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Quantification and assessment of changes in ecosystem service in the Three-River Headwaters Region, China as a result of climate variability and land cover change

Chong Jiang[a,b,c,d,*], Daiqing Li[c,d], Dewang Wang[c,d], Linbo Zhang[c,d,*]

[a] College of Global Change and Earth System Science, Beijing Normal University, Beijing 100875, China
[b] Joint Center for Global Change Studies, Beijing 100875, China
[c] State Key Laboratory of Environmental Criteria and Risk Assessment, Chinese Research Academy of Environmental Sciences, Beijing 100012, China
[d] Key Laboratory of Regional Eco-Process and Function Assessment and State Environment Protection, Chinese Academy of Environmental Sciences, Beijing 100012, China

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ABSTRACT

Rapid and periodic assessment of the impact of land cover change and climate variability on ecosystem services at regional levels is essential to understanding services and sustainability of ecosystems. This study focused on quantifying and assessing the changes in multiple ecosystem services in the Three-River Headwaters Region (TRHR), China in 2000–2012. Based on the widely used biophysical models including Integrated Valuation of Ecosystem Services and Trade-Offs (InVEST), Revised Wind Erosion Equation (RWSQ), and Carnegie-Ames-Stanford Approach (CASA) models, this study assessed the historical flow of regulating services, including soil conservation, water yield, and carbon sequestration, and provisioning service food provision. The soil conservation function of ecosystem was slightly enhanced as a whole, and water yield increased sharply, with both the soil conservation and water yield showing an increasing spatial homogenization. The net primary productivity (*NPP*) and food production increased substantially from 2000 to 2012. Ecosystem services are closely and complexly interlinked. The correlation analyses indicated a trade-off between the water yield and carbon sequestration, however, a synergy between soil conservation and carbon sequestration. Congruence between the three different ecosystem provisioning services, including pasture, meat, and grain, was found. There was also a synergy between food production and ecosystem carbon sequestration in the TRHR. Climatic variability and vegetation restoration are important for the ecosystem services flow. Correlation analyses showed that the increase in precipitation significantly enhanced the water yield ($P < 0.01$) and soil erosion ($P < 0.01$), while the temperature increase influenced positively the *NPP* ($P < 0.1$). The experience of ecological rehabilitation and the change in key ecosystem services in the TRHR exemplified the positive effects of environmental policies and the necessity of adopting an adaptive management approach. Thus the ecological construction and policy making should take climate variability into account, and facilitate synergies on multiple ecosystem services in order to maximize human well-being and preserve its natural ecosystems.

1. Introduction

Ecosystems generate a range of goods and services collectively called ecosystem services that are important for human well-being (Nelson et al., 2009). Over the past decade, ecosystem services have been a central issue in the sustainable management of natural resources (Dearing et al., 2012) and progress has been made to understand them and their associated economy (National Research Council, 2005). Ecosystem services are affected by several factors including changes in the demography, economy, socio-politics, science, technology, religion, and physical and biological conditions (Millennium Ecosystem Assessment, 2005; Lü et al., 2012). Over the last 50 years, 60% of the worldwide ecosystem services degraded as a result of the global population increase and economic growth (Millennium Ecosystem Assessment, 2005). In China, widespread ecological degradation has constrained a sustainable socio-economical development in the recent decades. For instance, between the early 1980s and the 2000s, 23% of Chinese land suffered ecological degradation, upon which approximately

* Corresponding authors at: State Key Laboratory of Environmental Criteria and Risk Assessment, Chinese Research Academy of Environmental Sciences, Beijing 100012, China. Tel.: +86 010 84915171.
E-mail addresses: jiangchong1987@gmail.com (C. Jiang), zhanglb@craes.org.cn (L. Zhang).

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35% of the Chinese population depended for ecosystem services (Bai et al., 2009).

Land cover and climatic changes have been identified as two of the most important drivers of change in ecosystems and their services (Nelson et al., 2009; Millennium Ecosystem Assessment, 2005). Expansion of agricultural urban land contributes to land cover change and account for over 40% of the global total land area and more than 80% of the global total consumptive water use (Foley et al., 2005). Recent studies have revealed that increase in agricultural and urban land use can have direct consequences on ecosystem services, such as climate and water regulation, support of habitats, and food provisions (Dale and Polasky, 2007; Zhang et al., 2007). Mitigating these consequences requires effective management of ecosystem services and is essential to develop conservation and land management plans (Kremen, 2005).

Managing ecosystem services requires knowledge of their dynamic patterns, status, connections, interactions among ecosystem structures, functions, and landforms. Although several recent studies have quantified and mapped ecosystem services (e.g., Chan et al., 2006; Daily et al., 2008; Egoh et al., 2009; Leh et al., 2013), very few analyzed multiple services (Seppelt et al., 2011). A spatially explicit assessment of ecosystem services is critical for an informed land use and management decisions (Balmford et al., 2002; Millennium Ecosystem Assessment, 2005). Yet, spatially explicit ecosystem services across landscapes are rarely available because of their difficult reliable quantification (Balmford et al., 2002; Nelson et al., 2009). The impacts of human activity on ecosystem services are mostly reflected at local and regional levels (Lü et al., 2012). However, the consequence of land cover change with respect to ecosystem services and human well-being at local and regional scales has not been fully understood.

The TRHR is important for its large area of natural forest, grassland, and wetland ecosystem. The changes in the flow of multiple ecosystem services, especially since 2000, did not receive much attention in previous investigations (Zhang et al., 2012; Li et al., 2013; Tong et al., 2014). Therefore, this study quantified and mapped the TRHR ecosystem services to investigate the response of ecosystem processes and services to land cover change and vegetation restoration/degradation under a climate variability context and to understand the services and sustainability of the ecosystem. Millennium Ecosystem Assessment (2005) listed more than twenty kinds of ecosystem services, which can be grouped into four categories, including supporting service, provisioning service, regulating service, and cultural service. In consideration of data availability, feasibility of the assessment method, and dominant ecosystem service, this study just selected several ecosystem services to assess, including water yield, carbon sequestration, soil conservation, and food provision, which were grouped into categories of regulating and provisioning services, the explanations are as the following. The TRHR is the headwater of large Asian rivers, thus water supply (yield) is firstly considered; soil loss (degradation) induced by water erosion and wind erosion is also serious in this area (Liu et al., 2008), therefore this study respectively assessed the soil conservation and sand fixation functions of ecosystem; owing to carbon sink/source is a hot issue in the background of climate change, we also included it in assessment; The food production relates to human well-being, thus it is also included. In addition, recent assessments have emphasized the identification of the synergies and trade-offs among ecosystem services (Carpenter et al., 2009; Seppelt et al., 2011; Leh et al., 2013). Therefore, the objectives of this study were, for the TRHR, including natural reserve and non-natural reserve, in 2000–2012, (1) to quantitatively examine land cover changes, (2) to quantify and map the changes in multiple regulating services (carbon sequestration, soil conservation, and water yield) and one provisioning service (food production) as a result of land cover change and climate variability. In particular the comparison of effectiveness before and after the TRHR Project implemented in 2005, and (3) to investigate the synergies and trade-offs of multiple ecosystem services at a regional scale, and give advice for sustainable development through adaptive management.

2. Study area

The TRHR region, as the headwaters of the Yellow, Yangtze, and Lancang rivers, is located in southern Qinghai, in the hinterland of the Qinghai-Tibet Plateau (Fig. 1). Its total land area exceeds 39.5×10^4 km^2, and it is known as China's "Water Tower" due to its important freshwater supply function. Owing to its average elevation above 4000 m, annual temperatures of −5.6 to −3.8 °C, and annual precipitation between 262.2 and 772.8 mm from west to southeast, the TRHR region has a developed river system with numerous tributaries and plume or fan-shaped structures. As China's major extensive wetland, it has abundant river, lake, mountain snow, and glacier resources and is known as the world's largest alpine wetland ecosystem. In contrast, as one of the world's highest and most extensive and concentrated distribution of wetlands, the TRHR is one of the most sensitive and fragile regions in the world (Liu et al., 2008, 2014; Zhang et al., 2012; Li et al., 2013; Tong et al., 2014). Wetlands, glaciers, and permanent mountain ice and snow are not only distinctive ecosystems in the TRHR, but also important water suppliers (Tong et al., 2014; Liu et al., 2014). In recent years, particularly before 2000, the ecosystem experienced great changes due to climate warming and increasing human activities. For instance, the retreat of glaciers, rising snow line, grassland degradation, and decline of the water conservation capacity pose a direct threat to the ecological safety and ecosystem service function of the TRHR (Liu et al., 2008; Zhang et al., 2012). In order to protect the environment, the state council implemented the TRHR Project in 2005 to create a network of 18 nature reserves. The total project investment was 11.57 billion USD, including the return of pasture and farmland to forest, afforestation and comprehensive treatment for soil degradation in black soil beaches. The project known as "Returning Pasture and Farmland to Forest" accounted for the largest proportion of finances (41%) from the TRHR Project. Most projects were completed by 2013, as the budget implementation rate reached more than 95%.

3. Methods

3.1. Land use and land cover change (LUCC)

Enhanced Thematic Mapper (ETM) images from 2000 were used to extract land cover data for the TRHR. Prior to interpretation, remote sensing data was geo-referenced using 1:100,000 topographic maps. The land cover types were identified based on the spectral reflectance and structure of objects. The 21 land cover subtypes identified in the study area were further grouped into nine aggregated types: forest, shrub, grassland, farmland, urban area, wetland/water bodies, glacier/snow, desert, and bare land, with a classification accuracy of around 90% (Wu et al., 2014; Ouyang et al., 2015). Based on the land cover map from 2000, the land cover classification of the TRHR was updated for 2010 using China-HJ-1A/B Satellite images, with a 30 m ground resolution and a similar number of spectral bands as the Landsat ETM (Wu et al., 2014; Ouyang et al., 2015). To support image interpretation and validate the land cover map for 2010, a field survey was conducted to evaluate the classification accuracy. Field-measured land cover types and GPS-coordinated photos were collected for the whole study area (Wu et al., 2014; Ouyang et al., 2015).