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Ecological restoration enhances ecosystem health in the karst regions of southwest China

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ABSTRACT

Within the past decades, the karst region in the Guangxi province in southwest China has been in the focus of large scale ecological restoration projects. In this study, we adapt the pressure-state-response (PSR) framework (which includes measures for human pressure, the current state of the ecosystem and the human response) and propose a remote sensing based ecosystem health (ESH) index (0–1; 250 m spatial resolution), evaluating the pressure and state of the fragile karst ecosystem. We further apply inventory data of recovery actions (restoration areas at county level resolution) as response to ongoing degradation to test the impact of ecological restoration on the ESH. Our analysis was conducted for the years 2000, 2010 and 2016, and the results showed that 73% of the study area experienced an increase in the ESH (from 2000 to 2016) which was related to the improvements in vegetation vigor, organization, resilience, ecosystem service provisioning which offset a deterioration in fragmentation and population density. From 2000 to 2016, areas of increase in ESH were slightly larger in karst than in non-karst (37.5% and 35.1%, respectively), but also larger areas of decrease in ESH were observed in karst as compared to non-karst (16% and 11%, respectively). The results further showed that the share of areas with a high ESH (greater than 0.7) had increased by ~3% (from 67.16% to 70.21%) during the 17 years period. At county level, we found a clear relationship between increases in ESH and ecological restoration areas ($r = 0.58$, $p = 0.004$), with a high recovery rate (ratio between areas with increased ESH and restoration areas in a county) in karst than in non-karst. We conclude that restoration projects have caused a large scale transformation of farmland into forested areas (~5500 km^2), which has caused a general improvement in ecosystem parameters related to ESH.

1. Introduction

Karst regions cover about 12% of the global land areas and are currently characterized by widespread ecological degradation due to human pressure and the fragile nature of the upper soils (Wang and Li, 2007; Wang et al., 2004; Yue et al., 2012). The degradation of karst ecosystems is particularly severe in developing counties, causing deterioration of ecosystem services with adverse effects for the livelihood of local populations ultimately causing emerging symptoms of poverty (Gewin, 2002; Zhang et al., 2011). This leads to an increased exploitation of remaining natural resources, accelerating the effect of degradation and making karst areas one of the world's most vulnerable ecosystems. These challenges have placed karst areas in the focus of development programs to combat desertification (Yuan, 1997; Yue et al., 2010).

The process of degradation and attempts of human managed recovery are in the focus of the subtropical Chinese karst ecosystems, where anthropogenic over-exploitation of natural resources combined with the harsh humid monsoon climate have caused a steady deterioration in the vegetation cover (Tong et al., 2018). In particular, population pressure and food shortages forced farmers to expand their croplands from valleys and lowlands to sloping hills. As a result, most of the karst area was deforested and the shallow soils on steep slopes have become intensively cultivated. Consequently, soil erosion on karst hills progressed and forced farmers to further expand their farmlands to marginal and unsuited lands, leading to a vicious cycle of low food

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production, soil erosion and increased expansion (Wang and Li, 2007).

This change in the pressure on the environmental resources has resulted in land degradation and the loss of vital ecological services (e.g., food production, water retention, soil retention) over recent decades. Only if management practices are adjusted towards a sustainable use and/or promote actively restoration efforts, the karst in southwest China will stand a chance to recover to the state of functioning characterizing earlier centuries (Kelly et al., 2011; Tong et al., 2018).

Research about theory and practice concerning measures to recover the degraded karst ecosystems started in the 1970s (Lu et al., 1973; Wang et al., 1999; Yuan, 1997). Since the late 1990s, China has approved and implemented a large number of ecological restoration projects to mitigate desertification and restore ecosystem services for the local population (Ouyang et al., 2016; Xu et al., 2017; Zhao et al., 2006). Examples are the Natural Forest Protection Project, the Grain to Green Program, the Public Welfare Forest Protection and the Karst Rocky Desertification Restoration Project. These projects aim at increasing the vegetation cover, and in particular the forest cover, by converting marginal lands and farmlands on sloping hills into grasslands and forests. Farmers are provided with tree seedlings and compensation payments if farmlands are abandoned and replaced by tree plantations (Tong et al., 2018).

The effect of large scale efforts can only be monitored with Earth observation (EO) data and tools, and recent studies of the Chinese karst ecosystem based on EO technology have revealed a large scale increase in vegetation greenness, indicating a successful restoration of the vegetation cover (Cai et al., 2014; Tong et al., 2018, 2017). Rocky desertification is however a complex and dynamic process, and once degradation is progressed, its reversal and the possibility of recovery are affected by different natural (e.g., climate) and anthropogenic (e.g., population density) conditions.

In order to assess recovery that goes beyond changes in vegetation cover, we adapted the concept of ecosystem health. The concept of defining the health of an ecosystem was first proposed by Costanza (1992) who defined the health of an ecosystem as its ability to maintain an organizational structure, and to recover after disturbances with self-regulating processes. Myneni added that "ecosystem health is closely linked to the idea of sustainability, which is seen to be a comprehensive, multi-scale, dynamic measure of system resilience, organization, and vigor" (Myneni et al., 1992). In later works, Rapport incorporated socio-economic and human health in his earlier conceptual framework (Rapport et al., 1998).

Analyzing changes in vegetation cover is therefore only a first step in assessing the ecosystem's health (Peng et al., 2017), and additional assessment methods are necessary to understand and evaluate the health of an ecosystem as criteria for the state of recovery (Alexander and Allan, 2007; Palmer et al., 2005; Peng et al., 2015). It is however challenging to assess the terms "system resilience, organization and vigor" (Myneni et al., 1992) combined with human wellbeing in a comprehensive way at regional scale. There are several studies assessing the effects of ecological restoration on ecosystem health. The study of Xu et al. (2006) stated that the restoration projects contribute to combat environmental problems such as soil erosion, flooding, and desertification as well as mitigate climate change and losses in biodiversity. The study by Wang et al. (2017) showed that the Grain to Green Program, one of the largest restoration projects in human history, considerably improved soil conservation at large scales. Other studies assessed the effects of ecological restoration on ecosystem health by a combination of remote sensing and modelling techniques (Allen et al., 2002; Bertollo, 2001; Harris et al., 2006; Jiang et al., 2005). However, these studies only assessed a limited number of ecological service functions, without a quantitative assessment of ecosystem health.

One possible option for classifying environmental indicators based on the interaction between human and environmental factors is to apply the pressure-state-response framework (PSR), which includes measures for human pressure, the current state of the ecosystem (including ecosystem services and vegetation cover), and the human response (i.e. recovery actions) (Allen et al., 2002; Hammond et al., 1995; Rapport et al., 1998). Several studies have applied the PSR framework to evaluate the ecosystem health for a given date, and indicators based on the interaction and influence between human and environmental system were used (Neri et al., 2016; Schumacher et al., 2016; Sun et al., 2016; Yang et al., 2014). The PSR framework normally involves analyzing selected environmental processes (e.g. deforestation) to understand the relationships between human activities and environmental effects to subsequently identify related indicators or indices, and finally provides quantitative or qualitative descriptions of the causal relationships.

Here we implemented an EO-driven version of the PSR framework, only including indicators which can be assessed by remote sensing data, to study the pressure (P) and state (S) of the degraded Chinese karst region in the Guangxi province. We included NDVI (Normalized Difference Vegetation Index) data derived from MODIS, land cover data derived from Landsat as well as gridded population census data to calculate six indices characterizing the ecosystem health, formulated as an ecosystem health (ESH) index. To study the impact of human response (R) to ongoing degradation, we used inventory data (afforestation and reforestation areas) to test the relationship between changes in ESH and restoration efforts between 2000 and 2016.

2. Materials and methods

2.1. Study area

The study area located in the northwest of the Guangxi Province, China includes the major cities Baise and Hechi (104°28′–109°09′E, 22°51′–25°37′N) (Fig. 1). The region comprises 23 counties including 8,326,300 inhabitants in 2013. The study area is an ecologically fragile zone with a highly heterogeneous landscape consisting of karst (53%) and non-karst (47%) (Tong et al., 2009). The main landscapes of the study area are mountains, hills and depressions, with an elevation ranging from 15 to 2000 m above sea level. The study area is dominated by the mid-subtropical monsoon climate and has a mean annual precipitation of 1400 mm and a mean annual temperature of 23.5 °C. Dominant vegetation biomes are subtropical mixed evergreen and deciduous forests as well as shrublands (Fig. 1).

The Chinese government has implemented a series of ongoing ecological restoration projects in the study area to restore the natural

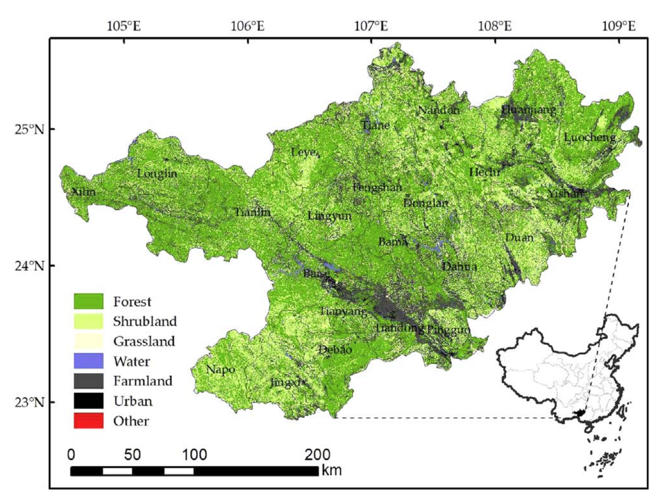

Fig. 1. The study area is located in the karst area of southwest China and the land types in 2016 (obtained from Beijing Yushi Lantu Information Technology Co., LTD) are shown. Although desertification is widespread, this process is rather local and happening at subpixel scale.