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Accuracy of root modeling and its potential impact on simulation of grain yield of wheat

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Abstract: Accurate modeling of root biomass and root distribution of crop plants has become increasingly important 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 caused by the difficulty to measure roots. In this paper, we present detailed measurement data on root biomass and distribution in 0-200cm deep 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 modeling root biomass and distribution, and to investigate the potential impact of errors in root modeling on simulated yield responses under different levels of water and nitrogen supplies through changes in irrigation and nitrogen applications.

The data were collected in two field experiments carried out in the 2003-04 (Exp 1) and 2008-09 (Exp 2) winter wheat growing seasons, each with three irrigation treatments and one fertilizer-N application rate of 158 kg/ha (urea N). Irrigation scheduling included: no irrigation (W0), one time of irrigation ($750m^3ha^{-1}$ = 75 mm each time) at jointing stage (W1), two times of irrigation at jointing and flowering stages (W2), three times of irrigation at upstanding (double ridges), booting and start of grain filling stages (W3) and four times of irrigation at upstanding (double ridges), jointing, flowering and start of grain filling stages (W4), all as flood irrigation. Irrigation treatments for Exp 1 were W0, W2 and W4, and for Exp 2 were W0, W1 and W3. All the experiments received 75 mm irrigation applied 5 days before sowing to ensure good emergence. In Exp 1 (2003-04), wheat root samples were collected using a drill (8cm in diameter) down to 200cm depth with a 20 cm interval before winter and at flowering and maturity time. In Exp 2 (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 (1mm diameter) by washing out the soil with water. In addition, shoot biomass was also measured in each experiment. All plant samples were oven dried at 70°C to constant weight to measure biomass.

APSIM version 7.5 was used to simulate the root and shoot growth of the winter wheat crop against the experimental data. Compared to the measurements from field experiments, 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%. The model also simulated simultaneous increase in both shoot and root biomass with increased irrigation supply, but measurements showed increase only in shoot biomass, not in root biomass. Correction to the simulations of rooting depth and root biomass based on the data led to little impact on simulated shoot biomass and grain yield under conditions of sufficient nitrogen supply, but higher simulated grain yield when nitrogen was deficient. Studies are needed to further investigate APSIM's ability to simulate root growth and its impact on biomass growth and carbon cycling in farming systems across different environments.

Keywords: *root biomass, rooting depth, winter wheat, North China Plain, APSIM*

1. INTRODUCTION

Accurate modeling of root biomass and root distribution of crop plants has become increasingly important to address issues related to carbon input into soil and resource use efficiency of crops under different environmental and management conditions. Crop models have been widely used to simulate shoot biomass growth and grain yield to evaluate the impact of possible changes and effectiveness of alternative management options. However, the ability of crop models to simulate root biomass and distribution has attracted much less attention, partly due to due to lack of detailed data caused by the difficulty to measure roots and insufficient understanding of the root systems (Hoad et al., 2001). Typically, Winter wheat roots can grow to 0.75 to 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 may also restrict root growth. Experimental studies have reported a wide range of root biomass for wheat crops. For example, in UK, 1.5 Mg ha^{-1} of root biomass was measured with a total shoot dry matter of 20 Mg ha^{-1} for winter wheat (Barraclough et al., 1991). This value was comparable to that reported by Gregory et al. (1978), but smaller than the reported values of 3 Mg ha^{-1} reported by others such as Hamblin et al. (1990), Siddique et al. (1990) and Zhang et al. (2004). To correctly simulate the observed range of root biomass across environments remains a challenge.

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 analysis the yield and resource use efficiency of the wheat-maize system in North China Plain (NCP) for the purpose of optimizing 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. So far, the performance of APSIM for simulating crop root biomass and distribution has been rarely tested.

In this paper, we present data on root biomass 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 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 impact of errors in root modeling on simulated yield responses under different levels of water and nitrogen supplies through changes in irrigation and nitrogen applications.

2. MATERIALS AND METHODS

2.1. Study site

Field experiments were carried out at Wuqiao (WQ) site (37°29′–37°47′ N, 116°19′–116°42′E, altitude 14-23 m above sea level, groundwater table 6-9 m) in the middle of Heilonggang Catchment in Hebei Province, China. The average annual rainfall at the site was 550 mm (1961-2010), 64% of which fell in the summer months from July to September. The mean annual temperature was 12.9^{o}C. 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. On average, the topsoil (0-20 cm) had a pH of 8.12 and contained about 11.2 g kg^{-1} organic matter, 1.1 g kg^{-1} total N, 49 mg kg^{-1} Olsen-P, and 132 mg kg^{-1} exchangeable K.

2.2. Field Experiments and data collection

Two field experiments were carried out, each in the 2003-04 (Exp 1) and 2008-09 (Exp 2) winter wheat growing season. Both experiments were conducted with randomized complete block design with three irrigation treatments and one fertilizer-N application rate of 158 kg/ha (urea N). The wheat cultivar ‘SJZ8’ and ‘SJZ15’ were sown with plant densities of 600 and 570 plants m^{-2} in 2003 and 2008, respectively, both with a row space of 15cm. Irrigation scheduling included: no irrigation (W0), one time of irrigation (750m^{3}ha^{-1} = 75 mm each time) at jointing stage (W1), two times of irrigation at jointing and flowering stages (W2), three times of irrigation at upstanding (double ridges), booting and start of grain filling stages (W3) and four times of irrigation at upstanding (double ridges), jointing, flowering and start of grain filling stages (W4), all as flood irrigation. Irrigation treatments for Exp 1 were W0, W2 and W4, and for Exp 2 were W0, W1 and W3. All the experiments received 75 mm irrigation applied 5 days before sowing to ensure good emergence. Weeds, insect pests and diseases were properly controlled and the crops were not limited by other nutrients.

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 (8cm in diameter) down to 200cm 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 (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 (1mm diameter) by washing out the soil with water. All plant samples were oven dried at 70°C to constant weight to measure biomass.

2.3. APSIM modeling of wheat growth and biomass partition to roots and shoots

The APSIM model (Wang et al., 2002; Keating et al., 2003) version 7.5 was used to simulate the biomass growth, grain yield and biomass partitioning to different organs of wheat against experimental data collected at Wuqiao. The model was firstly calibrated using data from the W0 treatment in Exp 1 and 2 respectively, so that it could re-produce the above ground biomass and grain yield. In Exp 1 no difference in crop biomass and yield was found between W2 and W4 treatments, and in Exp 2, W1 and W3 also had similar biomass and grain yield. Therefore, the W3 and W4 treatments were considered as representing conditions without water and nitrogen limitations. In the calibration, crop parameters for vernalization sensitivity, photoperiod sensitivity, and thermal time for the grain filling period were derived based on observed dates of emergence, flowering and maturity. The calibrated model was then used to predict above ground biomass, grain yield, and root biomass and distribution in the soil under other treatments.

Results from the above calibrated model indicated that shoot biomass and grain yield of wheat were very well simulated. However, simulated rooting front depth and final root biomass at maturity departed significantly from the observed values. We then further modified the rate of rooting front advance and the root/shoot ratios used in the model to obtain improved matches between the observed and simulated rooting depth and root biomass. The impact of these changes on shoot biomass, grain yield under different levels of water and nitrogen supplies were then investigated by running the model with both versions of the parameterization for 30 years from 1961 to 2010 with different levels of irrigation and nitrogen application rates. Table 1 shows the cultivar parameters and root parameters adopted in the simulations.

Table 1. Cultivar and root parameters used in the simulation

Cultivar Parameters	**SJZ8**	**SJZ15**
Vernalization sensitivity	2.3	2.3
Photoperiod sensitivity	3.3	3.5
Thermal time of grain filling (°Cd)	540	530
Root Growth Parameters	**Apsim7.5**	**Modified**
Rate of rooting advance (mm/d)	5.0, 30, 30[a]	10.0, 50, 50
Root/shoot ratios	1.0, 1.0, 0.3, 0.3, 0.3, 0.08, 0.01[b]	0.5, 0.5, 0.15, 0.13, 0.1, 0.03, 0.005

a. For stages of germination, emergence and juvenile in APSIM.

b. For stages of emergence, juvenile, end of juvenile, floral initiation, flag leaf, flowering and endhead in APSIM.

3. RESULTS AND DISSCUSSION

3.1. Root front advance and rooting depth

Compared to the observed data in Exp 2, APSIM version 7.5 significantly underestimated the rate of rooting front advances, especially during the early growing stages of winter wheat, resulting in an underestimation of final rooting depth at maturity (Figure 1). Similar results were also found for Exp 1 (data not shown). At the time when wheat stopped growing before winter (usually occurred in early December), the observed data showed that root depth of winter wheat had reached nearly 100 cm deep in field experiments in both 2003-04 and 2008-09. The maximum rooting depth was about 200 cm at flowering stage (early May) and maintained till maturity stage (early June). These observation data are consistent with results found in other studies in the North China Plain that the maximum rooting depth of winter wheat reached 200 cm depth at maturity in most years (Zhang et al., 2009). However, the APSIM simulated root front depth was less than 50 cm deep before winter, which was only half of the measured depth. And the simulated maximum rooting front depth was about 170 cm at flowering and maturity, which was 30 cm shallower than that observed maximum rooting depth.

3.2. Biomass partition to shoots, grain and roots

The calibrated APSIM model was able to accurately simulate the shoot biomass (Figure2a), which ranged from 12 Mg ha^{-1} to 19 Mg ha^{-1} under different levels of irrigation supplies from W0 to W4. The model also reasonably simulated the grain yield of wheat (Figure 2b), explained 89.3% variation in wheat grain yield caused by the irrigation treatments. These results imply that APSIM, once calibrated, was able to capture the changes in both shoot and grain yields in response to water supply or water stress. However, compared to the observed root biomass, APSIM overestimated root biomass by 100~200% (Figure 2c). This happened in both Exp 1 and Exp 2, with no correlation between the simulated and observed root biomass at maturity for the irrigation treatments.

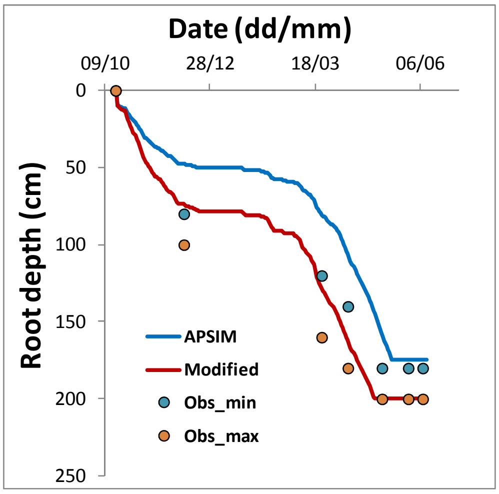

Figure 1. Comparison of APSIM simulated rooting depth dynamics with that observed in field experiments (Exp 2) at Wuqiao, China. The blue and red dots show the minimum and maximum observed root depth respectively.

Modifications to the rate of rooting front advance and root/shoot ratios for new growth led to improvement in simulations of both dynamics of rooting depth (Fig 1) and root biomass at maturity (Figure 2d). However, these improvements in rooting depth and root biomass modeling had almost no impact on the performance of the model to simulate wheat shoot biomass and grain yield in both the experiments (Data not shown).

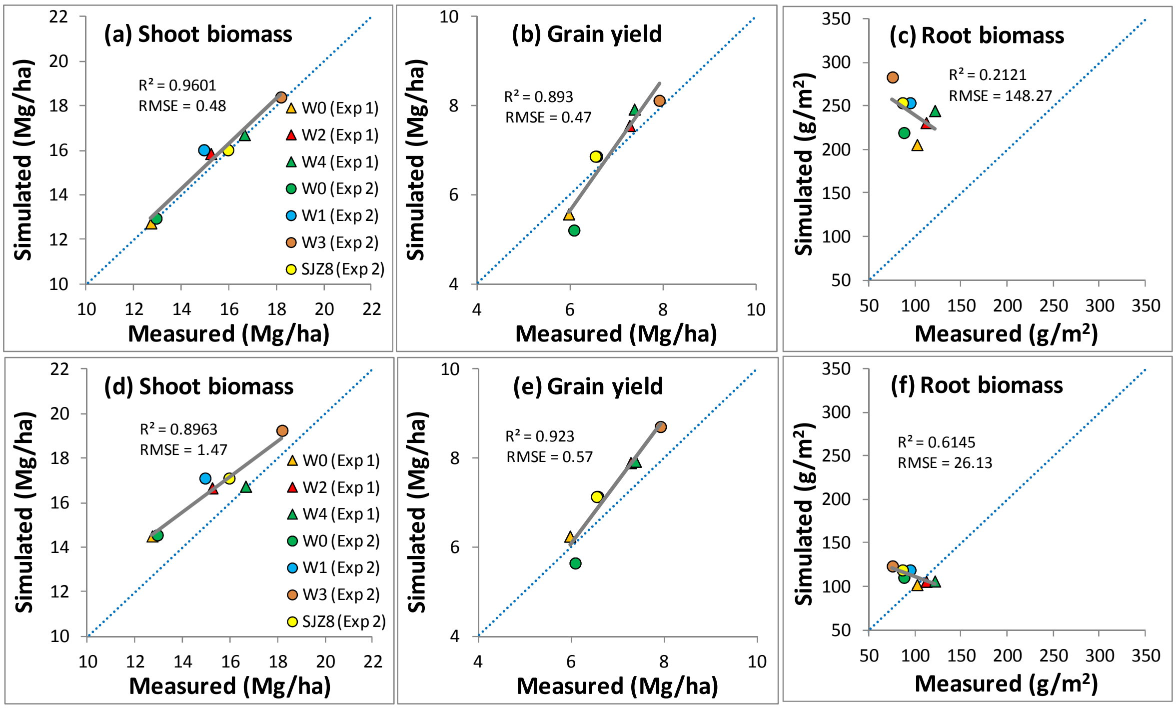

Figure 2. Comparison of simulated and observed shoot biomass (a, d), grain yield (b, e) and root biomass (c, f) of winter wheat at maturity at Wuqiao in North China Plain: a, b and c with original version of APSIM 7.5 and d, e and f with APSIM 7.5 adjusted for root shoot ratios and rooting front depth. Grey solid lines were the linear trend lines. The Blue dashed lines were the 1:1 lines.

3.3. Relationship between shoot and root biomass

A very tight linear relationship was found between the simulated root and shoot biomass at maturity, i.e., root biomass increased linearly with shoot biomass in the simulation results (Figure 3). Among the treatments, with increase of irrigation, shoot biomass increased from 12.4 to 18.2 Mg ha^{-1}. The model also simulated an increase in root biomass from 2 to 3 Mg ha^{-1}. However, this relationship was not found in the measured data. There were no significant changes in root biomass. In all the irrigation treatments, the root biomass at maturity was less than 1.5 Mg ha^{-1}.

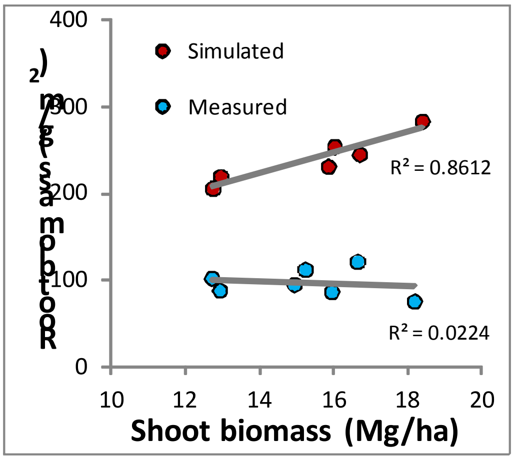

Figure 3. Relationships between root and shoot biomass (at maturity) of observed data and simulation results using APSIM 7.5 at Wuqiao, China.

3.4. Impact of modified root parameters on grain yield simulations

Fig 4 shows the comparison of simulated grain yield of wheat at the study site from 1961 to 2010 with 75 mm of irrigation water every year, and with the original and modified root parameters (Table 1). The limited irrigation amount plus the inter-annual variation of rainfall during the wheat season created different levels of water supply in different years, leading to significant inter-annual variation of simulated grain yields (Fig 4). Under sufficient nitrogen supply, the changed rooting depth and root shoot ratio had relatively small effect on the simulated grain yield (Fig 4a). However, under deficit nitrogen supply condition, the modified ASIM version with the new root parameters simulated higher grain yield, on average 10% higher than those simulated with the original APSIM 7.5 (Fig 4b). This was mainly due to the lower root biomass simulated in the modified APSIM, which required less nitrogen to be put in root, leaving more nitrogen to meet shoot nitrogen demand. Under nitrogen deficit conditions, smaller amounts of nitrogen are used by root, hence more amounts can be supplied to the above-ground part, thus increasing the shoot growth.

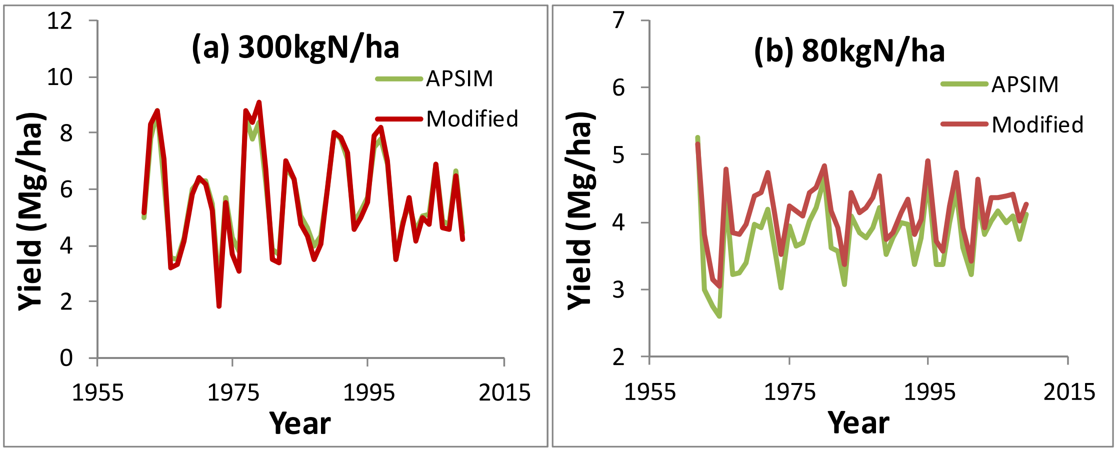

Figure 4. Comparison of simulated wheat yield under full nitrogen supply (a) and deficit N supply (b): green line with original version of APSIM 7.5 and red line with APSIM 7.5 adjusted for root shoot ratio and root depth rate to the field condition.

4. DISCUSSIONS

The APSIM-Wheat model has been widely used to simulate biomass and grain yield of wheat in response to climate variability and management interventions across climate zones. However, the ability of the model to simulate wheat root biomass and root distribution has been rarely tested. The results in this paper showed that while the model was able to simulate the shoot biomass and grain yield in response to irrigation water supply, it underestimated the rooting front advances and overestimated root biomass for the irrigated winter wheat grown at Wuqiao in the North China Plain.

One of the causes for the underestimation of rooting front advances, particularly during the early growing stage of winter when, could be due to the use of a lower rate of rooting front advances in the model. In the current model, the maximum rate of rooting front advance was set to 30 mm/day, which is modified using daily mean air temperature with base, optimum and maximum temperatures of 0, 25, and 35^{o}C respectively (Wang and Smith, 2004). A higher rate of 1.8 mm/ ^{o}Cday was reported by Barraclough (1984) for winter wheat using a base temperature of 0^{o}C, corresponding a rate of 45mm/day at temperature of 25^{o}C. Measurement in the Rhizolab at Wageningen showed that rates of downward movement of the rooting front of winter wheat ranged from 28 and 38 mm/day at 15 and 20^{o}C, respectively (Smit and Groenwold, 2005), corresponding a rate of 47.5mm/day at 25^{o}C. In Australia, Lilley and Kirkegaard (2011) also modified the rate to 1.44 mm/^{o}Cday (36mm/day) based on data reported by Richards et al. (2007) to simulate field grown wheat. Our modified rate was 50 mm/day (Table 1) that is close to the 47.5mm/day value mentioned above.

Another reason for the underestimation of rooting depth could be due to the use of daily temperatures to drive rooting front advance. When the daily mean air temperature reached 0^{o}C, the model simulated no advance of rooting front. In that case, the air temperature during daytime and in the soil could be well 0^{o}C and root may still be growing under such conditions. However, use of soil temperatures may not lead to improved modeling of root growth due to lack of measurements and uncertainty in simulations of soil temperatures. It is however warranted to test whether use of daytime temperatures could lead to improved simulation results.

APSIM uses radiation use efficiency (RUE) approach to simulate biomass growth of shoots. The RUE used in the model was derived only for the above ground biomass. The model uses RUE and daily light interception to calculate rate of shoot biomass growth, then uses the root/shoot ratio for new growth to estimate how much biomass needs to be put in roots. In that approach, shoot biomass growth is not directly affected by changes in root biomass growth. This is why modifying root biomass growth through changing the root/shoot ratio for new biomass did not have impact on simulations of shoot biomass and yield under sufficient water and nitrogen supply (Figure 4a). Under nitrogen deficient conditions, reduced root growth will result in less root nitrogen demand and more nitrogen available for shoots, thus leading to an increase in simulated biomass and yield (Figure 4b).

Although the correction on rooting front advance in the model did not have major impact on the simulated wheat grain yield at the study site, it may have impact on wheat growth and yield in drier environments like Australia. In semi-arid climate, faster rooting advance may enable the plant to access deeper soil water at earlier stage, which could be beneficial to early growth. More studies are needed to verify whether this could eventually affect crop final yield.

5. CONCLUSIONS

Compared to the measurements from field experiments at Wuqiao in the North China Plain, APSIM 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%. The model also simulated simultaneous increase in both shoot and root biomass with increased irrigation supply, but measurements showed increase only in shoot biomass, not in root biomass. Correction to the simulations of rooting depth and root biomass based on the data led to little impact on simulated shoot biomass and grain yield under conditions of sufficient nitrogen supply, but higher simulated grain yield when nitrogen was deficient. Studies are needed to further investigate APSIM's ability to simulate root growth and its impact on biomass growth and carbon cycling in farming systems.

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