Redefinition and Global Estimation of Basal Ecosystem

Respiration Rate

Wenping Yuan1*, Yiqi Luo2, Xianglan Li1, Shuguang Liu34, Guirui Yu5, Tao Zhou6, Michael Bahn7,
Andy Black8, Andrew D. Richardson9, Ankur R. Desai10, Alessandro Cescatti11, Barbara
Marcolla12, Cor Jacobs13, Jiquan Chen14, Mika Aurela15, Christian Bernhofer16, Bert Gielen17, Gil
Bohrer18, David R. Cook19, Danilo Drago120, Allison L. Dunn21, Damiano Gianelle22, Thomas
Grünwald23, Andreas Ibsen20, Monique Y. Leclerc25, Anders Lindroth26, Heping Liu27, Luca
Belletti Marchesini28, Leonardo Montagnani29, Gabriel Pita31, Mirco Rodeghiero22, Abel
Rodrigues32, Gregory Starr33, Paul C. Stoy34

1College of Global Change and Earth System Science, Beijing Normal University, Beijing 100875,
China
2Department of Botany and Microbiology, University of Oklahoma, Norman, Oklahoma 73019,
USA
3U.S. Geological Survey (USGS) Earth Resources Observation and Science (EROS) Center, Sioux
Falls, South Dakota 57198, USA
4Geographic Information Science Center of Excellence, South Dakota State University, Brookings,
South Dakota 57007, USA
5Key Laboratory of Ecosystem Network Observation and Modeling, Synthesis Research Center of
Chinese Ecosystem Research Network, Institute of Geographic Sciences and Natural Resources
Research, Chinese Academy of Sciences, Beijing 100101, China

*Author for correspondence: Wenping Yuan, Tel: 86-10-58807715; E-mail: wenpingyuancn@yahoo.com
6State Key Laboratory of Earth Surface Processes and Resource Ecology, Beijing Normal University, Beijing 100875, China

7Institut für Ökologie, Universität Innsbruck, Sternwartestr. 15, 6020 Innsbruck, Austria

8Department of Soil Science, University of British Columbia, Vancouver, B.C., V6T1Z4, Canada

9Department of Organismic and Evolutionary Biology, Harvard University, Cambridge, MA 02138, USA

10Atmospheric and Oceanic Sciences Department, Center for Climatic Research, Nelson Institute for Environmental Studies, University of Wisconsin-Madison, WI 53706, USA

11Institute for Environment and Sustainability, Climate Change Unit, Ispra, Italy

12Fondazione Edmund Mach, Research and Innovation Centre, Environment and Natural Resources Area, S. Michele all'Adige, Trento 38010, Italy

13Alterra-WUR, Earth System Science-Climate Change, Wageningen 6700 AA, The Netherlands

14Department of Environmental Sciences, University of Toledo, Toledo, OH 43606, USA

15Finnish Meteorological Institute, Climate and Global Change Research, Helsinki FIN-00101, Finland

16Department of Meteorology, Institute of Hydrology and Meteorology, Technical University of Dresden, Dresden, Germany

17Department of Biology, University of Antwerp, Universiteitsplein 1, B-2610, Wilrijk, Belgium

18Department of Civil & Environmental Engineering & Geodetic Sciences, Ohio State University, Columbus, OH 43210, USA

19Climate Research Section, Environmental Science Division, Argonne National Laboratory, Argonne, IL 60439, USA
Atmospheric Science Program, Geography Department, Indiana University, Bloomington, IN 47405-7100, USA

Worcester State College, Worcester, MA 01602, USA

IASMA, Research and Innovation Centre, Fondazione Edmund Mach, Environment and Natural Resources Area, Viote del Monte Bondone, Trento 38040, Italy

Institute of Hydrology and Meteorology, Technische Universität Dresden, Tharandt D-01737, Germany

Biosystems Division, Technical University of Denmark, Risø National Laboratory for Sustainable Energy, 2800 Kgs. Lyngby, Denmark

Department of Crop and Soil Sciences, College of Agricultural and Environmental Sciences, University of Georgia, Griffin, GA 30223, USA

Geobiosphere Science Centre, Physical Geography and Ecosystems Analysis, Lund University, Lund S-22100, Sweden

Department of Physics, Atmospheric Sciences, and Geoscience, Jackson State University, Jackson, Mississippi, USA

Department of Forest Science and Resources, University of Tuscia, Viterbo 01100, Italy

Forest Services of Autonomous Province of Bolzano, Bolzano, Italy

Laboratory of Chemical Physics, Agency for the Environment of Autonomous Province of Bolzano, Bolzano, Italy

Department of Mechanical Engineering, Instituto Superior Técnico, Lisboa 1049-001, Portugal

Instituto Nacional dos Recursos Biológicos, Departamento de, Silvicultura e Produtos Florestais, Quinta do Marquês, Oeiras 2780-159, Portugal
Abstract  Basal ecosystem respiration rate (BR), which is the ecosystem respiration rate at a
given temperature, is an important parameter in empirical models for quantifying ecosystem
respiration (ER) across regional scales. Numerous studies have indicated that BR shows spatial
heterogeneity. However, most empirical models still use a globally constant rate in projecting the
spatial and temporal patterns of ER largely due to the lack of spatial patterns of functional
description of BR. In this study, we redefined BR to be ecosystem respiration rate at the mean
annual temperature based on the latest findings in order to produce BR values globally. We
conducted a synthesis analysis to examine previous findings over broader regions based on 276
site-years of eddy covariance data, from 79 research sites located at latitudes ranging from ~3ºS to
~70ºN. Results showed that mean annual ER rate closely matches ER rate at mean annual
temperature across regional scales. Moreover, the relationship between mean annual ER and mean
annual gross primary production (GPP) has been re-examined at a larger spatial scale, observing a
strong correlation. According to these results ER at the mean annual temperature can be
considered as BR in empirical models, and can be estimated using the simulated GPP. In this study,
we used a light use efficiency GPP model (i.e. EC-LUE) to estimated GPP for retrieving global
patterns of BR. Incorporation of site-specific BR into global ER model substantially improved
simulated ER in comparison with those with the invariant BR at all sites. Global patterns of ER
were determined using the global MERRA (Modern Era Retrospective-Analysis for Research and
Applications) dataset and MODIS (MODerate resolution Imaging Spectroradiometer). The global
ER is 103 PgC yr⁻¹, with the highest respiration rate over tropical forests and the lowest value in
dry and high-latitude areas.

Key words  Ecosystem respiration; Basal ecosystem respiration rate; Gross primary production;
EC-LUE model;

Introduction  Increasing atmospheric CO₂ concentration has enhanced our need to better understand the
global sources and sinks of carbon, and their responses to environmental changes. Ecosystem respiration (ER) is the sum of soil heterotrophic respiration and plant autotrophic respiration, which combined determines ecosystem carbon balance with gross primary production (GPP). A major component of ER (i.e. soil respiration) accounts for a global annual carbon emission of 75–80 Pg C annually [Schlesinger, 1977; Raich and Potter, 1995], which is more than 11 times the current rate of fossil fuel combustion [Marland et al., 2000]. Thus, small changes in ER can have a significant impact on the global carbon budget and therefore on the atmospheric CO₂ concentration. Despite the considerable scientific efforts to study ER, there is still limited knowledge on temporal and spatial variations of ER and little understanding of the environmental controlling mechanisms and of the controlling factors involved, including climate, plant biophysics and soil properties [Reichstein et al., 2003; Rodeghiero and Cescatti, 2005; Davidson and Janssens, 2006; Palmroth et al., 2005, 2006].

In the past decades, quite different approaches have been taken in the global analyses of ER. There are a number of mechanistically based models [Schimel et al., 1997; Parton et al., 1998; Schimel et al., 2000; Cramer et al., 2001] that aim at providing a theoretical process level basis for understanding and analyzing the effects of environmental change on ecosystem carbon fluxes. Mechanistic models are built upon our current understandings of environmental and biological processes involved in ER. However, the accuracy of projections of mechanistic models relies on how well the processes are represented in the models. For example, carbon allocation is still one of the difficult processes to be well represented in models [Litton et al., 2007], although some rules have emerged [see e.g., Palmroth et al., 2006]. When some of the fundamental relationships are not well defined, mechanistic models cannot predict realistic ER of future climate scenarios. Moreover, comprehensive models attempting to incorporate many processes can suffer a drawback of having to estimate large number of parameters thus yielding substantial uncertainty. For example, a parameter inversion study showed that only four of seven parameters in a process-based respiration model could be reasonably estimated [Xu et al., 2006].

Since mechanistic models are limited by complex processes and parameterization, ER at regional and global scales is often modeled as a simple exponential or Arhennius-type function of temperature. For example, ER usually has been modeled by the modified exponential function [Luo and Zhou, 2007]:

\[ ER = A e^{\frac{B}{T}} \]
where \( BR \) is basal respiration rate at a given reference temperature \( (T_0; \text{e.g. } 0 \text{ or } 10^\circ C) \); \( Q_{10} \) is the relative change in \( ER \) per 10°C temperature increase; and \( T \) is air temperature (°C). \( BR \) is a crucial factor in the evaluation of the spatial variation and pattern of ER. When simulating ER or its components (i.e. soil respiration) at the global scale, \( BR \) is generally considered as globally invariant. One example is the study by Raich and coworkers, in which globally distributed soil respiration is simulated using a fixed \( BR \) value of 1.25 g C m\(^{-2}\) d\(^{-1}\) [Raich et al., 2002]. However, an increasing body of evidence suggests that the error introduced by the assumption of constant \( BR \) is not negligible [Tjoelker et al., 2001; Janssens and Pilegaard, 2003; Wang et al., 2010]. Sampson et al [2007] suggested that \( BR \) varies systematically with photosynthesis. At the larger spatial scales, spatial differences in \( BR \) have been linked to variation in leaf area index (LAI), which also suggests that photosynthetic activity correlates ER measurements [Curiel Yuste et al., 2004; Migliavacca et al., 2010; Mahecha et al., 2010]. Potential underlying mechanisms for spatially heterogeneous \( BR \) are changes in substrate supply to the soil linked to photosynthesis and respiring biomass [Davidson and Janssens, 2006].

So far, however, spatial patterns of \( BR \) have not been adequately derived [Reichstein et al., 2003]. Recently, a new finding, made by Bahn et al. [2009], on the relationship between mean annual soil respiration and soil respiration rate at mean annual temperature, provides an important implication for quantifying \( BR \) over the regional or global scales. Moreover, previous studies have showed the strong correlation between mean annual ecosystem respiration and gross primary production (GPP) [Janssens et al., 2001]. Therefore, we redefine \( BR \) to be ecosystem respiration at the mean annual temperature, and the latter can be easily simulated by combining correlation with GPP based on relationships of the above two findings. In this study, we verify the finding of Bahn et al. [2009] using ER measurements, and couple it with the correlation between GPP and ER to develop a novel method for estimating global \( BR \).

2. Materials and methods

2.1 Eddy covariance data

Eddy covariance (EC) data were used in this study to investigate the correlation of annual
mean ER with GPP as well as ER rate at mean annual temperature. The data were obtained from the AmeriFLUX (http://public.ornl.gov/ameriflux), EuroFLUX (http://www.fluxnet.ornl.gov/fluxnet/index.cfm; Valentini, 2003), and ChinaFLUX net (http://www.chinaflux.org). Seventy-nine sites encompassing 276 site-years were included in this study, covering 6 major terrestrial biomes: evergreen broadleaf forest (EBF), deciduous broadleaf forest (DBF), mixed forest (MIX), evergreen needleleaf forest (ENF), grassland (GRS) and tundra (TUN) (Table 1). Supplementary information on the vegetation, climate, and soil at each site is available on-line. Half-hourly or hourly averaged photosynthetically active radiation (PAR), air temperature (T_a), and friction velocity (u*) were used together with net ecosystem exchange of CO_2 (NEE) in this study. When available, datasets that were gap-filled by site primary investigators were used. For other sites, data filtering and gap-filling were conducted according to the following procedures.

An outlier (“spike”) detection technique was applied, and the spikes were removed, following Papale et al. [2006]. Because nighttime CO_2 flux can be underestimated by eddy covariance measurements under stable conditions [Falge et al., 2001], nighttime data with low-turbulence conditions were removed based on a u* threshold criterion (site-specific 99% threshold criterion following Reichstein et al., 2005; Papale et al., 2006).

Nonlinear regression methods were used for filling NEE data gaps [Falge et al., 2001]. Nonlinear regression relationships between measured fluxes and meteorological conditions were fitted using a 7-day moving window. The modified exponential function (Equation 1) was used to fill the missing nighttime fluxes (NEE_{night}), and BR and Q_{10} are the fitted model parameters. A Michaelis–Menten type light response function was used to fill the missing daytime fluxes (NEE_{day}) [Falge et al., 2001]:

\[ NEE_{day} = \frac{\alpha \times PAR \times F_{GPP,sat}}{F_{GPP,sat} + \alpha \times PAR} - A_{day} e^{(B_{day} T_a)} \]  

where \( F_{GPP,sat} \) (gross primary productivity at saturating light), \( \alpha \) (initial slope of the light response function), \( A_{day} \) and \( B_{day} \) are fitted parameters. The nonlinear regression procedure (PROC NLIN) in the STATISTICAL ANALYSIS SYSTEM (SAS Institute Inc., Cary, NC, USA) was applied to fit the relationships between measured fluxes and environmental factors.
To avoid uncertainties introduced by the extrapolation to daily ER (ER$_{\text{day}}$), we only used observed nighttime ER to examine the equivalence relationship between mean annual ER and its rate at the mean annual temperature. Nocturnal ER and nocturnal temperature were calculated based on half-hourly or hourly values. Daily values were excluded when missing hourly data represented >20% of the time on a given day. Based on the daily nighttime data set, yearly mean nocturnal ER and nocturnal mean temperature can be calculated. If missing daily data represented >20% of entire year data, the value of this year was indicated as missing. On average, 30% of the years were rejected due to insufficient nocturnal observations. The rejected years varied among sites from 60% (Blodgett) to 10% (Howland).

In order to characterize ER rate when nighttime air temperature equals to annual mean nighttime temperature, the data processing was conducted according to the following procedures. From the start of -30°C until the maximum air temperature, daily temperature ranges were set through every 1°C increments of air temperature. For example, the first temperature range is from -30 to -29°C, and so on. The daily nocturnal air temperature and ER were averaged through every temperature range over all years within individual sites. Then, the temperature curves of ER can be generated at each site. Typically, the temperature response curves of ER for each site can be derived as shown in Fig. 1, and ER rate at the mean annual temperature can be easily determined.

Vickers et al. [2009] argued that there is a spurious correlation between GPP and ER when these component fluxes are jointly estimated from the observed NEE. Lasslop et al [2010] recommend using independent estimates for correlation analysis between GPP and ER, which minimize spurious correlations. Therefore, daily ER was calculated as the sum of NEE$_{\text{night}}$ and daytime ER (ER$_{\text{day}}$) extrapolation by the Equation (1) using daytime air temperature with $BR$ and $Q_{10}$ fitted by half hourly nighttime measurements. Daily GPP was synthesized based on daily NEE and daytime ER (ER$_{\text{day}}$), which was estimated by the Equation (2) and $F_{\text{GPP,day}} \propto A_{\text{day}}$ and $B_{\text{day}}$ were fitted only based on daytime flux measurements using a 7-day moving window. Thus, daily ER was estimated only based on parameters derived from nighttime measurements and GPP was estimated based on parameters using daytime measurements, which avoid the spurious correlation. The same data filtering criterion as given above (i.e. 20%) was used to determining missing days
and years.

2.2 EC-LUE model

The spatial pattern of GPP is used in this study as a driver for driving global BR. We used a light use efficiency GPP model, EC-LUE model, to estimate global GPP values [Yuan et al., 2007]. The EC-LUE model may have the most potential to adequately address the spatial and temporal dynamics of GPP because its parameters (i.e. the potential light use efficiency and optimal growth temperature) are invariant across the various land cover types, and is driven by only four variables: normalized difference vegetation index (NDVI), photosynthetically active radiation (PAR), air temperature, and the ratio of sensible to latent heat flux (Bowen ratio). Recently, the ratio of evapotranspiration (ET) and net radiation was used instead of the Bowen ratio, and the revised RS-PM (Remote Sensing-Penman Monteith) model was used to quantify ET in order to strengthen the capability for application at the large scales [Yuan et al., 2010]. Fifty-four eddy covariance towers, including various ecosystem types, were selected to calibrate and validate the revised EC-LUE model. Using estimated ET by revised RS-PM model as input, the EC-LUE model showed good performance in both calibration and validation sites, explaining 75% and 58% of the observed 8-day variation of observed GPP respectively.

2.3 Model validation

Observed ER at eddy covariance sites was used to compare with simulations of ER using estimated BR. It was expected that the spatially heterogeneous BR could improve the fit of modeled ER to the measurements in comparison to that with the invariant BR in different spatial grid cells. To do so, Q_{10} equation (equation 1) was used to model ER at these two different parameterization schemes. Globally heterogeneous Q_{10} values of soil respiration estimated from assimilation of the spatial pattern of observed soil carbon content into the process-based terrestrial carbon model (Carnegie-Ames-Stanford Approach model) were used in this study to run Q_{10} equation at the validation sites [Zhou et al., 2009]. We assumed the temperature sensitivity (Q_{10} value) of ER is as same as that for soil respiration with the risk of inducing model errors. Relative Predicted Errors (RPE) and coefficient of determination (R^2) were used to quantify the improvement in model predictions using the spatially heterogeneous BR instead of the constant one. The relative predictive error (RPE) was computed as:
\[ RPE(\%) = \frac{\bar{S} - \bar{O}}{\bar{O}} \times 100\% \]  

where \( \bar{S} \) and \( \bar{O} \) are mean simulated and observed values, respectively.

2.4 Data at the global scale

For global estimates of GPP, we used input datasets for net radiation (\( R_n \)), air temperature (T), relative humidity (\( R_h \)) and photosynthetically active radiation (PAR) from the MERRA (Modern Era Retrospective-Analysis for Research and Applications) [Bosilovich et al., 2008] archive for 2000~2003 [Global Modeling and Assimilation Office, 2004]. MERRA is a NASA reanalysis for the satellite era using a major new version of the Goddard Earth Observing System Version 5 (GEOS-5). MERRA uses data from all available surface weather observations globally every 3 hours, and GEOS-5 was used to interpolate and grid these point data on a short time sequence, and produces an estimate of climatic conditions over the globe, at 10 meters above the land surface (approximating canopy height conditions) and at a resolution of 0.5º latitude by 0.6º longitude.

The global 8-day MODIS (MODerate resolution Imaging Spectroradiometer) leaf area index (LAI) (MOD15A2) and 16-day MODIS NDVI (MOD13A2) were used in this study. Quality control (QC) flags were examined to screen and reject NDVI and LAI data of insufficient quality. We temporally filled the missing or unreliable LAI and NDVI at each 1-km MODIS pixel based on their corresponding quality assessment data fields as proposed by Zhao et al. [2005]. If the first (or last) 8-day LAI (16-day NDVI) was unreliable or missing, it was replaced by the closest reliable 8-day (16-day) value. All of those satellite data sets were resampled to the same geographic projection and spatial resolution with global MERRA dataset.

3. Results and discussion

3.1 Equivalence relation between mean annual ecosystem respiration and ecosystem respiration rate at mean annual temperature

Analysis of data from 79 eddy covariance sites with 276 site-years worldwide shows the equivalence relation between mean annual nocturnal ER and ER rate at mean annual nocturnal air temperature (Fig. 2a). The slope of this correlation is not statistically different from 1, and the intercept does not significantly differ with 0 (p<0.05). This equivalence relation is observed at
various natural ecosystem types: evergreen broadleaf forest (EBF), deciduous broadleaf forest (DBF), evergreen needleleaf forest (ENF), mixed forest (MIX), grassland (GRS) and tundra (TUN) (Fig. 2b, c, d, e).

At several eddy flux sites, mean annual temperatures are below 0°C (e.g. Barrow, Boreas_NSA). Even at these sites, ER rate at mean annual nocturnal temperature still can represent mean annual nocturnal ER very well, which seems to be contradictory with the assumption that biological activity is minimal when temperatures are below freezing point. In fact, slow growth of roots has been reported throughout the winter at the northern ecosystems [Hansen et al., 1996]. Moreover, the ability of cold-adapted microbes to survive and grow below 0°C was discovered [Gilchinsky, 1995], and respiration in frozen soils has been demonstrated repeatedly in the laboratory [Clein and Schimel, 1995; Panikov, 1999]. Microbial activity is possible in soils below 0°C because small amounts of water remain unfrozen, allowing the diffusion of microbial substrates and waste products [Ostroumov and Siegert, 1996]. Recent work has confirmed that, although rates are low, the cumulative winter CO₂ flux from tundra soils may account for a significant component of their annual carbon budget [Fahnestock et al., 1999; Grogan et al., 1999; Welker et al., 2000].

The mechanism for this equivalence relation is still unclear, but the studies on thermal responses of respiration may provide some insights for understanding this finding. Temperature is the most fundamental climatic factor influencing the kinetics of biochemical reactions, and impacts almost all ecosystem carbon cycle processes. At undisturbed ecosystems, thermal conditions directly determine respiring substrate supply in soil, which strongly regulates the spatial heterogeneity of ER. For example, it is widely acknowledged that soil organic content decreases along gradients of increasing temperature [Jenny, 1980; Post et al., 1982, 1985]. Plant autotrophic respiration also represents the adaptation to the prevailing ambient temperature by adjustment of enzyme activity and substrate availability [Atkin and Tjoelker, 2003].

Moreover, annual mean temperature always is considered as a specific indicator for local thermal conditions because the temperatures through the entire year always fluctuate above and below around annual mean temperature. Typical frequency distribution of air temperature and
correlation analyses showed the highest frequency distribution occurs around the mean annual temperature (Fig. 3). Therefore respiration rate at the mean annual temperature has the most potential to represent the quantification of ecosystem respiration in a given area.

\[<<Figure 3>>\]

\textbf{3.2 Correlation between GPP and ecosystem respiration}

Annual mean ER strongly correlated with annual mean GPP at regional scale based on the flux measurements at eddy covariance sites (Fig. 4). This is consistent with previous studies including Janssens et al. [2001], Reichstein et al. [2007] and Baldocchi [2008] that ecosystem assimilation and respiration are strongly coupled on the annual time scale. However, recent study argued that there is a spurious correlation between GPP and ER, because these component fluxes are jointly estimated from the observed NEE [Vickers et al., 2009]. In this study, we estimated GPP and ER based on the method proposed by Lasslop [2010] (see method). We do not compute GPP as a difference, but moreover derive ER and GPP from quasi-disjoint NEE data subsets. Hence, we minimize spurious correlations and still find a strong and highly significant positive relation between annual GPP and ER.

\[<<Figure 4>>\]

Moreover, other lines of evidence also explain this significant correlation. Soil respiration, an important component of ER, has shown a strong correlation with NPP (Net Primary Production) across different vegetation biomes [Raich and Schlesinger, 1992], with aboveground net primary productivity in northern peatlands [Moore, 1986] and with aboveground litter production in forest ecosystems [Schlesinger 1977; Raich and Nadelhoffer, 1989]. These studies indicate a tight link between plant productivity and ecosystem respiration because primary production provides the organic substrate that drives soil metabolic activity. In general, plant autotrophic respiration is coupled to photosynthetic activity [Heilmeier et al., 1997]. Moreover, the largest fraction of heterotrophic respiration originates from decomposition of young organic matter (dead leaves and fine roots). Thus, both the root respiration and heterotrophic respiration are dependent on primary productivity over broad spatial scales [Janssens et al., 2001].

\textbf{3.3 Global estimate of basal ecosystem respiration rate}

In general, BR is defined as ER rate at a given temperature (e.g. 0 or 10°C), and the given
temperature usually is same for various geographical regions. In this study, we changed the traditional definition of BR into ER rate at the mean annual temperature. By coupling the two correlations shown in Fig. 2 and Fig. 4, we can easily simulate BR from estimated GPP, and the latter has been successfully addressed by the various models. We used nocturnal measurements to examine the relationship between mean annual ER and its rate at the mean annual temperature shown in Fig. 2 in order to avoid calculation errors of daytime ER (see Section 2.1). This equivalence relationship derived from nocturnal measurements was thought to hold between mean annual daily ER and its rate at the mean annual temperature. EC-LUE model may have the most potential to adequately address the spatial and temporal dynamics of GPP at the regional scales [Yuan et al., 2007], which can be used to produce spatial patterns of GPP as well as BR in this study. In practice, the correlation through all ecosystem types was used to estimate BR based on simulated GPP by EC-LUE model.

The derived spatial pattern of the BR at global scale shows a great spatial heterogeneity (Fig. 5). In this study, we redefined BR as ER rate at the mean annual temperature, so the spatial pattern of BR greatly depends on thermal condition. In general, the BR is high over the tropical rain forests and subtropical forest regions like the southeastern United States and the Pantanal region of South American. Basal rate decreases with latitude at the northern and southern hemispheres, which partly is caused by lower temperature.

3.4 Global estimation of ecosystem respiration

Incorporating the site-specific BR, $Q_{10}$ equation accounts for 71% of the variation of monthly ER across all study sites (Fig. 6a). Individually, the coefficients of determination ($R^2$) varies from 0.30 at Audubon site to 0.91 at the Tharandt site, with all of them being statistically significant at p<0.05 (data not shown). These results were compared with those obtained with a globally invariant BR, which was set to the mean value of global BR over the vegetation regions (2.16 g C m$^{-2}$ day$^{-1}$). In that case, the $Q_{10}$ equation only explained about 50% of variation of monthly ER across the all study sites (Fig. 6b), and the relative predictive errors (RPE) was 35% averaged over all sites, compared to 23% using the site-specific BR.

We assessed the global spatial and seasonal patterns of ET from 2000–2003 by the model
using our globally heterogeneous BR. The averaged seasonal pattern of ET from 2000-2003 is shown at Fig. 7. The southern hemispheric tropics remain consistently high throughout the year, while the major deserts of northern Africa and Australia remain consistently low. The major global change on a monthly scale occurs in the high northern latitudes, where ER shows high variation with increases into the northern summer while tapering off into the winter. The model estimates that ER releases 103 Pg C yr$^{-1}$ from the land ecosystems to the atmosphere (Fig. 8a). Rates of ER are highest in the tropical moist forest regions and lowest in cold tundra and dry desert regions.

Although validation of global ER is impossible, we are able to compare our result with other global estimates of carbon cycle components based on the acknowledged ecological proportion. Raich et al. [2002] estimated global soil respiration to be 80.4 (range 79.3 ~ 81.8) Pg C yr$^{-1}$ averaged from 1980 to 1994 using a climate-driven regression model, which is about 77% of our global annual ER. This ratio of soil respiration and ER is similar to those reported at various geographical areas and ecosystem types ranging from 43 to 99% [Goulden et al., 1996; Lavinge et al., 1997; Law et al., 1999; Janssens et al., 2001; Griffis et al., 2004; Davidson et al., 2006; Zhang et al., 2009]. However, other studies reported higher annual global soil respiration [Potter and Kloostedt, 1998; Bond-Lamberty et al., 2004]. For example, the recent study showed global soil respiration is 98 Pg C yr$^{-1}$, which is 20-30% higher than previous estimates [Bond-Lamberty et al., 2010]. The model methods and parameters should play the important role in differences of global soil respiration.

Due to lack of global Q10 maps for ER, we assumed the temperature sensitivity of plant autotrophic respiration is as same as soil respiration, and used soil respiration Q10 values reported by Zhou et al [2009] to estimate global ER patterns with the risk of inducing model errors. Although some studies have already reported differences in the Q10 values between soil respiration and plant autotrophic respiration, however the recent study showed that the autotrophic and heterotrophic respiration responded equally to the temperature increase [Schindlbacher et al., 2009]. Piao et al. [2010] reported that Q10 for plant autotrophic respiration from 1.9 to 2.5 across the global scales, which are close with the range of 1.2 - 2.6 with the mean value of 1.92 for soil respiration over the vegetation regions in the Zhou et al. [2009]. The results reported at Zhou et al.
[2009] are close to the $Q_{10}$ value of 1.5 based on global soil respiration dataset [Bond-Lamberty et al., 2010] and inversed values ranging from 1.96 to 2.16 by the observed interannual variability in atmospheric CO$_2$ using the UK Met Office Hadley Centre coupled global model [Jones et al., 2001]. Moreover, we compared mean inversed $Q_{10}$ values using Equation (1) with those from Zhou et al. [2009] over all sites, and found the significant correlation ($Q_{10\_inversed} = 0.69 \times Q_{10\_Zhou} + 0.48$, $R^2=0.36$, $P<0.01$; data not shown).

We compared global annual ER using two different methods: (1) ER estimation using only global GPP and the relation between annual GPP and ER ($ER_{GPP}$); (2) ER estimation using the $Q_{10}$ model and the spatially heterogeneous basal respiration in this study and $Q_{10}$ values derived by Zhou et al [2009] ($ER_{Q10}$). The results showed global mean annual $ER_{GPP}$ was 92 Pg C (Fig. 8a), which was 89% of $ER_{Q10}$ (103 Pg C; Fig. 8b). The higher estimations of $ER_{Q10}$ than $ER_{GPP}$ almost occurs over global regions. Many studies have showed $Q_{10}$ will decrease with increasing temperature [Andrews et al., 2000; Janssens and Pilegaard, 2003; Chen et al., 2010], and Fig. 1 also showed decreased ER at high temperature. Although $Q_{10}$ type equations have been widely used to estimate ecosystem respiration at the various temporal and spatial scales, however, our and other previous studies showed the estimation uncertainties resulting from temporal constant of $Q_{10}$. In this study, we developed and generated global patterns of variant BR. The improved $Q_{10}$ values considering temporal variation will strengthen the estimations of ER.

4. Summary

BR and its spatial variability are crucial for projecting climate change effects and atmospheric CO$_2$ concentration in the future. This study has quantified the equivalence relation between mean annual ER and ER rate at mean annual temperature at the global scale, which offers good opportunity to retrieve global pattern of BR by combining another correlation of mean annual ER with GPP. We redefine the BR as ER rate at mean annual temperature, and develop the correlation between new BR and GPP for estimating global patterns of BT. The results showed the spatially heterogeneous BR results in the better estimation of ER at different sites. Our study provides an innovative method for generating global BR, and will be useful to estimate spatial patterns of ER.
Acknowledgements

We acknowledge the financial support from National Key Basic Research and Development Plan of China (2010CB833504 and 2010CB950703) and the Fundamental Research Funds for the Central Universities. We acknowledge the work of principal investigators and collaborators in EC sites, who provided the eddy covariance flux measurements. The following networks participated with flux data: AmeriFlux, CarboEuropeIP, ChinaFlux and Fluxnet-Canada.

References

Atkin, O.K., and M.G. Tjoelker (2003), Thermal acclimation and the dynamic response of plant respiration to temperature, Trends Plant Sci., 8, 343-351.


Grogan, P., and F.S. Chapin (1999), Arctic soil respiration: effects of climate and vegetation...


Lasslop, G., M. Reichstein, D. Papale, A. D. Richardson, A. Arneth, A. Barr, P. Stoy, G. Wohlfahrt (2010), Separation of net ecosystem exchange into assimilation and respiration using a


Migliavacca, M., M. Reichstein, A.D. Richardson, R. Colombo, M.A. Sutton, G. Lasslop, E. Tomelleri, G. Wohlfahrt, N. Carvalhais, A. Cescatti, M.D. Mahecha, L. Montagnani, D.

Papale, S. Zaehle, A. Arain, A. Arneth, T.A. Black, A. Carrara, S. Dore, D. Gianelle, C.


Mahecha, M.D., M. Reichstein, N. Carvalhais, G. Lasslop, H. Lange, S.I. Seneviratne, R. Vargas,

C. Ammann, M.A Arain, A. Cescatti, I.A. Janssens, M. Migliavacca, L. Montagnani, and


Reichstein, M., E., D. Falge, D. Baldocchi, M. Papale, P. Aubinet, C. Berbigier, N. Bernhofer, T.


<table>
<thead>
<tr>
<th>Site</th>
<th>Ecosystem type</th>
<th>Latitude, Longitude</th>
<th>AP</th>
<th>AMT</th>
<th>Available years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bartlett</td>
<td>DBF</td>
<td>44.06°N, 71.28°W</td>
<td>1245</td>
<td>5.61</td>
<td>2004-2005</td>
</tr>
<tr>
<td>Burn87</td>
<td>DBF</td>
<td>63.92°N, 145.38°W</td>
<td>289</td>
<td>-2.10</td>
<td>2002-2003</td>
</tr>
<tr>
<td>Chestnut</td>
<td>DBF</td>
<td>35.93°N, 84.33°W</td>
<td>986</td>
<td>6.85</td>
<td>2006</td>
</tr>
<tr>
<td>Duke Hardwood</td>
<td>DBF</td>
<td>35.97°N, 79.10°W</td>
<td>1169</td>
<td>14.36</td>
<td>2001-2005</td>
</tr>
<tr>
<td>Goodwin Creek</td>
<td>DBF</td>
<td>34.25°N, 89.97°W</td>
<td>1425</td>
<td>15.89</td>
<td>2003-2006</td>
</tr>
<tr>
<td>Hainich</td>
<td>DBF</td>
<td>51.06°N, 10.45°E</td>
<td>780</td>
<td>7.15</td>
<td>2000-2003</td>
</tr>
<tr>
<td>Hesse</td>
<td>DBF</td>
<td>48.66°N, 7.05°E</td>
<td>793</td>
<td>9.24</td>
<td>1997-2003</td>
</tr>
<tr>
<td>Indianammsf</td>
<td>DBF</td>
<td>39.32°N, 86.41°W</td>
<td>1030</td>
<td>12.42</td>
<td>2002-2003</td>
</tr>
<tr>
<td>LaMandria</td>
<td>DBF</td>
<td>45.56°N, 13.58°E</td>
<td>970</td>
<td>7.35</td>
<td>1997-2003</td>
</tr>
<tr>
<td>Parco Ticino</td>
<td>DBF</td>
<td>45.20°N, 9.05°E</td>
<td>973</td>
<td>13.27</td>
<td>2002-2003</td>
</tr>
<tr>
<td>Roccarespampani1</td>
<td>DBF</td>
<td>42.40°N, 11.91°E</td>
<td>763</td>
<td>15.36</td>
<td>2002-2003</td>
</tr>
<tr>
<td>Roccarespampani2</td>
<td>DBF</td>
<td>42.38°N, 11.91°E</td>
<td>760</td>
<td>15.40</td>
<td>2002-2003</td>
</tr>
<tr>
<td>Toledo</td>
<td>DBF</td>
<td>41.55°N, 83.84°W</td>
<td>843</td>
<td>8.53</td>
<td>2004-2005</td>
</tr>
<tr>
<td>Walkerbrach</td>
<td>DBF</td>
<td>35.95°N, 84.28°W</td>
<td>1372</td>
<td>13.71</td>
<td>2000-2001; 2004</td>
</tr>
<tr>
<td>Willow Creek</td>
<td>DBF</td>
<td>45.90°N, 90.07°W</td>
<td>787</td>
<td>4.02</td>
<td>2000; 2002-2005</td>
</tr>
<tr>
<td>Gunnarsholt</td>
<td>DBF</td>
<td>60.83°N, 20.21°E</td>
<td>1214</td>
<td>4.40</td>
<td>1997-1998</td>
</tr>
<tr>
<td>Aspen</td>
<td>DBF</td>
<td>53.62°N, 106.19°W</td>
<td>430</td>
<td>0.34</td>
<td>2002-2005</td>
</tr>
<tr>
<td>Austincary</td>
<td>EBF</td>
<td>29.73°N, 82.21°W</td>
<td>1330</td>
<td>21.70</td>
<td>2001; 2003; 2005-2006</td>
</tr>
<tr>
<td>DingHuShan</td>
<td>EBF</td>
<td>23.17°N, 112.57°E</td>
<td>1956</td>
<td>20.90</td>
<td>2003-2005</td>
</tr>
<tr>
<td>Espirra</td>
<td>EBF</td>
<td>38.63°N, 8.60°E</td>
<td>634</td>
<td>16.80</td>
<td>2002-2003</td>
</tr>
<tr>
<td>MitraII</td>
<td>EBF</td>
<td>38.53°N, 8.00°E</td>
<td>628</td>
<td>16.17</td>
<td>2003</td>
</tr>
<tr>
<td>Puechabon</td>
<td>EBF</td>
<td>43.73°N, 3.58°E</td>
<td>734</td>
<td>12.96</td>
<td>2001-2003</td>
</tr>
<tr>
<td>Tapajoslog</td>
<td>EBF</td>
<td>3.01°S, 54.97°W</td>
<td>1965</td>
<td>24.65</td>
<td>2001-2003</td>
</tr>
<tr>
<td>Santarem_Pri</td>
<td>EBF</td>
<td>2.85°S, 54.95°W</td>
<td>2111</td>
<td>25.90</td>
<td>2002-2003</td>
</tr>
<tr>
<td>Black Hill</td>
<td>ENF</td>
<td>44.15°N, 103.56°E</td>
<td>560</td>
<td>6.60</td>
<td>2005-2006</td>
</tr>
<tr>
<td>Blackspruce</td>
<td>ENF</td>
<td>53.98°N, 105.12°W</td>
<td>405</td>
<td>0.79</td>
<td>2000-2005</td>
</tr>
<tr>
<td>Blodgett</td>
<td>ENF</td>
<td>38.89°N, 120.63°W</td>
<td>1290</td>
<td>10.40</td>
<td>2001-2004</td>
</tr>
<tr>
<td>Boreas_NSA</td>
<td>ENF</td>
<td>55.87°N, 98.48°W</td>
<td>420</td>
<td>-3.55</td>
<td>1994-2004</td>
</tr>
<tr>
<td>Control</td>
<td>ENF</td>
<td>63.88°N, 145.73°W</td>
<td>289</td>
<td>-2.10</td>
<td>2002-2003</td>
</tr>
<tr>
<td>Donaldson</td>
<td>ENF</td>
<td>29.75°N, 82.16°W</td>
<td>1330</td>
<td>21.70</td>
<td>1999; 2001-2003</td>
</tr>
<tr>
<td>Dukepine</td>
<td>ENF</td>
<td>35.97°N, 79.09°W</td>
<td>1169</td>
<td>14.36</td>
<td>1998-2005</td>
</tr>
<tr>
<td>ElSaler</td>
<td>ENF</td>
<td>39.33°N, 0.31°E</td>
<td>551</td>
<td>17.85</td>
<td>1999-2003</td>
</tr>
<tr>
<td>Fyodorovskoye</td>
<td>ENF</td>
<td>56.45°N, 32.91°E</td>
<td>711</td>
<td>3.90</td>
<td>1999-2003</td>
</tr>
<tr>
<td>Howland</td>
<td>ENF</td>
<td>45.20°N, 68.74°W</td>
<td>1070</td>
<td>5.27</td>
<td>1996-2004</td>
</tr>
<tr>
<td>Howland West</td>
<td>ENF</td>
<td>45.20°N, 68.74°W</td>
<td>1064</td>
<td>5.13</td>
<td>1999-2001</td>
</tr>
<tr>
<td>Jackpine</td>
<td>ENF</td>
<td>53.91°N, 104.69°W</td>
<td>405</td>
<td>0.12</td>
<td>2000-2003</td>
</tr>
<tr>
<td>Site</td>
<td>Type</td>
<td>Lat/Long</td>
<td>AP</td>
<td>AMT</td>
<td>YearRange</td>
</tr>
<tr>
<td>--------------</td>
<td>------------</td>
<td>----------------</td>
<td>-----</td>
<td>------</td>
<td>---------------------</td>
</tr>
<tr>
<td>LeBray</td>
<td>ENF</td>
<td>44.71°N, 0.76°E</td>
<td>924</td>
<td>12.49</td>
<td>1997-1998;2000-2003</td>
</tr>
<tr>
<td>Loobos</td>
<td>ENF</td>
<td>52.16°N, 5.73°E</td>
<td>786</td>
<td>9.36</td>
<td>1996-2002</td>
</tr>
<tr>
<td>Metolius Midpine</td>
<td>ENF</td>
<td>44.45°N, 121.55°W</td>
<td>704</td>
<td>7.88</td>
<td>2002-2005</td>
</tr>
<tr>
<td>Metolius Oldyoung</td>
<td>ENF</td>
<td>44.43°N, 121.56°W</td>
<td>522</td>
<td>6.28</td>
<td>2000-2002</td>
</tr>
<tr>
<td>Niwotridge</td>
<td>ENF</td>
<td>40.03°N, 105.54°W</td>
<td>595</td>
<td>0.43</td>
<td>1999-2004</td>
</tr>
<tr>
<td>Norunda</td>
<td>ENF</td>
<td>60.08°N, 17.46°E</td>
<td>561</td>
<td>5.45</td>
<td>1996-1997;1999-2003</td>
</tr>
<tr>
<td>Renon</td>
<td>ENF</td>
<td>46.58°N, 11.43°E</td>
<td>1010</td>
<td>4.20</td>
<td>1999</td>
</tr>
<tr>
<td>SanRossoresi</td>
<td>ENF</td>
<td>43.71°N, 10.28°E</td>
<td>897</td>
<td>14.77</td>
<td>1999-2003</td>
</tr>
<tr>
<td>Sodankylä</td>
<td>ENF</td>
<td>67.36°N, 26.64°E</td>
<td>499</td>
<td>1.0</td>
<td>2000-2003</td>
</tr>
<tr>
<td>Tharandt</td>
<td>ENF</td>
<td>50.95°N, 13.56°E</td>
<td>820</td>
<td>7.7</td>
<td>1997-2003</td>
</tr>
<tr>
<td>Uci1930</td>
<td>ENF</td>
<td>55.90°N, 98.52°W</td>
<td>499</td>
<td>-2.88</td>
<td>2002-2004</td>
</tr>
<tr>
<td>Uci1964</td>
<td>ENF</td>
<td>55.91°N, 98.38°W</td>
<td>502</td>
<td>-2.87</td>
<td>2002-2005</td>
</tr>
<tr>
<td>Wetzstein</td>
<td>ENF</td>
<td>50.45°N, 11.45°E</td>
<td>870</td>
<td>5.74</td>
<td>2002-2003</td>
</tr>
<tr>
<td>Windriver</td>
<td>ENF</td>
<td>45.82°N, 121.95°W</td>
<td>2451</td>
<td>9.45</td>
<td>2004-2006</td>
</tr>
<tr>
<td>Yatir</td>
<td>ENF</td>
<td>31.33°N, 35.05°E</td>
<td>276</td>
<td>17.56</td>
<td>2002-2003</td>
</tr>
<tr>
<td>QianYanZhou</td>
<td>ENF</td>
<td>26.73°N, 115.05°E</td>
<td>1542</td>
<td>17.90</td>
<td>2003;2005;2007</td>
</tr>
<tr>
<td>Amplero</td>
<td>GRS</td>
<td>41.94°N, 13.65°E</td>
<td>945</td>
<td>10.60</td>
<td>2003</td>
</tr>
<tr>
<td>Bugac</td>
<td>GRS</td>
<td>46.68°N, 19.60°E</td>
<td>562</td>
<td>10.40</td>
<td>2003</td>
</tr>
<tr>
<td>Burn99</td>
<td>GRS</td>
<td>63.92°N, 145.73°W</td>
<td>289</td>
<td>-2.10</td>
<td>2002-2003</td>
</tr>
<tr>
<td>Lethbridge</td>
<td>GRS</td>
<td>49.70°N, 112.94°W</td>
<td>398</td>
<td>5.36</td>
<td>1999-2004</td>
</tr>
<tr>
<td>MalgaArpaco</td>
<td>GRS</td>
<td>46.11°N, 11.70°E</td>
<td>1200</td>
<td>6.30</td>
<td>2003</td>
</tr>
<tr>
<td>MonteBondone</td>
<td>GRS</td>
<td>38.53°N, 8.00°E</td>
<td>1184</td>
<td>5.39</td>
<td>2003</td>
</tr>
<tr>
<td>Neustift</td>
<td>GRS</td>
<td>47.10°N, 11.31°E</td>
<td>1040</td>
<td>6.25</td>
<td>2002-2003</td>
</tr>
<tr>
<td>Oensingen</td>
<td>GRS</td>
<td>47.28°N, 7.71°E</td>
<td>944</td>
<td>9.13</td>
<td>2002-2003</td>
</tr>
<tr>
<td>Pianosa</td>
<td>GRS</td>
<td>42.58°N, 10.06°E</td>
<td>460</td>
<td>16.00</td>
<td>2002-2003</td>
</tr>
<tr>
<td>Walnut River</td>
<td>GRS</td>
<td>37.52°N, 96.85°W</td>
<td>406</td>
<td>15.46</td>
<td>2002-2004</td>
</tr>
<tr>
<td>XiLinHaoTe</td>
<td>GRS</td>
<td>43.88°N, 117.45°E</td>
<td>450</td>
<td>-0.40</td>
<td>2004;2006-2007</td>
</tr>
<tr>
<td>Brasschaat</td>
<td>MIX</td>
<td>51.30°N, 4.51°E</td>
<td>742</td>
<td>10.01</td>
<td>1999-2002</td>
</tr>
<tr>
<td>ChangBaiShan</td>
<td>MIX</td>
<td>42.40°N, 128.08°E</td>
<td>663</td>
<td>2.16</td>
<td>2003-2006; 2007</td>
</tr>
<tr>
<td>Lavarone</td>
<td>MIX</td>
<td>45.95°N, 11.26°E</td>
<td>757</td>
<td>8.74</td>
<td>2001-2002</td>
</tr>
<tr>
<td>Nonantola</td>
<td>MIX</td>
<td>44.68°N, 11.08°E</td>
<td>741</td>
<td>13.56</td>
<td>2001-2002</td>
</tr>
<tr>
<td>Soroe</td>
<td>MIX</td>
<td>55.48°N, 11.63°E</td>
<td>573</td>
<td>8.03</td>
<td>1999-2003</td>
</tr>
<tr>
<td>Sylvania</td>
<td>MIX</td>
<td>46.24°N, 89.34°W</td>
<td>826</td>
<td>3.81</td>
<td>2002-2006</td>
</tr>
<tr>
<td>Umichigan</td>
<td>MIX</td>
<td>45.55°N, 84.71°W</td>
<td>803</td>
<td>5.83</td>
<td>1999-2002</td>
</tr>
<tr>
<td>Vielsalm</td>
<td>MIX</td>
<td>50.30°N, 6.00°E</td>
<td>1065</td>
<td>7.37</td>
<td>1997-2003</td>
</tr>
<tr>
<td>Barrow*</td>
<td>TUN</td>
<td>71.32°N, 156.62°W</td>
<td>85</td>
<td>-12.77</td>
<td>2004-2005</td>
</tr>
</tbody>
</table>

DBF: deciduous broadleaf forest; EBF: evergreen broadleaf forest; ENF: evergreen needleleaf forest; GRS: grassland; MIX: mixed forest; TUN: tundra. *Data filtering did not follow the criterion of other sites. The days were indicated as missing when missing data was > 50%, and the years were indicated as missing when missing days were > 50%. AP: annual precipitation (mm); AMT: annual mean temperature (°C).
**Figure captions**

Fig. 1 Typical example of temperature response curves of ecosystem respiration with standard errors. DBF: deciduous broadleaf forest; EBF: evergreen broadleaf forest; ENF: evergreen needleleaf forest; GRS: grassland; MIX: mixed forest; TUN: tundra. Annual mean temperature at Barrow and Boreas NSA are below 0°C.

Fig. 2 Equivalence relation between mean annual nocturnal ecosystem respiration and nocturnal ecosystem respiration rate at mean annual nocturnal temperature across (a) all study sites: $y=0.96x-0.07$, $R^2=0.87$; (b) deciduous broadleaf forests: $y=0.87x+0.26$, $R^2=0.58$; (c) evergreen needleleaf forests: $y=0.98x-0.28$, $R^2=0.88$; (d) grasslands: $y=0.83x+0.12$, $R^2=0.89$; (e) evergreen broadleaf forests (solid dots; $y=0.88x+0.66$, $R^2=0.97$), mixed forests (open squares; $y=0.82x+0.32$, $R^2=0.60$) and tundra (open diamond). Short dashes are 1:1 line. Mean annual nocturnal ecosystem respiration are mean value for all available years which missing data are less than 20% of the entire year data at each site, and ecosystem respiration rate at the mean annual temperature are determined from temperature response curves of ecosystem respiration shown in Fig. 1.

Fig. 3 Frequency distribution of air temperature at Vielsalm site where mean annual temperature equals to 7.37°C (a) and the relation between mean annual temperature with temperature with largest distribution frequency (b).

Fig. 4 Correlation between mean annual GPP and ecosystem respiration across (a) all study sites: $y=0.76x+0.07$, $R^2=0.85$; (b) deciduous broadleaf forests: $y=0.60x+0.38$, $R^2=0.64$; (c) evergreen needleleaf forests: $y=0.74x+0.13$, $R^2=0.89$; (d) grasslands: $y=0.67x+0.49$, $R^2=0.90$; (e) evergreen broadleaf forests (solid dots; $y=1.07x-1.13$, $R^2=0.91$), mixed forests (open squares; $y=0.55x+0.89$, $R^2=0.68$) and tundra (open diamond). Short dashes are 1:1 line.

Fig. 5 Global pattern of basal ecosystem respiration rate ($g \ C \ m^{-2} \ day^{-1}$) in this study, which equals to ecosystem respiration rate at the mean annual temperature.

Fig. 6 Model validation of $Q_{10}$ equation across the all study sites using (a) globally heterogeneous basal ecosystem respiration rate and (b) invariant value. The short dash lines are 1:1 line and the solid lines are linear regression line.

Fig.7 Seasonal variations of global ecosystem respiration ($g \ C \ m^{-2}$) as predicted by $Q_{10}$ equation with spatially heterogeneous basal ecosystem respiration rate: (a) aggregated ER of January, February and March; (b) Aprial, May and June; (c) July, August and September; (d) October, November and December.

Fig.8 Global annual ecosystem respiration (ER) ($g \ C \ m^{-2} \ y^{-1}$) using only gross primary production
(GPP) derived by EC-LUE and relation of GPP and ER (a), using $Q_{10}$ equation with spatially heterogeneous basal ecosystem respiration rate (b) and the difference between these two methods (c).
(a) Histogram of air temperature (°C) with a peak at 7.5°C.

(b) Scatter plot of mean annual temperature (°C) vs. temperature with the largest frequency (°C). Regression line: $y = 0.75x + 3.36$, with $R^2 = 0.66$, $P<0.01$. The 1:1 line is also shown.
Simulated monthly mean nocturnal ecosystem respiration (g C m^{-2} d^{-1})

(a) y = 0.71x + 0.58
R^2 = 0.71

(b) y = 0.51x + 1.04
R^2 = 0.50

Observed monthly mean nocturnal ecosystem respiration (g C m^{-2} d^{-1})