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Climate control of terrestrial carbon exchange across biomes and continents

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Abstract

Understanding the relationships between climate and carbon exchange by terrestrial ecosystems is critical to predict future levels of atmospheric carbon dioxide because of the potential accelerating effects of positive climate–carbon cycle feedbacks. However, directly observed relationships between climate and terrestrial CO₂ exchange with the atmosphere across biomes and continents are lacking. Here we present data describing the relationships between net ecosystem exchange of carbon (NEE) and climate factors as measured using the eddy covariance method at 125 unique sites in various ecosystems over six continents with a total of 559 site-years. We find that NEE observed at eddy covariance sites is (1) a strong function of mean annual temperature at mid- and high-latitudes, (2) a strong function of dryness at mid- and low-latitudes, and (3) a function of both temperature and dryness around the mid-latitude belt (45° N). The sensitivity of NEE to mean annual temperature breaks down at ~16 °C (a threshold value of mean annual temperature), above which no further increase of CO₂ uptake with temperature was observed and dryness influence overrules temperature influence.

Keywords: NEE, climate control, terrestrial carbon sequestration, temperature, dryness, eddy flux, biomes, photosynthesis, respiration, global carbon cycle

1. Introduction

Determining the relationships between terrestrial carbon exchange and climate is fundamentally important because climate–carbon cycle feedback could significantly accelerate (or decelerate) future climate warming (Zeng et al 2004, 2005). Globally, the observed growth rate anomaly of atmospheric CO₂ concentration is correlated with the multivariate El Niño-Southern Oscillation index (Heimann and Reichstein 2008). Inversion modeling (Bousquet et al 2000) and biome-based analyses of climate anomalies (Zhou et al 2008) suggest that the oceanic carbon reservoir is a minor player in this variability. Instead, variations in the atmospheric CO₂ growth rate result largely from the impact of climate on terrestrial carbon sequestration (Nemani et al 2003, Xiao and Moody 2004), including regional impacts of extreme climate conditions such as heat waves and droughts (Ciais et al 2005, Xiao et al 2009).

On much smaller spatial scales, large amounts of data have been collected continuously over the last two decades using the eddy covariance technique to measure directly the net ecosystem exchange of CO₂ (NEE) between the biosphere and the atmosphere (Baldocchi et al 2001, Law et al 2002). Although a typical eddy covariance footprint is relatively small (ca. 1 km²), NEE variability at these sites is often representative of variability over much larger spatial scales as a result of the spatial coherence of climate anomalies (Ciais et al 2005, Nemani et al 2003, Xiao and Moody 2004). These temporal variations in NEE, the imbalance between photosynthesis (fixation of atmospheric carbon dioxide into organic carbon) and ecosystem respiration (plant and microbial respiration converting organic carbon into atmospheric carbon dioxide), are caused predominately by climatic drivers on daily and seasonal timescales (Law et al 2002). Although several synthesis efforts have been conducted across eddy-flux tower sites, the role of climatic drivers in causing NEE variability across multiple sites on annual or longer timescales is still not clear (Law et al 2002, Valentini et al 2000, Reichstein et al 2007).

Determining the environmental controls on NEE is complicated because NEE is the difference between photosynthesis and ecosystem respiration, and climate variations may affect these two components in different ways. Spatial variability in respiration is strongly correlated with temperature, precipitation and/or radiation, depending on the region (Law et al 2002). This paper seeks to identify the climate controls on spatial NEE variability globally as represented within FLUXNET, a global network of eddy covariance tower sites (Baldocchi et al 2001). Other studies have shown that non-climate factors, especially disturbance, are a major factor causing NEE variability (Oren et al 2006, Thornton et al 2002, Foley et al 2005). The role of disturbance history may be underplayed in FLUXNET synthesis studies because the number of recently disturbed sites is limited. However, we expect that other recent estimates that emphasize the effects of other non-climate factors such as nitrogen (Magnani et al 2007, Sutton et al 2008) have downplayed the role of climatic interactions.

2. Data and sites

The present analysis is based on 559 site-years of eddy covariance data measured from 125 sites throughout the world from 1992 to 2008 (supplementary table S1 available at stacks.iop.org/ERL/5/034007/mmedia). The latitudes

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118 Deceased.
vary from 37°S to 71°N, longitudes are broadly covered, and elevation ranges from −2 to 3288 m (supplementary figure S1 available at stacks.iop.org/ERL/5/034007/mmedia). The climatic zones of the sites include polar tundra, maritime temperate, continental temperate, humid subtropical, Mediterranean, arid, semi-arid, tropical monsoon, and tropical wet-and-dry climates. The vegetation types include grassland, evergreen needle-leaf forest, deciduous broad-leaf forest, mixed forest, permanent wetland, open shrubland, closed shrubland, savanna, evergreen broad-leaf forest, and tundra. Stand age ranges from young seedlings to 500 years old (Paw U et al 2004). Sites from all ecosystem types with at least one year of complete NEE and meteorological data are included. NEE and meteorological data used in this analysis are taken from standardized files archived in the FLUXNET-LaThuile database which includes data from the AmeriFlux, Fluxnet-Canada, CARBOEUROPE, USCCC, ChinaFlux, OzFlux, CarboAfrica, and AsiaFlux networks. These data have been quality controlled and gap-filled by consistent methods (Papale et al 2006, Moffat et al 2007, Reichstein et al 2005). Meteorological variables used include air temperature, net radiation and precipitation. We have developed a new method to gap-fill the half-hourly meteorological data to produce reliable annual averages (see Methods in the supplementary data available at stacks.iop.org/ERL/5/034007/mmedia). In many cases, the site principal investigators have submitted revised annual NEE estimates based on more detailed, site-specific reanalyses. The data were used in this analysis only in those years when temperature, precipitation, net radiation, and NEE all met the gap-filling criteria (see Methods in the supplementary data available at stacks.iop.org/ERL/5/034007/mmedia).

Eddy-flux measurements are inherently uncertain due to: (1) advection errors caused by complex terrain (Aubinet et al 2005, Feigenwinter et al 2008) and complicated canopy structure (Yi 2008); (2) imbalance errors in the energy budget (Massman and Lee 2002, Foken 2008), and (3) the stochastic nature of turbulence (Hollinger and Richardson 2005, Moncrieff et al 1996). These errors have been studied intensively and remain to be quantified exactly for all sites (Reichstein et al 2007). The largest sources of uncertainty that have been quantified in a standardized way in annual NEE result from \( u^* \) filtering, gap-filling of missing data, and turbulent sampling errors (supplementary materials available at stacks.iop.org/ERL/5/034007/mmedia).

3. Grouping analysis

We hypothesize that two direct climatic controls on NEE, temperature and dryness (Budyko 1974), interact in complex ways with non-climatic or indirect climatic factors such as disturbance history, species, soil type and nutrient availability. Although it is not possible to develop a predictive global relationship of NEE with these variables, we ask does the dominant climate factor at individual sites follow distinct geographic patterns? While it is overly simplistic to argue that NEE is a function of two climate variables, it is possible to gain insight into global scale processes through the use of an objective statistical method to group sites by their dominant climate control.

We used a mixture regression model (see supplementary materials available at stacks.iop.org/ERL/5/034007/mmedia) to segregate sites into three groups (supplementary table S1 available at stacks.iop.org/ERL/5/034007/mmedia): (1) T-group: variations in NEE are best explained by mean annual temperature alone; (2) D-group: variations in NEE are best explained by a dryness index alone; and (3) B-group: NEE is co-limited by both mean annual temperature and dryness. An independent approach—a nonparametric kernel regression (Wand and Jones 1995) analysis of NEE against mean annual temperature and dryness for all three groups—provides a strong foundation for grouping the sites in this way. The pattern of contour lines in the contour plot for all 125 sites indicates a complex and mixed relationship for temperature and dryness (figure 1(a)), in which NEE at colder sites is generally a function of temperature and at warmer sites is generally a function of dryness. The kernel regression also confirms that the sites are successfully segregated according to their functional dependence. The contour plot for the T-group (figure 1(b)) shows that the contour lines are almost parallel to the dryness index axis. This implies that NEE is a monotonic function of temperature, and that the dryness index does not significantly influence the NEE of the sites in the T-group.

The contour plot for the D-group (figure 1(c)) shows that the contour lines are almost parallel to the temperature axis. This implies that both the temperature and the dryness index are contributors to the amount of NEE in the sites in the B-group. Moreover, NEE seems to linearly decrease as temperature increases or the dryness index decreases (figure 1(d)).

In the T-group, 84% of spatial variations in NEE can be explained by mean annual temperature (figure 2(a)), while in the D-group, 81% of spatial variation in NEE can be accounted for by a dryness index (figure 2(b)). However, in the smaller B-group, NEE is co-limited by mean annual temperature and dryness, and the correlations between the NEE and individual climate factors are relatively weak (figures 3(a) and (b)). We speculate that the variance in NEE unexplained by the climate factors in these three groups is primarily driven by non-climate factors such as stand age, disturbance history, species composition, or canopy leaf area index, reflecting local variation in nutrient and water availability (Raich et al 2002). These non-climate factors are also likely to play a role in the grouping algorithm and account for sites with similar temperature and dryness being grouped differently.

4. Discussion and concluding remarks

The empirical subdivision of groups also corresponds to latitudinal zonation (supplementary figure S1 available at stacks.iop.org/ERL/5/034007/mmedia): most sites of the temperature-limited group were located in the zones of
Figure 1. Contour plots of site-average NEE (tC ha\(^{-1}\) yr\(^{-1}\)) of: (a) all the 125 sites; (b) the T-group (47 sites); (c) the D-group (47 sites); and (d) the B-group (32 sites). These contour plots of the regression surface were produced by two-dimensional kernel regression (Wand and Jones 1995) based on the grouping data of the T-group, the D-group, the B-group, and the entire 125 sites (see Methods section and supplementary table S1 available at stacks.iop.org/ERL/5/034007/mmedia). The kernel regression is a commonly used nonparametric regression technique, which assumes the regression function is a smooth function of predictor variables rather than imposing a pre-specific functional form (parametric model) on the regression function.

Figure 2. Climatic controls of the site-average net ecosystem exchange (NEE) across the FLUXNET sites (see supplementary table S1 available at stacks.iop.org/ERL/5/034007/mmedia): (a) temperature-limited group; and (b) dryness-limited group. The negative NEE values indicate that atmospheric carbon is assimilated by terrestrial ecosystems, while the positive NEE values indicate that terrestrial organic carbon is converted into atmospheric carbon. The filled circles with mango color in (a) are the site-average NEE of the sites in the prototype T-group with very high posterior probability (>99%) belonging to the temperature group, while the filled circles with mango color in (b) are the site-average NEE of the sites in the prototype D-group with very high posterior probability (>99%) belonging to the dryness group (see the Methods section and supplementary table S1 available at stacks.iop.org/ERL/5/034007/mmedia). The thick green lines represent model predictions.
temperate and boreal climate (76% are located above 45 °N, supplementary figure S2(a) available at stacks.iop.org/ERL/5/034007/mmedia), while most sites of the dryness-limited group were located in the zones of subtropical climate (63% are located below 45 °N, supplementary figure S2(b) available at stacks.iop.org/ERL/5/034007/mmedia). The B-group sites were almost symmetrically distributed around 45 °N (supplementary figure S2(c) available at stacks.iop.org/ERL/5/034007/mmedia). The controlling function of temperature for terrestrial carbon exchanges breaks down as mean annual temperature approaches 16 °C (see discussion in section 3 of supplementary materials available at stacks.iop.org/ERL/5/034007/mmedia). The B-group sites were almost symmetrically distributed around 45 °N (supplementary figure S2(c) available at stacks.iop.org/ERL/5/034007/mmedia). The B-group sites were almost symmetrically distributed around 45 °N (supplementary figure S2(c) available at stacks.iop.org/ERL/5/034007/mmedia). The B-group sites were almost symmetrically distributed around 45 °N (supplementary figure S2(c) available at stacks.iop.org/ERL/5/034007/mmedia). The B-group sites were almost symmetrically distributed around 45 °N (supplementary figure S2(c) available at stacks.iop.org/ERL/5/034007/mmedia). The B-group sites were almost symmetrically distributed around 45 °N (supplementary figure S2(c) available at stacks.iop.org/ERL/5/034007/mmedia). The B-group sites were almost symmetrically distributed around 45 °N (supplementary figure S2(c) available at stacks.iop.org/ERL/5/034007/mmedia). The B-group sites were almost symmetrically distributed around 45 °N (supplementary figure S2(c) available at stacks.iop.org/ERL/5/034007/mmedia).

The global empirical patterns of NEE driven by climate gradients found in this paper are partially supported by another global data analysis conducted by Nemani et al. (2003) based on correlation between 18 years climate data and net primary production (NPP) derived from spatially continuous satellite data. This modeling study found that NPP is largely controlled by temperature at mid-to-high latitudes, while at mid-to-low latitudes, it is controlled largely by dryness. The geographic region around 45°N is a transition zone where many sites are co-limited by both temperature and dryness.

The majority of the 125 sites are recovering from past disturbance rather than being actively disturbed, and thus are in the ‘slow in’ instead of the ‘rapid out’ phase of carbon flow in the terrestrial biosphere as conceptualized by Korner (2003). Disturbance history and stand age play a large role in NEE variability (Amiro et al. 2010), which is seen at chronosequence sites with similar climates (Ryan and Law 2005). Though

Figure 3. The site-averaged NEE of B-group sites that are sensitive to both: (a) temperature and (b) dryness.
the temperature and dryness groups are correlated well with their respective indices, the overlap of the two groups in temperature–dryness space suggests that NEE is controlled by a complex interaction of climate and non-climate factors. Our results do not support the recent suggestion that a single abiotic factor such as nitrogen supply dominates NEE (Magnani et al 2007, Sutton et al 2008).

Links between terrestrial CO2 exchanges and climate controls are clearly demonstrated by many site-years of data from the eddy-flux tower networks. Our findings are essential to understand how future climate change may affect terrestrial CO2 exchanges with the atmosphere in the 21st century (Qian et al 2010). In the IPCC 2007 report, projected warming in the 21st century is expected to be greatest over land and at high northern latitudes, while projected decreases in precipitation are likely in most subtropical land regions (IPCC 2007). Although climate controls on long-term changes in NEE may be different from controls on spatial variability of NEE, our results imply that the most likely future climate change scenarios could strongly intensify terrestrial CO2 uptake in high-latitudes and weaken CO2 uptake in low-latitudes.

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References

Aubinet M et al 2005 Comparing CO2 storage and advection conditions at night at different CARBOEUROFLUX sites Bound.-Layer Meteorol. 116 63–93
Bousquet P et al 2000 Regional changes in carbon dioxide fluxes of land and oceans since 1980 Science 290 1342–6
Budyko M I 1974 Climate and Life (New York: Academic) p 508
Ciais Ph et al 2005 Europe-wide reduction in primary productivity caused by the heat and drought in 2003 Nature 437 529–33
Feigenwinter C et al 2008 Comparison of horizontal and vertical advective CO2 fluxes at three forest sites Agric. Forest Meteorol. 148 12–24
Foley J A et al 2005 Global consequences of land use Science 309 570–4
Goulden M L et al 1996 CO2 exchange by a deciduous forest: response to interannual climate variability Science 271 1576–8
Heimann M and Reichstein M 2008 Terrestrial ecosystem carbon dynamics and climate feedbacks Nature 451 289–92
Hollinger D Y and Richardson A D 2005 Uncertainty in eddy covariance measurements and its application to physiological models Tree Physiol. 25 873–85
Kormer C 2003 Slow in, rapid out—carbon flux studies and Kyoto targets Science 300 1242–3
Law B E et al 2002 Environmental controls over carbon dioxide and water vapor exchange of terrestrial vegetation Agric. Forest Meteorol. 113 97–120

9
Leuning R et al 2005 Carbon and water fluxes over a temperate Eucalyptus forest and a tropical wet/dry savanna in Australia: measurements and comparison with MODIS remote sensing estimates Agric. Forest Meteorol. 129 151–73
Magnani F et al 2007 The human footprint in the carbon cycle of temperate and boreal forests Nature 447 848–51
Malhi Y 2002 Carbon in the atmosphere and terrestrial biosphere in the 21st century Phil. Trans. R. Soc. A 360 2925–45
Papale D et al 2006 Towards a standardized processing of net ecosystem exchange measured with eddy covariance technique: algorithms and uncertainty estimation Biogeosciences 3 571–83
Paw U K T et al 2004 Carbon dioxide exchange between an old-growth forest and the atmosphere Ecosystems 7 513–24
Reichstein M et al 2005 On the separation of net ecosystem exchange into assimilation and ecosystem respiration review and improved algorithm Glob. Change Biol. 11 1–16
Ryan M G and Law B E 2005 Interpreting, measuring and modeling soil respiration Biogeochemistry 73 3–27
Thornton P E et al 2002 Modeling and measuring the effects of disturbance history and climate on carbon and water budgets in evergreen needleleaf forests Agric. Forest Meteorol. 113 185–222
Valentini R et al 2000 Respiration as the main determinant of carbon balance in European forests Nature 404 861–5
Wand M P and Jones M C 1995 Kernel Smoothing (London: Chapman & Hall)
White J D, Running S W and Thornton P 1999 Impact of growing season length variability on carbon assimilation and evapotranspiration over 88 years in the eastern deciduous forest Int. J. Biometeorol. 42 139–45