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Simulating and estimating tempo-spatial patterns in global human appropriation of net primary production (HANPP): A consumption-based approach

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ABSTRACT

Anthropogenic alterations of biomass flows in earth's biogeochemical cycles may profoundly affect the amount of biomass available, the level of biodiversity and the extent of carbon sequestration in global terrestrial ecosystems. Quantitative assessments of humanity's impacts on ecosystem structures and services are therefore essential for projections of changes in terrestrial vegetation. Human appropriation of photosynthetic production (HANPP) has been extensively used as an ecological indicator for monitoring direct human interventions into terrestrial ecosystems. Here, we present the results of tempo-spatial estimations of the loss of net primary production by global terrestrial ecosystems due to human consumption-based appropriation (cHANPP, an aggregate ecological indicator for evaluating human impacts on terrestrial ecosystems due to harvesting and processing of plants for consumption) from 2000 to 2050. Our estimates are based on previously derived estimate of global biomass harvest and use for the year 2000 (Krausmann et al., 2008) through association with IPAT (Impact = Population × Affluence × Technology) model used for estimating the influence of changes in population, per capita consumption demands and technology employed during harvesting and processing of plants on biomass consumption. Our results show a distinct tendency toward increased global cHANPP by 0.17 Pg C yr^{-1} ($P<0.001$) from 2000 to 2050 (changes resulting from land conversion are excluded), mainly resulting from an increased global population size and intensified per capita consumption of agricultural products. Long-term trends and spatial patterns in cHANPP exhibit significant variations across countries and geographical zones owing to tempo-spatial variations of both population size and consumption patterns. The proportion of potentially available photosynthetic production appropriated by human consumption, estimated at approximately ~28% in the 2000s, is projected to increase to approximately ~33% in the 2040s. Our results also indicate that technology may play a crucial role for alleviating the growing impact of human activities on terrestrial ecosystems and provide potential insights for sustainable development in the context of management issues and decision making.

1. Introduction

Global climate change and the continuously escalating concentration of atmospheric carbon dioxide have been widely documented to enhance plant growth (Myneni et al., 1997; Sitch et al., 2008), particularly in northern latitudes (Myneni et al., 2001; Lucht et al., 2002), and therefore lead to a marked increase in global net primary production (NPP) (Nemani et al., 2003), the net amount of energy (mostly solar) biologically assimilated through photosynthesis. However, this might not result in an increase in the amount of NPP, actually available to all heterotrophs, because a loss of photosynthesis products is simultaneously caused by human appropriation through both harvest and anthropogenic changes in land cover and land use (Vitousek et al., 1986; Haberl et al., 2007; Zika and Erb, 2009).

Human appropriation of net primary production (HANPP) derives from both direct and indirect consumption of terrestrial photosynthesis products through agriculture and forestry as well as the loss of biomass caused by changes in human land use (Vitousek et al., 1986). The appropriation not only reduces the food sources available to other species, but it also distinctly alters the material and energy flows in Earth's biogeochemical cycles and within food webs (Haberl et al., 2007). HANPP is therefore an important ecological indicator of the magnitude of humanity's impacts on terrestrial ecosystems and is useful for examining the implication of these impacts for sustainable development at both global and regional

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scales (Haberl, 1997; Haberl et al., 2005; Imhoff and Bounoua, 2006; O'Neill et al., 2007; Bishop and Amaratunga, 2010).

HANPP has received considerable attention over the past several decades in attempts to address the basic question of how much of the biosphere's annual primary production is altered due to human intervention. Vitousek et al. (1986) conducted the first quantitative calculations of global HANPP using three estimate levels (low, intermediate and high). In these calculations, the low estimate was simply the amount of terrestrial NPP consumed directly by humans and domestic animals. The intermediate estimate calculated all the productivity of human-dominated lands entirely for socioeconomic activities. The loss of productive capacity of terrestrial ecosystems owing to land conversion was further included in the high estimate. Their results suggested that global HANPP in the early 1980s might be estimated as 7.2, 42.6 and 58.1 $\mathrm{Pg\,C\,yr^{-1}}$ (approximately 3%, 19%, and 40% of the global terrestrial NPP, respectively) for the three estimate levels, respectively. Rojstaczer et al. (2001) estimated global HANPP, in which changes in NPP resulting from land conversion were excluded, for the 1990s as 20 $\mathrm{Pg\,C\,yr^{-1}}$ (32% of the global NPP) with uncertainty of 10–55%. Imhoff et al. (2004) calculated the magnitude of global consumption-based HANPP in 1995 to be 11.5 $\mathrm{Pg\,C\,yr^{-1}}$ (approximately 20% of total NPP) using an intermediate estimate that excluded the contribution of land conversion. Haberl et al. (2007) presented a land-based estimate of 15.6 $\mathrm{Pg\,C\,yr^{-1}}$ (23.8% of the total NPP) for global HANPP around the year 2000 in which terrestrial NPP loss caused by land use change and human-induced fires were taken into account.

Although previous studies differed slightly in their quantitative estimates of global HANPP, largely because of differences in their definitions of HANPP, calculation methods and data sources, the results of these previous studies commonly suggest that a considerable proportion of global NPP may be appropriated by human activities. Although spatial patterns in HANPP for a specified year have been proposed (Imhoff et al., 2004; Krausmann et al., 2009), the long-term trends in global HANPP in relation to changes in world population size and spatial distribution, alterations in human demands on agricultural and forest products and the levels of technology employed in agricultural and forestry sectors, however, are not well addressed. Investigating shifts in the tempo-spatial patterns of global HANPP can help us to further assess anthropogenic effects on terrestrial ecosystems in terms of global carbon cycling, world food security, the provision of ecosystem services and global sustainability concerns (Haberl et al., 2007).

The primary objective of this study is to quantitatively investigate tempo-spatial variations in global consumption-based HANPP (cHANPP), which is defined as the loss of terrestrial NPP due to direct human consumption of biomass for food, feed and fiber as well as biomass loss during harvest. Based on the previous calculation of global biomass harvest and use by Krausmann et al. (2008), we simulated the tempo-spatial changes in global cHANPP for the period from 2000 to 2050 using the IPAT model (Impact = Population × Affluence × Technology) (Dietz and Rosa, 1994, 1997) in combination with three datasets: (1) the time series data of country-level agricultural and forest product consumption derived from the Food and Agriculture Organization (FAO, 2010), (2) country-level population size derived from the FAO (2010) and (3) potential terrestrial NPP derived from dynamic global vegetation models (Cramer et al., 2001). We then performed comparative analyses regarding tempo-spatial distribution patterns in global cHANPP: (1) the impacts of world population size, human demands and technology on cHANPP dynamics, (2) the differences in cHANPP trends between countries and latitudinal zones and (3) the changes in the spatial pattern of grid-based cHANPP.

2. Materials and methods

2.1. Calculation of cHANPP

From an ecological perspective, HANPP can been defined as the difference between the potential net primary production (NPP_0), the solar energy incorporated by the prevailing vegetation in the absence of human activities, and the NPP of the actual vegetation remaining in ecosystems after harvest (Haberl et al., 2007; O'Neill et al., 2007; Erb et al., 2009; Krausmann et al., 2009). Three different components are usually taken into account in the calculation of HANPP: (1) organic materials used directly by humans and domestic animals, (2) biomass destroyed and left on site during harvest, and (3) the loss of productive capacity of ecosystems due to human-induced land use changes, land degradation and human-induced fires. The results on estimation of HANPP may therefore vary depending upon the definition and scope used. In this study, we defined HANPP as the sum of components (1) and (2). Our estimates for long-term tempo-spatial trends in HANPP from 2000 to 2050 started with FAO country level consumption data in association with gridded population density data. We therefore use the term "cHANPP" to emphasize that we pay attention to the assessment of the "upstream" biomass losses associated with the consumption of biomass-based products (Haberl et al., 2009) while we do not include changes in NPP resulting from land conversion.

Krausmann et al. (2008) provided a comprehensive estimation of global patterns of socioeconomic biomass flows around the year 2000 derived from FAO country-level consumption datasets. Based on their quantitative approach to estimating global HANPP, we calculated cHANPP as the sum of three distinct components: food-related cHANPP, wood-related cHANPP and unused extraction ($\mathrm{cHANPP_{unused}}$):

$$\mathrm{cHANPP} = \mathrm{cHANPP_{food}} + \mathrm{cHANPP_{wood}} + \mathrm{cHANPP_{unused}} \quad (1)$$

where food-related cHANPP was defined as terrestrial NPP losses due to harvested crops, used crop residues and grazed biomass (in relation to animal food consumption). The amount of NPP lost due to wood (for building and fuel), paper and fiber consumption was treated as wood-related cHANPP. Unused extraction of NPP was defined as indirect human appropriation of terrestrial ecosystem production through unused residuals from both crop and wood harvests and belowground biomass of harvested crops and felled trees (Krausmann et al., 2008). Aquatic biomass consumption and the influences of transportation of photosynthetic products through regional and global trades were not taken into account in our estimates of tempo-spatial patterns in cHANPP because of the lack of data.

The long-term trends in country-level cHANPP were estimated using the IPAT model (Impact = Population × Affluence × Technology) (Dietz and Rosa, 1994, 1997) in association with quantitative estimates of cHANPP in the year 2000 for 175 countries provided by Krausmann et al. (2008) as:

$$\begin{aligned}\mathrm{cHANPP}(Y) = {} & \mathrm{PoM}(Y) \times \mathrm{TeM}(Y) \times [\mathrm{FoM}(Y) \times \mathrm{cHANPP_{food}}(2000) \\ & + \mathrm{WoM}(Y) \times \mathrm{cHANPP_{wood}}(2000) + (\alpha \mathrm{FoM}(Y) \\ & + \beta \mathrm{FiM}(Y)) \times \mathrm{cHANPP_{unused}}(2000)] \end{aligned} \quad (2)$$

where PoM, FoM, WoM and TeM are normalized multipliers of country-level population size, food-related consumption, wood-related consumption and technology employed during the harvesting and processing of biomass in the year Y with respect to the corresponding values in the year 2000. α and β are proportionality constants of food-related consumption and wood-related consumption in the year Y, respectively.