Agricultural and Forest Meteorology 149 (2009) 2012–2021

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet

Three scales of temporal resolution from automated soil respiration measurements

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ARTICLE INFO

Article history:
Received 5 January 2009
Received in revised form 17 April 2009
Accepted 14 July 2009

Keywords:
Soil respiration
Coherence analysis
Diel
Synoptic

ABSTRACT

Soil respiration (R_s) is a combination of autotrophic and heterotrophic respiration, but it is often modeled as a single efflux process, influenced by environmental variables similarly across all time scales. Continued progress in understanding sources of variation in soil CO_2 efflux will require development of R_s models that incorporate environmental influences at multiple time scales. Coherence analysis, which requires high temporal frequency data on R_s and related environmental variables, permits examination of covariation between R_s and the factors that influence it at varying temporal frequencies, thus isolating the factors important at each time scale. Automated R_s measurements, along with air, soil temperature and moisture were collected at half hour intervals at a temperate forest at Harvard Forest, MA in 2003 and a boreal transition forest at the Howland Forest, ME in 2005. As in other temperate and boreal forests, seasonal variation in R_s was strongly correlated with soil temperature. The organic and mineral layer water contents were significantly related to R_s at synoptic time scales of 2–3 days to weeks, representing the wetting and drying of the soils as weather patterns move across the region. Post-wetting pulses of R_s were correlated with the amount of precipitation and the magnitude of the change from pre-wet-up moisture content to peak moisture content of the organic horizon during the precipitation events. Although soil temperature at 8–10 cm depth and R_s showed strong coherence at a 24-h interval, calculated diel Q_{10} values for R_s were unreasonably high (6–74) during all months for the evergreen forest and during the growing season for the deciduous forest, suggesting that other factors that covary with soil temperature, such as canopy assimilatory processes, may also influence the diel amplitude of R_s. Lower diel Q_{10} values were obtained based on soil temperature measured at shallower depths or with air temperature, but the fit was poorer and a lag was needed to improve the fit (peak R_s followed peak air temperature by several hours), suggesting a role for delayed substrate supply from aboveground processes to affect diel patterns of R_s. High frequency automated R_s datasets afford the opportunity to disentangle the temporal scales at which environmental factors, such as seasonal temperature and phenology, synoptic weather events and soil moisture, and diel variation in temperature and photosynthesis, affect soil respiration processes.

1. Introduction

The increasing concentrations of atmospheric carbon dioxide and other greenhouse gases are primary contributors to observed increases in global temperature. These changes are likely to alter primary productivity, autotrophic respiration, and heterotrophic respiration, and the net carbon balance of ecosystems will depend on how each of these processes responds to changes in climate (Denman et al., 2007). Soil respiration (R_s), a combination of autotrophic (root respiration, R_{root}) and heterotrophic (microbial respiration, R_{micro}) respiration, is a major carbon flux from the terrestrial biosphere to the atmosphere. R_s is primarily correlated to temperature and precipitation (via soil moisture), although there is also a growing recognition that primary productivity and substrate supply (both in terms of amount and quality) are critical drivers of R_s (Davidson et al., 2006a).

A number of studies have examined the relationship between temperature and R_s on diel and seasonal scales (Xu and Qi, 2001; Irvine and Law, 2002; Janssens and Pilegaard, 2003; Yuste et al., 2004; Gu et al., 2008). Empirical models of R_s are expressed as a scalar function of temperature, often represented by an exponential Q_{10} (van't Hoff) value (the scalar multiple by which R_s increases when temperature increases by 10 °C). However, R_s is a complex process, combining R_{micro} and R_{root}, each of which typically

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doi:10.1016/j.agrformet.2009.07.008

emanates from a variety of species and which may respond differently to temperature and other covarying environmental factors such as soil water content and substrate availability (Gu et al., 2008). Responses of R_{micro} and R_{root} are also likely to differ at diel and seasonal time scales. Hence deriving one Q_{10} function representative of R_s on all time scales is overly simplistic.

In past work, when the components of R_s have been distinguished, diel responses of R_{micro} were correlated with soil temperature but R_{root} was decoupled from soil temperature and significantly related to plant phenology (Yuste et al., 2004; Tang et al., 2005a; Liu et al., 2006). R_{root} has been found to derive its carbon source from stored carbohydrates in early spring and recent photosynthate in late spring (Cisneros-Dozal et al., 2006), likely indicating new root growth in late spring. As such, diel trends in R_s during this period maybe more strongly affected by aboveground processes than soil temperature. Significant relationships have been demonstrated between R_s and leaf area index (LAI) and photosynthetically active radiation (PAR), both indicators of photosynthetic activity (Yuste et al., 2004, Liu et al., 2006). However, the time required for recently assimilated carbon to travel from leaves to roots is not well known, and studies have found both a time lag and no time lag between aboveground processes and inferred R_{root} (Davidson and Holbrook, 2009; Tang et al., 2005a; Lui et al., 2006; Gaumont-Guay et al., 2008).

The response of R_s to soil moisture is more complex and often confounded with its relationship to temperature. Soils of many temperate forests tend to dry out as evapotranspiration exceeds precipitation during summer months, thus confounding the effects of temperature on R_s (Davidson et al., 1998). Under drought conditions, water stress significantly decreases rates of R_s over weeks and months as soils gradually dry down (Savage and Davidson, 2001; Borken et al., 2006), primarily because of a decrease in R_{micro} (Cisneros-Dozal et al., 2006).

Increases in soil moisture generally result in increased R_s due to a combination of reduced microbial water stress, release of substrates from turnover of microbial biomass, and greater mobility of available substrate through soil water films (Birch, 1958; Bottner, 1985; Kieft et al., 1987; Xu et al., 2004). This response has been observed to be rapid (minutes to hours) but variable in duration (influence lasting hours to days) and magnitude (Irvine and Law, 2002; Borken et al., 2003). The magnitude and timing of pulse events can significantly influence the annual carbon budget, accounting for up to 11% of the observed seasonal flux (Lee et al., 2004; Tang et al., 2005b). The proportion of R_s derived from either R_{root} or R_{micro} differs under differing moisture conditions (Borken et al., 2006). Cisneros-Dozal et al. (2006) found that decomposition of leaf litter, an R_{micro} component of R_s, varied with moisture status, and changes in leaf litter moisture primarily drove the variability in total R_s fluxes, accounting for 1% under dry conditions and up to 42% of total R_s under wet conditions.

The objective of this study is to examine the response of R_s to changes in temperature and moisture at seasonal, diel and synoptic scales. Using high temporal frequency measurements of R_s, temperature, and moisture, we differentiate the effects of climatic variables at each temporal scale.

2. Methods

2.1. Study site

R_s was measured at the Harvard Forest near Petersham, Massachusetts USA (42°32N, 72°11W), and at the Howland Forest, near Howland Maine, USA (45°12N, 68°44W). Data presented here for Harvard Forest were collected from May 17th through November 11th, 2003, from a well drained mixed hardwood forest, approximately 70 years old. The dominant tree species is red oak. Soils are classified as Canton fine sandy loam, Typic Distrochrepts. Due to agricultural use in the 19th century, the upper mineral soil is partially disturbed. The mean annual temperature is +8.5 °C and the mean annual precipitation is 1050 mm. The precipitation total for 2003 was 1311 mm, approximately 25% greater than the annual average. See Compton and Boone (2000) and Savage and Davidson (2001) for further descriptions.

Data presented here for Howland were collected from May 4th through November 3rd, 2005, and are from a mature boreal transition forest dominated by red spruce and eastern hemlock stands that are at least 160-year old. The soils have never been cultivated and are classified as Skerry fine sandy loam, Aquic Haplorthods. The mean annual temperature is +5.5 °C, and the mean annual precipitation is 1000 mm. The precipitation total for 2005 was 1281 mm, 28% greater than the annual average. See Fernandez et al. (1993), Savage and Davidson (2001) and Hollinger et al. (2004) for further descriptions.

2.2. Automated measurements of R_s

The same automated R_s system and the same sampling strategies and protocols were used for both Harvard and Howland forests. Automated measurements of R_s were made at six chambers each of which was sampled once per half hour. For a description of the automated R_s system see Savage and Davidson (2003). Briefly, each chamber was active for a 5-min period over which time a vented chambertop would close onto the collar and a pump would circulate air from inside the chamber headspace to an infrared gas analyzer (IRGA-Licor 6252). A Campbell CR10X datalogger recorded the change in chamber headspace CO_2 concentration. Air temperature and pressure were used to correct for the number of moles of CO_2 in air. A linear regression was preformed on the increasing chamber headspace concentration to determine a flux rate. About 50,000 flux measurements were obtained for each site. A series of protocols designed to efficiently isolate suspect fluxes was utilized to analyze the data for quality (for a complete description of protocols see Savage et al., 2008). Following the data quality procedures, the final dataset for Harvard consisted of 39,876 R_s measurements and 43,673 for Howland.

2.3. Soil moisture, temperature and organic layer water content

At the Harvard Forest, soil pits were dug to a depth of 80 cm and Campbell Scientific Water Content Reflectometry probes (CS615) were installed at 4.5, 14, 36 and 61 cm. The 4.5 cm volumetric soil moisture (VSM, cm^3 H_2O cm^{-3} soil, Campbell Scientific supplied calibration equation) readings were used for subsequent analysis. Within this same pit, soil temperature was measured (type T-thermocouple) at 4.5, 8.5, 14 and 36 cm. Thirty-six DC-half bridges (for a description of DC-half bridge sensors see Borken et al., 2003) were used to measure the gravimetric water content (g H_2O g^{-1} -dry mass) of the organic layer. Briefly, the half bridge sensors are pieces of basswood (1.59 mm thick and 9 cm^2), which mimic the wetting and drying of the leaf litter. Soil temperature, organic layer water content (O_{WC}) and mineral layer VMS were measured at half hourly intervals and data were collected and stored on a Campbell Scientific CR10X datalogger.

At Howland, soil temperature was measured at 5.0, 10.0 and 20.0 depth using thermistor probes. These data we collected and maintained by the Agricultural Research Service (ARS). Data were available from ftp://130.111.198.38/DataArchives. O_{WC} was measured using 13 half bridge sensors inserted into the leaf litter layer, which consists primarily of conifer needles at Howland Forest. The VSM at the organic–mineral A interface (approximately 5–10 cm depth) was measured using Campbell Scientific Water Content