Available online at www.sciencedirect.com

ScienceDirect

ELSEVIER

Geoderma 145 (2008) 17 – 27

GEODERMA

www.elsevier.com/locate/geoderma

Sensitivity of simulated soil heterotrophic respiration to temperature and moisture reduction functions

J. Bauer *, M. Herbst, J.A. Huisman, L. Weihermüller, H. Vereecken

Agrosphere, ICG-4, Forschungszentrum Jülich GmbH, Leo Brandt Straße, 52425 Jülich, Germany

Received 27 April 2007; received in revised form 27 November 2007; accepted 21 January 2008
Available online 14 March 2008

Abstract

In this study, the influence of different soil temperature and moisture reduction functions for scaling decomposition rates of soil organic matter on the prediction of CO_2 production and fluxes was analysed. For this purpose, soil temperature and moisture reduction functions of six soil carbon decomposition models (CANDY, CENTURY, DAISY, PATCIS, ROTHC, and SOILCO2) were implemented in the modified SOILCO2-ROTHC model. As a test scenario, a respiration experiment on a silt loam in Columbia (USA) was chosen, which consists of two periods both including soil respiration measurements in a wheat stand and a subsequent bare soil period. Additionally, the dataset contains measured soil temperature, soil moisture as well as CO_2 concentrations within the soil profile. The cumulative CO_2 fluxes simulated with different temperature reduction functions showed deviations up to 41% (1.77 t C ha^{-1}) for the six-month simulation period in 1981. The influence of moisture reduction was smaller with deviations up to 2% (0.10 t C ha^{-1}). A combination of corresponding temperature and moisture reduction functions resulted in the highest deviations up to 41% (1.80 t C ha^{-1}). Under field conditions the sensitivity towards soil temperature reduction was 6 to 7 times higher compared to soil moisture reduction. The findings of this study show that the choice of soil temperature and soil moisture reduction functions is a crucial factor for a reliable simulation of carbon turnover.

Keywords: Reduction functions; Temperature; Water content; Sensitivity; CO_2 fluxes; SOM decomposition

1. Introduction

The atmospheric concentration of carbon dioxide as the most important greenhouse gas increased from the pre-industrial value of about 280 ppm to 379 ppm in 2005 (IPCC, 2007). As stipulated by the Kyoto protocol, appropriate strategies must be developed to counteract the increase of atmospheric CO_2 concentrations. Besides the development of new technologies to reduce anthropogenic CO_2 emissions, changes in land use and land management play an important role (Lal, 2004) as soil respiration is one of the largest fluxes of CO_2 to the atmosphere (Schlesinger and Andrews, 2000). The main processes contributing to soil respiration are root and heterotrophic respiration. Heterotrophic respiration is not only determined by the total amount of soil organic matter (SOM) within the soil profile but also by the composition of SOM because of the high variability of biodegradability of different organic substances. To describe the heterogeneous character of SOM, several multi-pool models have been developed over the last decade, such as ROTHC (Coleman and Jenkinson, 2005), CANDY (Franko et al., 1995), and DAISY (Hansen et al., 1990). These models differ in the number of pools and the interactions between the single pools. Furthermore, multi-pool models are necessary to describe both short-term and long-term responses of soil carbon (Schimel et al., 1994; Trumbore, 2000). Most multi-pool models were developed and validated for specific sites and datasets and should not be used straightforward for simulation of carbon turnover at different sites. This has been clearly demonstrated by Smith et al. (1997) using nine different soil carbon turnover models and twelve long-term datasets. The final results show that a number of models did well for a range of datasets, but none of the models was capable to satisfactorily simulate all scenarios. Prediction of SOM turnover at the global

---

* Corresponding author. Tel.: +49 2461 616136; fax: +49 2461 612518.
E-mail addresses: j.bauer@fz-juelich.de (J. Bauer), m.herbst@fz-juelich.de (M. Herbst), s.huisman@fz-juelich.de (J.A. Huisman), l.weihermueller@fz-juelich.de (L. Weihermüller), h.vereecken@fz-juelich.de (H. Vereecken).

0016-7061/$ - see front matter. © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.geoderma.2008.01.026

scale requires models that perform well under various environmental conditions.

Most SOM decomposition models are zero-dimensional without depth discretisation. Consequently, spatial variations in SOM concentration, soil temperature, moisture, and soil aeration cannot be considered. In contrast, physically-based models enable an accurate description of the transport of water, heat, and CO_2 in the soil profile, but often use very simplified approaches for calculation of SOM decomposition and are unable to describe carbon dynamics. Recently, Herbst et al. (in press) integrated the multi-pool concept of the ROTHC model into the 1D physically-based water, heat, and CO_2 transport model SOILCO2 (Simunek and Suarez, 1993) to simulate depth-dependent SOM turnover. The ROTHC model has been widely used for various simulations of SOM decomposition processes (e.g. Coleman et al., 1997; Jenkinson et al., 1999; Cerri et al., 2003; Yang et al., 2003; Diels et al., 2004) and is therefore well established. In ROTHC, SOM is separated into five pools. The first pool is inert organic matter (IOM), which is resistant to decomposition during the considered time period (≤100 y). The remaining four pools are decomposable plant material (DPM), resistant plant material (RPM), microbial biomass (BIO), and humified organic matter (HUM). In contrast to the original simple SOILCO2 approach for the CO_2 production by heterotrophic respiration, the ROTHC concept can describe quantitative changes of SOM due to plant input as well as qualitative SOM differences. Therefore, the coupling of SOILCO2 and ROTHC overcomes the weak points of both models.

Decomposition of the C-pools is usually described by first order kinetics with different decomposition rate constants. These constants are valid for optimal environmental conditions and a reference temperature and are transferred to the decomposition rates for the actual environmental conditions by reduction functions. The reduction concepts of the various SOM decomposition models include reduction functions using different dependencies and expressions. Soil temperature and moisture are considered as the most important variables for decomposition of SOM (Singh and Gupta, 1977). Moncrieff and Fang (1999) detected a two times higher sensitivity of CO_2 fluxes towards soil temperature than towards soil moisture after increasing the status variable values by 5%. Temperature dependence of SOM decomposition is often expressed as Q_{10}- or the related Arrhenius function, but other expressions are also used (Kirschbaum, 2000). Temperature sensitivity of SOM decomposition is more complex than the pragmatic modelling approaches discussed here, as has been illustrated in the review of Davidson and Janssens (2006). Conflicting results (e.g. Fang et al., 2005; Knorr et al., 2005) indicate that this is an unresolved topic.

The expressions for soil moisture reduction functions are more diverse. For example, different models use different variables to describe the influence of soil moisture, such as volumetric water content (Fang and Moncrieff, 1999) or matric potential (Hansen et al., 1990; Simunek and Suarez, 1993). Another difference between the soil moisture reduction functions is that some models implicitly include the effects of soil aeration in the soil moisture reduction function (Hansen et al., 1990; Simunek and Suarez, 1993).

The diversity of reduction functions in models with similar structures can on the one hand be attributed to different conditions of the test sites where the models were developed and validated (Heinen, 2006) and on the other hand to different conceptual ideas. Rodrigo et al. (1997) illustrated the variation of temperature and moisture reduction factors between nine C–N simulation models. They hypothesised that different reduction functions can lead to major differences in model outputs.

The aim of this study is to assess the influence of different soil temperature and moisture reduction functions on the simulation of SOM decomposition and CO_2 fluxes using a realistic scenario. In order to do so, we first validate the coupled SOILCO2-ROTHC model for the test scenario. In a next step, the sensitivity of soil CO_2 fluxes towards the reduction functions is quantified for the same test scenario.

2. Materials and methods

2.1. Modelling of SOM decomposition with the coupled SOILCO2-ROTHC model

In order to improve modelling of carbon dynamics in soils, the zero-dimensional ROTHC pool model (Coleman and Jenkinson, 2005) was integrated in the one-dimensional physically-based transport model SOILCO2 (Simunek and Suarez, 1993) as described by Herbst et al. (in press). Water flow is calculated using the Richards equation:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[k(h)\left(\frac{\partial h}{\partial z} - 1\right)\right] - Q \tag{1}$$

where h is the water pressure head [cm], θ is the volumetric water content [cm^3 cm^{-3}], k is the unsaturated hydraulic conductivity [cm d^{-1}], t is time [d], z is the depth [cm], and Q is a source/sink term [cm^3 cm^{-3} d^{-1}]. Soil water retention $\theta(h)$ and hydraulic conductivity $k(h)$ are described by the Mualem–van Genuchten approach (van Genuchten, 1980). Heat transport is calculated according to Sophocleous (1979) by:

$$C\frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left[\lambda(\theta)\frac{\partial T}{\partial z}\right] - C_w\frac{\partial J_w T}{\partial z} \tag{2}$$

where T is the soil temperature [°C], λ is the thermal conductivity of the soil [kg cm d^{-3} $°C^{-1}$], C and C_w are the volumetric heat capacities [kg d^{-2} cm^{-1} $°C^{-1}$] of the porous medium and the liquid phase, respectively, and J_w is the water flux [cm d^{-1}]. The first term on the right side of Eq. (2) represents the heat flow due to conduction and the second term the heat transported by water flow.

The transport of carbon dioxide is described by the following equation:

$$\frac{\partial c_T}{\partial t} = -\frac{\partial}{\partial z}(J_{da} + J_{dw} + J_{ca} + J_{cw}) - Qc_w + S \tag{3}$$

where J_{da} describes the CO_2 flux caused by diffusion in the gas phase [cm d^{-1}], J_{dw} the CO_2 flux caused by dispersion in the dissolved phase [cm d^{-1}], J_{ca} the CO_2 flux caused by convection in the gas phase [cm d^{-1}], and J_{cw} the CO_2 flux caused by convection in the dissolved phase [cm d^{-1}]. The total