Agricultural and Forest Meteorology 243 (2017) 9–18

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet

Climate controls over the net carbon uptake period and amplitude of net ecosystem production in temperate and boreal ecosystems

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ARTICLE INFO

Keywords:
Net ecosystem productivity
Interannual variation
Net carbon uptake period
Maximum carbon uptake amplitude
Phenology
Climate

ABSTRACT

The seasonal and interannual variability of the terrestrial carbon cycle is regulated by the interactions of climate and ecosystem function. However, the key factors and processes determining the interannual variability of net ecosystem productivity (NEP) in different biomes are far from clear. Here, we quantified yearly anomalies of seasonal and annual NEP, net carbon uptake period (CUP), and the maximum daily NEP (NEP_{max}) in response to climatic variables in 24 deciduous broadleaf forest (DBF), evergreen forest (EF), and grassland (GRA) ecosystems that include at least eight years of eddy covariance observations. Over the 228 site-years studied, interannual variations in NEP were mostly explained by anomalies of CUP and NEP_{max}. CUP was determined by spring and autumn net carbon uptake phenology, which were sensitive to annual meteorological variability. Warmer spring temperatures led to an earlier start of net carbon uptake activity and higher spring and annual NEP values in DBF and EF, while warmer autumn temperatures in DBF, higher autumn radiation in EF, and more summer and autumn precipitation in GRA resulted in a later ending date of net carbon uptake and associated higher autumn and annual NEP. Anomalies in NEP_{max} s were determined by summer precipitation in DBF and GRA, and explained more than 50% of variation in summer NEP anomalies for all the three biomes. Results demonstrate the role of meteorological variability in controlling CUP and NEP_{max}, which in turn help describe the seasonal and interannual variability of NEP.

1. Introduction

Climate controls the terrestrial carbon cycle by regulating plant physiological processes, including phenology. Climate thus determines both ecosystem carbon uptake capacity as well as the length of the carbon uptake period, which are important determinants of ecosystem carbon sequestration (Falge et al., 2002b; Gu et al., 2009; Xia et al., 2015; Zhou et al., 2016). It is far from clear how climatic or meteorological changes impact net ecosystem production (NEP) by changing carbon uptake phenology and physiology, given that models are largely unable to simulate the interaction between climate and ecosystem carbon dynamics to date (IPCC, 2013).

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http://dx.doi.org/10.1016/j.agrformet.2017.05.009
Received 5 January 2017; Received in revised form 9 May 2017; Accepted 11 May 2017
0168-1923/

Previous studies on the relationship between carbon uptake phenology and NEP primarily focus on growing season length (GSL). A longer GSL due to climate warming (Delpierre et al., 2015; Linderholm, 2006; Peñuelas and Filella, 2001) usually stimulates NEP (Baldocchi, 2008; Baldocchi and Wilson, 2001; Churkina et al., 2005; Dragoni et al., 2011; Richardson et al., 2013). Yet other studies have found no relationship between GSL and NEP (Dunn et al., 2007), or lower NEP with longer GSL (Hu et al., 2010b; Piao et al., 2007; Sacks et al., 2007). The reasons for this disparity are twofold; gross ecosystem productivity may be offset by concurrent increases in ecosystem respiration as NEP is the difference between the two, and longer GSLs may increase the likelihood of drought limitations to productivity.

With the advantage of quasi-continuous measurements of the net CO_2 exchange by the eddy covariance method, strong relationships between net carbon uptake period (CUP) and annual NEP have been characterized (Baldocchi et al., 2001; Baldocchi et al., 2005; Richardson et al., 2010; Richardson et al., 2013; Wu and Chen, 2013; Wu et al., 2013). Overall, annual NEP is more strongly correlated with CUP than GSL (Piao et al., 2007; White and Nemani, 2003; Wu et al., 2013). While climate controls on GSL have been well studied (Chmielewski and Rötzer, 2001; Delpierre et al., 2015; Matsumoto et al., 2003; Richardson et al., 2013), our understanding of climate controls over CUP and thus NEP across different ecosystems is still limited.

In addition to the CUP, the maximum daily ecosystem NEP (NEP_{max}, Fig. 1A) is another strong predictor of annual NEP, especially in temperate and boreal ecosystems that have obvious seasonal dynamics (Falge et al., 2002b; Xia et al., 2015; Zhou et al., 2016). With the same CUP, ecosystems that have a higher NEP_{max} tend to have larger annual NEP (Fig. 1D) (Churkina et al., 2005). Although a longer CUP may increase annual NEP, associated warmer and drier summers may suppress summer NEP_{max}, potentially offsetting any annual NEP increase (e.g. Fig. 1E) (Angert et al., 2005; Ciais et al., 2005; Cleland et al., 2007). Moreover, a longer CUP may decrease annual NEP because an earlier onset of the growing season may result from a shallow snowpack or increased transpiration, leaving less available water in the soil in summer and limiting plant growth later in the growing season (Hu et al., 2010a; Kljun et al., 2006; Sacks et al., 2007). Niemand et al. (2005) linked phenology observations to flux measurements in a Norway spruce forest and found that earlier spring phenology correlated well with increased NEP only when the drought year of 2003 was excluded, suggesting that water availability influences the relationship between CUP and annual NEP. These results indicate that the effects of summer water limitation on NEP_{max} may potentially offset positive spring warming influences on spring NEP, leading to smaller changes in annual NEP than otherwise expected (Fig. 1E). In addition, autumn warming may also advance the ending of carbon uptake and decrease autumn NEP, resulting in a small change in annual NEP in response to climate warming (Fig. 1F). We tested the hypothesis that, by separating annual NEP variability into CUP and NEP_{max}, we can better disentangle how meteorological drivers impact NEP variability in deciduous broadleaf forests (DBF), evergreen forests (EF), and grasslands (GRA) that experience pronounced seasonality in temperate and boreal climate zones.

In this study, we analyzed eddy covariance-measured CO_2 flux and micrometeorological variables from 24 flux tower sites that have long-term (multi-year) quasi-continuous measurements. The specific questions addressed in this study include: (1) how are CUP and NEP_{max} related to annual NEP in different biomes; (2) what are the climate factors that determine NEP_{max} and the beginning (BDOY) and end (EDOY) of the CUP; and (3) how are seasonal NEP anomalies related to annual NEP anomalies?

2. Data and methods

2.1. Site selection and data processing

Surface-atmosphere CO_2 flux and micrometeorological data used in this analysis were downloaded from standardized files of the FLUXNET LaThuille database released in 2007 (Baldocchi, 2008; Baldocchi et al., 2001). The data have been quality-controlled and gap-filled by consistent methods (Moffat et al., 2007; Papale et al., 2006; Reichstein et al., 2005). From the available 253 sites, we identified and examined temperate and boreal ecosystems (38–62°N, −125 to 24°E; Table A1) that have clear seasonal dynamics. We only chose sites that have eight or more years of data for a total of 24 sites with 228 site-

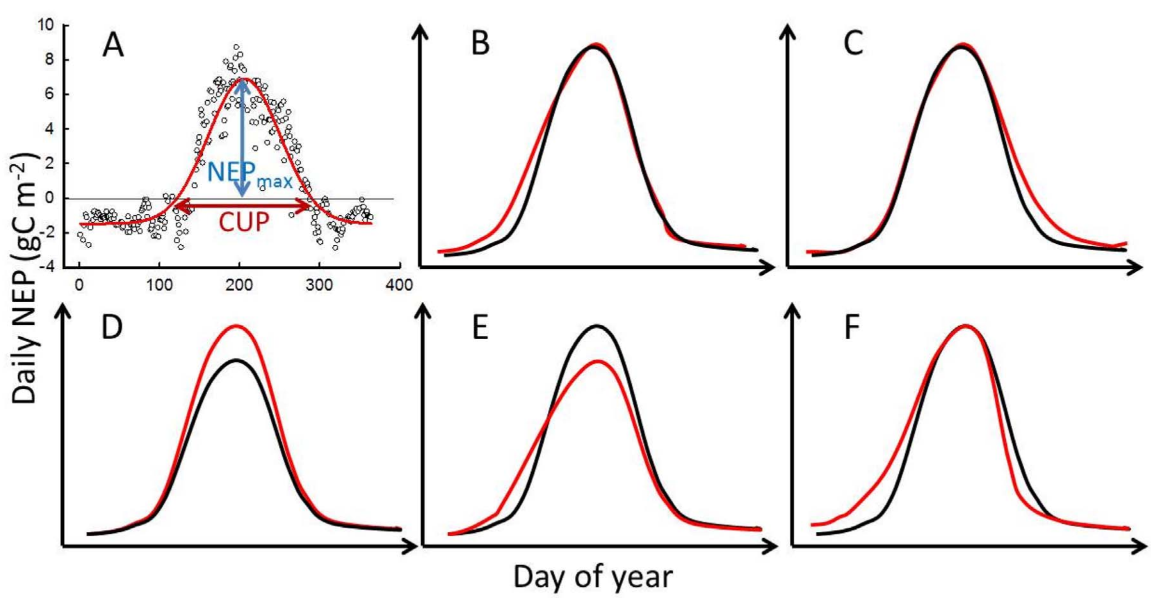

Fig. 1. Hypothesized changes in the regulation of annual NEP by net carbon uptake period (CUP) and the maximum daily net ecosystem productivity (NEP_{max}), and their roles in regulating annual NEP changes. Panel A defines the terminology used throughout the manuscript. Red lines in subsequent panels represent the change in a hypothetical warmer year versus the mean seasonal pattern in black. Panels (B) and (C) represent the phenological regulations by advancing net carbon sink beginning day (BDOY) or by delaying net carbon sink ending day (EDOY); (D) represents a change in NEP_{max}; (E) represents the larger spring NEP with an advancing BDOY but smaller summer NEP by decreasing NEP_{max}; and (F) represents larger spring NEP by early beginning of BDOY, but smaller autumn NEP with earlier EDOY. We only showed the representative scenarios rather than all possible interactions between NEP_{max}, BDOY and EDOY.