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Biophysical controls on carbon and water vapor fluxes across a grassland climatic gradient in the United States

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ABSTRACT

Understanding of the underlying causes of spatial variation in exchange of carbon and water vapor fluxes between grasslands and the atmosphere is crucial for accurate estimates of regional and global carbon and water budgets, and for predicting the impact of climate change on biosphere–atmosphere feedbacks of grasslands. We used ground-based eddy flux and meteorological data, and the Moderate Resolution Imaging Spectroradiometer (MODIS) enhanced vegetation index (EVI) from 12 grasslands across the United States to examine the spatial variability in carbon and water vapor fluxes and to evaluate the biophysical controls on the spatial patterns of fluxes. Precipitation was strongly associated with spatial and temporal variability in carbon and water vapor fluxes and vegetation productivity. Grasslands with annual average precipitation <600 mm generally had neutral annual carbon balance or emitted small amount of carbon to the atmosphere. Despite strong coupling between gross primary production (GPP) and evapotranspiration (ET) across study sites, GPP showed larger spatial variation than ET, and EVI had a greater effect on GPP than on ET. Consequently, large spatial variation in ecosystem water use efficiency (EWUE = annual GPP/ET; varying from 0.67 ± 0.55 to 2.52 ± 0.52 g C mm^{-1} ET) was observed. Greater reduction in GPP than ET at high air temperature and vapor pressure deficit caused a reduction in EWUE in dry years, indicating a response which is opposite than what has been reported for forests. Our results show that spatial and temporal variations in ecosystem carbon uptake, ET, and water use efficiency of grasslands were strongly associated with canopy greenness and coverage, as indicated by EVI.

1. Introduction

In the past two decades, eddy covariance systems have been established in several grassland sites in the United States (U.S.) for investigations of processes controlling carbon and water vapor fluxes, and site specific results have been reported (Baldocchi et al., 2004; Fischer et al., 2012; Krishnan et al., 2012; Ma et al., 2007; Scott et al., 2010; Suyker et al., 2003). However, these observation networks cover only a small portion of grasslands. Sole reliance on individual sites may lead to biased estimates of fluxes at large scales (Biondini et al., 1991; Rahman et al., 2001). The broad distribution of grasslands across contrasting climate and management gradients adds to the complexity of measuring and modeling of fluxes, and understanding the vulnerability of ecosystems to environmental change. It is commonly accepted that ecosystem responses to changes in climatic-forcing variables such as precipitation, temperature, and CO_2 concentration are nonlinear (Burkett et al., 2005; Gill et al., 2002). Grasslands are considered ideal for rainfall manipulation studies because they are highly responsive to interannual variability in precipitation (Knapp et al., 2002). However,

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precipitation manipulation experiments at individual sites rarely capture this nonlinearity as they tend to have few (only two or three) treatments different from the control and do not manipulate temperature, which can co-vary with precipitation. Flux tower sites now allow comparative analysis, synthesis, modeling, and upscaling of site-level flux measurements (Falge et al., 2002; Gilmanov et al., 2003, 2010; Turner et al., 2003; Xiao et al., 2014). Synthesis of flux data from multiple sites across a climatic gradient allows analysis of the influences of a wider range environmental condition compared with manipulative studies at a single site. Several studies have investigated spatial variability of carbon fluxes (Churkina et al., 2005; Gilmanov et al., 2005; Kato and Tang, 2008; Law et al., 2002; Soussana et al., 2007; Yu et al., 2013; Yuan et al., 2009). These studies have shown that spatial variability of carbon fluxes is significantly correlated with mean annual temperature (MAT) and precipitation (MAP). However, most of the synthesis studies assembled all biomes together, which masked differences in response over spatial gradients within a biome type, such as grasslands. Compared to carbon fluxes, spatial variability in water vapor fluxes and water use efficiency at the ecosystem level, and the mechanistic understanding of the underlying controlling mechanisms in grasslands is still unclear. In addition, very little is known regarding the relative sensitivity of different grassland communities (C_4, mixed C_3/C_4, and C_3 dominant) across broadly distributed grasslands to climate. High frequency eddy covariance measurements allow calculation of net ecosystem CO_2 exchange (NEE), evapotranspiration (ET), gross primary production (GPP), ecosystem respiration (ER), and synthetic metrics such as ecosystem water use efficiency (EWUE, which reflects the tradeoff between water loss and carbon uptake in carbon assimilation process), thereby facilitating investigation of responses of carbon and water vapor fluxes to environmental drivers (Huxman et al., 2004; Law et al., 2002).

Satellite remote sensing provides a feasible approach for monitoring vegetation dynamics at ecosystem to global scales (Myneni et al., 1997; Zhang et al., 2003). A better understanding of phenological patterns of vegetation and their drivers is essential to improve climate and biogeochemical cycle models and also to better simulate the exchange of carbon and water vapor fluxes between land surface and the atmosphere (Running and Hunt, 1993). Previously, phenological dynamics have been shown to play a vital role in the variability of carbon and water vapor fluxes at the ecosystem scale for a broad range of ecosystems (DeForest et al., 2006; Hutyra et al., 2007; Ma et al., 2013; Richardson et al., 2010; Wagle et al., 2015). However, the major drivers of spatial variability of phenological metrics and the role of phenological dynamics on spatial variability of fluxes have not been specifically examined for broadly distributed grasslands in the U.S. This greatly hampers our understanding of the impacts of future climate change on phenological dynamics and the carbon and water budgets of U.S. grasslands. Further, an establishment of a robust relationship between tower fluxes and remotely sensed data can facilitate extrapolation of site-level fluxes to obtain regional estimates of carbon and water budgets across complex landscapes (Gilmanov et al., 2005; Xiao et al., 2008).

This study covers 12 AmeriFlux grassland sites that represent the distribution of grasslands within the conterminous U.S., including C_4 dominated semi-arid shortgrass prairie of the Southwest (AZ), C_3 dominated Mediterranean grassland (CA), C_3/C_4 mixed temperate grassland of the Northwest (MT) and Southeast (MS), C_4 dominated temperate continental tallgrass prairie of the Midwest (IL, KS) and South Central (OK), and C_3/C_4 mixed humid continental grassland of the Midwest (SD). The objectives of this study were: (1) to analyze the spatial variability in grassland carbon and water vapor fluxes, (2) examine whether a satellite measurement of green biomass (as quantified by the Moderate Resolution Imaging Spectroradiometer (MODIS) enhanced vegetation index, EVI) captures the observed spatial variability in carbon and water vapor fluxes, and (3) determine the responses of GPP and ET to major climatic variables. The time series measurements quantify the conditional statistics associated with seasonal changes in climatic variables and the results provide important insights about predicting the impact of climate change on biosphere–atmosphere feedbacks of grasslands under current and future climatic conditions.

2. Materials and methods

2.1. Site descriptions

The 12 grassland sites used in this study (Fig. S1) cover a broad range of geographic location, grassland type (warm-season C_4 dominant, mixed C_3 and C_4 species, and cool-season C_3 dominant), and climate (semi-arid, temperate/temperate continental, humid continental, and Mediterranean). Long term MAT ranged from 5 to 17 °C and MAP ranged from 345 to 1455 mm across sites. General site characteristics for the study sites are provided in Table 1. Detailed site information can be found in previous studies (see references in Table 1) or AmeriFlux website (http://ameriflux.ornl.gov/).

Supplementary Fig. S1 related to this article can be found, in the online version, at http://dx.doi.org/10.1016/j.agrformet.2015.08.265.

2.2. Meteorological, eddy flux, and MODIS EVI data

Site-specific climate data [i.e., air temperature (T_a), precipitation, volumetric soil water content (SWC), vapor pressure deficit (VPD)] and Level-4 eddy flux (half hourly, daily, and weekly) were acquired from the AmeriFlux website (http://ameriflux.ornl.gov/) or from published data by the site PI (R. Scott, Kendall grassland). Carbon and water vapor fluxes were measured at each site using the eddy covariance technique. GPP was derived by partitioning NEE data (Reichstein et al., 2005). Some study sites (Flagstaff Wildfire, El Reno burn and control, Fermi Prairie, Walnut, and Brookings) had a total of only 2–3 years of data and measurements were not available for the entire year (mainly missing during winter, non-growing season). In this case, NEE, GPP, ER, and ET data over the available period were averaged for the same date into a single composite year and integrated for the entire year to derive annual sums of NEE (NEE_{yr}), GPP (GPP_{yr}), ER (ER_{yr}), and ET (ET_{yr}) at each site. Moreover, due to data availability during most of the growing season, growing season sums of NEE (NEE_{GSL}), GPP (GPP_{GSL}), ER (ER_{GSL}), and ET (ET_{GSL}) at each site were also computed for each year. For the rest of the sites where multiple years of data were available for the entire year, annual and growing season sums of carbon fluxes and ET at each site were computed for each year. Since flux data were available for the peak growing season across all site-years, maximum values of fluxes (NEE_{max}, GPP_{max}, and ET_{max}) at each site were computed for each year.

The 8-day composite MODIS land surface reflectance (MOD09A1) data for single pixels (500 m × 500 m) containing the geo-location coordinates of a flux tower were downloaded from the data portal of the Earth Observation and Modeling Facility, the University of Oklahoma (http://eomf.ou.edu/visualization/). Although the spatial resolution of the MODIS pixels and flux tower footprints may vary, Fig. S2 shows that the MODIS pixels mostly cover uniform grasslands. Blue, green, red, and near infrared (nir) bands were used to derive EVI (Huete et al., 2002) as shown below:

$$\mathrm{EVI} = 2.5 \times \frac{\rho_{\mathrm{nir}} - \rho_{\mathrm{red}}}{\rho_{\mathrm{nir}} + (6 \times \rho_{\mathrm{red}} - 7.5 \times \rho_{\mathrm{blue}}) + 1} \qquad (1)$$

where ρ is surface reflectance in the wavelength band. EVI, widely used as a proxy of canopy greenness, is an optimized version of normalized difference vegetation index (NDVI) to account for