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How well can APSIM simulate nitrogen uptake and nitrogen fixation of legume crops?

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ABSTRACT

It is important to quantify the nitrogen (N) uptake and dinitrogen (N_2) fixation of legumes and estimate the N contribution that these crops make to subsequent crops for sustainable agricultural production. The growth and development of legumes and their impact on soil N fertility can be simulated by the Agricultural Production Systems Simulator (APSIM). However, the model performance has not been evaluated in simulating the dynamic processes of N accumulation and N_2 fixation. The parameterised model was tested for the simulation of N uptake and N_2 fixation in above-ground biomass of four crop legumes (lupin, chickpea, field pea and peanut). The simulations varied in location, cultivar, sowing date, climate, soil type, water regime (irrigated or dryland) and starting soil N and applied fertiliser N in tropical, subtropical, semiarid and Mediterranean environments across Australia. In general, the absolute amount of N uptake and N_2 fixation in above-ground biomass (unit: kg ha^{-1}) were reasonably well simulated, with 92% of the variation in observed N accumulation in above-ground biomass and 84% in N_2 fixation being explained by APSIM. The model was also able to simulate the responses of N_2 fixation by chickpea and peanut to differences in soil mineral N status. However, the simulations of N_2 fixation efficiency (NFE, calculated as fixed N_2 per unit above-ground dry matter (DM; unit: g N kg^{-1} DM) were much less accurate, especially for lupin. Sensitivity analysis showed that improving the definition of the model parameter of crop N_2 fixing capacity (the potential to fix atmospheric N_2 per unit above-ground DM; unit: g N g^{-1} DM) would improve the simulations of NFE. We therefore propose that to successfully simulate the absolute amount of N accumulation and N_2 fixation, the above-ground biomass as the major driving factor must first be simulated well, and future work should focus on accurately determining the parameter of crop N_2 fixing capacity through optimisation of N_2 fixation data obtained from field or controlled experiments to fine-tune the simulations of the relative efficiency of N_2 fixation.

1. Introduction

In many regions, soil nitrogen (N) supply is a major factor limiting agricultural production. This is particularly the case in Australia, where most soils are inherently infertile (Nichols et al., 2007; McNeill and Penfold, 2009). The soil's ability to supply plant available N can be supplemented with applications of fertiliser N or through the mineralisation of N derived from previous legume residues. Legumes can potentially contribute substantial quantities of N to the farming systems (Peoples et al., 1995; Unkovich et al., 1995). Thus cropping systems often include legume crops or pastures as part of a rotation as the biological dinitrogen (N_2) fixation from legumes benefits both the legumes themselves and subsequent crops in the rotation (Hossain et al., 1996; McCallum et al., 2000; Jensen and Hauggaard-Nielsen, 2003; Liu et al., 2013). Furthermore the process of biological N_2 fixation is independent of non-renewable energy resources, its use should be encouraged in the absence of cheap nitrogenous fertiliser (Jensen et al., 2012; Crews and Peoples, 2004; Peoples et al., 2004). For such reasons, it is essential to quantify the N uptake and N_2 fixation of legumes and the residual N that legumes may contribute to subsequent crops (Hardy and Havelka, 1975; Vitousek et al., 2002).

The process of biological N_2 fixation is complicated and affected by many factors such as weather, water availability, soil acidity,

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soil phosphorus, mineral nutrition, legume species and degree of nodulation (Loomis, 1992). Such aspects of the complex interplay between season, soil chemistry, legume species and the N cycle have been studied experimentally from plant to field scale (Moore, 1974; Schubert, 1986; Unkovich and Pate, 2000; Hungria et al., 2006; Masson-Boivin et al., 2009). Experimental attempts to determine amounts of N_2 fixation based on biophysical measurements would have been appropriate (Evans and Heenan, 1998; Evans et al., 2001; Unkovich et al., 2010). However, much of this information is restricted to a particular site and/or season for a certain crop. And collecting long-term data from field experiments for understanding and investigating the role of N_2 fixation in legume-based cropping systems is time-consuming and therefore expensive. In contrast, process-based simulation models are valuable tools to improve our knowledge of plant and soil processes and their interactions in response to climate and management changes (Sinclair, 1986; Cabelguenne et al., 1999; Herridge et al., 2001; Corre-Hellou et al., 2009; Liu et al., 2013). These models are able to simulate the dynamics of N cycling, N uptake and N_2 fixation by the legumes, and the flows of N through to the subsequent cereal crop (Liu et al., 2011). The Agricultural Production Systems Simulator (APSIM; Keating et al., 2003; Holzworth et al., 2014) is one such model that operates on a daily time step to simulate growth and development of diverse legume species and their N demand, N uptake and N_2 fixation. Nitrogen demand on a given day is the sum of the demands from the pre-existing biomass of each part and today's potentially assimilated biomass required to reach or maintain critical N concentrations. The daily rate of N uptake is the minimum N demand by the crop and potential supply of N from the soil (Van Oosterom et al., 2010). This method used in APSIM was comparable to those used in the models of CROPGRO (Ma et al., 2009), InfoCrop (Aggarwal et al., 2006), CropSyst (Stöckle et al., 2003) and SPACSYS (Wu et al., 2007). The APSIM model uses a simple approach to simulate the potential daily rate of N_2 fixation, which is a function of the crop N_2 fixation capacity and standing crop biomass, discounted for soil water stress. The potential or maximum fixation rate is the current most popular method to estimate the rate of legume N_2 fixation (Liu et al., 2011). Many simulation models (such as Sinclair model, EPIC, CROPGRO, STICS) have estimated N_2 fixation using a pre-defined potential N_2 fixation rate, adjusted by the response functions of soil temperature, soil or plant water status, soil mineral N or substrate N concentration in plant tissues, plant carbon supply and crop growth stage (Liu et al., 2011). Above-ground biomass is used as the main factor to calculate N_2 fixation in APSIM, which has also been used to estimate N_2 fixation in other studies (Denison et al., 1985; Sinclair, 1986; Bell and Wright, 1994; Yu et al., 2002). Although some studies have used nodule size/biomass (Weisz et al., 1985; Voisin et al., 2003; Wu and McGechan, 1999) or root biomass (Voisin et al., 2007), the biomass of both nodules and roots are difficult to measure in the field.

For several legume crops, the performance of APSIM in simulating the biomass, grain yield and N uptake has been evaluated (Robertson et al., 2002). However, the model's ability to predict N_2 fixation has not been well validated. It is still unclear whether the model is able to capture the main factors that affect legume N_2 fixation, such as impact of legume types, soil water and mineral N levels, and the critical N concentrations in plant parts throughout the crop life cycle. This limits the further application of the model for understanding the roles of legumes in farming systems. To successfully simulate the N cycle within the legume-based cropping system, APSIM must adequately simulate N uptake, N_2 fixation and N partition to leaf, stem and grain throughout the various growth stages of legume crops.

Legume crops have played an important role in Australian farming systems over the past decades, because of attractive cash returns from their yield, inputs of biologically fixed N_2 to soil and beneficial effects on controls of diseases and weeds when they were rotated with cereals (Evans et al., 1989; Jensen et al., 2006). Lupin (*Lupinus angustifolius*), chickpea (*Cicer arietinum* L.) and field pea (*Pisum sativum*) have been the major grain legumes grown in winter in Australia (Siddique and Sykes, 1997; Siddique et al., 2013). Lupin has been mainly grown in deeper, coarse textured and acidic soil, while chickpea and field pea are usually suited to the neutral to alkaline soils with higher clay content (Siddique and Sykes, 1997; Krishnamurthy et al., 2011; French, 2002). Peanut (*Arachis hypogaea*) is a legume grown in summer, mainly in Queensland, for both direct consumption and oil production (Bell et al., 1991; Bryceson, 2003). Assessing the model's ability to simulate N_2 fixation component for the four legume crops against published (Anderson et al., 1998a,b; Turpin et al., 2002; Armstrong et al., 1994a,b) and unpublished (provided by M. Bell) experimental results across Australia would provide a representative evaluation in model performance. This paper presents such a test on the APSIM-legume model. First, we would test whether the observed dynamics of N cycle (N accumulation, N_2 fixation in above-ground biomass and N_2 fixation efficiency (NFE, calculated as N_2 fixed per unit above-ground dry matter (DM), unit: $g\,N\,kg^{-1}$ DM) can be reasonably reflected by using a simple approach. Second, we test whether the model has captured the biological and environmental factors that mainly determine above-ground biomass to affect N_2 fixation. A sensitivity analysis was performed to explore the effects of changes in the parameters that are likely difficult to obtain through field or controlled experiments on N_2 fixation and NFE to better inform future directions of research into better simulation of N_2 fixation in cropping systems.

2. The APSIM model and N_2 fixation simulation

APSIM (Agricultural Production Systems sIMulator, v.7.6) is a modelling framework, which allows models of crop and pasture, residue, soil water and nutrient to be configured to simulate various production systems, including crop sequences, rotations and intercropping (Holzworth et al., 2014). The concepts used in APSIM-legume have been extended from the modelling approaches developed by Ritchie (1986, 1991), Sinclair (1986) and Monteith (1986). The APSIM-legume model has the functionality to simulate the development, growth, crop N uptake, N_2 fixation and N partitioning for a wide range of legume species, such as lupin, chickpea, field pea and peanut (Robertson et al., 2002; Farré et al., 2004; Chen et al., 2008), using a generic crop model template (Wang et al., 2002). It is also able to indirectly simulate the effect of legumes on the following cropping systems (e.g. residual carbon and N) under varying climate, soil water and N supply conditions (Robertson et al., 2002).

In the APSIM model, demand, uptake and re-translocation of N are simulated using a modified version of the method used in the CERES model (Robertson et al., 2002). APSIM simulations assume that legumes are either inoculated or there are high enough populations of effective rhizobia in the soil so neither nodulation nor N_2 fixation are constrained. The crop has a defined minimum, critical, and maximum N concentration for each plant part, i.e. leaf, stem, root, and grain (Herridge et al., 2001; Robertson et al., 2002). On any day, demand for N is the sum of the N demand from the pre-existing biomass of each part required to reach the critical N concentration (non-stressed), plus the N required to grow new biomass at the critical N concentration. Based on the approach of Sinclair (1986), N uptake is assumed to comprise of three processes: 'Mass flow' (Eq. (1)), estimated as the product of transpiration and the nitrate concentration in soil solution, 'Active uptake' or 'diffusion' (Eq. (2)), estimated in terms of the rate at which plants can assimilate nitrate from soil and 'Fixation' (Eq. (3)). If N demand cannot be satisfied by