A compiled soil respiration dataset at different time scales for forest ecosystems across China from 2000 to 2018

Hongru Sun[1, 2], Zhenzhu Xu[1], and Bingrui Jia[1*]

[1]*State Key Laboratory of Vegetation and Environmental Change, Institute of Botany, Chinese Academy of Sciences, Beijing 100093, China*

[2]*University of Chinese Academy of Sciences, Beijing 100049, China*

[*]Corresponding author:

Bingrui Jia

Institute of Botany, Chinese Academy of Sciences,

20 Nanxincun, Xiangshan, Haidian District, Beijing 100093, China

E-mail: jiabingrui@ibcas.ac.cn

Tel: 86-10-62836289

Fax: 86-10-82595962

Abstract. China's forests rank fifth in the world by area and cover a broad climatic gradient from cold-temperate to tropical zones, and play a key role in the global carbon cycle. Studies on forest soil respiration (*Rs*) are increasing rapidly in China over the last two decades, but the resulting *Rs* data need to be summarized. Here, we compile a comprehensive dataset of *Rs* in China's undisturbed forest ecosystems from literatures published up to December 31, 2018, including monthly *Rs* and the concurrently measured soil temperature (N=8317), mean monthly *Rs* (N=5003), and annual *Rs* (N=634). Detailed plot information was also recorded, such as geographical location, climate factors, stand characteristics, and measurement description. We examine some aspects of the dataset – *Rs* equations fitted with soil temperature, temperature sensitivity (Q_{10}), monthly variations and annual effluxes in cold-temperate, temperate, subtropical and tropical

zones. We hope the dataset will be used by the science community to provide a better understanding of carbon cycle in China's forest ecosystems and reduce uncertainty in evaluating of carbon budget at the large scale. The dataset is publicly available at https://doi.pangaea.de/10.1594/PANGAEA.943617 (Sun et al., 2022).

1 Introduction

Soil respiration (*Rs*) refers to the total amount of CO_2 released by undisturbed soil, including autotrophic respiration and heterotrophic respiration, the former from plant roots and their microbial symbionts, and the latter from microorganisms decomposing litter and soil organic matter. As the second-largest terrestrial carbon flux, the recent estimations of global annual *Rs* (80–98 Pg C year^{-1}) are above ten percent of the atmospheric carbon pool (750 Pg C) (Bond-Lamberty and Thomson, 2010b; Hashimoto et al., 2015; Raich et al., 2002; Warner et al., 2019), thus accelerating soil respiration rates with climate warming have a strong potential to influence atmospheric CO_2 levels. It is thus important to understand better soil respiration dynamics and response to climate changes.

Forest area in China ranks fifth in the world (FAO, 2020) and covers a broad climatic gradient, including cold-temperate, temperate, subtropical and tropical zones. In China, most *Rs* measurements began only after 2001 (Chen et al., 2010), but have rapidly increased during the last 20 years (Jian et al., 2020). Several studies have summarized annual *Rs* in China’s forest ecosystems, but with the small samples (e.g., N=50 in Zheng et al., 2010; N=62 in Chen et al., 2008; N=120 in Zhan et al., 2012; N=139 in Song et al., 2014). Yu et al. (2010) established a geostatistical model with a total of 390 monthly *Rs* data from different ecosystems in China. With 1782 monthly *Rs* in forest ecosystems across China, Jian et al. (2020) analyzed the spatial patterns and temporal trends from 1961 to 2014. However, amounts of *Rs* data are still unexploited, because they were only displayed in the forms of monthly dynamics in the original papers' figures. *Rs* data at a subannual timescales are important for upscaling global *Rs* (Jian et al., 2018), which may derive different conclusions and deserve further exploration (Huang et al., 2020).

The lack of the large-scale and observation-driven *Rs* data is a main constraining factor in quantifying regional- to global-scale carbon budget (Bond-Lamberty and Thomson, 2010a; Rayner et al., 2005). *Rs* data and concurrently measured temperature thus provide not only a solid base to understand the critical factors influencing *Rs*, but the opportunity to better simulate *Rs* at the large scale. We attempted to compile a complete forest *Rs* dataset at different temporal scales in China, and analyze temperature sensitivity (Q_{10}), monthly and annual *Rs* in cold-temperate, temperate, subtropical and tropical zones.

2 Data and methods

2.1 Data sources

The terms of "soil respiration", "soil carbon (or CO_2) efflux", or "soil carbon (or CO_2) emission" were searched from publications before 2018 in the China Knowledge Resource Integrated Database (http://www.cnki.net/), China Science and Technology Journal Database (http://www.cqvip.com), ScienceDirect (http://www.sciencedirect.com/), ISI Web of Science (http://isiknowledge.com/), and Springer Link (http://link.springer.com/). Means, minimums and maximums of soil respiration during the observation periods were usually given in these published studies, and monthly patterns of soil respiration rates and the corresponding temperature were frequently shown with figures. WEBPLOTDIGITIZER, a graphic digitizing software, was used to take data from figures when values were not reported in the text (Burda et al., 2017).

2.2 Data collection criteria

The following criteria were used to ensure data consistency and accuracy: i) *Rs* was measured in the field without obvious disturbances or manipulation experiments, e.g., fire, cutting, nitrogen addition treatments, etc. ii) Forested swamps and commercial plantations (e.g., orchard, rubber, etc.) were not examined. iii) *Rs* was measured either by static chamber/gas chromatography (GC) or by dynamic chamber/infrared gas analyzers (IRGA, model Li-6400, Li-8100, Li-8150 (LI-COR Inc., Lincoln, Nebraska, USA)), which are the most popular methods and provide methodological consistency (Sun et al., 2020; Wang et al., 2011; Yang et al., 2018; Zheng et al., 2010).

Based on these criteria, a total of 10288 monthly soil respiration data and 634 annual soil respiration data were assembled from 568 publications. Meanwhile, the related information was recorded, including geographical location (province, study site, latitude, longitude and elevation), climate (mean annual temperature and mean annual precipitation), stand description (forest type, origin, age, density, mean tree height and diameter at breast height), measurement regime (method, time, frequency, collar area, height and numbers) (Table 1). There were 155 study sites from 28 provinces in China (18.61–52.86° N, 84.91–129.08° E, 7–4200 m) (Fig. 1). This forest region encompasses a large gradient of climate regimes, mean annual temperature ranging from -5.4 to 23.8 °C and mean annual precipitation ranging from 105 to 3000 mm. The observation years were from 2000 until 2018.

2.3 Data verification

Soil temperature as a main influencing factor, was usually concurrently measured with *Rs*. Monthly dynamics of *Rs* and soil temperature at 5 cm depth (T_5) and/or 10 cm depth (T_{10}) were shown with figures in many literatures. In this study, most of the *Rs* data (~82%)

and the concurrent T_5 and/or T_{10} were extracted with WEBPLOTDIGITIZER, others (e.g., minimum, maximum) were directly given in the original papers. To verify the accuracy of the digital software, the means (*Rs*, T_5, T_{10}) averaged from the extracted data were compared with the corresponding means directly given in the original papers (Fig. S1). The Root Mean Square Errors (RMSE) of *Rs*, T_5 and T_{10} were 0.09 μmol m^{-2} s^{-1}, 0.35 °C and 0.44 °C, respectively, and the coefficients of determination (R^2) were all larger than 0.99, indicating that the accuracy of WEBPLOTDIGITIZER is excellent. Moreover, the data from the same authors and different sources (e.g., master or Ph. D. dissertation and journal article) has been carefully cross-checked and supplemented.

2.4 Monthly and annual soil respiration calculation

Long-term continuous *Rs* could be monitored with infrared gas analyzers (e.g., Li-8100, Li-8150), but there are few published studies of such continuous data (Bond-Lamberty et al., 2020; Tu et al., 2015; Wu et al., 2014; Yu et al., 2011). The observation frequency was 1–12 days per month—high during the growing season, but low in winter. *Rs* was measured throughout the day (16%) or at representative time, e.g., 9:00 a.m.–11:00 a.m. (45%), 9:00 a.m.–12:00 a.m. (22%), etc., which had been validated to be close to the diurnal mean value (Xu and Qi, 2001; Yan et al., 2006; Yang et al., 2018; Yao et al., 2011; You et al., 2013; Zheng et al., 2010). Annual soil carbon efflux was integrated with soil respiration model (i.e. integration method) or interpolated the average soil respiration rate between sampling dates (i.e. interpolation method) (Shi et al., 2014). Finally, monthly *Rs* and annual soil carbon efflux were converted to the common unit of μmol CO_2 m^{-2} s^{-1} and g C m^{-2} $year^{-1}$, respectively (Bond-Lamberty and Thomson, 2010a).

2.5 Statistical analysis

Monthly and annual *Rs* were averaged arithmetically in cold-temperate, temperate, subtropical and tropical zones. Independent-Samples T Tests (2 groups) and One-Way

ANOVA (≥3 groups) at the $P = 0.05$ significance level were used to test the differences among different forest types in the same climate zone and among the same forest type in different climate zones. Temperature sensitivity (Q_{10}) is defined as the factor by which Rs is multiplied when temperature increases by 10 °C (Davidson and Janssens, 2006; Lloyd and Taylor, 1994), which is usually calculated with the van't Hoff equation (Rs=a$e^{\beta T}$ & Q_{10}=$e^{10\beta}$), where Rs is soil respiration rate (μmol m^{-2} s^{-1}), T is temperature (°C). All statistical analyses were performed with SPSS Statistics 21 (SPSS Inc., Chicago, USA).

3 Results

3.1 Relationship between soil respiration rate and soil temperature

Temperature is often the main factor determining soil respiration rates. The samples of the paired Rs & T_5 and Rs & T_{10} were 6341 (69%) and 2878 (31%) in the dataset, respectively. There were significantly exponential relationships of Rs with T_5 and T_{10} in forest ecosystems across China, which could explain about 48% and 52% of the Rs variations, respectively (Fig. S2). The exponential correlations were all significant in four climatic zones(R^2=0.23–0.93) (Fig. 2). RMSEs in cold-temperate and temperate zones (1.52–1.67 μmol m^{-2} s^{-1}) were larger than those in subtropical and tropical zones (1.04–1.32 μmol m^{-2} s^{-1}), except the smallest RMSE from T_{10} in cold-temperate zone (0.42 μmol m^{-2} s^{-1}).

Q_{10} could be calculated with the exponential equations between Rs and soil temperature. At the national scale, the Q_{10} values in China's forest ecosystems from T_5 (-16.51–33.58 °C) and T_{10} (-16.40–33.46 °C) were 2.05 and 2.17, respectively. The Q_{10} was the largest in cold-temperate zone (T_5: 3.74 & T_{10}: 3.32), secondary in temperate zone (T_5: 2.69 & T_{10}: 3.00), and the smallest in subtropical zone (T_5: 2.15 & T_{10}: 2.20) and tropical zone (T_5: 2.28 & T_{10}: 1.63).

3.2 Monthly dynamics of soil respiration

Monthly *Rs* appeared as a single-peak curve (Fig. 3), which derived from the similar years in cold-temperate (2003–2016), temperate (2002–2018), subtropical (2000–2017) and tropical zones (2003–2015). The largest values occurred in August (4.18–4.36 μmol m^{-2} s^{-1}) in cold-temperate and temperate zones, larger than the largest values in July (3.58–3.83 μmol m^{-2} s^{-1}) in subtropical and tropical zones. The lowest values occurred in January in cold-temperate (0.20 μmol m^{-2} s^{-1}), temperate (0.49 μmol m^{-2} s^{-1}), subtropical (1.10 μmol m^{-2} s^{-1}) and tropical zones (1.62 μmol m^{-2} s^{-1}). Monthly variations were largest in cold-temperate and temperate zones, secondary in subtropical zone, and smallest in tropical zone.

Annual mean *Rs* in January–December from low to high was cold-temperate (1.63 μmol m^{-2} s^{-1}), temperate (1.93 μmol m^{-2} s^{-1}), subtropical (2.47 μmol m^{-2} s^{-1}) and tropical zones (2.57 μmol m^{-2} s^{-1}). Meanwhile, annual soil carbon emissions were calculated with the annual mean *Rs*: 621.91 g C m^{-2} yr^{-1} in cold-temperate zone, 733.31 g C m^{-2} yr^{-1} in temperate zone, 937.15 g C m^{-2} yr^{-1} in subtropical zone, and 973.35 g C m^{-2} yr^{-1} in tropical zone. Soil carbon emissions in growing season (May–October) and winter (November–April) accounted for 85% and 15% in cold-temperate zone, 80% and 20% in temperate zone, 69% and 31% in subtropical zone, 61% and 39% in tropical zone. Subtropical and tropical zones still keep high soil respiration rates in November–April, which is the main source of their larger annual soil carbon emissions.

3.3 Annual soil carbon effluxes

There were 634 annual soil carbon effluxes, and most of the observations were conducted in subtropical zone (61%) and temperate zone (32%) (Fig. 4). The spanning years were 2003–2014 in cold-temperate zone, 2000–2018 in temperate zone, 2002–2017 in subtropical zone and 2003–2017 in tropical zone. The annual soil carbon effluxes ranged from 260.10 g C m^{-2} yr^{-1} to 2058.00 g C m^{-2} yr^{-1} in China's forest ecosystems, and the mean was 851.88±12.75 g C m^{-2} yr^{-1}. The annual soil carbon effluxes increased with the increasing of mean annual temperature and precipitation at the national scale (Fig. S3). Mean annual soil carbon emissions in tropical, subtropical, temperate and cold-temperate zones were 1042.01±68.55, 928.91±16.68, 697.85±16.39 and 684.29±61.81 g C m^{-2} yr^{-1}, respectively. The former two was significantly higher than the latter two, but the differences were not significant between tropical and subtropical zones, and between temperate and cold-temperate zones. The differences were not significant for evergreen broadleaf forest (EBF), evergreen needleleaf forest (ENF) and deciduous needleleaf forest (DNF) among different climate zones. Deciduous broadleaf forest (DBF) in temperate (748.59±25.18 g C m^{-2} yr^{-1}) and subtropical zones (755.41±58.26 g C m^{-2} yr^{-1}) was similar, both of which were larger than that in cold-temperate zone (284.20±21.36 g C m^{-2} yr^{-1}). Broadleaf and needleleaf mixed forest in subtropical zone (977.35±43.56 g C m^{-2} yr^{-1}) had significantly higher emissions than that in temperate zone (733.44±45.29 g C m^{-2} yr^{-1}).

Evergreen forests were usually larger than deciduous ones in the same climatic zone, for example, ENF (866.98±63.74 g C m^{-2} yr^{-1}) and DNF (734.56±83.67 g C m^{-2} yr^{-1}) in cold-temperate zone, ENF (699.96±32.77 g C m^{-2} yr^{-1}) and DNF (555.15±24.19 g C m^{-2} yr^{-1}) in temperate zone, EBF (1073.50±26.44 g C m^{-2} yr^{-1}) and DBF (755.41±58.26

g C m^{-2} yr^{-1}) in subtropical zone. Broad-leaved forests showed significantly larger annual fluxes than coniferous forests in temperate zone (DBF: 748.59±25.18 g C m^{-2} yr^{-1} vs. DNF: 555.15±24.19 g C m^{-2} yr^{-1}) and subtropical zone (EBF: 1073.50±26.44 g C m^{-2} yr^{-1} vs. ENF: 717.50±17.61 g C m^{-2} yr^{-1}). However, DNF (734.56±83.67 g C m^{-2} yr^{-1}) was larger than DBF (284.20±21.36 g C m^{-2} yr^{-1}) in cold-temperate zone, which was from high-latitude Great Xing'an Mountains (~51° N) and high-altitude Gongga Mountain (2800–2950 m). Additionally, bamboo is a special type in subtropical areas, exhibiting the highest soil carbon emissions (1133.55±42.74 g C m^{-2} yr^{-1}).

4 Discussion

4.1 Temperature sensitivity (Q_{10}) of soil respiration

Q_{10} is a key parameter in modelling the effects of climate warming on soil carbon release. The Q_{10} calculated with the exponential equations of T_5 and T_{10} were 2.05 and 2.17 at the national scale (Fig. S2), which were lower than the averaged Q_{10} from different studies in the syntheses of China's forest ecosystems (T_5: 2.28–2.51 and T_{10}: 2.74–3.00, Peng et al., 2009; Song et al., 2014; Xu et al., 2015; Zheng et al., 2009) and global forest ecosystems (T_5: 2.55–2.70 and T_{10}: 3.01–3.31, Wang et al., 2010 a; b). Our results were close to the Q_{10} of 2 commonly used in many biogeochemical models (e.g., Cox et al., 2000; Sampson et al., 2007) and the mean Q_{10} of 2.11 estimated with inverse modeling in forest soils across China (Zhou et al., 2009).

Temperature was the most important limiting factor for soil microbial activity and root growth in cold regions, thus, *Rs* was more sensitive to temperature changes (Lloyd and Taylor, 1994; Peng et al., 2009; Zheng et al., 2009; Zheng et al., 2020). The Q_{10} increased from tropical zone to cold-temperate zone in this study, and varied from 1.63

to 3.74. Soil temperature at the depth of 5 cm and 10 cm could only explain 29% and 23% of the *Rs* variations and RMSEs were 1.09 μmol m^{-2} s^{-1} and 1.13 μmol m^{-2} s^{-1} in tropical zone, respectively (Fig. 2d). The difference of the mean *Rs* between tropical moist forests (1260 g C m^{-2} yr^{-1}) and tropical dry forests (673 g C m^{-2} yr^{-1}) was about 2-fold (Raich and Schlesinger, 1992), indicating that soil moisture might play more important roles.

4.2 Comparisons of monthly and annual soil carbon effluxes

The lowest monthly *Rs* occurred in January, and the largest values occurred in August in cold-temperate and temperate zones and in July in subtropical and tropical zones (Fig. 3). Similarly, monthly *Rs* of global terrestrial ecosystems reached their minima in February and peaked in July and August (Hashimoto et al., 2015; Raich et al., 2002). Due to the limitation of low temperature, winter observations of *Rs* were relatively fewer in the cold-temperate and temperate zones. The *Rs* in winter (November–April) was usually assumed to account for 20% of the total annual *Rs* (Geng et al., 2017; Yang and Wang, 2005), which was in agreement with the proportion in temperate zone, but greater than 15% in cold-temperate zone.

Annual soil carbon emission had been synthesized in forest ecosystems across China, and the mean was 745.34 g C m^{-2} yr^{-1} (Zheng et al., 2010), 764.11 g C m^{-2} yr^{-1} (Zhan et al., 2012), 917.73 g C m^{-2} yr^{-1} (Song et al., 2014) and 975.50 g C m^{-2} yr^{-1} (Chen et al., 2008), and the mean of 851.88 g C m^{-2} yr^{-1} in the present study was in the mid-range. The mean annual *Rs* in China's forest ecosystems was slightly lower than the mean *Rs* of 990.00 g C m^{-2} yr^{-1} in global forest ecosystems (Chen et al., 2010). Warner et al. (2019) modelled global *Rs* and found that the smallest and greatest annual soil carbon emissions were in deciduous needleleaf forest (Mean=344.10 g C m^{-2} yr^{-1}) and evergreen broadleaf forest (Mean=1310.47 g C m^{-2} yr^{-1}), respectively. Compared with the predicted annual *Rs*, deciduous needleleaf forest in cold-temperate (Mean=734.56 g C m^{-2} yr^{-1}) and temperate zones (Mean= 555.15 g C m^{-2} yr^{-1}) had larger values, but those of evergreen broadleaf forest in subtropical (Mean=1073.50 g C m^{-2} yr^{-1}) and tropical zones (Mean=1065.09 g C m^{-2} yr^{-1}) were lower (Fig. 4).

Mean annual soil carbon emissions from 634 annual *Rs* and 5003 mean monthly *Rs* were 684.29 and 621.91 g C m^{-2} yr^{-1} in cold-temperate zone, 697.85 and 733.31 g C m^{-2} yr^{-1} in temperate zone, 928.91 and 937.15 g C m^{-2} yr^{-1} in subtropical zone, and 1042.01 and 973.35 g C m^{-2} yr^{-1} in tropical zone (Fig. 4 and Fig. 3). The differences between the directly averaged annual *Rs* and the accumulative mean monthly *Rs* were smallest in tropical zone (-8.24 g C m^{-2} yr^{-1}), secondary in temperate zone (-35.46 g C m^{-2} yr^{-1}), and largest in cold-temperate and tropical zones (62.38–68.66 g C m^{-2} yr^{-1}). From Fig. 4 we could also found that the standard errors in tropical and temperate zones (~16 g C m^{-2} yr^{-1}) were smaller than those in cold-temperate and tropical zones (~65 g C m^{-2} yr^{-1}). Mean annual soil carbon emissions in temperate, subtropical and tropical ecosystems were 745 g C m^{-2} yr^{-1}, 776 g C m^{-2} yr^{-1} and 1286 g C m^{-2} yr^{-1} at the global scale, respectively (Bond-Lamberty and Thomson, 2010a), which were comparable with our results.

4.3 Improvements of the dataset

Rs measurements were mainly from Li-8100 (47%) and Li-6400 (33%), secondary from gas chromatography (18%), and Li-8150 only accounted for 2%. The differences of the four common measurement methods had been proved to be small (~10%) (Wang et al., 2011; Yang et al., 2018; Zheng et al., 2010). The sample sizes of annual *Rs* were 50–139 (Chen et al., 2008; Song et al., 2014; Zhan et al., 2012; Zheng et al, 2010) and 634 in the current study, and increased above 4-fold. The global soil respiration database (SRDB-V5) collected 523 undisturbed annual *Rs* in China's forest ecosystems (Jian et al., 2021), but all methods were included, e.g., alkali absorption, gas chromatography and various infrared gas analyzers. Alkali absorption method could underestimate *Rs* (Chen et al., 2008; Jian et al., 2020). The total samples of mean monthly *Rs* were 5003, which was much larger than the other dataset's monthly samples of 1782 in China's forest ecosystems (Jian et al., 2020; Steele and Jian, 2018). Additionally, we extended the dataset with the digital software (WEBPLOTDIGITIZER) from the monthly dynamics figures of the original papers, including the paired *Rs* & T_5 (N=6341) and *Rs* & T_{10} (N=2878). Predicting soil respiration from soil temperature has gained extensive acceptance (Shi et al., 2014; Song et al., 2014; Sun et al., 2020). These data could be used to establish the large-scale soil respiration equation and acquire the key parameters of carbon cycle. Compared with the above-mentioned monthly or annual databases, this study collected all available *Rs* data at different time scales. Fig. S4 showed the length of the individual time series from the different sites, the high frequencies were 12 months (38%), 6–7 months (20%) and 13–24 months (15%). Bamboo forests were seldom considered in the previous databases (Chen et al., 2008; Steele and Jian, 2018; Zhan et al., 2012; Zheng et al, 2010), which exhibited the highest soil carbon emissions (Mean=1133.55 g C m^{-2} yr^{-1}, Fig. 4). With the area increasing at a high rate of 3.1% per year (Song et al., 2017), bamboo forests would play an important role in regional and even national carbon cycle. It's worth noting that the *Rs* studies were fewer in the regions of latitude larger than 48° (~2%) or elevation higher than 3000 m (~4%). The potentially under-represented forest types might affect the evaluation of temperature sensitivity of soil respiration and annual soil carbon emission at the regional and national scale.

5 Data availability

The soil respiration dataset in China's forest ecosystems used to produce the results in this study is free to the public for scientific purposes and can be downloaded at https://doi.pangaea.de/10.1594/PANGAEA.943617 (Sun et al., 2022).

6 Conclusions

In this study, we reviewed the *Rs*-related literatures and collected in situ *Rs* measurements with common infrared gas analyzers (i.e. Li-6400, Li-8100, Li-8150) or gas chromatography to assemble a comprehensive and uniform dataset of China's forest ecosystems at different time scales. Besides the *Rs* data directly given in the original papers, the monthly patterns of *Rs* and the concurrently measured soil temperature at 5 cm and/or 10 cm depth in the figures were digitized. Meanwhile, we have made a preliminary analysis of the data. The results showed that soil temperature could explain 22.5%–93.4% of the *Rs* variations. Temperature sensitivity **(**Q_{10}**)** was about 2.05–2.17 at the national scale, increasing from 1.63 in tropical zone to 3.74 in cold-temperate zone. Monthly *Rs* showed a single-peak curve, and the largest values occurred in August (4.18–4.36 μmol m^{-2} s^{-1}) in cold-temperate and temperate zones, larger than the largest values in July (3.58–3.83 μmol m^{-2} s^{-1}) in subtropical and tropical zones. Mean annual soil carbon emissions decreased from tropical (1042.01 g C m^{-2} yr^{-1}), subtropical (928.91 g C m^{-2} yr^{-1}), temperate (697.85 g C m^{-2} yr^{-1}) to cold-temperate zones (684.29 g C m^{-2} yr^{-1}). This study provides basic data and scientific basis for quantitative evaluation of soil carbon emissions from forest ecosystems in China.

Author contributions. BJ designed the soil respiration dataset and searched the papers until 2018. HS and BJ collected and digitized soil respiration data and compiled the associated information. HS and BJ prepared the manuscript. ZX provided many useful suggestions and reviewed the paper.

Competing interests. The authors declare that they have no conflict of interest.

Acknowledgements. We are grateful to the scientists who contributed their work to the dataset. We thank Ben Bond-Lamberty and four anonymous reviewers for their constructive comments and improvements to this manuscript. This work was supported by the National Natural Science Foundation of China (32071592) and the National Key Research and Development Program of China (2017YFC0503906).

References

Bond-Lamberty, B., Christianson, D. S., Malhotra, A., Pennington, S. C., Sihi, D., AghaKouchak, A., Anjileli, H., Arain, M. A., Armesto, J. J., Ashraf, S., Ataka, M., Baldocchi, D., Black, T. A., Buchmann, N., Carbone, M. S., Chang, S. C., Crill, P., Curtis, P. S., Davidson, E. A., Desai, A. R., Drake, J. E., El-Madany, T. S., Gavazzi, M., Görres, C. M., Gough, C. M., Goulden, M., Gregg, J., del Arroyo, O. G., He, J. S., Hirano, T., Hopple, A., Hughes, H., Järveoja, J., Jassal, R., Jian, J. S., Kan, H. M., Kaye, J., Kominami, Y., Liang, N. S., Lipson, D., Macdonald, C. A., Maseyk, K., Mathes, K., Mauritz, M., Mayes, M. A., McNulty, S., Miao, G. F., Migliavacca, M., Miller, S., Miniat, C. F., Nietz, J. G., Nilsson, M. B., Noormets, A., Norouzi, H., O'Connell, C. S., Osborne, B., Oyonarte, C., Pang, Z., Peichl, M., Pendall, E., Perez-Quezada, J. F., Phillips, C. L., Phillips, R. P., Raich, J. W., Renchon, A. A., Ruehr, N. K., Sánchez-Cañete, E. P., Saunders, M., Savage, K. E., Schrumpf, M., Scott, R. L., Seibt, U., Silver, W. L., Sun, W., Szutu, D., Takagi, K., Takagi, M., Teramoto, M., Tjoelker, M. G., Trumbore, S., Ueyama, M., Vargas, R., Varner, R. K., Verfaillie, J., Vogel, C., Wang, J. S., Winston, G., Wood, T. E., Wu, J. Y., Wutzler, T., Zeng, J. Y., Zha, T. S., Zhang, Q., and Zou J. L.: COSORE: A community database for continuous soil respiration and other soil-atmosphere greenhouse gas flux data. Glob. Change Biol., 26, 7268–7283, https://doi.org/10.1111/gcb.15353, 2020.

Bond-Lamberty, B. and Thomson, A.: A global database of soil respiration data.

Biogeosciences, 7, 1915–1926, http://doi.org/10.5194/bg-7-1915-2010, 2010a.

Bond-Lamberty, B. and Thomson, A.: Temperature-associated increases in the global soil respiration record. Nature, 464, 579–582, https://doi.org/10.1038/nature08930, 2010b.

Burda, B. U., O'Connor, E. A., Webber, E. M., Redmond, N., and Perdue, L. A.: Estimating data from figures with a web-based program: Considerations for a systematic review. Res. Synth. Methods, 8, 258–262, https://doi.org/10.1002/jrsm.1232, 2017.

Chen, G. S., Yang, Y. S., Lv, P. P., Zhang, Y. P., and Qian, X. L.: Regional Patterns of soil respiration in China's forests. Acta Ecol. Sin., 28, 1748–1761, http://www.cnki.com.cn/Article/CJFDTotal-STXB200804047.htm, 2008.

Chen, S., Huang, Y., Zou, J., Shen, Q., Hu, Z., Qin, Y., Chen, H., and Pan, G.: Modeling interannual variability of global soil respiration from climate and soil properties. Agr. Forest Meteorol., 150, 590–605, http://doi.org/10.1016/j.agrformet.2010.02.004, 2010.

Cox, P. M., Betts, R. A., Jones, C. D., Spall, S. A., and Totterdell, I. J.: Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model. Nature, 408, 184–187, http://doi.org/10.1038/35041539, 2000

Davidson, E. A. and Janssens, I. A.: Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. Nature, 440, 165–173, http://doi.org/10.1038/nature04514, 2006.

FAO: Global Forest Resources Assessment 2020: Main report. Rome. https://pipap.sprep.org/content/global-forest-resources-assessment-2020-main-report, 2020.

Geng, Z. P., Mao Z. J., Huang, W., and Han, Y. Y.: Comparative study on the soil respiration and component characteristics of primary broad-leaved Korean Pine forest and *Betula costata* secondary forest in Xiaoxing’an Mountains, China. Bull. Bot. Res., 37, 312–320, http://www.cnki.com.cn/Article/CJFDTotal-MBZW201702021.htm, 2017.

Hashimoto, S., Carvalhais, N., Ito, A., Migliavacca, M., Nishina, K., and Reichstein, M.: Global spatiotemporal distribution of soil respiration modeled using a global database. Biogeosciences, 12, 4121–4132, https://doi.org/10.5194/bg-12-4121-2015, 2015.

Huang, N., Wang, L., Song, X. P., Black, T. A., Jassal, R. S., Myneni, R. B., Wu, C. Y., Wang, L., Song, W. J., Ji, D. B., Yu, S. S., and Niu, Z.: Spatial and temporal variations in global soil respiration and their relationships with climate and land cover. Sci. Adv., 6, eabb8508, https://doi.org/10.1126/sciadv.abb8508, 2020.

Jian, J., Steele, M. K., Thomas, R. Q., Day, S. D., and Hodges, S. C.: Constraining estimates of global soil respiration by quantifying sources of variability. Glob. Chang. Biol., 24, 4143–4159, http://doi.org/10.1111/gcb.14301, 2018.

Jian, J., Vargas, R., Anderson-Teixeira, K., Stell, E., Herrmann, V., Horn, M., Kholod, N., Manzon, J., Marchesi, R., Paredes, D., and Bond-Lamberty, B.: A restructured and updated global soil respiration database (SRDB-V5). Earth Syst. Sci. Data, 13, 255–267, https://doi.org/10.5194/essd-13-255-2021, 2021.

Jian, J., Yuan, X., Steele, M. K., Du, C., and Ogunmayowa, O.: Soil respiration spatial and temporal variability in China between 1961 and 2014. Eur. J. Soil Sci., 72, 739–755, https://doi.org/10.1111/EJSS.13061, 2020.

Lloyd, J. and Taylor, J. A.: On the temperature dependence of soil respiration. Funct. Ecol., 8, 315–323, http://doi.org/10.2307/2389824, 1994.

Peng, S., Piao, S., Wang, T., Sun, J., and Shen, Z.: Temperature sensitivity of soil respiration in different ecosystems in China. Soil Biol. Biochem., 41, 1008–1014, http://doi.org/10.1016/j.soilbio.2008.10.023, 2009.

Raich, J. W., Potter, C. S., and Bhagawati, D.: Interannual variability in global soil respiration, 1980-94. Glob. Chang. Biol., 8, 800–812, http://doi.org/10.1046/j.1365-2486.2002.00511.x, 2002.

Raich, J. W. and Schlesinger, W. H.: The global carbon dioxide flux in soil respiration and its relationship to vegetation and climate. Tellus. 44, 81–99, http://doi.org/10.3402/tellusb.v44i2.15428, 1992.

Rayner, P. J., Scholze, M., Knorr, W., Kaminski, T., Giering, R., and Widmann, H.: Two decades of terrestrial carbon fluxes from a carbon cycle data assimilation system (CCDAS). Glob. Biogeochem. Cycle., 19, GB2026, https://doi.org/10.1029/2004 GB002254, 2005.

Sampson, D. A., Janssens, I. A., Curiel Yuste, J., and Ceulemans, R.: Basal rates of soil respiration are correlated with photosynthesis in a mixed temperate forest. Glob. Chang. Biol., 13, 2008–2017, https://doi.org/10.1111/j.1365-2486.2007.01414.x, 2007.

Shi, W. Y., Yan, M. J., Zhang, J. G., Guan, J. H., and Du, S.: Soil CO_2 emissions from five different types of land use on the semiarid Loess Plateau of China, with emphasis on the contribution of winter soil respiration. Atmos. Environ., 88, 74–82, https://doi.org/10.1016/j.atmosenv.2014.01.066, 2014.

Song, X., Chen, X., Zhou, G., Jiang, H., and Peng, C.: Observed high and persistent carbon uptake by Moso bamboo forests and its response to environmental drivers. Agr. Forest Meteorol., 247, 467–475, https://doi.org/10.1016/j.agrformet. 2017.09.001, 2017.

Song, X., Peng, C., Zhao, Z., Zhang, Z., Guo, B., Wang, W., Jiang, H., and Zhu, Q.: Quantification of soil respiration in forest ecosystems across China. Atmos. Environ., 94, 546–551, http://doi.org/10.1016j.atmosenv.2014.05.071, 2014.

Steele, M. K. and Jian, J.: Monthly global soil respiration database (MGRsD). Blacksburg, VA: VTechData, 2018.

Sun, H. R., Xu, Z. Z., and Jia, B. R.: Soil respiration at different time scales from 2000 to 2018 in forest ecosystems across China. PANGAEA, https://doi.pangaea.de/10.1594/PANGAEA.943617, 2022.

Sun, H. R., Zhou, G. S., Xu, Z. Z., Wang, Y. H., Liu, X. D., Yu, H. Y., Ma, Q. H., and Jia, B. R.: Temperature sensitivity increases with decreasing soil carbon quality in forest ecosystems across northeast China. Clim. Change, 160, 373–384. https://doi.org/10.1007/s10584-019-02650-z, 2020.

Tu, Z. H., Pang, Z., Zhao, Y. Zheng, L. W., Yu, X. X., and Chen, L. H.: Soil respiration components and their controlling factors in a *Platycladus orientalis* plantation in west mountain area of Beijing. Acta Sci. Circumstantiae, 35, 2948–2956, http://www.cnki.com.cn/Article/CJFDTotal-HJXX201509037.htm, 2015.

Wang, W., Chen, W., and Wang, S.: Forest soil respiration and its heterotrophic and autotrophic components: Global patterns and responses to temperature and precipitation. Soil Biol. Biochem., 42, 1236–1244, https://doi.org/10.1016/j.soilbio.2010.04.013, 2010a.

Wang, X., Piao, S., Ciais, P., Janssens, I. A., Reichstein, M., Peng, S., and Wang, T.: Are ecological gradients in seasonal Q_{10} of soil respiration explained by climate or by vegetation seasonality? Soil Biol. Biochem., 42, 1728–1734, https://doi.org/10.1016/j.soilbio.2010.06.008, 2010b.

Wang, Y., Li, Q., Wang, H., Wen, X., Yang, F., Ma, Z., Liu, Y., Sun, X., and Yu, G. Precipitation frequency controls interannual variation of soil respiration by affecting soil moisture in a subtropical forest plantation. Can. J. For. Res., 41, 1897–1906, https://doi.org/10.1139/x11-105, 2011.

Warner, D. L., Bond-Lamberty, B., Jian, J., Stell, E., and Vargas, R.: Spatial predictions and associated uncertainty of annual soil respiration at the global scale. Glob. Biogeochem. Cycle., 33, 1733–1745, http://doi.org/10.1029/2019GB006264, 2019.

Wu, Y. C., Li, Z. C., Cheng, C. F., and Ma, S. J.: Characteristics of soil respiration in a *Phyllostachys pubescens* plantation in the northeast of subtropics. Adv. Mater. Res., 869-870, 832–835, https://doi.org/10.4028/www.scientific.net/AMR.869-870.832, 2014.

Xu, M., and Qi, Y.: Soil-surface CO_2 efflux and its spatial and temporal variations in a young ponderosa pine plantation in northern California. Glob. Change Biol., 7, 667–677, https://doi.org/10.1046/j.1354-1013.2001.00435.x, 2001.

Xu, Z., Tang, S., Xiong, L., Yang, W., Yin, H., Tu, L., Wu, F., Chen, L., and Tan, B.: Temperature sensitivity of soil respiration in China's forest ecosystems: Patterns and controls. Appl. Soil Ecol., 93, 105–110, https://doi.org/10.1016/j.apsoil.2015.04.008, 2015.

Yan, J., Wang, Y., Zhou, G., and Zhang, D.: Estimates of soil respiration and net primary production of three forests at different succession stages in south China.

Glob. Change Biol., 12, 810–821, http://doi.org/10.1111/j.1365-2486.2006.01141.x, 2006.

Yang, H., Liu, S., Li, Y., and Xu, H.: Diurnal variations and gap effects of soil CO_2, N_2O and CH_4 fluxes in a typical tropical montane rainforest in Hainan Island, China. Ecol. Res., 33, 379–392, http://doi.org/10.1007/s11284-017-1550-4, 2018.

Yang, J. Y. and Wang, C. K.: Soil carbon storage and flux of temperate forest ecosystems in northeastern China. Acta Ecol. Sin., 25, 2875–2882, https://www.cnki.com.cn/Article/CJFDTotal-STXB200511011.htm, 2005.

Yao, Y. G., Zhang, Y. P., Yu, G. R., Sha, L. Q., Deng, Y., and Tan, Z. H.: Representative time selection analysis on daily average value of soil respiration in a tropical rain forest. J. Nanjing For. Univ., 35, 74–78, http://www.cnki.com.cn/Article/CJFDTotal-NJLY201104014.htm, 2011.

You, W., Wei, W., Zhang, H., Yan, T., and Xing, Z.: Temporal patterns of soil CO_2 efflux in a temperate Korean Larch (*Larix Olgensis* Herry.) plantation, Northeast China. Trees, 27, 1417–1428, http://doi.org/10.1007/s00468-013-0889-6, 2013.

Yu, G., Zheng, Z., Wang, Q., Fu, Y., Zhuang, J., Sun, X., and Wang, Y.: Spatiotemporal pattern of soil respiration of terrestrial ecosystems in China: The development of a geostatistical model and its simulation. Environ. Sci. Technol., 44, 6074–6080, http://doi.org/10.1021/es100979s, 2010.

Yu, X., Zha, T., Pang, Z., Wu, B., Wang, X., Chen, G., Li, C., Cao, J., Jia, G., Li, X., and Wu, H.: Response of soil respiration to soil temperature and moisture in a 50-year-old *Oriental arborvitae* plantation in China. PLoS ONE, 6, e28397, https://doi.org/10.1371/journal.pone.0028397, 2011.

Zhan, X. Y., Yu, G. R., Zheng, Z. M., and Wang, Q. F.: Carbon emission and spatial pattern of soil respiration of terrestrial ecosystems in China: Based on geostatistic estimation of flux measurement. Progress in Geography, 31, 97–108, http://www.cnki.com.cn/article/cjfdtotal-dlkj201201016.htm, 2012.

Zheng, J. J., Huang, S. Y., Jia, X., Tian, Y., Mu, Y., Liu, P., and Zha, T. S.: Spatial variation and controlling factors of temperature sensitivity of soil respiration in forest ecosystems across China. Chin. J. Plant Ecol., 44, 687–698, http://doi.org/10.17521/cjpe.2019.0300, 2020.

Zheng, Z. M., Yu, G. R., Fu, Y. L., Wang, Y. S., Sun, X. M., and Wang, Y. H.: Temperature sensitivity of soil respiration is affected by prevailing climatic conditions and soil organic carbon content: A trans-china based case study. Soil Biol. Biochem., 41, 1531–1540, http://doi.org/10.1016/j.soilbio.2009.04.013, 2009.

Zheng, Z. M., Yu, G. R., Sun, X. M., Li, S. G., Wang, Y. S., Wang, Y. H., Fu, Y. L., and Wang, Q. F.: Spatio-temporal variability of soil respiration of forest ecosystems in China: Influencing factors and evaluation model. Environ. Manage., 46, 633–642, http://doi.org/10.1007/s00267-010-9509-z, 2010.

Zhou, T., Shi, P. J., Hui, D. F., and Luo, Y. Q.: Spatial patterns in temperature sensitivity of soil respiration in China: Estimation with inverse modeling. Sci. China Ser. C-Life Sci., 52, 982–989, https://doi.org/10.1007/s11427-009-0125-1, 2009.

Table 1. Variable information of soil respiration dataset in China's forest ecosystems, available at https://doi.pangaea.de/10.1594/PANGAEA.943617. N/A refers to values that are not applicable.

Column	Description	Unit	Numbe	Range
ID	Unique identification number of each record	N/A	11297	1–11297
Province	Province location of study site	N/A	28	N/A
Study site	Name of study site	N/A	155	N/A
Latitude	Latitude (N) of study site	°	208	18.61–52.86
Longitude	Longitude (E) of study site	°	218	84.91–129.08
Elevation	Altitude of study site	m	329	7–4200
MAT	Mean annual temperature	°C	122	-5.4–23.8
MAP	Mean annual precipitation	mm	180	105–3000
Forest type	Forest community characterized by the dominant tree species, or the ecological similarities (e.g., life form and biotope)	N/A	180	N/A
Origin	Stand origin was classified into planted and natural (i.e. secondary, primary) forests	N/A	4	N/A
Age	Stand age, estimated from historical records or dominant tree rings in natural forest, defined since planting in planted forest	years	769	2–400
DBH	Mean diameter at breast height	cm	610	2.40–51.96
H_{tree}	Mean tree height	m	538	2.50–48.00
Density	Stem density and/or canopy coverage	trees ha^{-1}	548	209–17000,0.23–0.98
Instrument	Measurement instrument of *Rs*, i.e. gas chromatography, infrared gas analyzers (Li-6400, Li-8100, Li-8150)	N/A	4	N/A
Time	Observation time of *Rs* per day (Beijing time)	Hour:Minute	749	0:00–23:00
Frequency	Observation frequency of *Rs*, i.e. days per month	days	961	0.5–31
Area	Observation area of *Rs*, i.e. area of soil collar or base	cm^2	976	50–2500
Height	Height of soil collar or chamber	cm	828	4–50
Replication	Numbers of soil collar or chamber	N/A	968	1–768
Date	Observation month of *Rs* per year	Month-Year	10288	01-2000–03-2018
Rs	Soil respiration rate, monthly means or a few values per month	$\mu mol\ m^{-2}\ s^{-1}$	10288	0.01–11.84
T_5	Soil temperature at 5 cm depth concurrently measured with R_S	°C	6341	-16.51–33.58
T_{10}	Soil temperature at 10 cm depth concurrently measured with R_S	°C	2878	-16.40–33.46
Mode	The ways to obtain *Rs* data, 1. extracted with WEB PLOTDIGITIZER, 2. directly given in the original study	N/A	2	1–2
Period	Period of annual soil carbon efflux	Month-Year	631	01-2001–03-2018
Annual *Rs*	Annual soil carbon efflux	g C m^{-2} $year^{-1}$	634	260.10–2058.00
Method	Method to calculate annual soil carbon efflux, i.e. integration method and/or interpolation method	N/A	3	N/A
Reference	Data sources	N/A	568	N/A

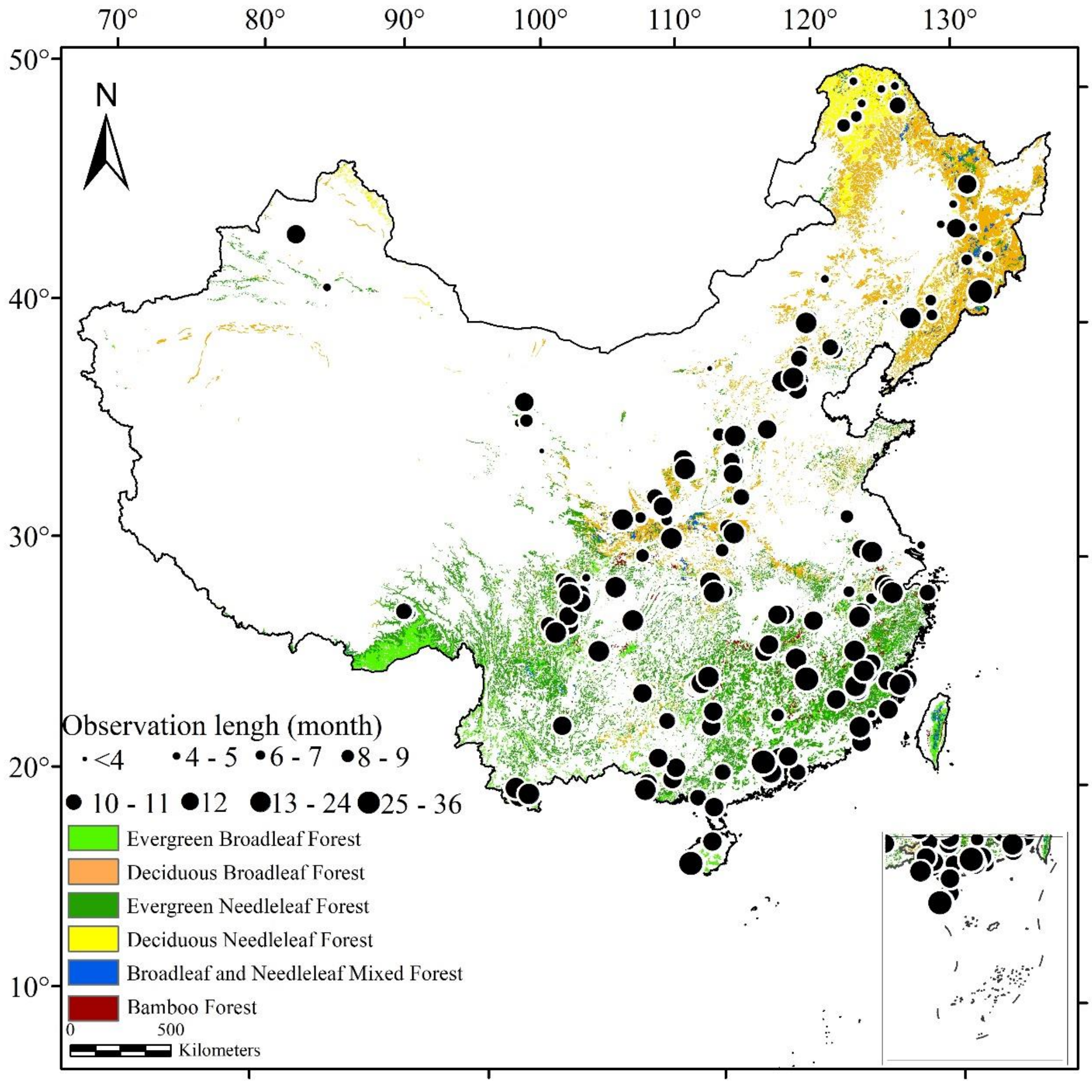

Figure 1. Distribution of study sites used to develop the forest soil respiration dataset in China.

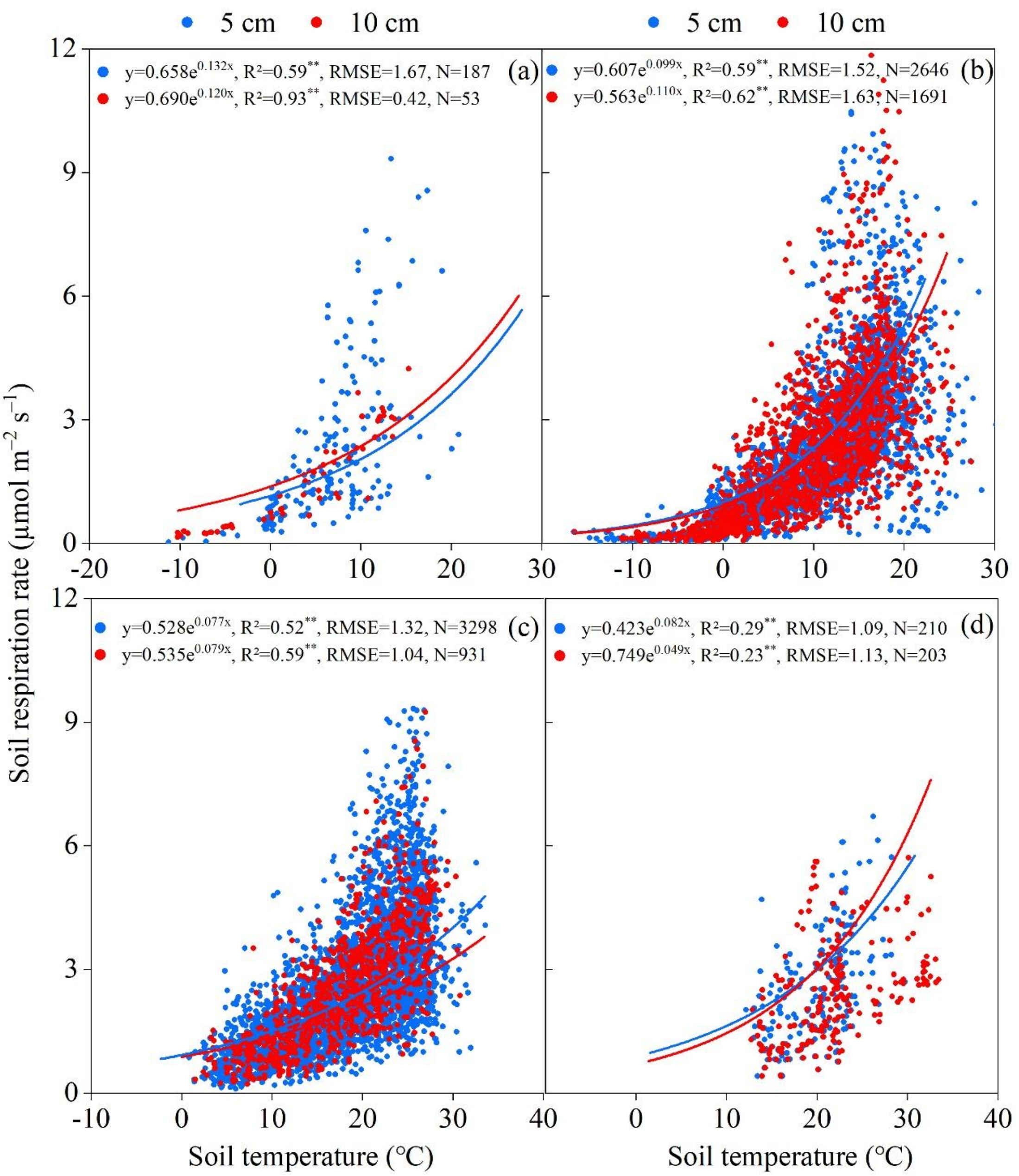

Figure 2. Exponential relationships of forest soil respiration rates with soil temperature at 5 cm depth and 10 cm depth in cold-temperate (a), temperate (b), subtropical (c) and tropical zones (d). *P* value below 0.01 was described by **. RMSE: Root Mean Square Error.

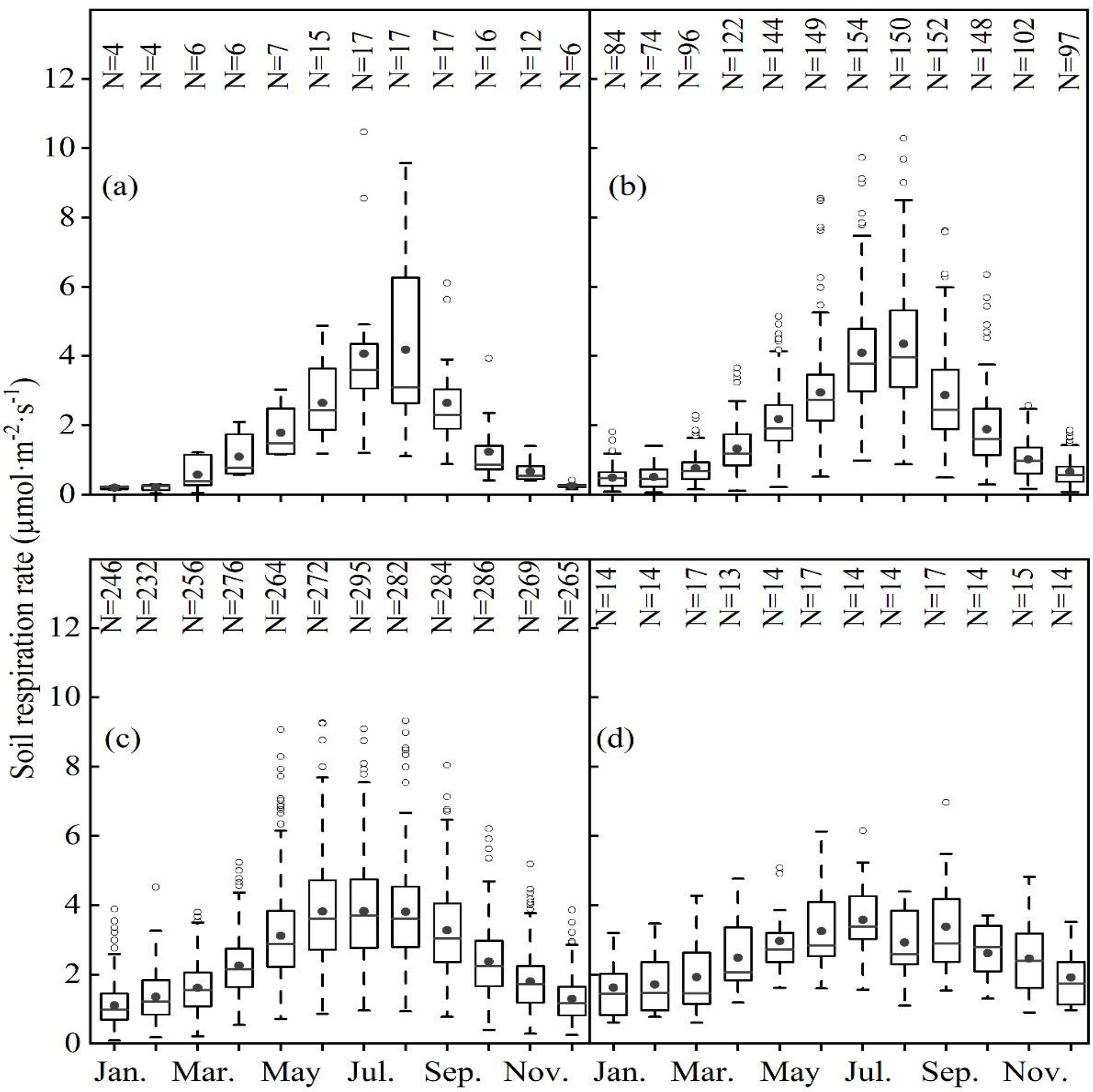

Figure 3. Monthly patterns of forest soil respiration rates in cold-temperate (a), temperate (b), subtropical (c) and tropical zones (d). Solid circle: mean value; Solid horizontal line: median; Box: 25th to 75th percentiles; Whisker: 1.5 times interquartile range; Open circle: data points beyond the whiskers. The samples per month were listed in the upper part of the figure.

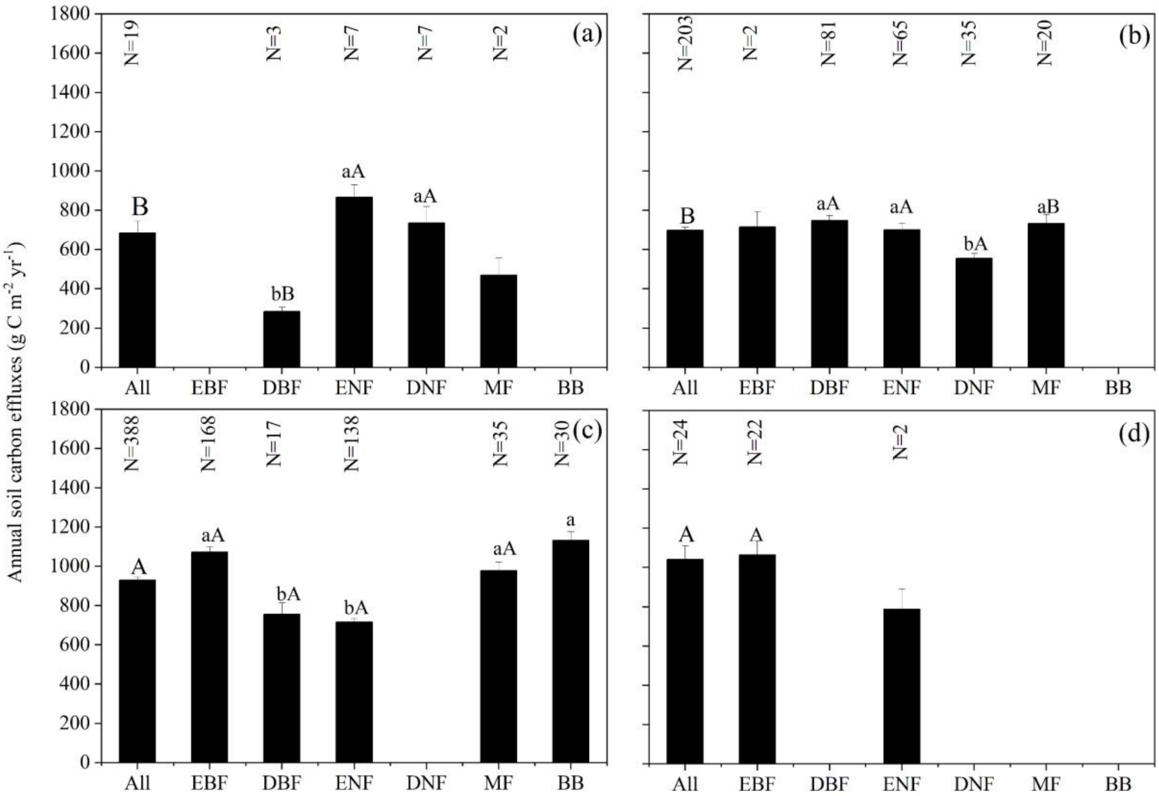

Figure 4. Comparisons of annual soil carbon effluxes (mean ± standard error) among different forest types across China in cold-temperate (a), temperate (b), subtropical (c) and tropical zones (d). Lowercase letters are the comparisons of different forest types in each climatic zone, while capital letters are the comparisons of the same forest type in different climatic zones. The samples were listed in the upper part of the figure, and the samples larger than 3 were compared. EBF: evergreen broadleaf forest, DBF: deciduous broadleaf forest, ENF: evergreen needleleaf forest, DNF: deciduous needleleaf forest, MF: broadleaf and needleleaf mixed forest and BB: Bamboo forest.