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Measurement strategies to account for soil respiration temporal heterogeneity across diverse regions

Jinshi Jian[a,*], Meredith K. Steele[a], Susan D. Day[a,b], R. Quinn Thomas[b], Steven C. Hodges[a]

[a] School of Plant and Environmental Sciences, Virginia Tech, Blacksburg, VA, USA
[b] Department of Forest Resources & Environmental Conservation, Virginia Tech, Blacksburg, VA, USA

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ABSTRACT

Soil respiration (Rs) rates fluctuate daily and seasonally; therefore, the timing of measurements is critical when estimating the daily mean and scaling up to annual Rs rates. Temporal fluctuations also vary with climate and biome, yet the current recommendation for when to measure Rs (e.g., 09:00 to 12:00) has not been evaluated for different climates, biomes, and seasons. To provide more refined recommendations for measuring Rs, we: 1) analyzed the diurnal and seasonal fluctuations of Rs and tested the accuracy of typical measurement practices under different climates and biomes, and 2) identified the measurement frequency necessary for different climates and biomes to achieve certain levels of accuracy in estimating annual Rs. Across biomes, diurnal variation in Rs is considerable in spring and summer, moderate in autumn, and minimal in winter, and closely related with soil temperature. Based on these diurnal patterns, the best measurement time for estimating the daily mean Rs was 10:00 in all climates and biomes, which is within the recommended range of 9:00 and 12:00 previously identified for temperate forests. Measurements made between 20:00 and 23:00 also accurately estimated the daily mean Rs. Regions with high plant coverage over the year have lower seasonal variation and require less measurement frequency. For global scale estimates, Rs needs to be measured once per day to attain an accuracy of ± 10% of the Rs population mean with 95% confidence, and once per month to achieve ± 30% with a confidence of 80%. Results from this study provide guidelines that reduce measurement frequency while retaining reasonable accuracy for better Rs estimates using manual chamber systems.

1. Introduction

Soil respiration (Rs) represents a large flux within the terrestrial carbon cycle and has been measured for decades using non-steady-state portable manual chamber systems (Luo and Zhou, 2006). Rs is influenced by a complex interaction of biophysical factors, thus Rs shows complex fluctuations even within a day. Numerous studies have described Rs diurnal and seasonal fluctuations in different climates and biomes (Chen et al., 2014; Davidson et al., 1998; Parkin and Kaspar, 2004; Savage and Davidson, 2003; Sheng et al., 2010; Xu and Qi, 2001). Daily fluctuations in Rs are usually driven by changes in soil temperature (Rixon, 1968; Medina and Zelwer, 1972; Larionova et al., 1989), soil water content (Davidson et al., 2000), and precipitation (Rochette et al., 1991). Environmental factors such as soil moisture and canopy photosynthesis also affect diurnal variation in Rs and complicate measurement timing (Tang and Baldocchi, 2005). Given the substantial heterogeneity in the diurnal patterns observed in past studies, the timing of Rs measurements should be carefully considered when those measurements are used to estimate the daily mean. Automatic dynamic chamber equipment is recognized as the best technique for capturing the substantial temporal heterogeneity of Rs; however, automatic Rs measurements are too expensive for use over large areas and long periods (Luo and Zhou, 2006). Manual chamber systems can complete a Rs measurement within few minutes, making manual chamber systems flexible for Rs spatial sampling (Luo and Zhou, 2006). One disadvantage of manual chamber systems, however, is the difficulty in evaluating temporal variation of Rs. The manual chamber systems require intensive labor to capture the Rs diurnal fluctuations, especially when used to extrapolate weekly or monthly measurements to an annual carbon budget Rs (Davidson et al., 1998). Systematic bias in discrete Rs measures may lead to substantial error as those measures are used to upscale to regional and global scales, which are in turn used to predict how soil carbon pools will respond to climate change. Therefore, it is critical to choose an appropriate time to measure that is close to the daily mean Rs and measure frequently enough to account for seasonal dynamics.

* Corresponding author. 185 Ag Quad Lane, 342 Smyth Hall, Blacksburg, VA, 24061, USA.
E-mail address: jinshi@vt.edu (J. Jian).

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Currently, the timing of Rs measurements within a day and year varies substantially among studies. For examples, Chen et al. (2014) conducted their measurements from 13:00 to 15:00, Saiz et al. (2006) measured Rs from 10:00 to 16:00, and Savage et al. (2008) measured from 09:00 to 15:00 to represent the daily mean Rs. Davidson et al. (1998) reported that Rs measured from 09:00 to 12:00 most accurately represented the daily mean of Rs in a temperate mixed-hardwood forest. Many subsequent experiments thus measured Rs during a similar period to represent Rs daily means (Xu and Qi, 2001; Savage and Davidson, 2003; Parkin and Kaspar, 2004; Sheng et al., 2010; Zhang, 2011; Chen et al., 2014). However, Davidson et al. (1998) made their conclusion based on Rs measured in a temperate mixed hardwood forest, with no study of applicability to regional or global scales, or to other seasons. Whether the 09:00 to 12:00 window (local time) is appropriate in other climates, biomes, and seasons is uncertain.

The frequency of Rs measurements also varies by study. To estimate the annual Rs at a site, Rs measurements have been taken once per week, once per month, or even once per season in different studies (Chen et al., 2014; Davidson et al., 1998; Sheng et al., 2010; Cueva et al., 2017). Thus, in addition to diurnal variation, quantification of annual Rs can be affected by seasonal Rs variation. Seasonal effects influence Rs in almost all ecosystems (Luo and Zhou, 2006), driven largely by changes in temperature. Rs rates are usually higher in warm periods and lower during colder periods. Seasonal differences in soil moisture is another important limiting factor of Rs, particularly in arid and semiarid ecosystems (Davidson et al., 2000). In addition, within a given climate region, the controlling factors of Rs variation may change from season to season. For instance, in the Great Plains of the USA, neither temperature nor moisture is a limiting factor for Rs in the spring, but moisture becomes a limiting factor in the summer and temperature becomes a limiting factor in the winter (Wan et al., 2005). In Mediterranean climates, water usually constrain Rs during the hot, dry summers, but temperature limits Rs in cold, wet winters (Xu and Qi, 2001). In addition to physical conditions, the plant phenology, such as the differential timing of root growth, root turnover, leaf area index, and litterfall, also influences seasonal variation in Rs (Curiel Yuste et al., 2004; Bond-Lamberty and Thomson, 2010a). In young *Pinus radiata* trees in Christchurch, New Zealand, seasonal increases in Rs were closely related to increases in root production and biomass (Thomas et al., 2000). On a global scale, Rs was found to positively correlate with annual gross primary production (Raich and Potter, 1995). As a result of differences in temperature, moisture, and vegetation, the seasonal Rs variation shows clear spatial patterns among different biomes. To avoid the uncertainty caused by Rs seasonal variations, high measurement frequency (e.g., once per day for at least one year) is required when measuring annual Rs rates (Luo and Zhou, 2006). However, taking Rs measurements 365 days of the year with manual chamber systems are not usually feasible. When sampling is more infrequent, the seasonal variation of Rs can introduce errors to upscaled estimates if that variation of Rs is not considered in the sampling design.

Multiple studies quantified the fine-scale Rs temporal dynamics in ecosystems across the globe. However, researchers lack a consensus protocol to help make decisions regarding Rs measurement timing and frequency because the Rs temporal dynamics among climates and biomes has not been synthesized with respect to measurement timing (Bond-Lamberty and Thomson, 2010b; Cueva et al., 2017). The time period within which Rs measurements are taken, and the frequency with which they are taken, must be carefully considered to avoid systematic errors and biasing global Rs estimates. In this study, our objectives were to establish protocols for Rs measurements used to estimate annual Rs, quantify the effect of sampling frequency on uncertainty, and to identify the minimum frequency to attain 95% confidence a certain level of accuracy. Specifically, we explored: (1) the best measurement times to capture the daily mean Rs in different climates and biomes, (2) the Rs diurnal variation and how it relates to temperature and soil water content, (3) the difference between Rs measured during the daytime or nighttime versus daily mean Rs, and (4) the measurement frequency necessary for different climates and biomes to achieve certain levels of accuracy in estimating annual Rs.

2. Materials and methods

2.1. Data collection

Rs diurnal variation analysis requires hourly timescale data that we obtained by developing an hourly global Rs database (HGRsD) from digitized published articles. We used the key words "soil respiration," "soil CO_2 flux", "soil carbon emission", and "soil respiration diurnal patterns" in the ISI Web of Science and the China National Knowledge Infrastructure (CNKI) databases to search peer-reviewed papers. We used the following criteria to determine whether the publication would be included in our hourly global Rs database: (1) Rs measurements were conducted in the field; (2) the publications included either diurnal Rs measurements or allowed diurnal Rs to be calculated with no or few assumptions; and (3) continuous diurnal Rs records were included if there were four or more measurements per day, and the measurements were evenly distributed across a day (i.e., daily Rs measured at least

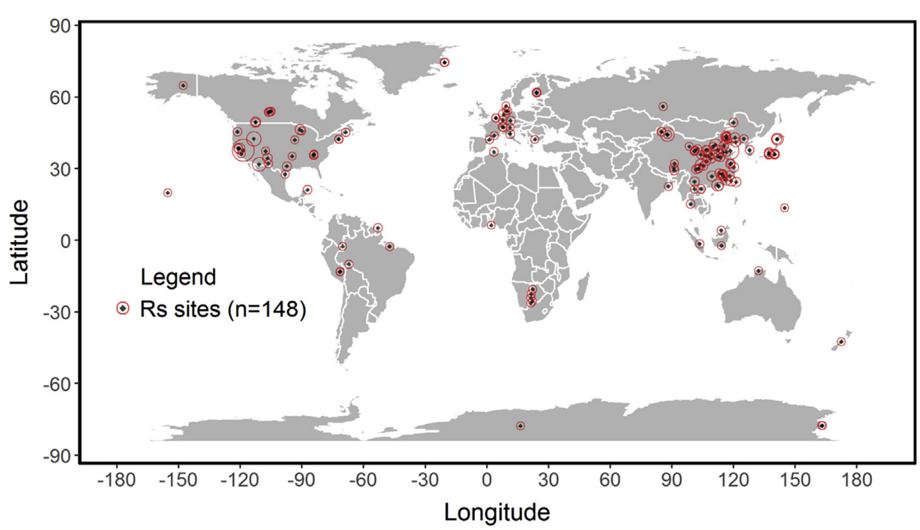

Fig. 1. The spatial distribution of sites in the hourly global soil respiration database (HGRsD). Note that multiple studies may have Rs measurements for a same site, and the circle size in Fig. 1 represents the number of studies in a site.