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Original Articles

Spatial and temporal variability of grassland yield and its response to climate change and anthropogenic activities on the Tibetan Plateau from 1988 to 2013

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ABSTRACT

Accurate and periodic assessment of grassland yield (GY) is of great importance for the management of high altitude plateau grasslands. The Tibetan Plateau (TP) is a very important pastoral area that provides a microcosm of typical alpine grassland ecosystems. Based on remote sensing data, meteorological datasets and observational plant biomass data, we used the Global Production Efficiency Model and Soil and Atmosphere Model (GLOPEM-CEVSA) to estimate GY and its response to climate change and anthropogenic activities on the TP from 1988 to 2013. We quantitatively analyzed spatiotemporal dynamic changes of GY for four geomorphological divisions and five main grassland types. For the 26 years of the study, average annual total GY was 515.8 kg/ha/yr and gradually decreased from the southeast to the northwest of the TP. Annual GY fluctuated from year to year but had an overall positive trend (4.2 kg/ha/yr). Spatiotemporal variation of GY was greatly influenced by spatial heterogeneity. For the total area, the proportion showing a significant increase in GY was 45.2%, while only 12.6% showed a significant decrease. For the main grassland types, GY of Alpine Meadow was highest and had the highest slope of increase. The pattern of decrease of GY from the southeast to the northwest was predominantly related to climate gradients. Regional correlation analysis indicated that warming temperature promoted positive increase of GY for almost all the region. Annual precipitation was related to a less significant decreasing trend of GY over all the TP apart from an increase of GY in the middle area of the north. The grazing pressure index decreased over the years by control of livestock numbers, the reduction of grazing pressure assisting restoration of alpine grasslands. However, grazing pressure on the TP in 2013 remained too high and overloaded. Nevertheless, grassland protection and restoration projects have mitigated grassland degradation in some areas, promoted grassland restoration, and increased incomes of herdsmen. The study indicates that continuation of these projects is critical for the restoration and sustainable use of the TP grasslands.

1. Introduction

Grasslands as the largest terrestrial ecosystem in China, cover about 41.7% of country's territory (Department of Animal and Husbandry and Veterinary of Ministry of Agriculture of China, 1996). They provide vital natural resources for human survival and play an important role in ecosystem services. Nevertheless, in recent years, grasslands have suffered from pronounced warming, droughts and extreme climatic events that have changed their phenology (Ni, 2000; Zhang et al., 2013), reduced their primary productivity (Wu et al., 2011; Harrison et al., 2016), and strained their livestock carrying capacity (Deng et al., 2017; Qian et al., 2012). Human activities, particularly overgrazing by

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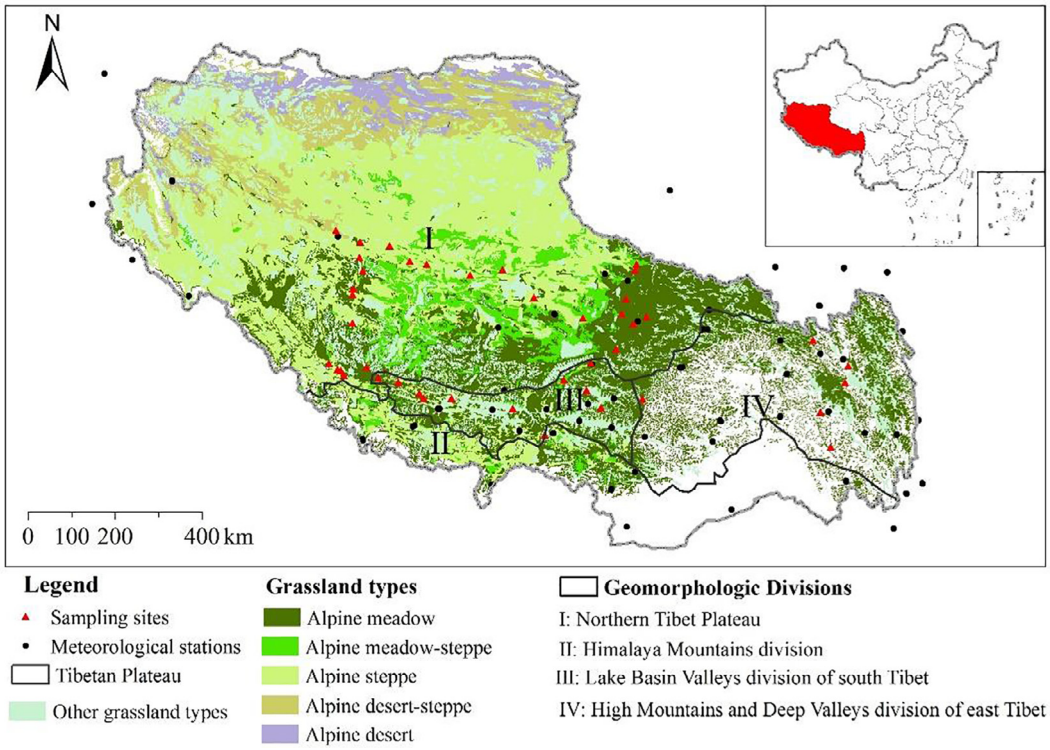

Fig. 1. Spatial distribution of grassland types, geomorphological divisions, meteorological stations and sampling sites on the Tibetan Plateau. (*White areas are not covered by grassland.*)

domestic livestock and clearance for cultivation and urbanization, have had negative effects on grasslands. As a result, grasslands have developed serious problems, including grassland degradation, aggravated soil erosion and water loss, biodiversity reduction and decline of service function (IPCC, 2013). To mitigate these problems and to protect grassland resources, the Chinese government has made considerable effort to implement a series of ecological protection and restoration projects (Lü et al., 2015).

Grassland yield (GY) is a vital measurement index of grassland resource dynamic research and also a key factor in determining forage utilization and balanced animal carrying capacity. However, GY's long-term responses to climate change and anthropogenic activity are not yet fully understood. Grazing pressure is an immediate and dominant source of natural grassland degradation. Achieving balance between grazing animal numbers and forage is beneficial for the protection of grassland ecosystem environments and promoting development of sustainable animal husbandry.

Several studies have concentrated on vegetation activity dynamics by using representative indicators based on remote sensing data through models, such as normalized difference vegetation index (NDVI), fractional vegetation cover (FVC), and net primary productivity (NPP), and have paid particular attention to climatic factors affecting these (Zhang et al., 2013; Zhang et al., 2014). Most of these studies have paid insufficient attention to GY and its response to specific human activities, e.g. livestock grazing and ecological engineering (Mao et al., 2014). Furthermore, they have lacked quantitative description and direct evaluation of the carrying capacity of natural pasture.

The Tibetan Plateau (TP), described as the roof of the world and the water tower of Asia (Immerzeel et al., 2010), supports the world's largest area of typical alpine grassland ecosystems that are particularly vulnerable to climate change and human activities (Piao et al., 2012). Furthermore, functioning of the TP has an important effect on local economic development and ecological security (Sun et al., 2012; Zhang et al., 2015). With fragile and complicated environments, many ecological problems have developed on the TP, including grassland degradation, soil erosion, biodiversity decline, desertification and related economic recession (Chen et al., 2014b; Harris, 2010; Yu et al., 2012). Consequently, the TP provides an ideal area to study the responses of grassland ecosystems to climate change and anthropogenic activities.

Based on an overall consideration of grassland management practices, availability of remote sensing and meteorological data, feasibility of the assessment method, and completeness and consistency of statistical and field data, we chose 1988–2013 as the study period, simulated NPP by using GLOPEM-CEVSA, and calculated GY by reliable formulae. The main objective of this study was to measure the spatial and temporal variability of grassland yield from 1988 to 2013 in relation to climate change and grazing activity on the TP. Also, it took into account the influence of grassland protection and restoration projects on the TP grasslands. Furthermore, we endeavored to investigate mechanisms of grassland changes from the perspective of natural and anthropogenic causes. The study aims to promote sustainable development of China's high-altitude grasslands and to further understanding of the function of the national ecological security shelter plan. Our findings intend to assist ecological monitoring and to provide a reference for grassland ecological protection policy-making and planning.

2. Materials and methods

2.1. Study area

The Tibetan Plateau, surrounded by the Himalaya, Kunlun and Tanggula Mountains, forms the main body of the Qinghai-Tibetan Plateau and has complex and diverse topography and geomorphology. Its area is 1.2×10^6 km^2 (78°15′–99°07′E, 26°50′–36°29′N) and it has a population of more than 3 million people, 80 percent of whom are herdsmen. It has four geomorphological divisions: Northern Tibetan Plateau, Himalaya Mountains division, Lake Basin Valleys division of south Tibet, and High Mountains and Deep Valleys division of east Tibet