Ecological Indicators 60 (2016) 184–191

Contents lists available at ScienceDirect

Ecological Indicators

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

A modified framework for the regional assessment of climate and human impacts on net primary productivity

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ARTICLE INFO

Article history:
Received 29 August 2014
Received in revised form 9 June 2015
Accepted 14 June 2015

Keywords:
$\mathrm{NPP}_{\mathrm{gap}}$
HANPP
Plant functional traits
Precipitation legacy
Tibetan Plateau

ABSTRACT

Improving models that depict the components of net primary production (NPP) in ecosystems will help us to better understand how climate change and human activities affect the biosphere. In this study, $\mathrm{NPP}_{\mathrm{gap}}$ was introduced into the present human appropriation of net primary production (HANPP) framework. We introduced $\mathrm{NPP}_{\mathrm{gap}}$ in this study as potential NPP ($\mathrm{NPP}_{\mathrm{pot}}$) minus the sum of ecosystem NPP ($\mathrm{NPP}_{\mathrm{eco}}$) and HANPP, which relates to the ability of models to depict NPP components. Using the Lhasa River region of the Tibetan Plateau, we examined temporal and spatial variations in the components of NPP over a 10-year period. Results showed that $\mathrm{NPP}_{\mathrm{pot}}$, HANPP and $\mathrm{NPP}_{\mathrm{eco}}$ increased from 2000 to 2010, but at different rates and with different spatial patterns. $\mathrm{NPP}_{\mathrm{gap}}$ each year ranged from −9.2% to 13.1% for each site and on average composed 1.2% of the total $\mathrm{NPP}_{\mathrm{pot}}$. $\mathrm{NPP}_{\mathrm{gap}}$ was significantly correlated with precipitation, plant biodiversity, plant height and soil properties. $\mathrm{NPP}_{\mathrm{gap}}$ increased if either of the previous 2 years had been wet years with relative high precipitation. An increase in the richness of palatable species would lead to a larger $\mathrm{NPP}_{\mathrm{gap}}$ through more compensatory growth. The large fluctuation level of $\mathrm{NPP}_{\mathrm{gap}}$ reflected the higher stability of vegetation productivity, which is caused by higher plant heights and soil maximum water capacity. This study showed the potential of the HANPP framework in regional assessment of climate and human impacts on net primary productivity. The use of the $\mathrm{NPP}_{\mathrm{gap}}$ measure reflects the gap in our knowledge and our ability to accurately estimate the components of NPP.

1. Introduction

Net primary production (NPP) is the net amount of carbon accumulated by plants in a given period (Haberl et al., 2007). NPP is the fundamental ecosystem service that mediates an ecosystem's ability to supply other services, such as producing food and fiber, regulating climate and water, and supplying recreation and cultural benefits (Millennium Ecosystem Assessment, 2005). A framework of human appropriation of net primary production (HANPP) was introduced and developed to help us to understand climate and human impacts on ecosystems (Wright, 1990; Haberl, 1997; Imhoff et al., 2004; Haberl et al., 2007, 2014). HANPP is defined as the difference between the NPP of the natural vegetation thought to exist in the absence of land use (Haberl et al., 2014). In the latest definition, HANPP equals the NPP of potential natural vegetation ($\mathrm{NPP}_{\mathrm{pot}}$) minus the NPP remaining in the ecosystem after harvest under current conditions ($\mathrm{NPP}_{\mathrm{eco}}$) (Haberl et al., 2014). HANPP comprises the harvested NPP ($\mathrm{HANPP}_{\mathrm{harv}}$) and changes in NPP resulting from land conversion and land use ($\mathrm{HANPP}_{\mathrm{luc}}$) (Haberl et al., 2014).

HANPP is an indicator of the extent of human interference on the NPP partitioning process. HANPP has, in general, been calculated at the global scale. Global HANPP doubled in the 20th century, comprising 24% of potential NPP in 2000, of which 53% was harvested, 40% lost as a result of changes in land use, and 7% lost in human-induced fires (Haberl et al., 2007; Krausmann et al., 2013). The global HANPP quantification showed us the tremendous scale of human intervention on ecosystems.

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http://dx.doi.org/10.1016/j.ecolind.2015.06.017
1470-160X/

Applying the HANPP framework at a regional scale can quantify the NPP loss by human intervention in more detail but, more importantly, find ways to optimize ecosystem management. The HANPP framework can be used to underpin regional sustainability, based on a detailed understanding of the impact of climatic change and human activities on net primary productivity (Cardoch et al., 2002; Mao et al., 2014). For HANPP to be an effective tool, the global HANPP framework needs to be amended and developed in line with the regional differences in climate and human activities.

The Tibetan Plateau is the highest plateau in the world with a dominant ecosystem of alpine grassland, which supports both the livelihood of local residents and the hydrological and carbon cycles of the Asia continent (Pan et al., 2014). In the shoot–root–soil system of an alpine meadow on the Tibetan Plateau, 58.3% of total assimilated carbon was transferred to belowground pools, which was much higher than the proportion in perennial grasses, such as ryegrass (Wu et al., 2010). Grazing in this system could possibly lead to less carbon being lost through shoot respiration and more being translocated belowground (Hafner et al., 2012). However, increased human populations and grazing activities consumed an increasing amount of aboveground NPP, leaving less in the ecosystem. This could lead to tradeoffs between regional ecosystem provisioning and regulating services (Pan et al., 2014). Vegetation change due to climate change may also lead to a more difficult situation for decision makers trying to balance support for local livelihoods and for the continent's environment. The HANPP framework plays an important role in quantifying the impacts of climate change and grazing on vegetation dynamics. However, the framework needs to be downscaled from the global scale to account for variations in the dominant human activity of livestock grazing and the regional climate.

Local quantification of each part of NPP is the key purpose of the regional application of the HANPP framework. Of the total NPP, climatic potential NPP (NPP_{pot}) refers to the maximum NPP driven by climatic factors, which includes the NPP consumed or lost by human activities, and the NPP left in the ecosystem (Chen et al., 2014). NPP_{pot} can be simulated by models (Adams et al., 2004), including biogeographical (correlative) models such as Miami (Lieth, 1975) and BIOME (Prentice et al., 1992), and biogeochemical (process-based) models such as the Terrestrial Ecosystem Model (TEM) (Chen et al., 2014; Raich et al., 1991). Ecosystem NPP (NPP_{eco}) is the fraction of NPP remaining in the ecosystem after human intervention (Haberl et al., 2014). NPP_{eco} can be simulated with the Carnegie–Ames–Stanford Approach (CASA) model (Chen et al., 2014; Field et al., 1995; Potter et al., 1993), or estimated using a Moderate Resolution Imaging Spectroradiometer (MODIS). NPP_{eco} equals NPP_{pot} minus HANPP in the original definition (Haberl et al., 2014). NPP_{eco} is connected with the supply of many regulating services, such as water regulation, carbon sequestration and soil retention (Pan et al., 2014).

Gaps remain in our knowledge of NPP and this has limited model accuracy. For example, there is a time lag associated with the response of NPP_{pot} to precipitation changes (Jin and Goulden, 2014; Lauenroth and Sala, 1992; Peters et al., 2012, 2014; Reichmann et al., 2013; Sala et al., 2012). In addition, current HANPP models seldom include the feedback of harvest or land use to the ecosystem, including the fertilizing effects of grazing animals (Xu et al., 2013) and the compensatory growth of damaged plant tissue (Hawkes and Sullivan, 2001; Leriche et al., 2001, 2003; Schonbach et al., 2011; Wise and Abrahamson, 2007). These knowledge gaps may lead to estimation errors because NPP_{pot} may not equal the sum of NPP_{eco} and HANPP.

In this study, we introduced an NPP_{gap} into the current HANPP framework. We attempted to find the temporal and spatial patterns of NPP_{gap} in the context of changing climate and human activities. Further, we attempted to identify how ecosystem properties, biodiversity, plant functional traits and soil properties affect the heterogeneous patterns of NPP_{gap}. The aim of introducing NPP_{gap} is to improve the NPP simulation in the HANPP framework via the consideration of precipitation legacies and grazer-driven compensatory plant growth.

2. Materials and methods

2.1. Theoretical framework

The net primary production includes four components of NPP_{pot}, HANPP, NPP_{eco} and NPP_{gap} (Fig. 1). NPP_{gap} was proposed in this study to be NPP_{pot} minus the sum of NPP_{eco} and HANPP. NPP_{pot} was simulated by a process-based model, representing the regional maximum NPP, only affected by climate change. HANPP comprise harvest biomass ($HANPP_{harv}$) and biomass loss from land conversion and land use ($HANPP_{luc}$) (Haberl et al., 2014). $HANPP_{harv}$ was calculated based on meat production and cattle breeding, representing the NPP lost to grazing. $HANPP_{luc}$ were not considered in this study because there was no land conversion in last decade of the sampling area. NPP_{eco} is the NPP remaining in ecosystem supplying ecosystem regulating services. For this study, we assumed that the NPP_{gap}, including the mean value and the fluctuation level, was affected by ecosystem properties, plant functional traits, plant diversity, soil properties and precipitation in previous years, as precipitation legacies (Reichmann et al., 2013; Sala et al., 2012) and the compensatory growth (Leriche et al., 2003) may play an important role in NPP.

2.2. Study region

The Lhasa River region lies in the south of the Tibetan Plateau, and in the center of the Tibet Autonomous Region (29°0′–31°45′N, 90°1′–94°10′E), comprising eight counties (Fig. 2). The altitude ranges from 3563 to 6836 m. Grasslands occupy 70% of the total area in this region, mostly alpine meadows with small areas of warm steppe in the river valley areas. Not much land-use conversion has occurred in the last decade of the whole Lhasa River region, only 0.17% land converted from grassland to wet land and 0.08% from grassland to settlements. And no land converted in the sampling area. The mean annual precipitation was 594 mm in 2010 and has been decreasing by an average of 13.36 mm each year since 2000. The mean air temperature in 2010 was −0.49 °C and has been increasing by an average of 0.10 °C annually since 2000 (Fig. 3b and Table 1). The main human impact on NPP in this region is grazing, specifically by yak, sheep and goats. Overgrazing is a common problem in recent years as the livestock inventories increased steadily from 2001 to 2008, although numbers decreased from 2008 to 2010, possibly related to ecological compensations implemented around 2003 (Chen et al., 2014).

2.3. Data collection and processing

Annual NPP_{Pot} values for 2000–2010 were calculated using Terrestrial Ecosystem Model (TEM), as described in Chen et al. (2014), using a pixel level of 1 km × 1 km. Annual NPP_{eco} (also using a pixel level of 1 km × 1 km) from 2000 to 2010 were taken from MODIS 17A3 (Smith et al., 2014) (http://e4ftl01.cr.usgs.gov/MOLT/). Annual precipitation and air temperature data (Fig. 2) were retrieved from the China Meteorological Administration (http://www.cma.gov.cn/) and interpolated to pixel data with spatial resolution of 1 km using ANUSPLIN ver. 4.2 (Chen et al., 2014). Yak, sheep and goat stocks and meat production at the county level were taken from Tibetan year books (2001–2011). All stock data were converted to sheep units, with one yak equaling four sheep units and one sheep or goat equaling one sheep unit, and then transformed to