Modelling soil and root respiration in a cotton field using the DNDC model

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Abstract

The DNDC model was able to simulate the temporal variation in soil respiration, although it underestimated the cumulative CO_2 emission by 15%. A good correlation was found between predicted and measured root respiration. However, this model is limited in its ability to simulate heterotrophic respiration which was underestimated by 59%. The sensitivity tests showed that temperature, precipitation, soil organic C content, fertilization, and irrigation had a positive effect on soil respiration.

Key words: soil respiration / root respiration / DNDC model / cotton field

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1 Introduction

Soil respiration normally refers to the total CO_2 emission from the soil surface and consists of autotrophic and heterotrophic respiration (*Hanson* et al., 2000). Agricultural soils are important sources of CO_2 emission and the mean value of annual soil respiration for cultivated lands in the terrestrial ecosystem is 5.44 t C ha^{-1} (*Raich* and *Schlesinger*, 1992). In the arid region of China, soil respiration in agricultural ecosystem is approx. 2 to 5 times greater than that in natural ecosystems because of crop growth and management practices (*Lai* et al., 2012), and root respiration accounts for approx. 64% of total soil respiration (*Li* et al., 2011). Soil respiration predicted by using DNDC model includes root respiration and heterotrophic respiration (*Li* et al., 1994), which provides a useful tool for calculating CO_2 emissions from roots and soil microorganisms. To our knowledge, previous studies only reported root respiration predicted by DNDC (*Abdalla* et al., 2011; *Wang* et al., 2011) and seldom validated the DNDC model using measured root respiration data. Thus, the objectives of this study were: (1) to evaluate the suitability of the DNDC model to simulate soil respiration and to distinguish between autotrophic and heterotrophic respiration; and (2) to assess the effect of climate, soil properties, and management practices on soil respiration in an oasis cotton field.

2 Material and methods

The DNDC (denitrification–decomposition) model contains four sub-models (soil climate, crop growth, denitrification, and decomposition). The detailed model structure can be found in *Li* et al. (1994). In this model root respiration is described using the crop growth sub-model and heterotrophic respiration is simulated using the decomposition sub-model. To simulate soil respiration from the cotton field, the DNDC model was run using local climate data (Fig. 1), soil properties, and farming management information. In this study, the soil texture is silt loam in the upper (0–20 cm) horizon, with a bulk density of 1.33 g cm^{-3}. The soil organic C (SOC) content and soil pH are 0.008 kg C kg^{-1} and 7.6, respectively. Cotton was sown on April 17, 2012, and the seeds were spaced at a distance of 10 cm between rows and 50 cm within rows. During the growing period, the field was irrigated 9 times to provided 360 mm water: July 07, July 18, July 25, August 02, August 08, August 14, August 23, August 30, and September 07. The urea was dissolved in the irrigation water and applied 6 times to provide 240 kg N ha^{-1} from July 07 to August 14. The cotton was harvested on October 30, and all of the residues were left and incorporated into the soil during the next tillage. The maximum biomass production was 2,400, 4,960 and 910 Kg C ha^{-1} y^{-1} and biomass C/N ratios were 13, 34, and 50 for grain, straw, and root, respectively. Measured values were used to validate the model outputs. To quantify the discrepancy between the simulated and measured values, the statistical criteria of root mean square error (*RMSE*) and model efficiency (*ME*) were calculated as described by *Abdalla* et al. (2011). To determine the factors that significantly affect soil respiration, different climate, soil properties, and agricultural management scenarios were used to quantify the sensitivity degree of the DNDC model. Alternative scenarios were constructed by changing the values of a single input factor while keeping all the other input parameters constant (*Wang* et al., 2011). According to the research conducted by *Li* et al. (1994), the mean annual temperature, total annual precipitation, SOC content, soil texture, fertilization, and irrigation were used for the sensitivity test (Table 1). The baseline scenario used local climate and agricultural management practices in 2012. The ranges in the soil properties were based on the second national soil survey that was conducted during 1979–1994 and which covered all counties in Xinjiang (*Nationally Soil Census Office*, 1996).

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Table 1: Ranges of variation in climate, soil, and management scenarios for sensitivity analysis.

Parameters	Baseline	Range
Annual mean temperature / °C	11.35	7.35, 9.35, 13.35, 15.35
Annual precipitation / mm	60.2	30.1, 45.15, 75.25, 90.3
SOC content / %	0.8	0.5, 1.0, 1.5, 2.0
Soil texture	silt loam	sand (S), sandy clay loam (SCL), clay loam (CL), silty clay (ZC)
Fertilization / kg N ha^{-1}	340	220, 280, 400, 460
Irrigation / mm	320	200, 260, 380, 440

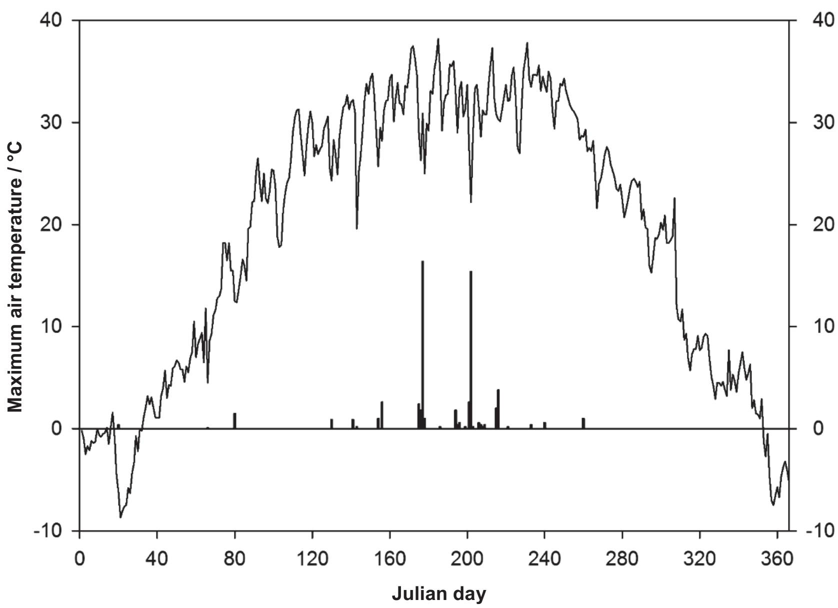

Figure 1: Maximum air temperature and precipitation during the experimental period (2012).

Soil respiration was measured using an infrared gas analyzer system (CIRAS-1, PP System, Hitchin, UK) equipped with a flow-through closed chamber. The chamber was left in position for 5 d before the measurements to reduce soil disturbance and erroneous values. During the experimental period, three plots were randomly selected for the removal of aboveground vegetation on July 06, and we periodically measured soil respiration from August 08 to October 26. We found that the CO_2 emission from decaying roots accounted for only 3% during the experiment period using DNDC (Fig. 2). Therefore, we are confident that there was little CO_2 contribution in heterotrophic respiration from the plots where the aboveground vegetation was removed. We regarded the soil respiration from the cotton field as the total belowground respiration (R_t) and the temperature normalized soil respiration from the bare land where the aboveground vegetation was removed from a relatively large area as heterotrophic respiration (R_h). Therefore, the difference in R_t and R_h was ascribed to root respiration (R_r).

3 Results and discussion

3.1 Model validation

Previous studies reported that the DNDC model produced favorable correlations between measured and simulated daily fluxes, but that it underestimated the cumulative CO_2 emissions (*Abdalla* et al., 2011; *Chen* et al., 2013). *Chen* et al. (2013) showed that this model underestimated the cumulative CO_2 emissions by 27% and 39% for straw incorporation treatment and straw burning treatment, respectively. *Abdalla* et al. (2011) also found that DNDC underestimated the cumulative annual CO_2 emissions from an arable field by 9% and 8% for conventional and reduced tillage. In this study, the DNDC model provided an acceptable simulation of soil respiration from the cotton field and the calculated *RMSE* and *ME* values for R_t were 8.48 kg C (ha · d)$^{-1}$ and 0.67, respec-

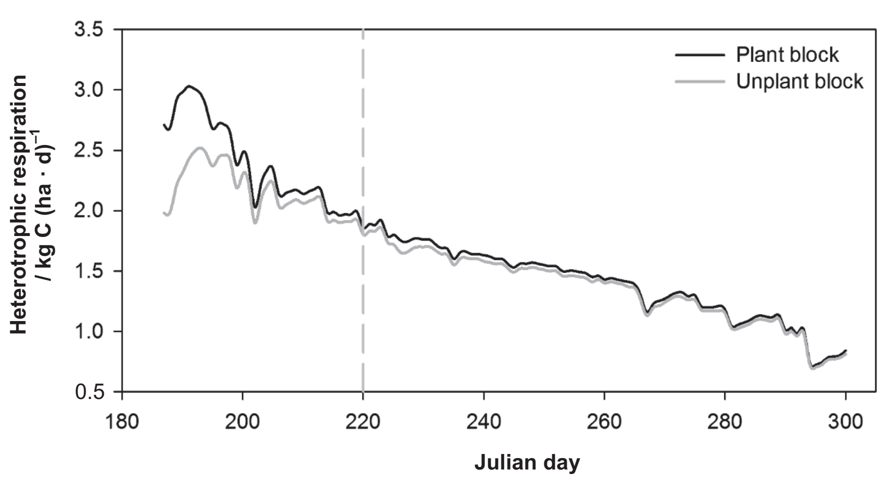

Figure 2: Heterotrophic respiration from un-plant block and the block where aboveground vegetation had been removed.

tively (Table 2), although it slightly underestimated the cumulative CO_2 emission by 15% (Fig. 3).

Table 2: Statistics of DNDC simulations *versus* observations with regard to concerned variables.

Concerned variables	Linear equation	R^2	RMSE / kg C (ha · d)$^{-1}$	ME	*n*
R_t	y = 1.12x – 6.37	0.81	8.48	0.67	49
R_r	y = 1.34x – 5.55	0.80	8.88	0.43	49
R_h	y = 0.26x + 1.02	0.58	5.10	–0.93	49

Both the DNDC-simulations and observations showed that R_r was the main source of soil respiration during the experimental period, with the contribution of R_r to R_t ranging from approximately 57% to 87% (Fig. 3). This result is consistent with *Li* et al. (2011) who estimated that the contribution of root respiration to total soil respiration was 64%. Nevertheless, the simulations still showed some discrepancies in R_r (Fig. 3) and the calculated *RMSE* and *ME* values for R_r were 8.88 kg C (ha · d)$^{-1}$ and 0.43, respectively (Table 2). This discrepancy is most likely related to the ability of the DNDC model to simulate root respiration. In the crop growth sub-model, root respiration is based on a generalized crop growth curve used for all crops, and CO_2 produced by root growth and N uptake is considered to be the main source of root respiration (*Li* et al., 1994). This probably led the model to overestimate the root activity during the growth period but underestimate the duration of root growth and nitrogen uptake, which consequently caused the inconsistencies in this study. In fact, a previous study showed that root growth of cotton continued during the whole growing period (*Zhao* et al., 2010), which is not well reflected in this model. Despite these differences, this model predicted a cumulative CO_2 emission of 1.67 t C ha^{-1} compared with the measured value of 1.68 t C ha^{-1}. Unfortunately, the DNDC model underestimated the cumulative CO_2 emissions from R_h by 59% (Fig. 3), and the calculated *RMSE* and *ME* values for R_h were 5.10 kg C (ha · d)$^{-1}$ and –0.93, respectively (Table 2). This result is greater than the value reported by *Chirinda* et al. (2011), who suggested that parameterization of C pools in this model may lead to a reduction in the C turnover rate and consequently, a 10–40% underestimation in heterotrophic respiration. In addition, the DNDC model performed well in predicting the soil temperature and moisture (Fig. 4).

3.2 Sensitivity tests

In this study, DNDC-simulated soil respiration under different temperature scenarios produced different results, and the variation was mainly attributed to changes in root respiration (Fig. 5a). First, this model predicted that soil respiration increased by 16% as the temperature increased from 7.35°C to 13.35°C. This result is consistent with previous studies, which suggested that soil respiration has a significant positive correlation with temperature if soil water content is not a limiting factor (*Zhao* et al., 2013; *Kainiemi* et al., 2015). Second, several publications suggested that the temperature sensitivity of soil respiration decreased with increasing temperature (*Zheng* et al., 2009; *Zhao* et al., 2013). Accordingly, in this study, the increased rate of soil respiration decreased as temperature further increased from 11.35°C to 13.35°C. Lastly, soil respiration decreased as temperature further increased by 2°C. This was probably attributed to the impact of a higher temperature on plant biomass and physiological processes, which further inhibited CO_2 emission from root respiration following global warming (*Zhao* et al., 2013). The impacts of precipitation change on soil respiration were mainly attributed to an increase in the number of periods with higher soil moisture content, which enhanced root biomass and activity and consequently increased soil respiration (*Jiang* et al., 2013). In our study, precipitation had a significant positive effect on root respiration in the DNDC simulations. A similar result was reported by *Wang* et al. (2011) who found greater CO_2 emissions under higher precipitation scenarios compared with the baseline values in an oasis farmland using DNDC-modelled data.

The SOC content played an important role in controlling modelled soil respiration compared with soil texture (Fig. 5b). As the initial SOC content increased from 0.5% to 2%, the simu-

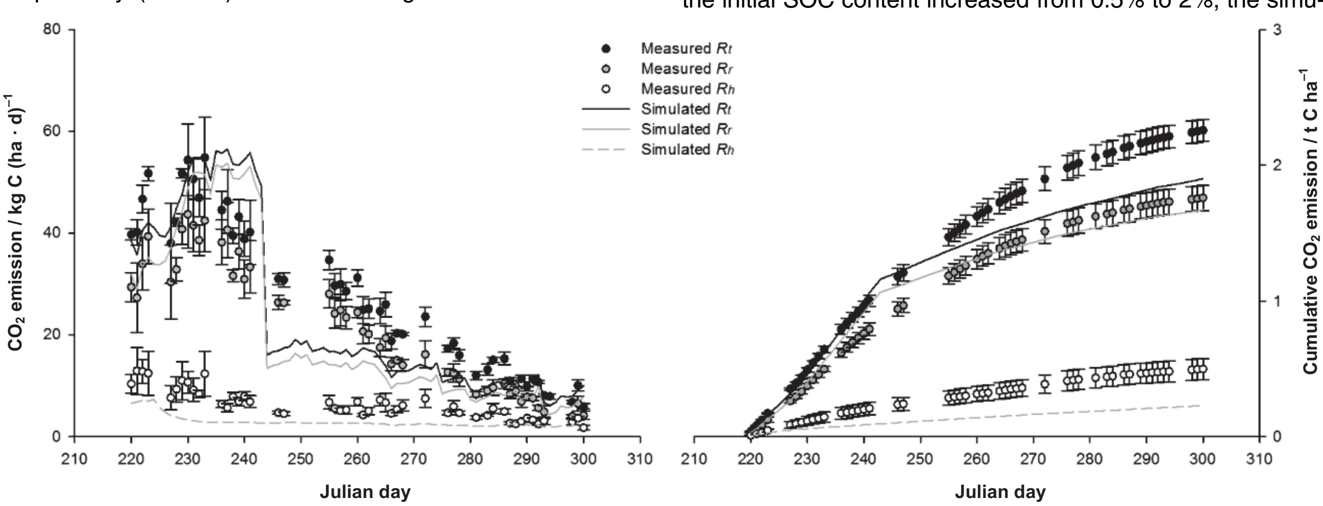

Figure 3: Measured and DNDC-simulated daily and cumulative CO_2 emissions from total belowground respiration (R_t), root respiration (R_r), and heterotrophic (R_h) respiration in the cotton field. The vertical bars indicate the standard errors of three replicates.

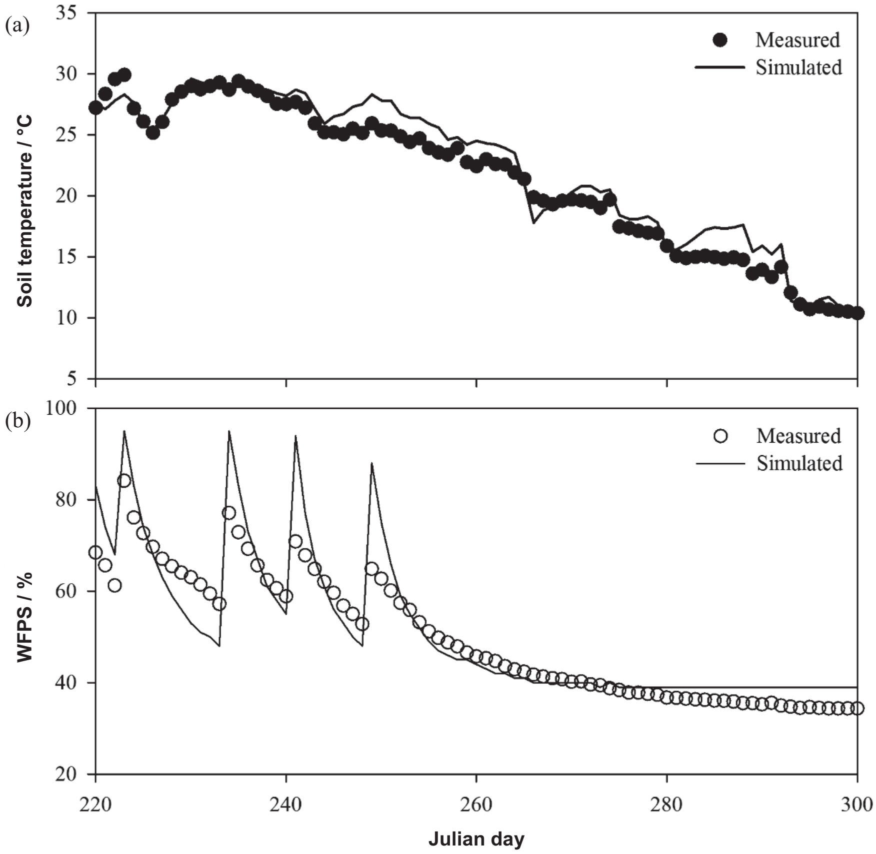

Figure 4: Measured and DNDC-simulated soil temperature [(a) RMSE = 1.36°C; ME = 0.95) and WFPS [(b) RMSE = 6.34%; ME = 0.80) in the top soil (0–10 cm).

lated R_t, R_r, and R_h increased by 47, 14, and 251%, respectively. Similar conclusions were drawn in several other studies (*Li* et al., 1994; *Wang* et al., 2011). Indeed, SOC is not only the determining material basis for CO_2 production by microbial decomposition but also efficiently influences crop growth and subsequently affects root respiration (*Wang* et al., 2011). In our study, the increase in soil respiration with an increase in SOC was mainly attributed to higher heterotrophic respiration. The influence of soil texture on soil respiration was mainly through its effect on soil hydraulic characteristics and soil aeration (*Wang* et al., 2011). In our study, soil respiration increased from sand soil to silt loam soil and then decreased from silt loam soil to silty clay soil (Fig. 5b). This result was probably because soil aeration decreases in clay soil, which further reduces CO_2 emission (*Wang* et al., 2011).

The DNDC model predicted that the effect of management practices on simulated soil respiration were mainly attributed to the change in root respiration (Fig. 5c). Soil respiration decreased when fertilization or irrigation were below the baseline levels due to lower aboveground and root biomass, which contributed to lower root respiration (*Wang* et al., 2011). However, the increased rate of soil respiration decreased with an increase in fertilization or irrigation when these management scenarios were above the baselines. Based on the DNDC model, *Wang* et al. (2011) showed that the increase rate of soil respiration in a maize field was slightly decreased as the nitrogen fertilizer reached certain values due to a decrease in nitrogen utilization efficiency of the crops, which reduced autotrophic respiration. With respect to irrigation intensity, *Zhao* et al. (2010) suggested that an irrigation amount under the baseline scenario led to optimal root length density in an oasis cotton field and more CO_2 was produced through root respiration compared with the values from higher or lower irrigation treatments.

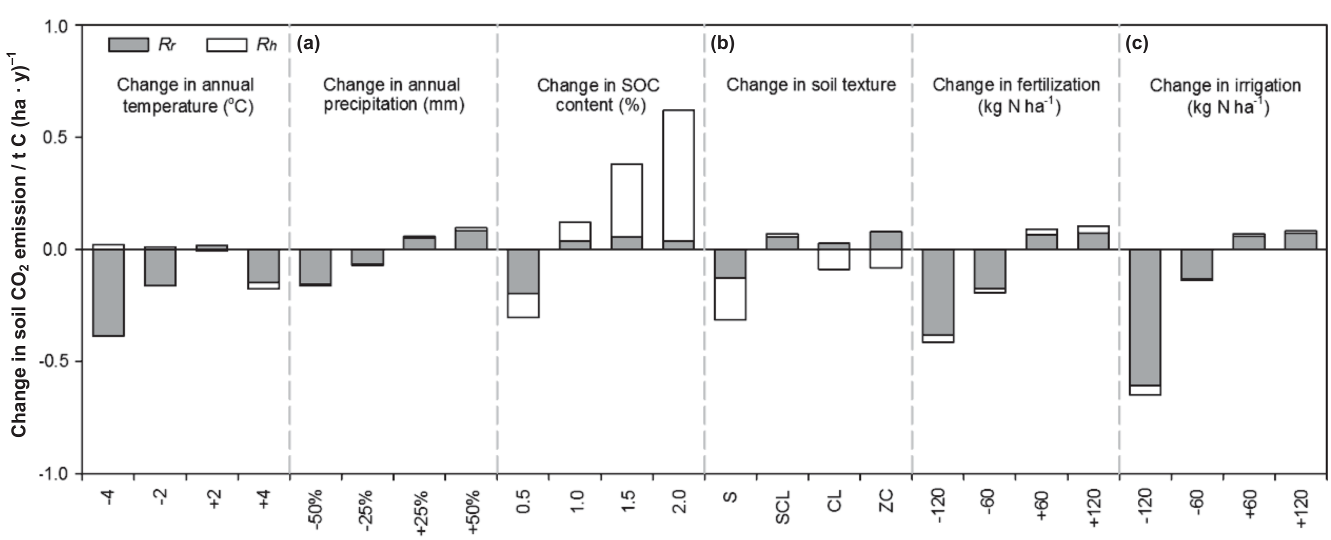

Figure 5: Sensitivity of root respiration and heterotrophic respiration to the changing scenarios compared with baselines: (a) climate, (b) soil, and (c) management.

4 Conclusion

Our results indicate that the DNDC model can be valuable to simulate soil and root respiration in oasis cotton cropping systems. The scenario analysis showed that temperature, precipitation, SOC content, fertilization, and irrigation have a positive effect on soil respiration, and root respiration was more sensitive to climate and management practices than to soil properties. Moreover, it needs to be noted that an air temperature increase of 4°C will lead to a decrease in CO_2 emission, which might not be representative of this region.

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