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Appropriation of potential net primary production by cropland in terrestrial ecoregions

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ABSTRACT

Terrestrial ecoregions of the world have been extensively converted to croplands as a result of human demand for food, fibers, fuels and fodder. Agricultural land cover change has been listed as one of the main drivers of biodiversity loss and change in ecosystem biogeochemical budgets. To provide a quantitative estimate of human impacts on ecosystems, we estimate the amount of net primary production appropriated by the world's croplands from potential natural vegetation cover. Potential net primary production embodied in the 170 crops analyzed was determined using a combination of existing spatial data on crop production and yield statistics, distribution of terrestrial ecoregions and net primary production of potential vegetation. We found that global croplands directly appropriate 9.1 Gt of carbon annually, which is about 14% of potential net primary production. The intensity of human impacts on terrestrial ecoregions differs according to the level of anthropogenic conversion to croplands. Temperate grasslands and savannas have been traditionally converted into croplands and therefore productivity appropriation reaches the highest levels of 34% in aggregate. In addition to the analysis of appropriation of net primary productivity in terrestrial regions, we also report intensity factors describing the embodied amount of productivity lost by conversion of natural regions into croplands. The results of appropriation of original natural net primary production by croplands contribute to discussion of the differences in land use intensity in different countries.

1. Introduction

Humans convert natural ecosystems to cropland to harness food, fodder, fibers and fuels. Land use change induced by the demand for crops has been accelerating in recent decades (Gibbs et al., 2010). The majority of this conversion has been located in biomes and ecoregions suitable for agriculture, and in tropical areas (Hoekstra et al., 2005). Human transformation of the biosphere has reached an unprecedented extent and rate. With the majority of natural biomes transformed, several planetary boundaries have been transgressed by human actions (Ellis et al., 2010; Rockström et al., 2009). Vegetation intactness as a measure of ecosystem integrity in terrestrial ecoregions has been suggested as a key component to assess future vulnerability to climate change and habitat modification (Watson et al., 2013). Intact ecosystems provide valuable regulating ecosystem services which are further degraded as a result of land use change, especially in tropical regions (Costanza et al., 2014).

Land transformation induced by agricultural crops has been the predominant driver of natural habitat loss. People have been converting productive ecosystems into croplands since the start of the Neolithic period, and the onset of farming has been proposed as one of the possible Anthropocene boundaries (Lewis and Maslin, 2015). In 2000, cropland area was estimated at 15 million km^2 (Ramankutty et al., 2008), with only a minor change up to 2013 according to FAOSTAT (FAO, 2015).

Net primary productivity (NPP) is the amount of biomass generated in an ecosystem over a particular time period. It has been frequently used as an ecological outcome of environmental processes (Costanza et al., 2007; Haberl et al., 2014). Through photosynthesis as one of the basic biosphere's energy flows, net primary production determines the amount of biomass and carbon available in ecosystems for humans and other species. The quantity of energy available in an ecosystem is also considered to be one of the major determinants of species diversity, especially species richness (Bailey et al., 2004). Human appropriation of net primary productivity (HANPP) has been used as a measure of various human

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Abbreviations

i	Cell identifier within the grid
j	Crop identifier
k	Country index
A	Cropland area (measured in hectares)
HA	Harvested area (measured in hectares)
NPP	Net primary production (measured in tons of carbon per year)
C	Carbon
NPP0	Potential net primary production (measured in tons of carbon per year)
P	Harvest (production) (measured in tons)
Y	Yield (Y = P/HA)
eNPP0	NPP0 embodied in a product or crop (measured in tons of carbon per year)
eNPP0f	NPP0 per ton of crop (measured in tons of carbon per year per ton of crop)
FCU	Factor of cropland utilization (considers successive cropping and fallow land)

impacts on ecosystem integrity, through the analysis of NPP influenced by humans or remaining in ecosystems after human intervention (Allred et al., 2015; Haberl et al., 2014). The productivity of potential vegetation has been suggested as a proxy for ecosystem capacity to provide energy to ecosystems and goods and services supporting human society (Millennium Ecosystem Assessment, 2005).

Previous studies of human appropriation of net primary production have focused on general patterns in the effects of land conversion and harvest on net primary productivity (Haberl et al., 2014). This approach enables differentiation of the effect of land cover change on actual net primary productivity and the effects of harvesting and biomass extraction from ecosystems. In this analysis, we quantify the direct appropriation of net primary production of potential vegetation by croplands. The conversion of land for productive purposes has been documented as the predominant driver of natural ecosystem productivity loss (DeFries, 2002; Haberl et al., 2014; Smith et al., 2014). Our approach is therefore different from previous studies of HANPP, which account for land conversion and harvesting (Haberl et al., 2007) or allocate NPP supply based on human demand (Imhoff et al., 2004).

In this article, we present an analysis of appropriation of the potential productivity of natural ecosystems by global croplands. We focus on appropriation in the terrestrial ecoregions of the world as they represent relatively homogeneous natural units with regard to natural conditions, and hence net primary productivity patterns. We analyze the appropriation of potential net primary productivity embodied in 170 individual crops harvested on the site of the original vegetation. Following this analysis, we estimate factors which enable quantification of embodied net primary productivity in individual crops produced in world ecoregions and countries, respectively. These factors are constructed to assess the impact of crop production on natural ecosystems and can be applied in various analyses of the human transformation of Earth's land surface connected to crop production. This work is an essential step in consumption based accounting for appropriation of potential NPP.

2. Methods

We define appropriation of potential net primary production (NPP0) by cropland as the NPP0 of the natural area actually altered by cropland. We allocate this appropriation to crop products directly harvested from cropland (such as wheat or rice) to derive NPP0 embodied in those products (eNPP0, also called NPP0 footprint), based on the actual cropland area occupied by the crop and NPP0 of this area.

Using spatially specific data and assuming homogenous spatial units, eNPP0 can be expressed in grid cell i for crop j as:

$$eNPP0_{i,j} = NPP0'_i \cdot A_{i,j}$$

where i is a cell identifier within the grid, j is a crop identifier, $NPP0_i'$ is NPP0 per unit of area and $A_{i,j}$ is the actual cropland area allocated to crop j in cell i. In accordance with NPP0, eNPP0 is reported in the amount of carbon (e.g. tons) per year.

In order to estimate the eNPP0 of individual crops it is necessary to derive $A_{i,j}$. As a hectare of cropland can be harvested more times a year (successive or multiple cropping), it is necessary to divide it among the harvested crops and therefore decrease the cropland area assigned to each crop accordingly. Conversely, cropland can also remain unharvested, which increases the cropland area with no additional harvest. We allocate the unharvested area to the harvested crops proportionally to their harvested area and therefore increase their assigned cropland area. In order to incorporate successive cropping and unharvested area to the eNPP0 calculation, we introduce a factor of cropland utilization (FCU) for adjustment of the rate of utilization of land use specific to each grid cell i. We calculate this factor by dividing the harvested area of all crops harvested in spatial unit i by the total cropland in this spatial unit:

$$FCU_i = \frac{\sum_j HA_{i,j}}{A_i}$$

where $HA_{i,j}$ is the harvested area of crop j in cell i and A_i is the total cropland in cell i. This expression reflects the data availability, as harvested area is available for each crop in each cell and counts the total harvested area each time it is harvested (therefore, for multiple cropping it counts the harvested area multiple times), while the total cropland is available only as an aggregate over all crops and counts the cropland only once.

We estimate cropland by crop and cell $A_{i,j}$ from the crop and cell specific harvested area and cell specific factor of cropland utilization as:

$$A_{i,j} = \frac{HA_{i,j}}{FCU_i}$$

Hence, $eNPP0_{i,j}$ can be expressed as:

$$eNPP0_{i,j} = \frac{NPP0'_i \cdot HA_{i,j}}{FCU_{i,j}} = \frac{NPP0'_i \cdot P_{i,j}}{Y_{i,j} \cdot FCU_{i,j}} \quad (1)$$

After substituting

$$HA_{i,j} = \frac{P_{i,j}}{Y_{i,j}}$$

where $P_{i,j}$ is the actual harvest of crop j in cell i and $Y_{i,j}$ is the yield of crop j in cell i.

By summing $eNPP0_{i,j}$ over all spatial units within a defined area we obtain the total $eNPP0_j$ attributed to crop j within this area. The defined area can be an eco-region, country, or any other area of interest, e.g. a combination – an ecoregion within a country: