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Mapping global land system archetypes

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ABSTRACT

Land use is a key driver of global environmental change. Unless major shifts in consumptive behaviours occur, land-based production will have to increase drastically to meet future demands for food and other commodities. One approach to better understand the drivers and impacts of agricultural intensification is the identification of global, archetypical patterns of land systems. Current approaches focus on broad-scale representations of dominant land cover with limited consideration of land-use intensity. In this study, we derived a new global representation of land systems based on more than 30 high-resolution datasets on land-use intensity, environmental conditions and socioeconomic indicators. Using a self-organizing map algorithm, we identified and mapped twelve archetypes of land systems for the year 2005. Our analysis reveals similarities in land systems across the globe but the diverse pattern at sub-national scales implies that there are no 'one-size-fits-all' solutions to sustainable land management. Our results help to identify generic patterns of land pressures and environmental threats and provide means to target regionalized strategies to cope with the challenges of global change. Mapping global archetypes of land systems represents a first step towards better understanding the global patterns of human–environment interactions and the environmental and social outcomes of land system dynamics.

1. Introduction

Not only is the world experiencing rapid changes in climate and biodiversity patterns, but increasing consumption of goods and services is placing an enormous pressure on natural ecosystems and the resources they harbour (Butchart et al., 2010; Foley et al., 2005). Particularly, land use has become a major driver of global change because human populations drastically alter land in order to satisfy their basic needs for food, fibre, energy and housing. Human utilization of the biosphere has reached such a magnitude that now more than 75% of ice-free land shows evidence of marked human alteration (Ellis and Ramankutty, 2008) and almost 30% of global terrestrial net primary production is appropriated for human use (Haberl et al., 2007). Current land-use practices result in changes in the Earth's biogeochemical cycles and ultimately in the ability of ecosystems to deliver services critical to human well-being (MEA, 2005). While land use is essential for human societies, it is also becoming increasingly clear that the current global land-use system is unsustainable. Transitioning to sustainable land-use systems that would balance growing resource demands with the conservation of ecosystems and biodiversity is therefore a central challenge for science and society (Foley et al., 2007).

Land-based agricultural production is expected to increase further to meet future demands for food and other commodities, such as biofuel or fibre (Kearney, 2010; Kiers et al., 2008). However, as fertile land resources are getting scarcer and ecosystem functions and services degraded, further agricultural expansion becomes hardly acceptable. Future production increases will have to be, to a large part, achieved via intensifying existing production systems in order to reach global food security and environmental sustainability (Tilman et al., 2011, 2002). Whereas the distribution of agricultural expansion is relatively well mapped (DeFries et al., 2010; Klein Goldewijk, 2001; Klein Goldewijk et al., 2011; Ramankutty et al., 2008, 2002), the patterns of land-use intensity remain poorly understood at the global scale. To identify the potential for sustainable intensification and to better understand the environmental and

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social trade-offs, constraints, and opportunities connected to it, we urgently need to move beyond mapping broad agricultural classes towards mapping land use systems (DeFries and Rosenzweig, 2010).

Traditional models of land systems focus on broad-scale representations of land cover with limited consideration of human influence or land-use intensity (GlobCover, Arino et al., 2007; GLC 2000, Bartholome and Belward, 2005). However, the recent surge in global-scale geospatial data pertaining to land management, such as cropland densities (Ramankutty et al., 2008), fertilizer use (Potter et al., 2010), or soil erosion (Van Oost et al., 2007), provide opportunities to incorporate indicators of land-use intensity. Mapping land systems, and thereby incorporating the multidimensional aspects of land-use intensity and land management practices, can help us to (i) better understand the interactions and feedbacks among different biophysical and social components, (ii) measure impacts that are currently difficult to quantify (e.g. effects of changing land use intensity on biodiversity or social implications of land system transitions), (iii) address global trade-offs and distant impacts of land-use change (Seppelt et al., 2011), and (iv) develop better policies and spatially explicit solutions adapted to regional conditions (Foley et al., 2011). These efforts require a global analysis of land systems that would help identify both the intensity and geographical manifestation of human–environment interactions.

Several new studies made critical strides towards better integrating land management patterns in global representations of the earth's surface. For instance, Ellis and Ramankutty (2008) suggested a new classification of anthropogenic biomes as an innovative view of the human-dominated biosphere. These anthromes are based on empirical analyses of global land cover, irrigation and population data, assuming that population density is a sufficient indicator of sustained human interactions with ecosystems. The anthrome concept was developed further by Letourneau et al. (2012) who proposed a classification of global land-use systems based on additional data on irrigation, livestock type and market accessibility. Most recently, van Asselen and Verburg (2012) improved the representation of land systems by including fractional land cover, livestock density and the efficiency of agricultural production for wheat, maize and rice. These studies used either indirect or a few direct indicators of land-use intensity. They also applied top-down approaches to define land system classes based on expert's rules or a priori classification. To complement these efforts and reduce the level of subjectivity in the classification, an alternative approach is needed that would account for the multiple dimensions of land-use intensity and provide a typology of land systems driven mostly by data rather than by predefined assumptions. Such analysis may help us better understand the global patterns of human–environment interactions and land use intensity and examine the social and environmental outcomes of land system dynamics.

In this study, we propose a new approach for representing human–environment interactions as global archetypes of land systems, which we define as unique combinations of land-use intensity, environmental conditions and socioeconomic factors, with patterns that appear repeatedly across the terrestrial surface of the earth. We aim to move beyond the abovementioned representations by explicitly addressing the multidimensional aspects of land-use intensity and both the drivers of land use and its impacts. Our analysis takes advantage of globally continuous, high spatial resolution datasets on more than 30 indicators of land systems and adopts a bottom-up approach driven solely by the data. We hypothesize that (1) land systems can be clustered in consistent groups based on the similarity of available indicators of global land-use and that (2) the same land system archetypes (LSAs) can be identified across the globe, while diverse patterns can be found at the sub-national scale. By mapping LSAs, we offer a broad view of the most relevant characteristics of human–environment interactions while still preserving local context

Table 1
Datasets used for classification of land system archetypes.

Archetype factor	Spatial resolution	Unit	Source
Land-use intensity factors			
Cropland area	5 arc-minutes	km^2 per grid cell	Klein Goldewijk et al. (2011)
Cropland area trend	5 arc-minutes	km^2 per grid cell	Klein Goldewijk et al. (2011)
Pasture area	5 arc-minutes	km^2 per grid cell	Klein Goldewijk et al. (2011)
Pasture area trend	5 arc-minutes	km^2 per grid cell	Klein Goldewijk et al. (2011)
N fertilizer	0.5 arc-degrees	kg ha^{-1}	Potter et al. (2010)
Irrigation	5 arc-minutes	Ha per grid cell	Siebert et al. (2007)
Soil erosion	5 arc-minutes	Mg ha^{-1} year^{-1}	Van Oost et al. (2007)
Yields (wheat, maize, rice)	5 arc-minutes	t ha^{-1} year^{-1}	http://www.gaez.iiasa.ac.at/
Yield gaps (wheat, maize, rice)	5 arc-minutes	1000 t	http://www.gaez.iiasa.ac.at/
Total production index	National level	Index	http://faostat.fao.org/
HANPP	5 arc-minutes	% of NPP$_0$	Haberl et al. (2007)
Environmental factors			
Temperature	10 arc-minutes	°C × 10	Kriticos et al. (2012)
Diurnal temperature range	10 arc-minutes	°C × 10	Kriticos et al. (2012)
Precipitation	10 arc-minutes	mm	Kriticos et al. (2012)
Precipitation seasonality	10 arc-minutes	Coeff. of variation	Kriticos et al. (2012)
Solar radiation	10 arc-minutes	W m^{-2}	Kriticos et al. (2012)
Climate anomalies	5 arc-degrees	°C × 10	http://www.ncdc.noaa.gov/cmb-faq/anomalies.php#grid
NDVI – mean	4.36 arc-minutes	Index	Tucker et al. (2005)
NDVI – seasonality	4.36 arc-minutes	Index	Tucker et al. (2005)
Soil organic carbon	5 arc-minutes	g C kg^{-1} of soil	Batjes (2006)
Species richness	Calculated from range polygons	# of species per grid cell	http://www.iucnredlist.org/technical-documents/spatial-data
Socioeconomic factors			
Gross domestic product	National level	$ per capita	http://faostat.fao.org/
Gross domestic product in agriculture	National level	% of GDP	http://faostat.fao.org/
Capital stock in agriculture	National level	$	http://faostat.fao.org/
Population density	2.5 arc-minutes	persons km^{-2}	CIESIN (2005)
Population density trend	2.5 arc-minutes	persons km^{-2}	CIESIN (2005)
Political stability	National level	Index	http://www.govindicators.org
Accessibility	0.5 arc-minutes	Minutes of travel time	http://bioval.jrc.ec.europa.eu/products/gam/index.htm