Agriculture, Ecosystems and Environment 168 (2013) 46–52

Contents lists available at SciVerse ScienceDirect

Agriculture, Ecosystems and Environment

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

Interpreting the dependence of soil respiration on soil temperature and moisture in an oasis cotton field, central Asia

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ARTICLE INFO

Article history:
Received 8 May 2011
Received in revised form 22 January 2013
Accepted 25 January 2013
Available online 21 March 2013

Keywords:
Carbon cycle
Temperature sensitivity
Oasis cotton field
Soil CO_2 efflux

ABSTRACT

To determine how temperature and moisture affect soil respiration, we took half-hourly measurements of soil temperature, water content, and respiration under plants and between rows in a cotton field in central Asia from August through November 2009. We chose the Arrhenius model as the optimum temperature respiration model for this study on the basis of the temperature sensitivity of soil respiration. To normalize soil respiration, we calculated the ratios of measured soil respiration values to predicted soil respiration values. We obtained the effect of water content on respiration by analyzing the relationship between normalized soil respiration using the best fit of the Arrhenius function with soil temperature at a 10-cm depth and water content in the 0–10 cm soil layer. On the basis of these results, we created a two-dimensional model to describe the dynamics of soil respiration. We found that predictions of soil respiration were better when soil temperature and water content were combined into one equation than when the temperature-respiration equation was used. The effects of soil temperature and water content on soil respiration varied by location (under plants vs. between rows).

1. Introduction

Soil respiration (R_s) is a major component of CO_2 exchange between soil and the atmosphere. The response of R_s to climate change (Prentice et al., 2001) is likely to have a significant impact on the CO_2 sink strength of land ecosystems and on future atmospheric CO_2 concentrations. Predicting the response of R_s to climate change requires a thorough understanding of the dependence of this process on soil temperature (T_s) and water content (W_s). Despite the abundant literature dealing with this subject, many questions remain unanswered because of the complexity of below-ground respiration processes and their interaction with the environment. Soil respiration integrates several biological and physical processes, including the production of CO_2 by roots, mycorrhizal fungi, microorganisms, and soil fauna throughout the soil profile, and the subsequent release of CO_2 at the soil surface. It is often affected by interactions of T_s and W_s and the effects of these factors on soil respiration are difficult to separate. Some studies show that R_s is not sensitive to W_s at lower temperatures, but becomes more responsive at higher temperatures (Brumme and Borken, 1999; Carlyle and Bathan, 1988; Curiel Yuste et al., 2003; Drewitt et al., 2002). Similarly, other studies show that R_s is not sensitive to temperature under low moisture conditions, but responds to temperature as moisture content increases (Griffis et al., 2004; Harper et al., 2005; Irvine and Law, 2002; Joffre et al., 2003). However, the seasonal dependence of R_s on W_s remains poorly understood because variations in T_s and W_s are often correlated and the independent effect of each variable is difficult to detect or interpret (Davidson et al., 1998).

The use of the well-known exponential model to describe the response of R_s to temperature has been criticized because of constant temperature sensitivities over a wide range of soil temperatures (Lloyd and Taylor, 1994). Increasing empirical evidence suggests that the temperature sensitivity ($1/R_S \times dR_S/dT_S$) of R_s decreases with increasing soil temperature within and among stands (Janssens and Pilegaard, 2003; Kirschbaum, 1995; Lloyd and Taylor, 1994). Loss of temperature control and a decrease in the temperature sensitivity of R_s has also been found to occur under drought conditions (Borken et al., 1999; Curiel Yuste et al., 2005; Qi et al., 2002; Xu et al., 2004; Xu and Qi, 2001a,b). Despite the apparent unsuitability of the exponential model, it has been widely used for modeling R_s processes (Heimann et al., 1989; Raich et al., 1991; Running and Hunt, 1993; Schimel et al., 2000). Unlike the Arrhenius equation and the Lloyd and Taylor (1994) modification, the exponential model relates the rate of soil respiration to varying temperature through an exponential stand parameter, which determines the rate of change of soil respiration with respect to temperature. This temperature sensitivity measure provides for

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0167-8809/$ – see front matter.
http://dx.doi.org/10.1016/j.agee.2013.01.013

easy understanding of ecosystem carbon dynamics in response to global climate change.

In this study, we analyzed temperature sensitivity variations of R_s to evaluate five basic temperature-respiration models. Based on the results of this analysis, we selected the optimum function to analyze the effect of temperature on R_s. We then normalized R_s (R_{sN}) using the best fit temperature-respiration model to analyze the relationship between R_{sN} and soil moisture and quantify the dependence of R_s on W_s.

Using CO_2 sensors that enable soil CO_2 concentrations to be continuously monitored at different depths to deduce R_s, we measured soil CO_2 concentrations in a cotton field of the Aksu National Experimental Station, Xinjiang, China. We then deduced soil respiration rates using Fick's first law of diffusion. To validate the results, we also periodically measured R_s using chambers.

Our hypotheses were: (1) that the constant temperature sensitivities of exponential functions cannot describe the variations of temperature sensitivities of R_s in the study region, and (2) that the activity of cotton plants in the study region should be considered when analyzing the dependence of soil respiration on soil temperature and moisture.

2. Materials and methods

2.1. Site description

We conducted this study at the Aksu National Experimental Station of the Oasis Farmland Ecosystem (40°37′N, 80°45′E, altitude 1028 m), located in the Aksu Oasis. The 20-year mean minimum and maximum temperature during the study period (August to November) at the station are 16.6 °C and 34.8 °C, respectively. The total annual precipitation is 45.7 mm, of which about 75% occurs in the 4 months from June to September. The alkaline desert soil has a pH of 7.6.

2.2. Environmental measurements

Air temperature, air pressure, and precipitation were measured by an automated weather station (ENVIS Environmental Monitoring System, Instrumentation Consultancy Technologies, A1708) located on the experimental cotton field. We measured T_s every half hour at depths of 5 cm, 10 cm, 15 cm, 20 cm, 40 cm, 60 cm, and 100 cm with a copper-constantan thermocouple profile located near each sensor. Likewise, we measured W_s every half hour within the 0–5 cm, 5–10 cm, 10–15 cm, and 15–20 cm soil layers at the same location using Moisture Point type B segmented Time Domain Refrectometry probes (Model MP-917, ESI Environmental Sensors Inc., Victoria, BC, Canada). The probes were calibrated based on gravimetric measurement of W_s in the 0–10 cm soil layers.

2.3. Experiment design

We located CO_2 monitoring sensors (GMM222), Vaisala Inc., Finland) under cotton plants (P_u) and beneath the gaps between rows of cotton plants (P_g). We buried four sensors at each measurement location at depths of 5 cm, 10 cm, 15 cm, and 20 cm; the sensors were separated horizontally by about 3 cm. We performed each measurement in triplicate. A schematic design of the sample plot is shown in Fig. 1.

A cable connected each soil probe with a transmitter body placed on the ground. The transmitter sent output signals from the probe to a data logger (CR1000, Campbell Scientific Inc., Logan, UT, USA) and to an optional LCD display on the transmitter. The soil CO_2 concentrations were measured half-hourly during the experimental period (19 August to 8 November). On 12 November, we excavated the sensor, brought them to the laboratory and recalibrated them; we found no change in the slop**e** or offset. We calculated half-hourly R_s (μmol CO_2 m^{-2} s^{-1}) using Fick's first law of diffusion:

$$R_s = -D_s \frac{d_c}{d_z} \tag{1}$$

where D_s is the CO_2 diffusion coefficient in the soil and d_c/d_z is the vertical soil CO_2 gradient (Tang et al., 2003). D_s can be estimated as

$$D_S = \xi D_a \tag{2}$$

where ξ is the gas tortuosity factor and D_a is the CO_2 diffusion coefficient in free air. The effect of temperature and pressure on D_a is given by

$$D_a = D_{a0}\left(\frac{T}{293.15}\right)^{1.75}\left(\frac{P}{101.3}\right) \tag{3}$$

where T is the temperature (K), P is the air pressure (kPa), and D_{a0} is a reference value of D_a at 20 °C (293.15 K) and 101.3 kPa, and is given as 14.7 mm^2 s^{-1} (Jones, 1992).

Several empirical models are available for computing ξ (Sallam et al., 1984). We used the Millington–Quirk model (Millington, 1959):

$$\xi = \frac{\alpha^{10/3}}{\phi^2} \tag{4}$$

where α is the volumetric air content (air-filled porosity) and φ is the porosity. Note,

$$\phi = \alpha + \theta = 1 - \frac{\rho_b}{\rho_m} \tag{5}$$

where ρ_b is the bulk density, ρ_m is the particle density for the mineral soil and θ is the volumetric water content.

Soil surface CO_2 efflux was calculated using the CO_2 gradient flux method based on CO_2 concentrations within the soil profile (Vargas and Allen, 2008). Briefly, the flux of CO_2 between any two layers in the soil profile was calculated using the Moldrup model (Moldrup et al., 1999). Assuming a constant rate of CO_2 production in the soil profile, R_s was calculated as:

$$R_s = \frac{z_{i+1}F_i - z_i F_{i+1}}{z_{i+1} - z_i} \tag{6}$$

where F_i and F_{i+1} are CO_2 effluxes (μmol m^{-2} s^{-1}) at depths z_i and z_{i+1}, respectively (Baldocchi et al., 2006).

2.4. Soil respiration measurements using closed chambers

To validate the R_s values measured using the CO_2 sensors, we periodically measured R_s using chambers in the two locations (under plants and between rows). Each location contained four measurement points; the mean of the four measurements was used to validate R_s measured by the CO_2 sensors. We measured all sampling points using an infrared gas analysis system (CIRAS-1, PP Systems, Hitchin, UK) equipped with a flow-through chamber. During measurements, the chamber (area of 78 cm^2 and volume of 1170 cm^3), was inserted 3 cm deep into the soil. Measurement with the equipment at each sampling point took 120 s, which was long enough to obtain reliable estimates of soil CO_2 respiration (Koerber et al., 2010). Measurements were made between 12:00 pm and 4:30 pm, which estimated midday values of soil CO_2 respiration. Midday values typically are representative of daily averages in scrublands (Mielnick and Dugas, 2000).

2.5. Data analysis

Since the spatial variability of R_s both under plants and between rows was low (coefficient of variation = 0.17 and 0.11), we averaged the half-hourly measurements made at the three plots to obtain a