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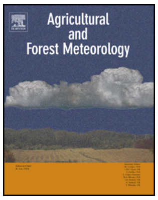

Response and biophysical regulation of carbon dioxide fluxes to climate variability and anomaly in contrasting ecosystems in northwestern Ohio, USA

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ABSTRACT

Recent climate variability and anomaly in the Great Lakes region provided a valuable opportunity in examining the response and regulation of ecosystem carbon cycling across different ecosystems. A simple Bayesian hierarchical model was developed and fitted against three-year (2011–2013) net ecosystem CO_2 exchange (F_{CO_2}) data observed at three eddy-covariance sites (i.e., a deciduous woodland, a cropland, and a marsh) in northwestern Ohio. The model was designed to partition the variation of gross ecosystem production (GEP), ecosystem respiration (ER) and F_{CO_2} that resulted directly from the short-term environmental forcing (i.e., direct effect) and indirectly from the changes of ecosystem functional traits (e.g., structural, physiological, and phenological traits) (i.e., indirect effect). Interannual variation of F_{CO_2} was mainly driven by indirect effects, accounting for 54%, 89%, and 86% of the interannual variation at the woodland, cropland, and marsh sites, respectively. On the other hand, direct climatic effects accounted for 33% of interannual F_{CO_2} variation at the woodland site and became irrelevant (<10%) at the cropland and marsh sites. In general, annual GEP and ER at each site tended to co-vary and dampen the interannual variability in F_{CO_2}. Yet, year-to-year changes of GEP and ER were not spatially synchronous, suggesting that the ecosystem's response to climate was strongly site-specific in terms of the annual net CO_2 uptake. Future research should focus on the disparate response among ecosystems and develop a suitable framework to examine the mechanisms that drive differences in closely co-located ecosystems.

1. Introduction

Net ecosystem CO_2 exchange (F_{CO_2}), which is the balance of two large and opposite carbon fluxes-gross ecosystem production (GEP) and ecosystem respiration (ER)—has been studied across a range of spatial and temporal scales in recent decades to understand how climatic variability and disturbance regulate the regional-to-global carbon balance (Baldocchi, 2014; Braswell et al., 1997; Melillo et al., 2014; Yi et al., 2010). Environmental drivers, such as solar radiation, temperature, and air/soil moisture, are generally accepted as the major factors regulating the variation of CO_2 fluxes (i.e., F_{CO_2}, GEP, ER) at the hourly to synoptic (multi-daily) scales (Baldocchi et al., 2001; Baldocchi, 2008; Stoy et al., 2005). On the other hand, the response of CO_2 fluxes to climatic variability becomes more complex at a longer scale (e.g., seasonal to interannual) and often involves indirect effects (i.e., prolonged, muted, and lagged responses) through altering the biotic characteristics (Barr et al., 2009; Humphreys and Lafleur, 2011; Richardson et al., 2010; Stoy et al., 2005). The interaction of direct and indirect effects is of great importance because the similarity or difference in their response magnitudes/directions to climatic variability may reveal the potential resilience or vulnerability of ecosystem carbon cycling to prospective climate change (Cox et al., 2000; Heimann and Reichstein, 2008; Luo et al., 2009).

Different statistical frameworks, such as the homogeneity-of-slopes model (e.g., Hui et al., 2003; McVeigh et al., 2014; Polley et al.,

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2008; Teklemariam et al., 2010) and the cross-year model simulation (e.g., Richardson et al., 2007; Shao et al., 2014; Wu et al., 2012), have been adopted to disentangle the direct/indirect effects. In general, these approaches took advantage of our current understanding of environmental forcing on the short-term variability of CO_2 fluxes. They structured the statistical models explicitly to incorporate all relevant short-term environmental drivers (e.g., radiation, temperature, moisture) and allowed the model parameters to vary across a longer time span (e.g., yearly, in most cases). Once the models were fitted, the variation of CO_2 fluxes (e.g., among years) was then partitioned into the effects of environmental drivers (i.e., direct effect) and model parameters (i.e., indirect effect). The changes of model parameters were interpreted as "functional changes" (Hui et al., 2003), which comprised of all effects that were unexplained by direct and instantaneous environmental forcing.

Potentially, the functional changes may result from the changes of plant phenology (Richardson et al., 2009, 2010), physiological characteristics (Luo et al., 2001; Sala et al., 2010), canopy structure (Barr et al., 2004; Humphreys and Lafleur, 2011), soil microbial community (Sowerby et al., 2005), substrate availability (DeForest et al., 2009), or the interplay of autotrophic and heterotrophic respiration (DeForest et al., 2006; Xu et al., 2011). Studies showed that the indirect effects often played a dominant role in driving interannual F_{CO_2} variability (Shao et al., 2015). In some cases, the indirect effects explained up to ~70–80% of the interannual variability of CO_2 fluxes (Shao et al., 2014; Wu et al., 2012). However, prior studies have not been applied to a collection of co-located sites experiencing a set of extreme climate anomalies, where the expectation would be similar responses given similar climate mean state and geographic distance.

Recent research also highlighted the importance of rare but extreme weather events (e.g., heat/cold wave, rain storm, severe drought) for their disproportional influence on ecosystem carbon cycling (Ciais et al., 2005; Shi et al., 2014; Wu et al., 2012; Xiao et al., 2010). Climatic anomalies and extremes posed instantaneous effects on ecosystem carbon cycling by altering environmental conditions (i.e., temperature, moisture). More importantly, these events may alter the phenological, physiological, and structural traits of ecosystems, which then translate into indirect effects that last much longer than the duration of climatic anomalies and extremes (Ciais et al., 2005; Teklemariam et al., 2010; Thibault and Brown, 2008). These prolonged or lagged effects often resulted in more influence on carbon cycling than the short-term direct effects (Ciais et al., 2005; Desai, 2014; Thibault and Brown, 2008).

Most recently, severe weather and climate anomalies have been increasingly observed in United States (Karl et al., 2012; Wuebbles et al., 2014). In the Great Lakes region, the recent records included the earliest false spring of the century (2012), heat waves (2011, 2012), summer cool spells (2013), and record-breaking high precipitation (2011) (Ault et al., 2013; Chu et al., 2015; Karl et al., 2012). These anomalies triggered drastic year-to-year variation in plant phenology across the region and caused severe damages to crop and fruit production (Ault et al., 2013; Knudson, 2012). Our previous study found that a Lake Erie coastal marsh turned from a net carbon sink to a net carbon source recently in the past years (Chu et al., 2015). However, it remains unclear whether the influence was ecosystem-specific or region-wide, and to what extent the influence was caused by direct and indirect effects.

Here, we aimed to examine and compare the effects of recent climatic variability and anomalies on interannual variability of CO_2 fluxes at different ecosystems in the region. Specifically, we targeted the two largest carbon fluxes (GEP and ER) and their balance – F_{CO_2}. We asked the following questions. (1) Do spatially co-located but functionally different ecosystems respond similarly in magnitude and direction to climate variability and anomalies in terms of CO_2 fluxes? (2) What biophysical factors most influence how ecosystem CO_2 fluxes (GEP, ER, and F_{CO_2}) respond to recent climate variability and anomalies? (3) To what extent can the response of GEP, ER, and F_{CO_2} be explained by the direct and indirect effects at different ecosystems, respectively? Specifically, do these direct and indirect effects function synergistically (++) or antagonistically (+−) to the climate variability and anomalies?

2. Materials and methods

2.1. Experiment design

We adopted a similar cross-year model simulation approach as in Richardson et al. (2007) and Wu et al. (2012). We targeted the three most prevalent ecosystem types (i.e., agriculture, forest, and wetland) in the study region—northwestern Ohio, USA. A Bayesian hierarchical model was developed and the model parameters were estimated using the Markov Chain Monte Carlo (MCMC) technique. The models were fitted against three-year (2011–2013) F_{CO_2} data observed at three eddy-covariance sites in the region (Table 1).

We designed the model to incorporate the most relevant short-term (hourly-synoptic) environmental forcing on GEP and ER (i.e., solar radiation, temperature, air/soil moisture) and allowed model parameters to vary through the seasons and over years. Once the models were fitted, we ran a series of Monte Carlo simulations ($N = 1000$) at each half-hourly time step through a yearly time span (17,520 steps) by using model parameters from each year (2011–2013) with environmental drivers from each year (2011–2013). The cross-year simulation generated nine different scenarios of the parameter-driver combinations (e.g., 2011 driver × 2011 parameter, 2011 driver × 2012 parameter...). The simulated half-hourly GEP, ER, and F_{CO_2} were then integrated locally (i.e., every eight days) and annually.

Following Richardson et al. (2007), we adopted analysis of variance (ANOVA) to partition the variation of local and annual integrals

Table 1
Summary of the site location and vegetation types in the study.

Site	Oak Openings preserve (US-Oho)	Curtice Walter–Berger cropland (US-CRT)	Winous Point north marsh (US-WPT)
Location	N41°33′16.98″ W83°50′36.76″	N41°37′42.31″ W83°20′43.18″	N41°27′51.28″ W82°59′45.02″
Vegetation type	Deciduous broadleaf forest (~70-year)	Conventional rain-fed cropland	Freshwater coastal marsh
Dominant species	*Quercus rubra*, *Q. alba*, *Q. velutina*, *Acer rubrum*	*Glycine max*, *Triticum spp.*	*Nymphaea odorata*, *Nelumbo lutea*, *Typha angustifolia*, *Hibiscus moscheutos*
Soil type	Sandy mixed and mesic	Silty clay	Hydric
Groundwater level	0.3–3 m belowground	0.3–3 m belowground	0.2–1 m aboveground
Soil water content	17–25%	25–65%	Saturated
Reference	Noormets et al. (2008b) and Xie et al. (2014)	Chu et al. (2014)	Chu et al. (2014, 2015)