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Carbon exchanges and their responses to temperature and precipitation in forest ecosystems in Yunnan, Southwest China

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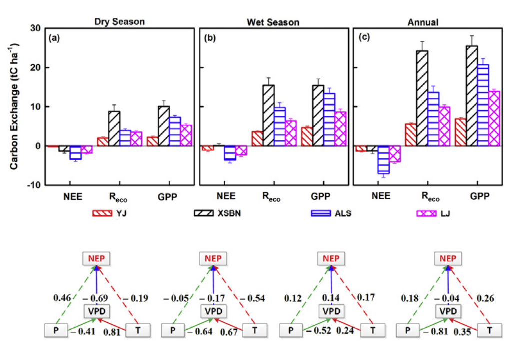
HIGHLIGHTS

- All four ecosystems were carbon sinks although contrasting seasonality of NEP.
- Relationship between NEP and GPP should be parabolic rather than linear.
- Path/redundancy analysis were applied to identify patterns of controls on C fluxes.
- Controls differed: T reduced NEP in rainforest, while P increased NEP in savanna.
- Variations in NEP were more sensitive to T than P in Yunnan's forest ecosystems.

GRAPHICAL ABSTRACT



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ABSTRACT

Forest ecosystems play an increasingly important role in the global carbon cycle. However, knowledge on carbon exchanges, their spatio-temporal patterns, and the extent of the key controls that affect carbon fluxes is lacking. In this study, we employed 29-site-years of eddy covariance data to observe the state, spatio-temporal variations and climate sensitivity of carbon fluxes (gross primary productivity (GPP), ecosystem respiration (R_{eco}), and net ecosystem carbon exchange (NEE)) in four representative forest ecosystems in Yunnan. We found that 1) all four forest ecosystems were carbon sinks (the average NEE was -3.40 tC ha^{-1} yr^{-1}); 2) contrasting seasonality of the NEE among the ecosystems with a carbon sink mainly during the wet season in the Yuanjiang savanna ecosystem (YJ) but during the dry season in the Xishuangbanna tropical rainforest ecosystem (XSBN), besides an equivalent NEE uptake was observed during the wet/dry season in the Ailaoshan subtropical evergreen broad-

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Critical factors
Path analysis
Redundancy analysis
Climate change
Forest ecosystems
Eddy covariance

leaved forest ecosystem (ALS) and Lijiang subalpine coniferous forest ecosystem (LJ); 3) as the GPP increased, the net ecosystem production (NEP) first increased and then decreased when the GPP > 17.5 tC ha^{-1} yr^{-1}; 4) the precipitation determines the carbon sinks in the savanna ecosystem (e.g., YJ), while temperature did so in the tropical forest ecosystem (e.g., XSBN); 5) overall, under the circumstances of warming and decreased precipitation, the carbon sink might decrease in the YJ but maybe increase in the ALS and LJ, while future strength of the sink in the XSBN is somewhat uncertain. However, based on the redundancy analysis, the temperature and precipitation combined together explained 39.7%, 32.2%, 25.3%, and 29.6% of the variations in the NEE in the YJ, XSBN, ALS and LJ, respectively, which indicates that considerable changes in the NEE could not be explained by variations in the temperature and precipitation. Therefore, the effects of other factors (e.g., CO_2 concentration, N/P deposition, aerosol and other variables) on the NEE still require extensive research and need to be considered seriously in carbon-cycle-models.

1. Introduction

Terrestrial ecosystems have a net carbon uptake from the atmosphere of 2.6 ± 1.2 Pg C yr^{-1} and therefore play a crucial role in the global carbon cycle by mitigating global warming (IPCC, 2013). A large portion of this uptake is absorbed by forest ecosystems, and the global spatio-temporal patterns of carbon exchange and their driving factors, especially in forest ecosystems, are the core of the global carbon cycle under climate change (Chapin et al., 2011; Heimann and Reichstein, 2008; IPCC, 2013; Le Quéré et al., 2016; Reichstein et al., 2013; Yu et al., 2014b). Therefore, exploring carbon exchanges and their responses to environmental factors is very important for understanding and projecting the carbon cycle and for providing information to policy-makers (Le Quéré et al., 2016). Such knowledge underpins the Paris Agreement, which aims to keep the rise in temperature well below 2 °C and calls for renewed efforts to limit global warming below 1.5 °C (Anderson and Peters, 2016; UNFCCC, 2015). So far, the most cost-effective approach to mitigate anthropogenic C emission is via ecosystem carbon uptake (IPCC, 2013). However, there remains a lack of knowledge on carbon fluxes and their spatio-temporal patterns, and the underlying mechanisms of critical factors impacting carbon fluxes.

The spatial representation of carbon fluxes is currently very limited and requires further comprehensive and cooperative research (Baldocchi, 2008; Yu et al., 2014b). Most recent studies have focused not only on the actualities of carbon exchange between forest ecosystems and the atmosphere, but also on the response of carbon fluxes to biophysical controls (Baldocchi et al., 2017; Beringer et al., 2016; Frank et al., 2015; Grace et al., 2014; IPCC, 2013; Reichstein et al., 2013; Yu et al., 2016). Many results showed that the decreased precipitation and increased temperature under climate change scenarios will decrease these ecosystems' carbon sinks (Chen et al., 2013; Ciais et al., 2005; Knapp et al., 2002; Weltzin et al., 2003; Wu et al., 2011), although a high degree of spatio-temporal heterogeneity exists, with marked influences from the topography, soil, vegetation and environmental factors in forest ecosystems (Baldocchi, 2008; Luyssaert et al., 2010; Luyssaert et al., 2008; Tagesson et al., 2016; Yu et al., 2014a; Yu et al., 2008). Undoubtedly, carbon exchanges and their controls differ between locations, with some ecosystems being especially vulnerable to climate change (Chen et al., 2013; IPCC, 2013; Jia et al., 2016; Mekonnen et al., 2016; Tagesson et al., 2016; Wu et al., 2011). Furthermore, biophysical-based models that predict the behavior of the global carbon cycle require much more knowledge derived from in situ research to drive and validate their results. National and global networks provide such data over time scales of years and even decades, and >900 observation stations were present in FLUXNET by the end of 2016 (http://fluxnet.fluxdata.org/sites/). Nevertheless, the spatio-temporal representativeness of flux recording is limited in many areas of the world (Pan et al., 2011; GR Yu et al., 2013a) despite attempts to improve our understanding of the global carbon exchange (Baldocchi, 2003; Baldocchi et al., 2001a; Baldocchi et al., 1996; Ciais et al., 2005; Falge et al., 2002; Law et al., 2002; Song et al., 2014; Yu et al., 2006; Zhang et al., 2010; Zhao et al., 2006). Clearly, we must comprehensively research carbon fluxes at a variety of scales (individuals, populations, communities, ecosystems, landscapes and regions) and infer their responses to climate change. Such studies should help to predict climate change, and the determined effects should also be helpful for regional carbon management to mitigate and adapt to climate change (Baldocchi, 2008; Wu et al., 2011; Yu et al., 2014b).

Southwest China has the second largest forest carbon biomass storage (Fang et al., 2001) and the largest carbon sink in China (Piao et al., 2009). However, this area is subject to climate change and may be vulnerable. Models suggested that Yunnan Province (the main portion of Southwest China) will experience decreased precipitation and increased temperatures (Gao et al., 2012; Qin et al., 2005). Therefore, it is imperative to understand the carbon exchanges and their responses to climate change in this region. An eddy covariance and meteorological observation system with long-term recording capability was applied at four contrasting forest ecosystems (YJ, XSBN, ALS, and LJ) along a large temperature and precipitation gradient in Yunnan to explore the carbon dynamics and their response to changing climate. The specific objectives of this study were to 1) quantify the carbon exchange state (gross primary productivity (GPP), ecosystem respiration (R_{eco}), and net ecosystem carbon exchange (NEE)) and its spatio-temporal patterns; 2) provide data to analyze the relationship among R_{eco}, NEE and GPP; 3) identify the influence of temperature (T) and precipitation (P) on the NEE, and 4) predict likely changes in carbon sinks under climate change. The over-arching aims are to predict the responses of forest ecosystems to climate change and thus contribute to the development and implementation of policies for regional ecosystem protection.

2. Materials and methods

2.1. Experimental sites

Four representative forest ecosystems, namely, the Yuanjiang savanna ecosystem (YJ), Xishuangbanna tropical rainforest ecosystem (XSBN), Ailaoshan subtropical evergreen broad-leaved forest ecosystem (ALS), and Lijiang subalpine cold-temperate coniferous forest ecosystem (LJ) (Fig. 1), were chosen to study the carbon exchanges and responses to climatic control in Yunnan, Southwest China.

The mean annual temperature over the study period (MAT) in the YJ, XSBN, ALS, and LJ was 24.3, 21.4, 11.7, and 7.9 °C, respectively, and the mean annual precipitation (MAP) was 734, 1415, 1728, and 1095 mm, respectively (Table 1). The climate is influenced by the southwestern monsoon and the Tibetan Plateau, and >80% of the MAP occurs during the wet season (May–October) in each of the four locations. The geographical location, altitude, dominant species, biophysical factors, and soil physical and chemical properties are listed in Table 1, and further information regarding the topography, climate, solar radiation, vegetation, and soil properties can be viewed in previous work (Cao et al.,

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