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Accuracy of root modelling and its impact on simulated wheat yield and carbon cycling in soil

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ABSTRACT

Accurate modelling of root biomass and root distribution of crop plants has become increasingly important in order to address issues related to carbon sequestration in soil and resource use efficiency of crops under different environmental and management conditions. However, the performance of crop models for simulating crop root system has been rarely tested in many environments due to lack of detailed data on roots. In this paper, we present detailed measurement data on root biomass and distribution in 0–200 cm soil profile at key developmental stages of wheat crop at Wuqiao in the North China Plain, and compare them with the root dynamics simulated by the agricultural systems model APSIM. The objectives are to test the model performance for simulating root biomass and distribution, and to investigate the potential impact of errors in root modelling on simulated wheat yield and soil carbon change. Compared to the measurements at the study site, APSIM version 7.5 underestimated the rooting front advance and final rooting depth of winter wheat, but overestimated the root biomass and root–shoot ratio at maturity by 100–200%. Modifications to root growth parameters in the model led to improved simulations of root depth and biomass dynamics. The modifications had little impact on simulated shoot biomass and grain yield under conditions of sufficient nitrogen supply, but led to higher simulated grain yield when nitrogen was deficient. They also resulted in reduction in simulated soil organic carbon in the top (0–20 cm) soil layer by 0.02%. A meta-analysis combining wheat root and shoot data from literature indicated that the APSIM model simulated a much tighter root–shoot relationship than that observed in the data, and that both versions of the model simulated the root–shoot relationships within the measured range. The relationship simulated from the original model better matched the data points from dry climate and dryland conditions. While the modified model based on Wuqiao data simulated a relationship better matching the data points from wet climate and irrigated conditions.

1. Introduction

Soil-plant systems models have been increasingly used to simulate crop biomass growth and grain yield, and to evaluate the impact of possible environmental changes and effectiveness of alternative management options. Facing the new challenges posed by future climate change, agricultural systems modelling is required not only to address solutions for advancing crop productivity and resource use efficiency (Chen et al., 2010a), but also to explore agricultural options for adapting and mitigating climate change (Wang et al., 2009; Luo et al., 2011). This new demand requires the models to be capable of simulating the coupled water, carbon and nutrient cycles in agro-ecosystems. For carbon cycling, crop primary productivity, i.e., production of above ground and root biomass, is the main carbon input into the soil-plant system. While the ability of crop models to simulate aboveground biomass and crop yield has been frequently tested, the accuracy of root modelling has attracted less attention. The potential impact of errors in root modelling on simulations of crop yield, resource use efficiency and carbon cycling across different environments has been rarely studied.

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The fact that less attention has been paid on test of root modelling is partly due to lack of detailed data caused by the difficulty to measure roots and insufficient understanding of the root systems (Hoad et al., 2001). For a given crop species or even a given cultivar, root growth can exhibit wide variations in terms of root biomass and root length distribution in soil, depending on soil and climate conditions. For wheat crop, a wide range of root biomass has been reported, ranging from less than 1 t/ha (Gregory et al., 1978; Barraclough et al., 1989; Bingham and Wu, 2011) to more than 3 t/ha (Xue et al., 2003; Fang et al., 2011), even the aboveground biomass was similar. Typically, Winter wheat roots can grow to 0.75–1.0 m in soil in spring time and reach the maximum depth in midsummer (Lupton et al., 1974; Gregory et al., 1978). Maximum rooting depth of winter wheat ranged from 140 to 200 cm (Gregory et al., 1978; Barraclough and Weir, 1988; Zhang et al., 2004; Zhou et al., 2008) and that of spring wheat was in the range of 80–120 cm (Siddique et al., 1990). For a particular region, poor soil conditions, i.e., water/nutrient deficiency or other soil constraints, can impact on root growth distinctly from the impact on shoot growth of wheat, which is yet poorly understood.

In recent years, the farming systems model APSIM (Wang et al., 2002; Keating et al., 2003) has been intensively used as an effective tool to analyse the yield and resource use efficiency of the wheat-maize system in North China Plain (NCP) for the purpose of optimising management practices like irrigation and N applications. Several studies showed that once the model was properly calibrated, it was able to predict the biomass growth, grain yield, crop water and nitrogen uptake in response to water and nitrogen supply (Chen et al., 2010a,b,c). Recently, the model has also been used to study the soil organic carbon change as affected by agricultural managements in Australia (Luo et al., 2011). So far, the performance of APSIM for simulating crop root biomass and distribution has been rarely tested, and has never been tested in NCP.

In this paper, we present data on root biomass, root–shoot ratio and dynamics of root front advances of winter wheat collected in the field experiments at Wuqiao County, Hebei Province in the NCP, and compare them with data from other regions of the world and with that simulated in the APSIM-wheat model (Wang et al., 2002). The objectives are to: (1) test APSIM for simulation of root depth and root biomass in NCP, and (2) investigate the potential uncertainty in root modelling through combining modelling with a meta-data analysis, and (3) examine the potential impact of uncertainties in root modelling on simulated wheat yield and soil organic carbon dynamics under the typical cropping systems in both NCP and the Murray Darling Basin (MDB) of Australia.

2. Materials and methods

2.1. Study site

Field experiments were carried out at Wuqiao (WQ) site (37°41′ N, 116°37′ E, altitude 20 m above sea level, groundwater Table 6–9 m) in the middle of Heilonggang Catchment in Hebei Province, China. The study site was characterised by a summer monsoon climate, with average annual temperature of 12.9 °C and annual rainfall of 550 mm (1961–2010). 64% of the annual rainfall fell in the summer months from July to September. The main cropping system was a winter wheat and summer maize rotation. The growing season for wheat is from mid-October to early June, and for maize from mid-June to early October. The soil at the site is classified as a Calcaric Fluvisol (FAO, 1990) with a sandy clay loam texture and a deep soil profile down to at least 200 cm. The topsoil (0–20 cm) had a pH of 7.8 and contained about 11.7 g kg^{-1} organic matter, 0.78 g kg^{-1} total N, 19.8 mg kg^{-1} available P, and 301.0 mg kg^{-1} available K. Detailed soil profile characterisation is given in Table 1.

2.2. Field experiments and data collection

Measured data from eight field experiments at Wuqiao were used in this study. The experiments were originally designed and conducted to investigate root growth of wheat, not for model testing purposes. All the field experiments were conducted with randomised complete block design with irrigation and fertilizer-N application rate (urea N) treatments and received 300 kg P ha^{-1} (as ammonium monoacid phosphate), 150 kg K ha^{-1} (as potassium sulfate), 15 kg Zn ha^{-1} (as zinc sulfate) and 15 m^3 ha^{-1} organic fertilizer (as chicken manure) before sowing. Weeds, insect pests and diseases were properly controlled and the crops were not limited by other nutrients. More details are given in Table 2.

Exp1–3 were three field experiments with measurements of both aboveground and below ground (root) part. In Exp 1 (2003–04), wheat plants from a 0.08 m^2 area were cut at soil surface to measure the biomass. Root samples were collected using a drill (8 cm in diameter) down to 200 cm depth with a 20 cm interval before winter and at flowering and maturity time. Each time six samples were collected and mixed together to measure root biomass. In Exp 2 and Exp 3 (2008–09), soil monoliths from a 20 cm (length) × 15 cm (width) area down to 200 cm were extracted, with 20 cm interval for the top two samples, and 40 cm interval for the samples at deeper depth. This was done five times: before winter, and at stages of upstanding, jointing, flowering and maturity. Roots were separated using double-layered sieves (1 mm diameter) by washing out the soil with water. All plant samples were oven dried at 70 °C to constant weight to measure biomass.

Exp4–8 were five field experiments without root measurements, and were only used for testing for simulation of leaf area index (LAI) and aboveground biomass. Three paralleled rows of wheat samples (each 0.5 m long) were cut off at ground level at main developmental stages. All plant samples were oven dried at 70 °C to constant weight to measure aboveground biomass.

2.3. Tube and pot experiments and data collection

In addition to the data from the field experiments, extra data from tube and pot experiments were also used for meta-data analysis in this study. Experiments in tubes were conducted in 2003–04 (Exp 9), 2008–09 (Exp 10 and Exp11) and 2010–2012 (Exp 12) (Table 2) at Wuqiao Experiment Station near the field experiment site. Polyvinyl chloride (PVC) tubes (20 cm in diameter × 200 cm high) were used for Exp 9 and hollow column made of bituminized felt tubes (36 cm in diameter × 200 cm high) were used for Exp 10–12. All tubes were filled with sieved soil, packed to mimic the texture and bulk density of the soil in the field. The tubes were buried into soil with the top edge at 5 cm above the ground. Soil was dug out at flowering and maturity, and separated into ten layers (each 20 cm) in Exp 9, Exp 11 and Exp 12, and into six layers in Exp 10 with 20 cm interval for the top two samples, and 40 cm interval for the samples at deeper depth. Root and shoot biomass and root length were measured at flowering and maturity stage. More details of the experiments can be found in Zhou et al. (2008).

Pot experiments were conducted at two wheat growing seasons from 2006 to 2008 (Exp 13) at the experimental station in Henan Agricultural University, using 26 leading winter wheat cultivars currently grown in Henan province. Plastic pots (30 cm in diameter × 27.5 cm high) were filled with 17 kg of sieved top soil which had a pH of 7.9 and contained about 17.8 g kg^{-1} organic matter, 0.99 g kg^{-1} total N, 44.4 mg kg^{-1} available P, and 84.8 mg kg^{-1} available K. Chemical fertilizers (2 g urea, 1.46 g KCl, and 4.08 g

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