecological feedbacks. Our paper thus emphasizes the importance of forward-looking policies for the long-term sustainability of human–nature interactions, especially under lagged biodiversity feedbacks.

2. A Simple Land-Biodiversity-Demography Model

2.1. Substitution of Production Inputs for Natural Capital

We build upon the model of Lafuite and Loreau (2017), which considers a population of consumers whose demand for agricultural ($i = 1$) and industrial ($i = 2$) goods requires the conversion of their common natural habitat. The two goods in the model are each produced using labor L_i and land A_i. We assume full-employment, i.e., total labor is equal to the size of the human population. Only converted land is capable of producing these goods, while land not converted for production remains as natural habitat capable of supporting a diversity of species, which provides a range of biodiversity-dependent ecosystem services to agricultural production (Cardinale et al., 2012).

By using Cobb-Douglas production functions (Eq. (1)), we allow for the partial substitution between production inputs (labor and land), natural capital (biodiversity-dependent services) and technology.

$$Y_1 = \underbrace{\mathrm{TB}^{\Omega}}_{TFP} L_1^{\alpha_1} A_1^{1-\alpha_1} \qquad Y_2 = \underbrace{\mathrm{T}}_{TFP} L_2^{\alpha_2} A_2^{1-\alpha_2} \tag{1}$$

Total factor productivity (TFP) increases with technological efficiency in both sectors, as well as with biodiversity-dependent ecosystem services in the agricultural sector. The ecosystem services provided by this community of species are assumed to increase with biodiversity and saturate at high levels of species richness, through a power-law relationship B^{Ω}, where $\Omega \in [0,1]$ (O'Connor et al., 2017). Technological efficiency is also assumed to follow a logistic growth towards a maximum efficiency, T_m, in order to reproduce past agricultural productivity rise and current stagnation (Zeigler and Steensland, 2016) (Fig. 1).

2.2. Dynamical System

The long-term behavior of the population is captured by a feedback loop between three dynamical variables: the human population H (Eq. (2)), biodiversity B (Eq. (3)), and technological efficiency T (Eq. (4)).

$$\dot{\mathrm{H}} = \mu \mathrm{H}(1 - \exp(y_1^{min} - y_1(\mathrm{B}, \mathrm{T})))\exp(-b_2 y_2(\mathrm{T})) \tag{2}$$

$$\dot{\mathrm{B}} = -\epsilon(\mathrm{B} - S(\mathrm{H})) \tag{3}$$