Climate control of terrestrial carbon exchange across biomes and continents

Citation for published version:

Digital Object Identifier (DOI):
10.1088/1748-9326/5/3/034007

Link:
Link to publication record in Edinburgh Research Explorer

Document Version:
Publisher's PDF, also known as Version of record

Published In:
Environmental Research Letters

Publisher Rights Statement:
This is an Open-Access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are properly cited.

General rights
Copyright for the publications made accessible via the Edinburgh Research Explorer is retained by the author(s) and / or other copyright owners and it is a condition of accessing these publications that users recognise and abide by the legal requirements associated with these rights.
Climate control of terrestrial carbon exchange across biomes and continents

Georg Wohlfahrt$^{30,117}$, Susumu Yamamoto$^{15,117}$, Guirui Yu$^{110,117}$, Roberto Zampedri$^{44,117}$, Bin Zhao$^{49,117}$ and Xinquan Zhao$^{116,117}$

1 School of Earth and Environmental Sciences, Queens College, City University of New York, NY 11367, USA
2 Environmental Sciences Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA
3 Department of Statistics, Pennsylvania State University, University Park, PA 16802, USA
4 Department of Forest Ecology, The Swedish University of Agricultural Sciences, SE-901 83 Umeå, Sweden
5 CESAM and Department of Environmental Engineering, School of Technology and Management, Polytechnic Institute of Leiria, Portugal
6 Department of Civil and Environmental Engineering, Duke University, Durham, NC 22708-0287, USA
7 Federal Research Station Agroscope Reckenholz-Täbin, Reckenholzstrasse 191, 8046 Zürich, Switzerland
8 School of Geography and Earth Sciences, McMaster University, Hamilton, ON, L8S 4K1, Canada
9 Instituto Nacional de Pesquisas da Amazonia, Programa LBA, Campus-II, Manaus—Amazonas 69060, Brazil
10 University of Liege, Gembloux Agro-Bio Tech, Unit of Biosystem Physics, 2 Passage des Déportés, 5030 Gembloux, Belgium
11 Finnish Meteorological Institute, Climate Change Research, FI-00101 Helsinki, Finland
12 Department of Meteorology, Eötvös Loránd University, H-1117 Budapest, Pázmány sétány 1/A, Hungary
13 Climate Research Division, Environment Canada, Saskatoon, SK, S7N 3H5, Canada
14 INRA, UR1263 EPHYSE, Villenave d’Ornon F-33883, France
15 School of Geography and Environmental Science, Monash University, Clayton, Victoria 3800, Australia
16 Institute of Hydrology and Meteorology, Dresden University of Technology, Piener Straße 23, D-01737, Tharandt, Germany
17 Land and Food Systems, University of British Columbia, Vancouver, BC, V6T 1Z4, Canada
18 University of Minnesota, 115 Green Hall 1530 Cleveland Avenue N. St Paul, MN 55108, USA
19 Royal Netherlands Meteorological Institute, 3730 AE De Bilt, The Netherlands
20 Forest Research, Alice Holt Lodge, Farnham, Surrey GU10 4LH, UK
21 ETH, Zurich, Institute of Plant Science, Universitätsstrasse 2, Zuerich 8092, Switzerland
22 National Center for Atmospheric Research, Boulder, CO 80307-3000, USA
23 UMR INRA-INA PG—Environment and Arable Crops Unit 78850 Thiverval-Grignon, France
24 Department of Geography, University of Toronto, Toronto, ON, M5S 3G3, Canada
25 Department of Environmental Sciences, University of Toledo, Toledo, OH 43606-3390, USA
26 LSCE, UMR CEA-CNRS, Batiment 709, CE, L’Orme des Merisiers, F-91191 Gif-sur-Yvette, France
27 School of GeoSciences, The University of Edinburgh, Mayfield Road, Edinburgh, EH9 3JU, UK
28 Biospheric Sciences Branch, NASA’s Goddard Space Flight Center, Greenbelt, MD 20771, USA
29 Department of Evolution, Ecology, and Organismal Biology, Ohio State University, Columbus, OH 43210, USA
30 Department of Plant, Soil, and Environmental Science, University of Maine, Orono, ME 04469, USA
31 Wind Energy Division, Risø National Laboratory for Sustainable Energy, Technical University of Denmark, PO 49, DK-4000 Roskilde, Denmark
32 Université Paris-Sud, Bâtiment 362, Ecologie, Systematique et Evolution, Orsay Cedex F-91405, France
33 Department of Atmospheric and Oceanic Sciences, University of Wisconsin, Madison, WI 53706, USA
34 Northern Arizona University, School of Forestry Northern Arizona University, Flagstaff, AZ 86001, USA
35 Atmospheric Science Program, Department of Geography, Indiana University, Bloomington, IN 47405, USA
36 Smithsonian Environmental Research Center, Edgewater, MD 21037, USA
37 Department of Physical and Earth Science, Worcester State College, 486 Chandler Street Worcester, MA 01602, USA
38 ESS-CC, Alterra Wageningen UR, 6700 AA Wageningen, The Netherlands
39 Atmospheric Science Group, LAW, UC Davis, Davis, CA 95616, USA
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-latitudinal 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

Online supplementary data available from stacks.iop.org/ERL/5/034007/mmedia

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

These authors are listed alphabetically and contributed equally to this work.

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 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 NEE is a monotonic function of the dryness index, and that the temperature does not significantly influence the NEE of the sites in the D-group. The contour plot for the B-group shows that the contour lines are neither parallel to the temperature axis nor parallel to the dryness index 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 for terrestrial carbon exchanges breaks down as mean annual temperature larger than 16°C is in the dryness group (figures 2(a) and 3(a)). Our findings suggest that NEE at mid-to-high latitudes is controlled largely by the mean annual temperature, 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 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 subtropical and tropical it is controlled by radiation and water, i.e. by dryness (ratio of net radiation to precipitation) as was used in our analysis. Even though the predicted ecological variables used here (NEE) and in Nemani et al (2003)’s analysis (NPP = NEE – soil respiration) were not the same, the consistent climate-driven spatial patterns derived from the two independently global datasets at least indicates that climate control plays an important role in the terrestrial carbon cycle. On the other hand, it is noted that our findings are different from the individual site analyses on climate control of NEE (e.g. Dunn et al 2007). These analyses study the temporal variability of NEE based on the measurements from a single site, i.e. how climate factors drive NEE changes from year to year. Our analysis studies the spatial variability of NEE based on measurements from many sites, i.e. how spatial gradients of climate drive NEE changes from location to location. Our data analysis demonstrated that spatial variability of NEE is 2.5 times greater than temporal variability of NEE (see discussion in section 3 of supplementary materials available at stacks.iop.org/ERL/5/034007/mmedia). Therefore, the existing differences between temporal variability and spatial variability are expected.

Why is the average annual temperature the main climate driver of NEE at mid- and high-latitudes? The most likely reason is that higher average annual temperature also reflects prolonged growing seasons in cold climate regions and hence increases carbon uptake in biomass (White et al 1999, Malhi 2002, Kato and Tang 2008) relative to heterotrophic decomposition. At many sites, respiration rates lag NPP rates proportionally after disturbance, and a larger NPP resulting from a longer growing season contributes to higher uptake (Goulden et al 1996, Leuning et al 2005). In the absence of other factors, we therefore expect higher carbon uptake at warmer sites within the temperature group. This speculation is partially supported by previous studies with limited data (Goulden et al 1996, Leuning et al 2005). In warm climate regions (low-latitudes), growing season length is less likely to be affected by temperature variations because these regions either experience a year-round growing season or a growing season that is limited by factors other than temperature, mainly water stress. The global-biome-climate data analysis (Zhou et al 2008) indicates that the mean annual temperature of C4 grassland biome is about 23°C, in other words it is much larger than the threshold value of 16°C, and hence C4 sites are much more likely to be in a dryness group according to our findings above. It is well known in physiology that the assimilation of C4 ecosystems, which resides mainly in the subtropical regions (Ehleringer et al 2005), is independent of temperature but is limited by water stress (Lambers et al 1998). This fact partially supports our findings that the NEE-driver of a site with mean annual temperature larger than 16°C is likely to be dryness and such sites are likely located in tropical or subtropical regions.

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
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.

Acknowledgments

This work was financially supported by part in the National Science Foundation (NSF-DEB-0949637) and the PSC-CUNY Faculty Research Award (Grant No 62787-00 40). This work was based on the database produced by the La Thuile FLUXNET project, which received financial support of CarboEuropeIP, FAO-GTOS-TCO, iLEAPS, Max Planck Institute for Biogeochemistry, National Science Foundation, University of Tuscia, US Department of Energy. We acknowledge database and technical support from Berkeley Water Center, Lawrence Berkeley National Laboratory, Microsoft Research eScience, Oak Ridge National Laboratory, University of California—Berkeley, University of Virginia. The following regional networks were involved with this work: AmeriFlux, CarboEuropeIP, Fluxnet-Canada, ChinaFlux, OzFlux, CarboAfrica, and AsiaFlux. AmeriFlux, is sponsored by the United States Department of Energy (Terrestrial Carbon Program, National Institutes of Global Environmental Change (NIGEC), National Institute for Climate Change Research (NICCR)), Department of Commerce (NOAA), and Department of Agriculture (USDA/Forest Service), NASA, and the National Science Foundation. European sites in the NitroEurope, Euroflux and Medeflu projects are supported by the European Commission Directorate General XII Environment, Climate Program and the Program CONSOLIDER-INGENIO 2010 (GRACCIE). Canadian sites are supported by the Canadian Foundation for Climate and Atmospheric Sciences (CFCAS), the Natural Sciences and Engineering Research Council (NSERC), and BIOCAP Canada (Fluxnet-Canada only). Chinese sites are supported by the Chinese Academy of Sciences and the Ministry of Science and Technology. Australian sites are supported by the Australian Research Council. The Japanese site is supported by the Ministry of Agriculture, Forest and Fisheries (MAFF), the Ministry of Industry Trade and Industry (MITI), and Ministry of Education, Science, Sports and Culture (MESSC). The Brazilian site is supported by the Brazilian Ministry of Science and Technology (MCT) and the LBA program. We thank the numerous scientists, students, and technicians responsible for the day-to-day gathering of the flux data, and the agency representatives who fund the respective projects. Without the dedicated efforts of so many individuals, this analysis would be impossible.

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
Clauis 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
Korner 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
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 Biogeoosciences 3 571–83
Petrie 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