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The global loss of net primary production resulting from human-induced soil degradation in drylands ☆

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ABSTRACT

Land degradation, the temporary or permanent reduction of land's productive capacity resulting from poor land management, has gained considerable attention as an environmental and development issue of global importance, in particular in the Earth's drylands. This study presents a global estimate of net primary production (NPP) losses caused by human-induced dryland degradation. Due to the large uncertainties related to international databases on dryland degradation, we compiled a world map of the extent and degree of desertification based on existing regional and global maps. Two distinct approaches were followed in order to estimate NPP losses due to degradation on drylands: in the first approach, we combined these maps with model results on global potential NPP, determined with the LPJ-DGVM, with a set of factors on NPP losses per degradation degree, derived from the literature. In a second approach, we made use of spatially explicit information on potential and current NPP of agricultural areas obtained from a global HANPP assessment [Haberl, H., Erb, K.-H., Krausmann, F., Gaube, V., Bondeau, A., Plutzar, C., Gingrich, S., Lucht, W. and Fischer-Kowalski, M., 2007. Quantifying and mapping the human appropriation of net primary production in earth's terrestrial ecosystems. Proceedings of the National Academy of Sciences of the United States of America, 104: 12942-12947.]. We used the difference between potential and current NPP on croplands situated in drylands in order to quantify the effect of dryland degradation on NPP. NPP losses were found to range between 799 and 1936 Tg C/yr in the first approach, and to amount to 965 Tg C/yr in the second approach. Overall, approximately 2% of the global terrestrial NPP are lost each year due to dryland degradation, or between 4% and 10% of the potential NPP in drylands. NPP losses amount to 20–40% of the potential NPP on degraded agricultural areas in the global average and above 55% in some world regions. The results reveal that the contributions of dryland degradation to the total HANPP in drylands is of similar dimension than the overall annual socioeconomic biomass harvest. Accordingly, strategies aimed at reducing dryland degradation could present promising options to sustain future population numbers without putting further pressures on dryland ecosystems.

1. Introduction

Land use strongly affects patterns and processes in global ecosystems. Humans dominate, transform and modify ecosystems in order to obtain ecosystem services and goods. While land use activities unquestionably support human well-being and economic development, they increasingly result in a degradation of ecological conditions, such as ecosystem functioning, nutrient cycling, or biodiversity, and subsequently jeopardize the ability of ecosystems to provide services to society (Turner et al., 1990; Vitousek et al., 1997; DeFries et al., 2004; Millennium Ecosystem Assessment, 2005a; Foley et al., 2005; Kareiva et al., 2007). In the course of the last century, land use activities have become major drivers at the planetary level, comparable in size to the natural forces which shape the land surface (Steffen et al., 2007).

The scale, together with the unintended consequences of global land use poses formidable challenges to society. Methods and models that are capable of identifying and monitor key interlinkages between biophysical forces and human drivers are required in order to improve our predicting and management capabilities. The metric "human appropriation of net primary production" (HANPP; Vitousek et al., 1986; Wright, 1990; Haberl, 1997; Haberl et al., 2004; Haberl et al., 2007) has proven to be useful in this context. HANPP has gained attention as an indicator that integrates natural and socioeconomic processes by measuring the changes in the availability of trophic (biomass) energy in ecosystems due to land use.

HANPP integrates aspects of land use quantity (the extent of land use) and land use quality (e.g. the intensity of land use and the potential productivity of used ecosystems), by quantifying the effects of two major land use processes: (a) changes in NPP induced by land conversions, denoted as ΔNPP_{LC} (Haberl et al., 2007), and (b) the withdrawal

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or destruction of biomass in the course of harvest. Several processes contribute to ΔNPP_{LC}: Changes in NPP due to changes in land cover, such as clearings of pristine ecosystems for agricultural purposes, or soil sealing by construction of infrastructure and settlement areas, and modifications of ecosystem patterns and processes without changing land cover (i.e. within-land-cover changes), such as alterations of NPP in consequence of modifications of vegetation structure, species compositions or soil fertility, for example in forests and natural grasslands.

Among those processes which contribute to ΔNPP_{LC}, land degradation has gained considerable attention as an environmental and development issue of global importance. Land degradation commonly refers to the temporary or permanent reduction in the productive capacity of land as a result of human action, mainly poor land management (United Nations, 1994). It is commonly agreed that land degradation is the result of a complex interplay of natural and socioeconomic factors, characterized by highly interrelated underlying mechanisms and drivers, and multiple, complex and context-specific consequences (Blaikie and Brookfield, 1987b; Reynolds and Stafford Smith, 2002; Geist and Lambin, 2004; Safriel et al., 2005; Ramankutty et al., 2006; Reynolds et al., 2007).Today, the largest fraction (78%) of the land area affected by soil degradation is situated in humid regions of the globe (Bai et al., 2008). A much smaller fraction of global degradation occurs in dryland regions, which cover about 40% of the global terrestrial land area (Safriel et al., 2005; Verón et al., 2006). Drylands are characterized by low and highly variable precipitation, high temperatures, and seasonally high rates of evapotranspiration. Degradation of drylands, also denoted as 'desertification', has been recognized as one of the most serious historic and contemporary environmental problems confronting society, directly related to critical sustainability threats such as global malnourishment and poverty (Geist and Lambin, 2004; Reynolds and Stafford Smith, 2002). Desertification directly affects income generation for farmers and pastoralists and entails costs for land restoration (Dregne and Chou, 1992). It is estimated that ecosystem degradation is associated with tremendous economic losses (Pimentel et al., 1995), severely affecting economic development of large global regions and threatening human well-being, in particular in dry climate zones (Daily, 1995; Safriel et al., 2005). Desertification is also a strong cause for large migration movements, which has the potential of adversely affecting local, regional, and even global political and economic stability (Millennium Ecosystem Assessment, 2005b). Coping with desertification is the goal of one of the three United Nation's environmental conventions — the United Nations Convention to Combat Desertification (UNCCD), that emerged in 1992 at the Rio summit in succession of the United Nations Conference on Desertification (UNCOD) of the year 1977.

However, the definitions of desertification remain heterogeneous and the causes and consequences of desertification are widely disputed (Geist and Lambin, 2004; Ramankutty et al., 2006; Verón et al., 2006; Safriel et al., 2005; Bakhit, 1993). Consensus prevails, nevertheless, that desertification is the outcome of the interaction of natural environmental change and variability and human causes, and that the complex interactions involve patterns and processes over a range of spatial and temporal scales. In consequence, even estimates of the areas affected by dryland degradation show large variations, depending on the definitions applied. Table 1 displays global estimates on the extent of dryland degradation as reported by different authors.

An influential estimate of the extent, degree, severity, causes and characteristics of global degradation is the Global Assessment of Human-Induced Soil Degradation (GLASOD; Oldeman et al., 1991). This database refers to global soil degradation in the year 1988 and is based on a qualitative expert approach, involving about 250 regional experts in its making. Although it is widely used for global assessments, it has been criticised widely due to its ambiguousness, its qualitative, inconsistent judgements and its arbitrary assumptions (Olsson, 1993; Oldeman and van Lynden, 1998; Reynolds, 2001; Prince, 2004; Warren and Olsson, 2004; Verón et al., 2006; Bai et al., 2008). Nevertheless, it remains the only comprehensive, spatially explicit assessment available at the global scale. Although ranging at the lower end of estimates (Table 1), more recent global studies indicate that the GLASOD estimate of degradation extent in drylands, which amounts to 20%, is plausible: Lepers et al., 2005) estimate an overall desertification extent of 10%, and Safriel et al., 2005) conclude that the most likely global desertification extent ranges between 10 and 20% of the world's drylands.

Table 1
Estimates of the global extent of dryland degradation.

	Dregne (1983)	Mabbutt (1984)	Oldeman et al. (1991) (GLASOD)	Dregne and Chou (1992)
	[million km^2]			
Africa	10.7	7.4	3.2	10.5
Europe	0.2	0.3	0.4	1.0
Asia	12.0	7.5	4.3	13.4
North America	2.2	1.0	0.6	3.0
South America and Mexico	4.4	2.1	1.0	4.3
Australia and Oceania	3.1	1.1	0.9	3.8
Total	32.5	19.4	10.3	35.9
% of total drylands[a]	64%	38%	20%	71%

[a] 50.8 million km^2, as calculated in this study on basis of the Global Humidity Index (Deichmann and Eklundh, 1991).

Large uncertainties are also associated with quantifications of the effects of degradation for the biological and on economic productivity of land. Although reductions of NPP, measurable e.g. via remote sensing, are used for detecting and quantifying the extent and rate of degradation (Prince et al., 1998; Prince, 2002; Wessels et al., 2004, 2008; Diouf and Lambin, 2001), no studies are currently available which comprehensively quantify the losses in productivity resulting from human-induced degradation beyond a local scale, i.e. at continental or global scales. This is surprising, given the acknowledged central role of degradation as a driver of land use change and alterations of biogeochemical cycles across temporal and spatial scales (Asner et al., 2004; Lepers et al., 2005; Bakker et al., 2005; Zhao et al., 2005; Reynolds et al., 2007).

The objective of this study is to explore dryland degradation in the context of HANPP. In order to take the large uncertainties associated with global dryland degradation data into account, we pursue two separate approaches for estimating the amount of NPP forgone due to dryland degradation. In the first approach, we calculate the possible range of ΔNPP_{LC} caused by dryland degradation by combining spatially explicit information on the extent of dryland degradation with information on potential NPP and assumptions on the amount of NPP lost as a function of different degradation degree classes. In the second approach, we make use of the spatially explicit information on potential and current NPP of agricultural areas presented in the global HANPP assessment by Haberl et al. (2007) and Erb et al. (2007). These datasets are consistent with statistical data on agricultural land use and production provided by FAO at the national level and allow for deriving an independent estimate based on other datasets.

Dryland degradation encompasses many effects, among others water and wind erosion, salinization, soil compaction and crusting, top soil losses and nutrient depletion, as well as alterations of vegetation composition and structure, i.e. vegetation degradation. This paper will be confined to the effects of soil degradation; effects of vegetation degradation will not be quantified. This is due to the large uncertainties of knowledge associated with NPP effects of vegetation degradation. Vegetation degradation affects mainly plant composition., e.g. by shrub encroachment (Hoffman et al., 1999; Kharin, 2002), and reduces the output of palatable biomass (Snyman, 1998; O'Connor et al., 2001; Asner and Martin, 2004; Wessels et al., 2007b). However, it is unclear if this leads to an overall reduction in NPP (Schlesinger et al., 1990, Huenneke et al., 2002, Asner and Martin, 2004, Asner and Heidebrecht, 2005, Verón et al., 2006). Furthermore, vegetation degradation is much more of short-term nature and in principle — although sometimes cost-intensive — reversible (Le Houérou et al., 1988; Huenneke et al., 2002; Herrmann et al., 2005; Wessels et al., 2007a). The assessment of HANPP