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Assessing the spatiotemporal dynamic of global grassland carbon use efficiency in response to climate change from 2000 to 2013

Yue Yang [a], Zhaoqi Wang [a], Jianlong Li [a, *], Chencheng Gang [a, b], Yanzhen Zhang [a], Inakwu Odeh [c], Jiaguo Qi [d]

[a] Department of Ecology, School of Life Science, Nanjing University, Nanjing, PR China
[b] Institute of Soil and Water Conservation, CAS, Yangling, PR China
[c] Department of Environmental Sciences, Faculty of Agricultural and Environment, The University of Sydney, Sydney, Australia
[d] The Center for Global Change & Earth Observations, Michigan State University, East Lansing, USA

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ABSTRACT

The carbon use efficiency (CUE) of grassland, a ratio of net primary production (NPP) to gross primary productivity (GPP), is an important index representing the capacity of plants to transfer carbon from the atmosphere to terrestrial biomass. In this study, we used the Moderate Resolution Imaging Spectroradiometer (MODIS) data to calculate the global grassland CUE, and explore the spatiotemporal dynamic of global grassland CUE from 2000 to 2013 to discuss the response to climate variations. The results showed that the average annual CUE of different grassland types follows an order of: open shrublands > non-woody grasslands > closed shrublands > woody savannas > savannas. The higher grassland CUE mainly occurred in the regions with cold and dry climate. By contrast, the regions with the lower grassland CUE were mostly in warm and wet environments. Moreover, the CUE exhibited a globally positive correlation with precipitation and a negative correlation with temperature. Therefore, the grassland CUE has considerable spatial variation associated with grassland type, geographical location and climate change.

1. Introduction

Grassland, one of the largest types of vegetation in the world, accounts for nearly 25% of the global land surface. Grassland ecosystem plays a significant role in maintaining material circulation and balancing greenhouse gas, particularly in terms of global carbon storage and further carbon sequestration (O'Mara, 2012; Scurlock and Hall, 1998). The carbon use efficiency (CUE) is an important indicator to measure how efficiently a grassland sequesters atmospheric carbon (Delucia et al., 2007; Gifford, 2003), and may be a critical control on carbon storage in ecosystems (Allison et al., 2010; Ise et al., 2010; Manzoni et al., 2011). The CUE refers to the ratio of net primary productivity (NPP) to gross primary productivity (GPP). GPP is the total mass of C assimilated by the photosynthesis, which represents the capacity of plant to capture energy and carbon. NPP is the net carbon stored as new plant material in an ecosystem which is the amount of C stored following the loss of C from GPP through autotrophic respiration (Chapin et al., 2002; Kwon and Larsen, 2012). A better understanding of how grassland CUE varies in relation to climate change factors can have the potential to advance global carbon sequestration accounting and improve the global change research.

Many studies have assumed a constant value of CUE among different species (Running and Coughlan, 1988), and different ecosystem types (Gifford, 1994, 1995; Landsberg and Waring, 1997; Ryan and Hubbard, 1994). Furthermore, the CUE remains constant across a range of temperatures and CO_2 levels for herbaceous and woody plants (Cheng et al., 2000; Dewar et al., 1999). A study made by Zha et al. (2013) of 18 sites in Canada's temperate and southern boreal forests shows that the aboveground CUE ratio is relatively constant (0.29 ± 0.06), with no consistent differences among species or age classes. Waring et al. (1998) suggested that a constant value of 0.47 was appropriate for most forest. Many ecosystem process models such as FOREST-BGC (Running and Coughlan, 1988) and CASA (Potter et al., 1993) assumed a constant CUE in quantifying plant respiration.

However, the assumption that the CUE ratio is constant has been

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* Corresponding author.
E-mail address: lijianlongnju@163.com (J. Li).

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tested only in a limited way as it ignores the impacts of factors such as species, environment and age on CUE, it is doubtful and controversial that the principle is globally applicable (Chapin et al., 2002; Delucia et al., 2007; Dewar et al., 1999; Xiao et al., 2003). These researches have suggested a variable CUE among different ecosystems, vegetation types and species (Amthor, 2000; Delucia et al., 2007; Iersel, 2003; Ryan et al., 1997; Zhang et al., 2009). Piao et al. (2010) found that CUE in tropical zone was quite different from that in south temperate zone. Research using field-based data and remote sensing data made by Kwon and Larsen (2012) in the eastern USA has indicated that the forest CUE significantly changes with forest type, climate and geographic location. A study made by Street et al. (2013) in European subarctic shows that the CUE of bryophyte is higher than vascular plant.

As we can see from the previous researches, most of the studies on CUE research mainly discuss a few ecosystem types and focus on the stand or site levels (Campioli et al., 2011; Iersel, 2003; Metcalfe et al., 2010; Smith and Dukes, 2012). The spatial and temporal dynamics of the grassland CUE have rarely been explored at the global scale. It is essential to discover how the ongoing climate variation affects the CUE of grassland ecosystems at the global scale.

Remote sensing has been used to calculate the CUE at the regional and global scale (Kwon and Larsen, 2012; Nemani et al., 2003; Zhao et al., 2006). Moderate Resolution Imaging Spectroradiometer (MODIS) products of GPP and NPP were monitored by using the remote sensing at the global scale, and these data provided a unique opportunity for calculating the value of global CUE. There is a fairly strong correlation between the MODIS GPP and ground flux tower-based GPP ($r^2 = 0.737$). And the resulting MODIS NPP data is consistent with the field-observed NPP estimation ($r^2 = 0.80$). These products are one of the most reliable data sources at the global scale (Heinsch et al., 2006; Zhao et al., 2005). Zhang et al. (2009, 2014) explored the spatial pattern of the global CUE and its relationship with climate factors using the MODIS GPP and NPP data. By comparing the CUE calculated by the field-based forest inventory and analysis (FIA) data and MODIS data, the result supported the use of the more easily obtained MODIS CUE (Kwon and Larsen, 2012) in research. Therefore, we used the MODIS GPP and NPP data to calculate the global grassland CUE in this study.

The objectives of this study are to: (1) explore the spatial and temporal dynamics of the global grassland CUE during the period 2000–2013; (2) compare the CUE ratio responses to climate variations among different grassland types; (3) investigate the correlations between the grassland CUE and the climatic factors to reflect how the climate factors affect grassland carbon cycles. These findings not only contribute to analysis of carbon sources or carbon sinks of grassland ecosystem, but also have great significance to predict the effect of global change and human disturbance on global grassland carbon balance.

2. Materials and methods

2.1. MODIS GPP data

Annual MODIS GPP data (1 km resolution) from 2000 to 2013 were obtained from the Numerical Terradynamic Simulation Group (NTSG) at the University of Montana (http://www.ntsg.umt.edu/). These datasets are in TIFF format and the WGS84 geographic coordinate system, and were converted into a grid format by using ArcGIS software (ESRI, California, USA).

The latest Collection 5 (MOD17) MODIS GPP values are calculated as follows:

$$\mathrm{GPP} = \varepsilon \times PAR \times FPAR \tag{1}$$

$$PAR = 0.45 \times SWrad \tag{2}$$

$$\varepsilon = \varepsilon_{max} \times T_f \times VPD_f \tag{3}$$

where ε is the light use efficiency parameter; ε_{max} is the max radiation use conversion efficiency of the vegetation; and VPD_f and T_f are the reduction scalars from water stresses (high daily vapour pressure deficit) and low temperature (low daily minimum temperature T_{min}), respectively. PAR is the downward photosynthetically active radiation; *SWrad* is the short-wave downward solar radiation, of which 45% is photosynthetically active radiation (PAR); FPAR is the fraction of incident PAR that is absorbed by the canopy. The FPAR is determined using remote sensing MODIS and ε_{max} is determined based on the theory of Monteith (1972) for each biome. PAR, *SWrad*, VPD_f and T_f are determined from meteorological field data. Each parameter value is obtained from the Biome Parameter Look-Up Table, which contains parameters for specific leaf area and respiration coefficients for representative vegetation in each biome type (Running et al., 2000; White et al., 2000a). The GPP product has been validated by comparison with data from 250 global eddy flux towers, and the results showed strong correlations between the modelled GPP and the site-derived GPP data (Heinsch et al., 2006).

2.2. MODIS NPP data

NPP is estimated from the global NPP product MOD17A3 (1 km spatial resolution), which was obtained from the NASA MODIS Land Science team website (http://landval.gsfc.nasa.gov/). NPP is calculated as the difference between GPP and respiration, which includes both maintenance and growth components. The newly developed NPP is calculated as follows:

$$\mathrm{NPP} = \sum_{1}^{365} GPP - R_{m\_lr} - R_{m\_w} - R_g \tag{4}$$

where R_{m_lr} refers to the maintenance respiration from living leaves and fine roots. R_{m_w} is the annual maintenance respiration of live cells in woody tissue, and R_g is the annual growth respiration. More detailed descriptions on the methods used for modelling MODIS NPP can be found in related publications (Heinsch et al., 2006; Zhao et al., 2004).

The NPP product was validated using the Ecosystem Model-Data Intercomparison (EMDI) NPP data set (Fig. 1), which is composed of 2523 sites that represent the majority of global biomes (Olson et al., 2001). The validation results showed that the modelled NPP results agree well with field NPP data.

2.3. Land cover data and climate factors data

To be consistent with the GPP and NPP results, we used land cover data from the MOD12Q1 product. In the global land cover map, the classes are defined according to the International Geosphere-Biosphere Project (IGBP) land cover system, which were based on satellite imagery of land cover and vegetation type (Loveland et al., 2000). The primary land cover scheme identifies 17 classes defined by the IGBP, including 11 natural vegetation classes, 3 human-altered classes, and 3 non-vegetated classes. It was used with the 1-km resolution MOD12Q1 product (land cover type 1 in the MOD12Q1 data sets). The grassland cover categories used in this study include closed shrublands, open shrublands, woody