Global Environmental Change 49 (2018) 73–84

Contents lists available at ScienceDirect

Global Environmental Change

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

Land use options for staying within the Planetary Boundaries – Synergies and trade-offs between global and local sustainability goals

Vera Heck[a,b,c,*], Holger Hoff[a,d,*], Stefan Wirsenius[e], Carsten Meyer[f,g], Holger Kreft[h]

[a] Earth System Analysis, Potsdam Institute for Climate Impact Research, Germany
[b] Department of Geography, Humboldt-Universität zu Berlin, Germany
[c] Water and Development Research Group, Aalto University, Finland
[d] Resources and Development, Stockholm Environment Institute, Sweden
[e] Department of Space, Earth and Environment, Chalmers University of Technology, Sweden
[f] Macroecology & Society, German Centre for Integrative Biodiversity Research (iDiv) Halle-Jena-Leipzig, Germany
[g] Faculty of Biosciences, Pharmacy and Psychology, University of Leipzig, Germany
[h] Biodiversity, Macroecology and Biogeography, Georg-August-University Göttingen, Germany

ARTICLE INFO

Keywords:
Land use
Optimisation
Biodiversity
Carbon sequestration
Planetary Boundaries
Sustainable Development Goals

ABSTRACT

In this paper we develop and assess alternative global land use patterns, guided by the Planetary Boundaries framework, to quantify land use opportunities for staying within the safe environmental operating space. Through a simulation based multi-criteria land use optimisation procedure, we determine the potential upper bounds of improved terrestrial carbon storage and of biodiversity conservation, while also meeting the Planetary Boundaries of land and water use and ensuring improved food supply for a population of 9 billion people. We present alternative global land use scenarios that could simultaneously yield better outcomes on all of these goals, in particular if substantial increases in agricultural productivity are realised. Terrestrial carbon sequestration potentials reach 98 GtC, whereas the potential reduction of the risk to biodiversity is 53%. Furthermore, we analyse the potential synergies and trade-offs of these global land use scenarios with national- and local-level environmental and developmental goals such as those specified in the SDGs, e.g. related to nature conservation, afforestation, bioenergy, employment and equity. This model-based information on synergies and trade-offs between different sustainability goals at different scales can be used in scientific assessments of transformation pathways, in policy making, in support of improved horizontal and vertical policy coherence and multi-level institutional solutions, as well as in SDG implementation, sustainable production and consumption (SDG 12) and global partnership mechanisms (SDG 17).

1. Introduction

There is increasing attention to global pressures and responses in the sustainability discourse (UN General Assembly, 2015). Global environmental sustainability criteria have been defined by the Planetary Boundaries framework (Rockström et al., 2009; Steffen et al., 2015). These boundaries delimit the environmental safe operating space as a pre-condition for human well-being and development. With that, the Planetary Boundaries also set guardrails within which the Sustainable Development Goals (SDGs) need to be implemented. The PBs address, for example, climate change, biodiversity loss, land use change and freshwater use (Steffen et al., 2015). Even though the PBs have been criticised for various reasons (e.g. for large uncertainties in boundary setting and their largely unknown interactions, dynamics and consequences of transgression (Barnosky et al., 2011; Brook et al., 2013)), they provide a valuable systemic and quantitative framework, encompassing multiple environmental dimensions at the global and regional scales (Steffen et al., 2015). While science is exploring and further developing each of the PBs in more detail (e.g. de Vries et al., 2013; Gerten et al., 2013; Mace et al., 2014; Newbold et al., 2016), there has been far less attention to the planetary opportunities for sustainable development within the PBs (DeFries et al., 2012).

In this paper, we use a simulation based optimisation procedure to explore this opportunity space, considering land use as a key issue for sustainability transitions (Obersteiner et al., 2016). While land use has repercussions at the global scale, e.g. in terms of carbon sequestration (Pielke et al., 2002; Houghton et al., 2012), biodiversity loss (Cardinale et al., 2012; Newbold et al., 2016) or moisture fluxes (Keys et al., 2012; Boisier et al., 2014), it manifests itself at the local scale and responds to drivers at all scales, such as local land use decisions, national legislation

---

* Corresponding authors at: Earth System Analysis, Potsdam Institute for Climate Impact Research, Germany.
E-mail addresses: heck@pik-potsdam.de (V. Heck), hhoff@pik-potsdam.de (H. Hoff).

https://doi.org/10.1016/j.gloenvcha.2018.02.004
Received 16 January 2017; Received in revised form 30 November 2017; Accepted 4 February 2018

or global trade. Thus, smaller scales of policy- and decision-making need to be integrated with a global PB perspective in order to concretely support sustainability transitions and guide sustainable environmental management and resource use.

This raises the question what top-down planetary opportunities imply for individual regions or countries and how consistent global approaches are with bottom-up local or national (e.g. energy) strategies, national development plans (e.g. Visions 2030) and solutions (e.g. agricultural intensification). The 2030 Agenda for sustainable development refers to this type of consistency across scales by requiring governments to set their own “national targets guided by the global level of ambition but taking into account national circumstances” (UN General Assembly, 2015). Thus, there is a need for complementing existing systems approaches addressing horizontal integration across sectors and disciplines, such as Integrated Water Resources Management (Agarwal et al., 2000), Ecosystem Approaches (CBD, 2000) or Landscape Approaches (Sayer, 2009; DeFries and Rosenzweig, 2010) with a vertical integration component across scales.

There have been numerous scenarios on future global land use (e.g. Pereira et al., 2010; Prestele et al., 2016). These depend on a wide range of assumptions about drivers such as population growth, technological progress and efficiency increase, lifestyle change and consumption patterns (Harfoot et al., 2014). In this paper, we combine multiple sustainability criteria for land use, in particular food production, carbon sequestration, biodiversity conservation, and implicitly, also forest cover and water use, in a spatially explicit model-based land use optimisation and scenario exploration. We explore alternative land use scenarios that would stay within the global environmental safe operating space, while feeding a population of 9.1 billion people (population projection for the year 2050 in the middle-of-the-road shared socioeconomic pathways (SSP2) scenario (KC and Lutz, 2014)) for different scenarios on improvements of agricultural (crop and livestock) productivity. We show that such top-down optimised land use patterns can reduce the transgression of the PBs for climate change and biosphere integrity, which we operationalise in our optimisation through the control variables terrestrial carbon storage and risk to biodiversity. We further account for the PBs for land system change (control variable: forest cover fraction) and freshwater use (control variable: consumptive blue water use) (Steffen et al., 2015).

By combining sustainability criteria at multiple spatial scales, i.e. global, regional and national, we explore opportunities for sustainable land use that integrates vertically across scales but also horizontally across sectors. Eventually we assess the consequences of the simulated global top-down solutions for individual regions and countries, e.g. in terms of meeting selected SDG targets.

2. Methods

Our method for optimising global land use (Fig. 1) is based on simulations with the state-of-the-art dynamic vegetation model LPJmL (ref. to Section 2.1, Bondeau et al., 2007) and data sets on indicators of biodiversity and land suitability (ref. to Section 2.4). The optimisation is driven by scenarios of agricultural productivity, global population and per-capita food demands (ref. to Section 2.5) and considers multiple constraints (ref. to Section 2.4) while maximising terrestrial carbon storage and minimising the risk to biodiversity. The optimisation model and its foundations are described in more detail in the following sections.

2.1. LPJmL model

We use the LPJmL model to simulate carbon pools on natural and agricultural land, crop harvest potentials and agricultural water consumption and water availability for different agricultural efficiencies (Section 2.5). LPJmL is a process-based dynamic global vegetation model with representations of natural and managed ecosystems. LPJmL simulates key ecosystem processes of the carbon (Sitch et al., 2003; Bondeau et al., 2007) and water cycle (Sitch et al., 2003; Gerten et al., 2004; Rost et al., 2008) at daily time steps with a spatial resolution of 0.5°. LPJmL has been extensively validated for its representation of carbon cycles (Sitch et al., 2003), agricultural crop production (Bondeau et al., 2007; Fader et al., 2010), irrigation requirements, river flows and water fluxes (Gerten et al., 2004; Rost et al., 2008).

Natural vegetation is represented by nine plant functional types which are dynamically distributed depending on climate (Sitch et al., 2003); agricultural vegetation is represented by 12 crop functional types (CFTs), grazing land and biomass functional types. The distribution and irrigation management of agricultural land and biomass plantations is prescribed (Bondeau et al., 2007; Beringer et al., 2011; Jägermeyr et al., 2015). Crop sowing and harvest dates are simulated based on CFT-specific parameters and climate characteristics (Bondeau et al., 2007; Waha et al., 2012). Agricultural management intensity is represented by three coupled CFT-specific parameters: maximum leaf area index (*LAImax*), a scaling factor for leaf-level photosynthesis (*alphaA*) and a *harvest index* describing the ratio of harvested storage organ to total above ground biomass. Agricultural crop production intensity is calibrated at the country level via *LAImax* which can range from 1 (lowest intensity) to 7 (highest intensity) to simulate the best approximation of national yield statistics of the Food and Agriculture Organization's FAOSTAT database from 1999 to 2003 (Fader et al., 2010). Crops that are not represented by the 12 CFTs are simulated as grasslands and here referred to as *other crops*. Grazing land and *other crops* are harvested to 50% as soon as the above-ground carbon pool threshold is reached.

2.2. LPJmL simulations

LPJmL is used to simulate potential carbon pool changes and yields under the cultivation of pastures, crops (irrigated and rainfed) and *other crops* (irrigated and rainfed) as well as irrigation water requirements and water availability for irrigation of crops and *other crops* as inputs to the optimisation model. For this purpose, LPJmL is driven by historical climate data from CRU TS3.10 (Harris et al., 2014). To bring soil carbon pools and vegetation distribution into equilibrium, all simulations are preceded by a 5000-year spinup with potential natural vegetation (PNV) repeating the climate data time series of the years 1901 to 1930. Subsequently, various potential land use configurations (see Table 1) are simulated with climate data from 1976 to 2005 with an additional spinup of 390 years allowing for the adjustment of carbon pools.

2.3. Optimisation model

We developed a spatially explicit (1°-grid) land use optimisation model (based on the R-package *lpSolveAPI* for linear optimisation (Konis, 2016)) that distributes agricultural land use while minimising global terrestrial carbon pool losses (L_c) and the global risk of biodiversity loss (R_b) as well as fulfilling scenario driven food supply constraints. To this end, the grid cell fractions (f_x) under cultivation of LPJmL crops (irrigated crops $x = c_i$ or rainfed crops $x = c_r$), LPJmL *other crops* (irrigated $x = o_i$ or rainfed $x = o_r$) and pastures (rainfed $x = p$) are varied on a 1.0°-grid until a global optimum is found:

$$\min_{f_{\mathrm{agr}}}(w_b R_b(f_{\mathrm{agr}}) + w_c L_c(f_{\mathrm{agr}})) \mid C_f,\ C_l,\ C_i,\ C_b, \tag{1}$$

$$\text{with } f_{\mathrm{agr}} = f_{\mathrm{ci}} + f_{\mathrm{cr}} + f_{\mathrm{oi}} + f_{\mathrm{or}} + f_p. \tag{2}$$

The distribution of agricultural land use is subject to scenario-driven food supply constraints on the global harvest of crops, *other crops* and pastures (C_f), constraints on land availability and suitability (C_l), constraints on irrigation water availability (C_i) and regional biodiversity conservation (C_b), described in Section 2.4. All input and constraint data to the optimisation are aggregated from their native resolution are