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Incorporating grain legumes in cereal-based cropping systems to improve profitability in southern New South Wales, Australia

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ABSTRACT

Grain legumes, such as lupins and field peas, are one of key rotation components in Australian agricultural systems, supplying nitrogen (N) to following crops, and potentially increasing farm profitability. In this study, we used a modelling approach to investigate the profitability of incorporating field pea (*Pisum sativum*) and narrowleaf lupin (*Lupinus angustifolius*) in cereal-based (wheat/canola) cropping systems in southern New South Wales (NSW), Australia. We calibrated and validated the Agricultural Production Systems sIMulator (APSIM) with three-year's experimental data to predict yields of field pea and lupin, and N contribution of grain legumes in cereal-based (wheat/canola) crop rotations. We conducted a gross margin analysis to analyse the profitability of adding grain legumes into cereal-based crop rotations at both crop and rotation levels. The simulated results showed that field pea and lupin could contribute 30–65 kg N ha^{-1} to the next crop and 60–110 kg N ha^{-1} to subsequent crops (wheat/canola) for two years, corresponding to 30–55% and 60–86% of net N inputs of legume-fixed N, respectively. This greatly increased the yields and profitability of wheat/canola in the following two years. Including grain legumes in cereal-based crop rotations was more profitable than non-legume crop rotations, even though the grain legumes were less profitable than wheat/canola in the year of growing. However, N and economic benefits would be reduced to zero if N fertilizer applied to wheat/canola was over the optimal level, i.e. 100–125 kg N ha^{-1} in terms of N benefit, or 75 kg N ha^{-1} for farm-economic profit. In general, incorporation of grain legumes into cereal-based crop rotations offers an obvious N benefit to subsequent crops and provides an economic benefit for farmers (reduced N applications). This suggests that the contribution of grain legumes to cereal-based cropping systems should be assessed as part of a rotation rather than as a stand-alone crop.

1. Introduction

Legumes have been used as a nitrogen (N) source in agricultural systems and as a protein food for humans and domestic animals since early civilization (Power, 1987). It is estimated that, globally, about 20–22 million tons N are fixed from the symbiotic fixation of atmospheric N_2 by soil bacteria (rhizobia) and legume crops each year (Herridge, 2008; Peoples et al., 2009). This biologically fixed N is an important source of N in legume-included rotation systems, providing extra N fertilizer to subsequent crops ('nitrogen effect', Ewing et al., 1992; Jensen, 1997; Peoples et al., 2009). In addition to the 'nitrogen effect', dicotyledonous break crops are reported to increase subsequent cereal yields by 15% to 25% because they reduce the potential impacts of pests, diseases and weeds, and improve soil fertility ('break-crop effect', Kirkegaard et al., 2008). For example, some experiments show that much of the yield benefit from legumes can be attributed to lower incidence of leaf and root diseases in the following cereal crops (Evans et al., 1989; Jensen et al., 2006; Stevenson and van Kessel, 1997). The nitrogen benefit and break crop effects mean that legume crops are an important component in crop sequences and are recommended for

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incorporation into cereal-based cropping systems (McCallum et al., 2000; Peoples et al., 2009; Preissel et al., 2015).

Field pea (*Pisum sativum*) and narrowleaf lupin (*Lupinus angustifolius*) are the two major winter legume crops in Australian farming systems (JCS Solutions, 2014; Siddique et al., 2013; Siddique and Sykes, 1997). From 1990 to 2007, lupin occupied about 20% of Australian cropping areas, contributing around 85% of world lupin production (ABARES, 2016). However, Australia's lupin production areas declined from 1.4 million ha in 1997 to 0.5 million ha in 2014 (ABARES, 2016; FAO STAT, 2016). Similarly, field pea production areas declined from 0.46 million ha in 1994 to 0.25 million ha in 2014. The declines were possibly due to the insignificant benefit of legume-fixed N to the next crop, and the apparently uncompetitive farm economic value of legume crops against other crops (ABARES, 2016; Lehmann et al., 2013; Li et al., 2010; Peoples et al., 2009). Peoples et al. (2009) reviewed estimates of legume crops' N contribution to the subsequent crop and stated that direct N contribution from legume crops to the following crop might be not significant, and less important than N fertilizer. Furthermore, the farm economic return from grain legumes is generally lower than wheat and canola (Li et al., 2010).

However, the benefit of including grain legumes in crop sequence needs to be fully evaluated at rotational level because the released N from legume residues contributes to the soil organic matter pool in subsequent years (Rochester and Peoples, 2005; Schwenke et al., 2002). Increasing the frequency of grain legumes in rotations has increased the profitability of cropping systems in Europe (Reckling et al., 2016) and Western Australia (Robertson et al., 2010). After reviewing over three decades of rotation research in Western Australia, Seymour et al. (2012) found that including grain legumes in the rotation could increase wheat yield and improve water use efficiency. Zentner et al. (2002) demonstrated that including grain legumes in the rotation contributed to higher and more stable net farm income in Canada. Peoples et al. (2009) and Preissel et al. (2015) reviewed the amount of legume-fixed N and the net input of fixed N in cropping systems around the world and concluded that legume-fixed N might improve the productivity of the following crops, and gain farm-economic values comparable to cereal rotations.

Evaluating the profitability of incorporating grain legumes in crop rotations is more complex than evaluating a single crop due to increased rotation combinations (Preissel et al., 2015), so researchers have used rule-based frameworks, statistical models and process-based models to compare the profitability of rotations with and without grain legumes (Kollas et al., 2015; Reckling et al., 2016; Robertson et al., 2010). Reckling et al. (2016) and Robertson et al. (2010) used a static model and rule-based framework to assess the profitability of incorporating grain legumes in crop rotations. The rule-based framework and static models have less limitations on data requirements, but have the disadvantages to simulate the response to crop production to variable climatic conditions, agricultural practice and economic inputs (Kollas et al., 2015), in comparing to process-based models. Because process-based models have considered the interaction between impacts of climate, soil and management practices on crop growth and development (Gabrielle et al., 2002; Holzworth et al., 2014; van Diepen et al., 1989). Therefore, with sufficient observations, process-based crop models might be more powerful to explore crop productivity variations in multiple crop rotation systems under various climatic conditions and economic inputs. Process-based crop models such as APSIM and RZWQM have been used widely to simulate productivity response, water use efficiency, N use efficiency, soil organic carbon change to climate variations, irrigation and N fertilizer applications in different rotation systems in the North China Plain and Australia (Chen et al., 2010; Fang et al., 2010; Liu et al., 2016). To simulate the impact of the previous crop to subsequent crops, process-based models mainly use soil moisture and nutrients (e.g. nitrogen) in the soil profile after the previous crop, and nutrients from above- and under-ground residues of the previous crop (Holzworth et al., 2014; Kollas et al., 2015; O'Leary et al., 2016; Verburg et al., 2012). Therefore, most process-based models could simulate the pure N effect of the pre-crop to the subsequent crop, but have the limitations to simulate the break-crop benefit because of the inability to consider plant health effects.

Unlike wheat and maize models/modules, legume models/modules are less focused and tested against available observed datasets on growth, N uptake and biological N_2 fixation of legume crops (Liu et al., 2013; Liu et al., 2011; Robertson et al., 2002; Robertson et al., 2001; Soltani et al., 2004; Soltani et al., 2005). In addition, although grain N concentration of legumes is essential for estimating net N inputs from legume biological N_2 fixation to subsequent crops, few of these datasets are available for model performance evaluations. This limits the modelling approach to investigate N contributions of legume crops to subsequent crops, and prevents analysis of the farm-economic values of legume incorporation in crop sequences.

In this study, three-year field experimental datasets on phenology, productivity, biological N_2 fixation and N concentration in field pea and lupin grain in southern NSW were used to calibrate and validate the performance of the Agricultural Production Systems sIMulator (APSIM; Holzworth et al., 2014). The calibrated APSIM was employed to (i) explore the N contributions of field pea and lupin to subsequent crops and (ii) investigate the farm economic profit of adding legume crops in cereal-based crop rotations in Australian rain-fed cropping systems.

2. Materials and methods

2.1. Site description

Two field experiments were conducted at two paddocks (fields), 3 km apart, at Wagga Wagga, NSW (35°01′45″ S, 147°20′36″ E; 210 m a.s.l) in a Red Kandosol (Isbell, 1996), classified as Chromic Luvisol by FAO (http://www.fao.org/soils-portal/soil-survey/soil-classification/world-reference-base/en/). The baseline soil chemical analysis showed that the soil was slightly acidic with a pH of 5.1 in $CaCl_2$ and soil organic carbon content was 1.64% at the soil surface (0–0.1 m). Details of the soil properties are given in Table 1. Wagga Wagga has a semi-arid continental climate with an annual average minimum/maximum temperature of 9.1/22.4 °C and a mean annual rainfall of 558 mm.

Table 1
Soil chemical and physical properties at the experimental site at Wagga Wagga NSW.

Soil depth (m)	pH in $CaCl_2$	Soil total N (%)	Soil total C (%)	Bulk density (g/cm^3)	LL (mm/mm)	DUL (mm/mm)	SAT (mm/mm)
0.0–0.1	5.1	0.15	1.64	1.41	0.10	0.30	0.35
0.1–0.2	4.9	0.06	0.67	1.49	0.12	0.30	0.34
0.2–0.4	5.7	0.05	0.46	1.43	0.16	0.30	0.32
0.4–0.6	6.1	0.05	0.36	1.35	0.18	0.29	0.33
0.6–0.9	6.2	–	–	1.49	0.19	0.29	0.35
0.9–1.2	6.2	–	–	1.55	0.22	0.28	0.34

Note: –, not measured. LL, lower limit for plant available soil water, DUL, drained upper limit; SAT, saturated water content.