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Potential and environmental control of carbon sequestration in major ecosystems across arid and semi-arid regions in China

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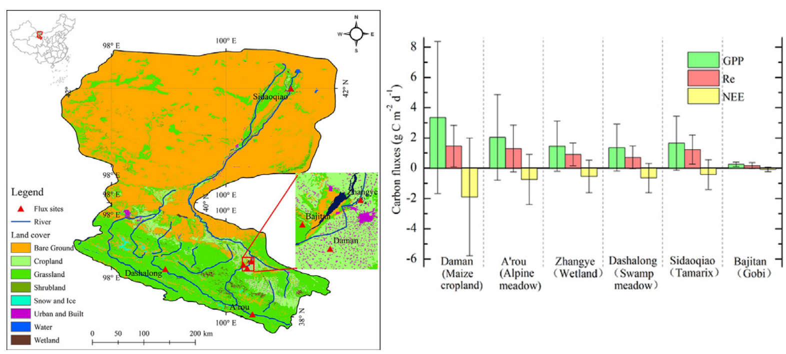
HIGHLIGHTS

- Few attempts are made to systematically analyze carbon sequestration capacity of dryland ecosystems.
- All typical ecosystems acted as carbon sinks with varied magnitudes on an annual time scale.
- Distinct seasonality in carbon sequestration existed over dryland ecosystems except Gobi Desert.
- Water balance, instead of rainfall, is the primary environmental control for carbon sequestration.

GRAPHICAL ABSTRACT



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ABSTRACT

With the continuous expansion of drylands in the context of global climate change, governments have implemented a series of greening policies such as afforestation, to reduce ecological degradation. However, owing to historical conditions and technical constraints, few attempts have been made to quantitatively assess the differences in carbon sequestration capacity and the associated environmental controls among major ecosystems in the arid and semi-arid areas. Based on six flux towers located in northwestern China measuring the carbon fluxes in a maize (*Zea mays* L.) cropland, alpine meadow, wetland, swamp meadow, Tamarix, and gobi desert, this work revealed that all ecosystems sequestered CO_2 at various magnitudes. The cropland had the highest carbon uptake, followed by the alpine meadow, swamp meadow, wetland and Tamarix, respectively. Distinct seasonal dynamics in carbon sequestration were observed across these ecosystems with the peak values in summertime, whereas the gobi desert exhibited as a weak carbon sink with considerable fluctuations around the year. In this water-limited region, soil water content instead of rainfall, is expected to be the primary environmental control on the land–atmosphere carbon fluxes, and regarded as a key linkage between hydrologic and ecologic processes. Therefore, not only the appropriate vegetation types, but also the water availability controlled by the local climatic constraints and soil characteristics, should be addressed in order to identify management strategies for ecological restoration in the dry areas.

1. Introduction

The terrestrial carbon budget represents the net CO_2 flux between the surface and the atmosphere during a specific period, which can

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not only mitigate climate change through carbon absorption, but also accelerate climate warming through carbon release (Cox et al., 2000). Increased fossil fuel burning, cement production, uncontrolled deforestation and other anthropogenic activities since the industrial revolution have resulted in considerable increase in the emissions of CO_2, CH_4 and other greenhouse gases (Knox et al., 2015; Tang et al., 2017a). The atmospheric CO_2 concentration has increased by nearly 40% with 400 ppm (Betts et al., 2016). Moreover, the global-mean surface temperature is expected to rise by 1.5–4.5 °C by the middle of the 21st century, and precipitation may increase by 7–15% (Millar et al., 2017). These effects will significantly impact the carbon cycle of terrestrial ecosystems. Meanwhile, global climate warming will accelerate the snow melt and glacier thaw in polar and alpine regions, threatening the sustainable development of human society in the ecologically fragile areas (Yang et al., 2015; Liu et al., 2016a). Terrestrial ecosystems in the temperate and boreal regions are especially sensitive to climate change (Schlaepfer et al., 2017), which has attracted a great deal of attention from scientific community and international society in order to explore vegetation feedbacks to climate systems.

Arid and semi-arid ecosystems cover about 29.8% of the total surface area of the Earth (Wang et al., 2014). However, it is an indispensable part of terrestrial ecosystems and provides significant ecosystem services. Meanwhile, ecosystems in such regions are vulnerable to environmental changes because of insufficient rain, strong light and high water evaporation throughout the year (Nyantakyi-Frimpong and Bezner-Kerr, 2015). The responses of drylands to local climate mainly reflect in the distribution driven by water scarcity, community structure and functions which are controlled by ecohydrological interactions. Despite global drylands expanded by 4–8% over the past century, model projections revealed that the expansion would continue during the next century owing to frequent drought-inducing weather disasters (Milly and Dunne, 2016). The adverse consequences will threaten ecosystem services and influence human livelihoods through water scarcity, vegetation die-offs and land degradation (Reed et al., 2015). Through experimental observations and model simulations, the carbon sequestration capacity of terrestrial ecosystems on different time and space scales and their responses to the climatic changes have also been analyzed (Schimel et al., 2015). However, the ecological role of arid and semi-arid ecosystems to global carbon cycle has long been neglected.

As one of the highly sensitive areas around the world to climate variability, arid and semi-arid ecosystems covered a vast and continuous region in Northwest China (Xia et al., 2017). Currently, studies in the dry areas remain scarce until the integrated research network entitled "Heihe Watershed Allied Telemetry Experimental Research" (HiWATER) was implemented in China in May 2012 (Li et al., 2017). A series of flux towers across various ecosystems were installed from the upstream to downstream, and aimed to enhance the cognition of hydrological and biogeochemical processes, to build an international leading watershed observing system, and to manage limited water resources in the fragile environment by integrating multi-source data. Therefore, on the basis of measurements collected in 2014 from six flux tower sites in the typical ecosystems including maize (*Zea mays* L.) cropland, alpine meadow, wetland, swamp meadow, Tamarix and gobi desert, this study aimed to i) compare the magnitudes of the carbon sequestration capacity across various dryland ecosystems; ii) reveal the differences of seasonal dynamics in net carbon flux (NEE) and its two components–gross primary productivity (GPP) and ecosystem respiration (R_e) systematically; and iii) analyze the dominant environmental controls of different ecosystems in dry areas. Information on these aspects is vital to develop appropriate management measures for ecological restoration in the dry areas and to predict the potential effects of future trends of climatic changes.

2. Materials and methods

2.1. Study region

This study was conducted at the Heihe River Basin in the arid and semi-arid area of Northwest China (Fig. 1), the 2nd largest inland valley with an area of about 143,000 km^2 (Wu et al., 2017). This area is a temperate continental monsoon climate, with remarkable temperature differences among four seasons. Precipitation exhibits spatiotemporal heterogeneity affected by the geographic factors and atmospheric circulation. The distinct cold and arid landscapes in the basin from the upstream to downstream include alpine meadow, glaciers, desert, frozen soil, irrigated crops, forest, and riparian ecosystem (Li et al., 2017). In detail, the water source area is located in the upper reach, with obvious vertical zonation and abundant types of surface vegetation cover including alpine meadow, swamp, permafrost, snow and ice. The largest consumptive area lies in the middle reach of the basin with more than 91% of the population and more than 80% of the gross domestic product (GDP) in the region (Deng et al., 2015). Most of the land has been reclaimed as agricultural area.

2.2. Flux site description

The eddy covariance (EC) system has been widely used to measure the CO_2 and H_2O fluxes between a specific ecosystem and the atmosphere, which becomes a direct and effective method to examine the carbon budget of terrestrial ecosystems (Baldocchi, 2014). Based on the available carbon fluxes and meteorological data of typical vegetation types in the Heihe River Basin, this study selected six flux sites including Daman, A'rou, Zhangye, Dashalong, Sidaoqiao, Bajitan to represent various ecosystems. Key information and spatial distribution of these stations can be seen in Table 1 and Fig. 1.

The Daman superstation is located in the central oasis with a 40-m boundary layer tower constructed in September 2012. It is one of the artificial oasis experimental areas (irrigated cropland) in the midstream of the Heihe River Basin (Li et al., 2017). The annual total precipitation and mean temperature were 127.2 mm and 7.06 °C, respectively. In this region, corn is the typical crop type. The seeds are generally sown in the end of April, reach the maximum height of about 1.8 m during the summertime and then they are reaped in mid-September (Tang et al., 2017b). The A'rou superstation was installed in the end of 2012. It is situated in the upstream of the basin. A valley existed in the east-west direction with a maximum width (approximate 3 km) along north-south paths. The terrain around the A'rou site is generally flat despite of a small decline. Alpine meadow was the main vegetation in this area. Annual total precipitation and mean temperature were 484.8 mm and 0.85 °C, respectively.

The Zhangye wetland station is located in the middle of the Hexi Corridor, and data have been collected since June 2012. This site has an extraordinarily complex ecosystem including rivers, marshes, wet meadows and an arid irrigated cropland (Zhang et al., 2016). The Dashalong station lies in Qilian County of Qinghai Province with the high-cold swamp meadow distribution, and the EC system began to work in August 2013. The land cover at the site is alpine meadow, always covered by snow most of the time in the late autumn, winter, and early spring (Wang et al., 2017). The Sidaoqiao superstation is situated in the downstream of the Heihe River Basin. The flux tower is installed in Ejin Banner of Inner Mongolia, where a great number of Tamarix are distributed. Dataset of this site started from July 2013. The Bajitan gobi desert station has been operated since September 2012, which is situated in the middle reaches of the basin as well as the Daman and Zhangye wetland station (Liu et al., 2016b; Zeng et al., 2016).