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Ecosystem carbon use efficiency in China: Variation and influence factors

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ABSTRACT

Ecosystem carbon use efficiency (CUEe), one of the most important ecological indicators of ecosystem, represents the capacity of transferring carbon from atmosphere to potential carbon sink. Understanding the variation of CUEe and its controlling factors is paramount for regional carbon budget evaluation. In this study, we conducted a synthesis of 50 field measurements on CUEe to examine the variations of CUEe across China's terrestrial ecosystems. The results showed that the CUEe values of China's ecosystems varied from −0.44 to 0.53 with the mean value of 0.19. Grassland had a lower CUEe than forest, cropland and wetland. However, the apparent effects of vegetation types on CUEe were eliminated by accounting for the covariates of climate. Variations of CUEe were correlated with temperature (MAT), precipitation (MAP) and nitrogen deposition (Ndep) in different relationships depend on climate and Ndep condition. CUEe was increased with the augment in MAT only for wet and low Ndep ecosystems. Ndep facilitated the increase of CUEe for wet ecosystems while oppositely restrained the CUEe for dry ecosystems. The results clarify the integrated roles of climate and nitrogen deposition on variations of CUEe that would be valuable for regional ecosystem function evaluation.

1. Introduction

Carbon use efficiency at the ecosystem level (CUEe), defined as the ratio of net ecosystem production (NEP) to gross primary production (GPP), indicates the capacity of ecosystem to store carbon from the atmosphere (Fernández-Martínez et al., 2014a). On the global scale, GPP is estimated to 123 ± 8 Pg C y^{-1} (Beer et al., 2010), which is nearly 15 times the current rate of fossil fuel combustion (Le Quéré et al., 2013). Hence, how efficient of ecosystem could convert GPP into plant and soil storage greatly determines the carbon sequestration of terrestrial ecosystems and their feedbacks to climate change (Baldocchi et al., 2014).

CUEe contains the CUE of plant (CUEa) as well as the subsequent carbon cost efficiency by microbial heterotrophic respiration (Sinsabaugh et al., 2017). Previous studies indicate that the fraction of photosynthate incorporated into plant tissues is nearly a constant of 0.47–0.52 (Waring et al., 1998; Zhang et al., 2009). Upscaling from the individual to ecosystemic level, more interactive heterogeneous processes and environmental factors involved, it is interesting to doubt that whether CUEe remains a constant across biomes. Fernández-Martínez et al. (2014b) indicates that mean CUEe differs very little among biomes across the global forests. However, this convergence goes against when diverse ecosystem types are considered. For example, the CUEe of grasslands is reported to be greater than those of deciduous broadleaf and coniferous forests since less investment in respiring plant tissue relative to forests (Law et al., 2002). Kato and Tang (2008) suggest that the CUEe of deciduous broadleaf forests is nearly two times for coniferous forests in Asia.

In addition to the influence of ecosystem type, variation in CUEe is thought to be affected by environmental condition, soil nutrient availability, stand age, nitrogen deposition and so on (Law et al., 2002; Luyssaert et al., 2007; Fernández-Martínez et al., 2014b; Chen et al., 2015). The analysis of individual factor reveals that net carbon sequestration and CUEe are enhanced by the increase in mean annual temperature (MAT) and precipitation (MAP) (Kato and Tang, 2008; Yu et al., 2013). Warm and humid environment significantly improve GPP and thus CUEe by the prolonged growing season length and enhanced photosynthetic capacity (Hirata et al., 2008; Kato and Tang, 2008; Yu et al., 2013). For forests, CUEe generally varies with stand age that presents initial increase and then decrease along the plant succession (Pregitzer and Euskirchen, 2004; Goulden et al., 2011). However, Magnani et al. (2007) indicates that after factoring out the effects of

Abbreviations: CUEe, Ecosystem Carbon Use Efficiency; CUEa, Plant Carbon Use Efficiency; NEP, Net Ecosystem Production; GPP, Gross Primary Production; MAT, Mean Annual Temperature; MAP, Mean Annual Precipitation; Ndep, Nitrogen deposition

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stand age, forest carbon sequestration and CUEe are overwhelmingly driven by nitrogen deposition. Nitrogen deposition could increase the fraction of GPP to woody biomass and thereby increasing the residence time of assimilated C, and thus ecosystems are expected to have higher CUEe values (Litton et al., 2007; Fernández-Martínez et al., 2014b). Plant types, climate and nitrogen deposition most likely influence on CUEe interactively rather than separately, however, how the interactive roles of climate and nitrogen deposition on CUEe are less discussed.

China has distinct geographic regimes ranging from eastern lowlands to western high mountains where mean elevation over 4000 m (Fang et al., 2001). The typical topography and climates support a set of ecosystems ranging from the boreal deciduous coniferous forest to tropical rainforest along the North-South transect of Eastern China, and ranging from typical steppe to desert and alpine meadow in the Tibet Plateau (Fang et al., 2001). In addition, China has experienced a sharply increased nitrogen deposition over the past decades (Liu et al, 2013). The nitrogen deposition exhibits an intensively varied gradient from southern to western and northern China (Jia et al., 2014). Such diverse climates, plant types and nitrogen deposition condition provide a unique field for examining the variation and its controls of CUEe.

In the present study, we compiled database on CUEe observed in different ecosystems over China with specific aim to address these questions: (1) Is CUEe a constant across biomes? (2) How climate factors and nitrogen deposition interactively affect the variation of CUEe in China?

2. Material and method

2.1. Data collection

2.1.1. Carbon fluxes and meteorological data

To analyze the variation of CUEe, we collected ecosystem carbon fluxes (NEP, GPP) and CUEe data from published literatures during the period of 2000–2017 in China. To avoid bias in publication selection, we only selected the literatures that satisfy the following three criteria: (1) the NEP and GPP values were measured using eddy covariance technique (such as LI-7500, LI-7700); (2) The data was derived from at least one entire year of measurement; (3) the data was calibrated by processes including storage correction, WPL correction, night flux calculation and so on. For articles with NEP and GPP data, the CUEe values were estimated by equation of CUEe = NEP/GPP.

Following these constraints, we obtained 156 estimates of CUEe from 50 sites. These sites distribute from 18 to 51°N in latitude, 87 to 133°E in longitude and 4 to 4250 m in elevation (Fig. 1). The studied sites covered forests (17), grasslands (17), croplands (6), and wetlands (10) which belong to tropical, subtropical, temperate, boreal and alpine biomes (Fig. 1). For each site, we also recorded the supporting information including topography, soil type, mean annual temperature (MAT), mean annual precipitation (MAP), forest age, period of measurement, and stand management. The detailed supporting information for each study site was shown in Table 1.

2.1.2. GPP data from MODIS

To test the robustness of variations of CUEe, we downloaded the product of MOD17A2 to obtain the yearly GPP values from MODIS (Moderate Resolution Imaging Spectroradiometer) as an independent estimation available from the Oak Ridge National Laboratory's Distributed Active Archive Center (http://daac.ornl.gov/MODIS/). Considering the location errors, we extracted the nearby 9 pixels of stand location and calculate their mean values for each site. There were four sites (Dongtan-high, Dongtan-high, Dongtan-high and Anqing site) failed to extract the corresponding GPP values since they are close to the waterbody. Thereby, in the analysis of correlation between NEP and GPP from MODIS estimate these four sites were excluded.

2.1.3. Nitrogen deposition data

Nitrogen deposition (Ndep) data were derived from the interpolated gridded maps of China. The national-scale Ndep maps for the 1990s and 2000s were produced based on ground observations (Jia et al., 2014). According to the geographic coordinate, we extracted nitrogen deposition for each site.

2.2. Data uncertainty

As in most integrated analysis, uncertainties of carbon flux estimates were rarely explicitly reported in each literature. Therefore, we estimated the total uncertainty for component flux of NEP and GPP, as well as CUEe in the database similar to Luyssaert et al. (2007). The NEP was assumed to most likely range from -100 to 600 g C m^{-2} yr^{-1}. In current study, the NEP ranged from -100 to 900 g C m^{-2} yr^{-1}. Therefore, the absolute range of the NEP estimate was ± 500 g C m^{-2} yr^{-1}, and the precision was evaluated to be 30% of 500 namely 150 g C m^{-2} yr^{-1} based on the reported precision of the eddy covariance method (Luyssaert et al., 2007). Since calculating the multiple-year mean value for each site, the uncertainty was reduced in interannual variability by accounting for multiple-year observations. The uncertainty was thus estimated to be the inverse of square root of the length of observation time series. Consequently, the uncertainty of NEP was assessed to be 45 to 150 g C m^{-2} yr^{-1} which was in agreement with the reported uncertainty estimation (Oren et al., 2006). Similar approach was followed to estimate the uncertainty of GPP and CUEe. The collected GPP values ranged from 100 to 2500 g C m^{-2} yr^{-1}, and the CUEe ranged from -0.5 to 0.5. After adjusting for the precision of the eddy covariance method and the length of the observation period, the uncertainty of GPP was within the range of 120–390 g C m^{-2} yr^{-1} and the uncertainty was 0.05–0.15 for CUEe. Specific uncertainty for each study site was shown in Table 1.

2.3. Data analysis

We analyzed data with the General Linear Model (GLM) and regression analyses (SPSS 16.0, Chicago, IL, USA). The linear regression was performed to analyze the correlation between NEP and GPP, and then followed by using the GLM to examine the effect of different estimate methods (Eddy covariance and Modis remote sensing) on the slopes of relationship (Chow, 1960). Analysis of covariance (ANCOVA) was used for checking interactions between the covariate and fixed effects. The levels of fixed effect were assumed to not differ in their relationship to the covariate if an interaction was not detected (DeLucia et al., 2007). We conducted the ANCOVA to investigate the possible interactive effects of vegetation types and climate factors on CUEe values. Vegetation type (eight levels) was included as a fixed effect with climate factors (temperature and precipitation) as a covariate. To further test the mixed effects of MAT, MAP and Ndep on CUEe, we classified studied ecosystems into two levels by each factors. According to the ecological principle of the minimum constraint, the threshold for MAT and MAP was defined as 5 °C and 400 mm in line with previous studies (Luyssaert et al., 2007; Gao et al., 2014). Ecosystems with MAT ≤ 5 °C were classified as cold ecosystems, and with MAT ≥ 5 °C were classified as warm ecosystems. Ecosystems with MAP ≤ 400 mm were classified as dry ecosystems, and with MAP ≥ 400 mm were classified as wet ecosystems. In addition, according to the observed nitrogen deposition levels for most forests and grasslands in China (Liu et al., 2011), ecosystems with Ndep ≥ 20 kg N Gaoha^{-1} yr^{-1} were considered as high nitrogen deposition ecosystems, and with Ndep ≤ 20 kg N ha^{-1} yr^{-1} were considered as low nitrogen deposition ecosystems in current study. The linear regression was performed to examine the correlation among CUEe, MAT, MAP and nitrogen deposition with the significance level of $\alpha = 0.05$.