Agricultural Systems 154 (2017) 112–123

Contents lists available at ScienceDirect

Agricultural Systems

journal homepage: www.elsevier.com/locate/agsy

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

Hongtao Xing[a,b,c,*], De Li Liu[a], Guangdi Li[a], Bin Wang[a,b], Muhuddin Rajin Anwar[a], Jason Crean[d], Rebecca Lines-Kelly[e], Qiang Yu[b,f]

[a] NSW Department of Primary Industries, Wagga Wagga Agricultural Institute, Wagga Wagga, NSW 2650, Australia
[b] School of Life Sciences, Faculty of Science, University of Technology Sydney, PO Box 123, Broadway, NSW 2007, Australia
[c] Key Laboratory of Water Cycle and Related Land Surface Processes, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China
[d] NSW Department of Primary Industries, Orange Agricultural Institute, Orange, NSW 2800, Australia
[e] NSW Department of Primary Industries, Bruxner Highway, Wollongbar, NSW 2477, Australia
[f] State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Institute of Soil and Water Conservation, Northwest Agriculture and Forest University, Yangling, Shaanxi 712100, China

A R T I C L E I N F O

Keywords:
Field pea
Lupin
Biological N_2 fixation
N contribution
Gross margin
APSIM

A B S T R A C T

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

* Corresponding author at: NSW Department of Primary Industries, Wagga Wagga Agricultural Institute, Wagga Wagga, NSW 2650, Australia.
E-mail address: Hongtao.Xing@uts.edu.au (H. Xing).

http://dx.doi.org/10.1016/j.agsy.2017.03.010
Received 4 November 2016; Received in revised form 8 March 2017; Accepted 12 March 2017
Available online 27 March 2017
0308-521X/

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.

Table 2
List of key parameters for simulating photoperiod, biomass, and yield of field pea and lupin in APSIM.

Parameter	Units	Description	Lupin	Field pea
Phenological parameters				
x_pp_end_of_juvenile_min	Hours	Lower limit for photoperiod	11.9	11.8
x_pp_end_of_juvenile_max	Hours	Upper limit for photoperiod	17.8	17.6
y_tt_end_of_juvenile	°C days	Thermal time from end juvenile to floral initiation	765	579
y_tt_floral_initiation	°C days	Thermal time from initiation to flowering	117	32
y_tt_flowering	°C days	Thermal time from flowering to start grain fill	200	151
y_tt_start_grain_fill	°C days	Thermal time from start grain fill to end grain fill	358	392
Dry matter and yield parameters				
y_hi_incr	1/day	Daily increase rate of harvest index (HI)	0.008	0.011

2.2. Crop sequences and agronomic measurements

Four types of crops were included in those 3-year crop rotation experiments. Narrowleaf lupin (cv. Jenabillup) and field pea (cv. Gunyah) were grown as break crops; wheat (*Triticum aestivum* cv. Lincoln) and canola (*Brassica napus* cv. Hyola 555) were the two non-legume crops. In experiment 1, field pea (P) or lupin (L) was sown in year 1 or year 2 in the rotation, while wheat (W) or canola (C) was sown in the other years. There were 12 crop sequences with grain legumes as break crops, namely PWW, PWC, PCC, PCW, LWW, LWC, LCC, LCW, WPC, WPW, WLC, WLW. The continuous cereal crops (WWW, WCW, CWW) were also included in the experiment design as controls. All crop sequences were arranged in a complete randomised block design with three replicates. For all wheat and canola crops except for those following legume crops, 25 kg N ha^{-1} was applied at sowing, and 50 kg N ha^{-1} top-dressed in the tillering stage for wheat, and branching stage for canola. In experiment 2, wheat was sown in year 1 and canola in year 2, followed by field pea or lupin in year 3. The experiment was a split-plot design with tillage (tilled vs no-till) as the whole plot and N application rates (0, 25, 50 and 100 kg N ha^{-1}) as the subplot, replicated three times. In this study, only the dataset from no tillage treatment were used in analysis, to be consistent with farmer practice in the region. More detailed experimental designs are described in Li et al. (2015) and Li et al. (2016).

Field pea and lupin plant samples were collected at anthesis and maturity in each year to measure above-ground biomass and grain yield. The AOAC Official Combustion Method (AOAC, 2012) was used to analyse plant nitrogen content in crop residues, while grain protein was analysed using the NIR method (Foss NIR Systems 6500). Whole plant samples of field pea and lupin, together with cereal reference plant samples, were taken at peak biomass for biological N_2 fixation estimation using the ^{15}N natural abundance method as described by Unkovich et al. (2008).

2.3. APSIM and APSIM-legume module

The Agricultural Production Systems sIMulator (APSIM) (Holzworth et al., 2014) is a farming systems model that simulates the key biophysical processes related to crop growth and production, water, carbon and N cycling in the soil-plant system. It has been extensively used to study the impact of agricultural practices (e.g. fertilization, irrigation and residue returns) on growth and production, water and nitrogen use efficiency of cereal crops and oil crops (e.g. winter-wheat, canola and maize) and soil organic carbon changes in the various cropping systems and rotations (Archontoulis et al., 2014; Asseng et al., 2001; Liu et al., 2016; Luo et al., 2011; Probert et al., 1994; Robertson and Holland, 2004; Thorburn et al., 2001; Wang et al., 2004). APSIM simulates above- and under-ground growth of crops, and decomposition of organic matter on the soil surface and in soil profiles (including roots and the incorporated residue), so it is able to simulate the effect of residue N on subsequent crop productivity.

The APSIM-Legume module is a modified version of the generic crop model template in the APSIM framework (Wang et al., 2002), and has been used for simulating crop development and growth, N uptake, biological N_2 fixation and N partitioning for a wide range of legume species, including field pea and lupin (Chen et al., 2016; Lecoeur and Sinclair, 2001; Robertson et al., 2002). Its performance in simulations of legume crop contributions to cropping rotation productivity is generally acceptable (Anderson et al., 1998; Chen et al., 2016; Farre et al., 2004). A detailed description of N demand, uptake, re-translocation and biological N fixation of legume crops in the APSIM-Legume module is given in Chen et al. (2016). As not all cultivars are included in the genetic parameter data sets, it is recommended that the model be calibrated against new experimental data sets when it is used (Chen et al., 2016), especially in untested regions such as southern NSW.

In this study, the observed data collected in 2012 from experiment 1 were used to calibrate APSIM-Legume in simulating the development, growth and biological N_2 fixation of field pea and lupin. As there were no available cultivar parameters for lupin (cv. Jenabillup) and field pea (cv. Gunyah) in APSIM v7.7 crop parameter sets, the default genetic coefficients for lupin (cv. Merrit) and field pea (cv. Parafield) were adopted. The key genetic parameters calibrated for field pea and lupin are listed in Tables 2 and 3. The calibrated model was then validated using the experimental data collected in experiment 2 and experiment 1 except the 2012 data.

The coefficient of determination (r^2) and root mean square error (RMSE) were used to evaluate the performance of APSIM in modelling the growth and biological N fixation of field pea and lupin in the study site.

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(P_i - O_i)^2} \quad (1)$$

where P_i and O_i are the model-predicted and experimentally measured (observed) points, respectively, and n is the number of observations.

2.4. Rotation simulations

The legume cereal-based crop rotations included one legume crop (field pea (F) or lupin (L)), and one or two non-legume crops (wheat (W)/canola (C)) in a 3-year crop sequence, resulting in six rotation options: 1) field pea-canola-canola (FCC), 2) field pea-wheat-wheat (FWW), 3) field pea-canola-wheat (FCW), 4) lupin-canola-canola (LCC), 5) lupin-wheat-wheat (LWW), and 6) lupin-canola-wheat (LCW). Non-legume cereal crop rotations included continuous canola, wheat, and canola-wheat rotations. In the simulation, the phytosanitary problems in the non-legume rotations were ignored as APSIM is unable to capture them.

To assess the rotation effects due to inter-annual climate variations, we simulated each crop in a rotation at the starting year (1901). For example, the FCC rotation was run three times in 1901 for each crop so the three runs were F-C-C, C-C-F and C-F-C. In the canola and wheat phases, N was applied at 9 rates from 0 to 200 kg N ha^{-1} y^{-1} at 25 kg N ha^{-1} intervals. There was a 12-year spin-up (1889–1900) in

Table 3
Parameters related to the simulations of N_2 fixation and concentrations in crop residues and grain of field pea and lupin in APSIM.

Parameter	Units	Description	Lupin			Field pea		
			6[a]	7[b]	9[c]	6[a]	7[b]	9[c]
N_fix_rate	g N/g DM	Potential N fixation rate in different stage	0.015	0.010	–	0.015	0.015	0.015
y_n_conc_max_leaf	%	Maximum N concentration in Leaves in different stage	–	0.010	0.005	–	–	–
y_n_conc_crit_leaf	%	Critical N concentration in Leaves in different stage	–	0.010	0.005	–	–	–
y_n_conc_min_leaf	%	Minimum N concentration in Leaves in different stage	–	0.005	0.001	–	–	–
y_n_conc_max_stem	%	Maximum N concentration in stem in different stage	–	0.005	0.005	–	–	–
y_n_conc_crit_stem	%	Critical N concentration in stem in different stage	–	0.006	0.006	–	–	–
y_n_conc_min_stem	%	Minimum N concentration in stem in different stage	–	0.001	0.001	–	–	–
y_n_conc_max_pod	%	Maximum N concentration in pod in different stage	–	0.005	0.005	–	–	–
y_n_conc_crit_pod	%	Maximum N concentration in pod in different stage	–	0.006	0.006	–	–	–
y_n_conc_min_pod	%	Maximum N concentration in pod in different stage	–	0.001	0.001	–	–	–
n_conc_crit_grain	%	Maximum N concentration in grain			0.048			0.047
n_conc_max_grain	%	Maximum N concentration in grain			0.052			0.044
n_conc_min_grain	%	Maximum N concentration in grain			0.030			0.020

Note: –, not changed.
[a] Flowering.
[b] Start grain filling.
[c] Maturity.

the continuous wheat cropping systems with typical farmers' N fertilizer input (40 kg N ha^{-1} y^{-1}) to establish the initial soil conditions. After the spin-up, APSIM was run continuously for all rotation and N input scenarios during 1901–2014.

Daily weather variables, including maximum and minimum air temperature, solar radiation, and rainfall from 1890 to 2014 for Wagga Wagga were obtained from the SILO Patched Point Dataset, managed by Queensland Department of Natural Resources and Mines (https://www.longpaddock.qld.gov.au/silo).

2.5. Estimation of nitrogen contribution

Net inputs of legume-fixed N (N_I) to subsequent crops and soil N pools were calculated as the difference between total legume-fixed N (NF) and N removed from the system in harvested legume grain (Espinoza et al., 2012). In this study, both biological N_2 fixation (BNF) estimated by the above-ground biomass and by the whole plant biomass (above- and under-ground biomass), were calculated. BNF estimated by the whole plant biomass was regarded as the total biological legume-fixed N.

$$N_I = NF - Y_L \times [N]_{Grain} \quad (2)$$

where Y_L is the simulated legume yield and $[N]_{Grain}$ is the legume grain N concentration at harvest.

The N contribution (NC) of a legume crop (lupin or field pea) to the subsequent crop was calculated as:

$$NC = N_{IR} - N_R \quad (3)$$

where N_{IR} (kg N ha^{-1}) is the N fertilizer application rate required for canola or wheat to produce the same yield in the non-legume crop rotation as in legume cereal-based crop rotations, and N_R (kg N ha^{-1}) is the rate of N fertilizer applied to canola or wheat in the legume cereal-based crop rotations. N_{IR} was estimated by the simulated response of canola or wheat yields to N inputs in the non-legume crop rotations (Fig. 1). The response of canola (or wheat) yield to N fertilizer applications generated in CCC (or WWW) cropping systems (Fig. 1a) was used to estimate the N contribution of grain legumes in the LCC and FCC (or LWW and FWW) rotations. The response of canola (or wheat) yield to N fertilizer applications generated in canola-wheat rotations (Fig. 1b) was used to estimate the N contribution of grain legumes in the LCW and FCW rotations. This approach can minimize the confounding effects of non-legume crops (i.e., W to C or C to W) with the N benefit of legume on the subsequent crops.

Our NC calculation is similar to the fertilizer nitrogen equivalent

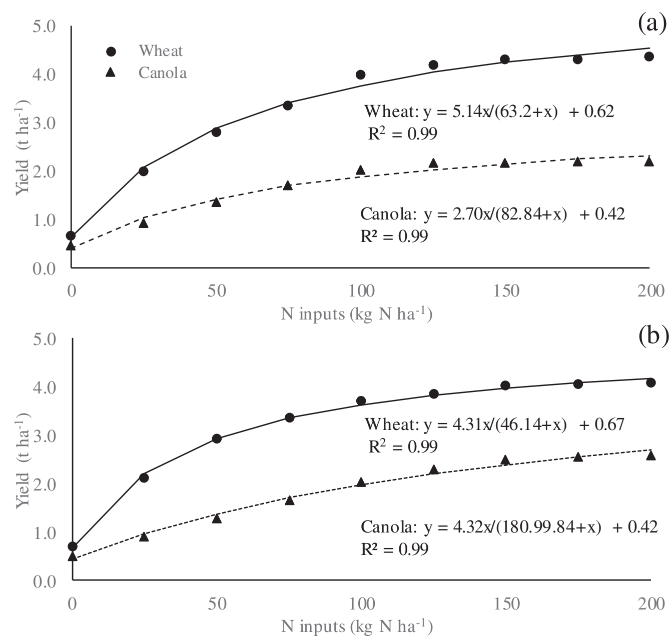

Fig. 1. The response of canola and wheat yields to net N fertilizer applications in monocropping systems (a) and canola-wheat rotations (CWW) at Wagga Wagga, NSW, Australia. CWW represents CWW, CCW, CWC, WWC, WCW and WCC, etc., canola-wheat rotation combinations.

(FNE) in the studies of Köpke and Nemecek (2010) and Preissel et al. (2015), defined as the fertilizer reduction in cereal crop stages after grain legumes that leads to yields comparable to those after a cereal pre-crop. However, as APSIM only simulates the pure N benefit of grain legumes to the subsequent crops and is unable to simulate the break-crop benefits, such as disease and weed control, our NC calculation was equal to the N contribution defined in previous studies (Beckie et al., 1997; Peoples et al., 2009).

In this study, the N contribution of grain legumes to the subsequent crop (NC) and rotation (NC_R) were calculated. NC was based on the crop yield sowed in the first crop of the rotation after grain legumes. We then summed up the values of NC from the two subsequent crops after the legume crop to assess the total legume N contribution (NC_R) at rotation level. This approach separated the contribution of legume-fixed N to subsequent crops from the total N contribution of legume crops to subsequent crops and soil N pools.

Table 4
Details of economic costs of agricultural management for wheat, canola, field pea and lupin, and on-farm grain price of these four crops.

Variable costs	Items	Unit	Wheat	Canola	Lupin	Field pea
Cost						
Cultivation		($/ha)	32.08	32.08	32.08	32.08
Sowing	Machinery	($/ha)	15.58	15.58	15.58	15.58
	Seeds	($/ha)	21	38.55	32	36
Fertilizer & application	Sowing	($/ha)	76	117	53	53
	Top dressing	Machinery	5.5	5.5	–	–
	(Urea)	($/kg)	0.66	0.66	–	–
Herbicide & application		($/ha)	83.76	63.9	76.66	93.1
Insecticide & application		($/ha)	28.56	8.41	17.59	26.13
Labour[a]		($/ha)	20.1	20.81	9.07	12.03
Contract harvesting[b]		($/ha)	37.07	50	49.4	49.4
Crop Insurance		% of on farm value	2.22	3.8	2.72	3.8
Levies		% of on farm value	1.02	1.02	1.02	1.02
Income						
On-farm grain price		$/t	200	520	200	220

The data is from the guide of Farm Enterprise budgets (NSW Department of Primary Industries, http://www.dpi.nsw.gov.au/content/agriculture/farm-business/budgets) and the study of Li et al. (2010).
[a] The cost of labour is to operate machinery for cultivation, sowing and the applications of Herbicide and Insecticide with sowing.
[b] The cost of contract harvesting includes the labour cost for operating machinery for harvesting.

The proportion of N contribution to net N inputs of legume-fixed N (CF) was calculated for the crop (CF_C) and the rotation (CF_R) to show the proportion of N_I contributing to the productivity of subsequent crops at crop and rotation levels.

$$CF = \mathrm{NC}/N_I \tag{4}$$

2.6. Gross margin analysis

The gross margin (GM) was calculated using the assumptions and methods given in Li et al. (2010):

$$\mathrm{GM} = \mathrm{GI} \times (1.0 - \mathrm{I} - \mathrm{L}) - \mathrm{C_S} - \mathrm{C_T} - \mathrm{C_F} - \mathrm{C_H} - \mathrm{C_I} - \mathrm{C_W} \tag{5}$$

where GI is the on-farm grain income ($ ha^{-1}) estimated by the on-farm price ($ Mg^{-1}) and grain yield (Mg ha^{-1}). The on-farm price for each crop is given in Table 4. L and I are the government levy ($ ha^{-1}) and crop insurance ($ ha^{-1}), which are a constant percentage of the on-farm grain income for each crop (Table 4). C_S, C_T, C_F, C_H, C_I and C_W are the costs for sowing, tillage, fertilizer, harvest, pest and grass weed control ($ ha^{-1}), respectively, including all labour costs. Labour costs for cultivation, crop sowing, fertilizer, and herbicide and insecticide application (listed as Labour in Table 4) were added into sowing in our calculations; harvesting labour costs were added into harvest contract. The economic costs of field management practices are also described in Table 4. Costs and calculations were coded in APSIM-Manager so that at each harvest economic analysis could be incorporated with other APSIM simulated results.

Gross margins (GM_R) for the rotation were calculated as the sum of the single crop gross margins in each rotation and N input scenario. As mentioned previously, APSIM is not able to consider the break-crop benefits. This means the GM difference of canola or wheat in the crop rotations with and without grain legumes is due only to yield differences in the different rotations. Potential farm economic benefits of grain legumes into crop sequences, such as pest control, plant protection and saved tillage costs, were not considered in the study.

3. Results

3.1. Model performance for simulating plant growth and biological N_2 fixation

As shown in Fig. 2, observed data of phenological stages, above-ground biomass, biological N_2 fixation and N concentrations in crop parts for both field pea and lupin were well predicted by the calibrated parameters (Tables 2 and 3).

The calibrated APSIM-Legume module performed well against the measured phenological stages (Fig. 3a and d) at flowering and maturity, with RMSE values of 3.2 and 5.2 days for field pea and lupin respectively. The model also predicted biomass (RMSE = 1.32 and 0.39 t ha^{-1} for field pea and lupin respectively), grain yield (RMSE = 0.32 and 0.22 t ha^{-1} for field pea and lupin respectively) (Fig. 3d–f), and observed N concentrations in crop residues (Fig. 3g–l). In general, the relationship between simulated and observed variables in Fig. 3, denoted with higher r^2 and lower RMSE values, implied good model performance. However, simulated grain N concentrations and N fixation were a poor fit with observed values, due to lack of variation in simulated and/or observed values. APSIM-canola and APSIM-wheat modules were also calibrated and validated against observed field data collected in our rotation experiments. The observed values of the above-ground biomass and yields of canola and wheat were well matched by APSIM (data not shown).

3.2. Grain yield and biological N_2 fixation in response to N fertilizer applied in wheat/canola growing seasons

Simulated grain yields and biological N_2 fixation (BNF) of field pea and lupin were influenced by both N fertilizer inputs in wheat/canola growing seasons and rotation systems (Fig. 4). BNF of field pea and lupin declined with increased N fertilizer inputs in wheat/canola growing seasons and the proportion of canola in crop sequences (Fig. 4a–b). The negative impact of the proportion of canola related to the lower residual water in the 0–120 cm soil profile when grain legumes were sown after canola in comparison to after wheat (data not shown). This agrees with Heenan (1995) and Kirkegaard et al. (2008) who showed that in semi-arid environments negative impacts of broadleaf break crops on residual water would lead to the negative impacts of production in the following crops. BNF values estimated by above-ground biomass were 25–40% lower than BNF estimated by the whole plant biomass (Fig. 4c–d).

3.3. Yield benefits to the subsequent non-legume crops

In both non-legume crop rotations and legume cereal-based crop rotations, canola and wheat yields increased as N fertilizer inputs increased from zero to optimal levels, and plateaued once N inputs exceeded optimal levels (about 150 and 125 kg N ha^{-1} for canola and wheat respectively, Fig. 5). Inclusion of field pea or lupin in crop

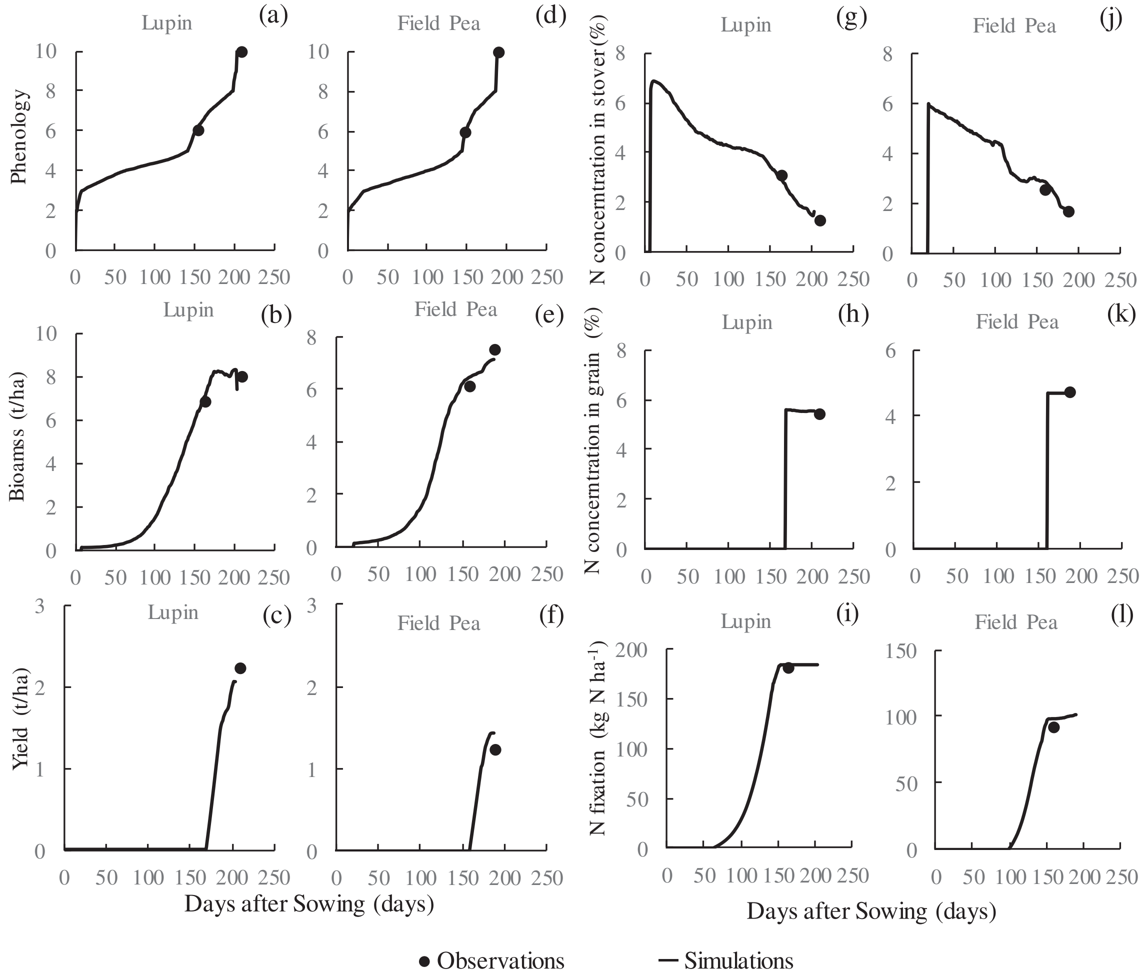

Fig. 2. Calibration of APSIM in modelling phenology (flowering and harvest days after sowing), above-ground biomass, yield, N concentrations of crop residues and grain, and N fixation of field pea and lupin in rainfed cropping systems at Wagga Wagga in 2011.

sequences increased canola and wheat grain yields, especially when N inputs were lower than optimal (Fig. 5). Lower residual soil water availability after canola lead to slightly lower wheat yield in LCW and FCW rotations in comparison to the wheat yield in LWW and FWW rotations (data not shown).

3.4. Nitrogen contributions of grain legumes

The contribution of legume-fixed N to the subsequent crop (NC) and the proportion of N contribution to the net N inputs of legume-fixed N (CF) were determined by N inputs in the subsequent crops (Fig. 6). NC and CF were highest (30–65 kg N ha^{-1} y^{-1} and 30–55% CF) with no N fertilizer application. Levels decreased exponentially as N fertilizer inputs increased to 125 and 50–75 kg N ha^{-1} in canola and wheat crops respectively, beyond which there was no N contribution from grain legumes. In general, assimilated N from grain legumes that fixed N_2 was greater in canola than wheat (Fig. 6).

Fig. 7 illustrates the N contribution of grain legumes in different rotation combinations. Legume-fixed N contributed 60–110 kg N ha^{-1} y^{-1} to subsequent crops over two years (Fig. 7a), corresponding to 60–85% of net input of legume-fixed N (Fig. 7b). The N contribution decreased exponentially to zero as N fertilizer inputs in wheat/canola growing seasons reached 75–125 kg N ha^{-1} (Fig. 7).

3.5. Gross margin competitiveness between cereal-based crop rotations with and without legumes

Comparisons of crop gross margins (GM) in different rotations in response to N fertilizer inputs are summarized in Fig. 8. For individual crops, there were large GM variations in response to N fertilizer inputs. When N inputs in the wheat/canola growing seasons were lower than 25 kg N ha^{-1} (Fig. 8), returns were canola AU$100–700 ha^{-1} y^{-1}, wheat AU$150–350 ha^{-1} y^{-1}, and legume AU$ 150–200 ha^{-1} y^{-1}. In general, canola and wheat GM increased in rotations as N fertilizer inputs increased to optimal levels, and decreased slightly (about AU $50 ha^{-1} y^{-1}) beyond the optimal rate (Fig. 8). In contrast, field pea and lupin GM decreased slightly with increased N fertilizer inputs in the wheat/canola growing seasons (Fig. 8c–d). Canola and wheat GM in legume cereal-based crop rotations were higher than those in non-legume crop rotations, notably when N input was lower than 75–100 kg N ha^{-1}.

GM values in response to N fertilizer inputs varied significantly across rotations (Fig. 9). In general, GM of legume cereal-based and non-legume crop rotations increased with increasing N input to optimal N input levels, and plateaued or slightly decreased beyond optimal levels. Optimal N input levels with the highest GM varied (75–125 kg N ha^{-1}) with rotations (Fig. 9). There was a break-even GM between the legume cereal-based and non-legume crop rotations in response to N input levels. For instance, break-even GM of rotations of continuous canola (CCC), field pea-canola-canola (FCC) and lupin-canola-canola (LCC) was 75 kg N ha^{-1} (Fig. 9). Below this level, GMs of

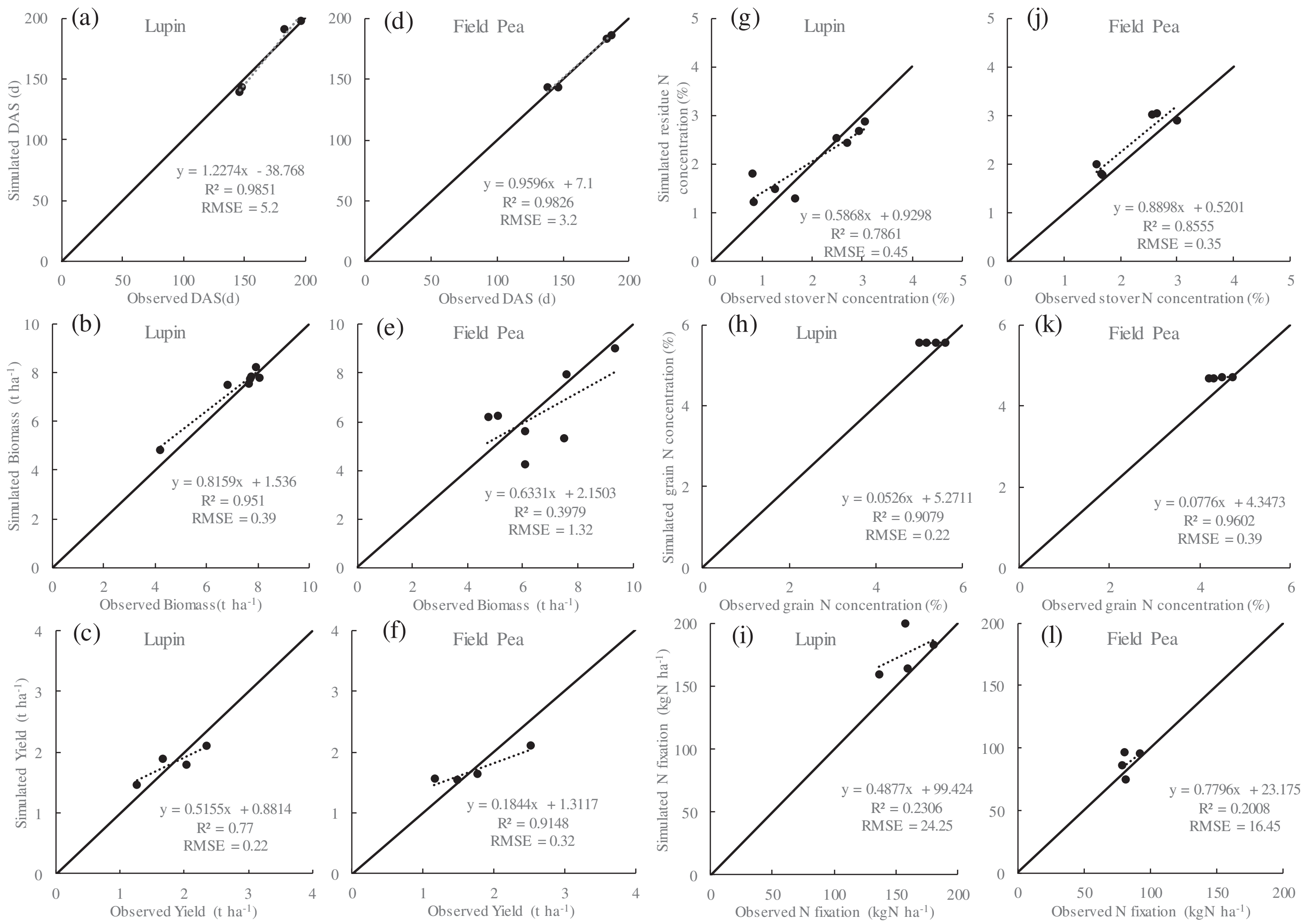

Fig. 3. Comparisons of observed and simulated phenology (flowering and harvest days after sowing), above-ground biomass, yield, N concentrations of crop residues and grain, and N fixation of field pea and lupin in rainfed cropping systems at Wagga Wagga, NSW, Australia.

legume cereal-based crop rotations were higher than those of non-legume crop rotations; above this level they were lower. Incorporation of grain legumes into crop sequences would be profitable when N fertilizer input in the wheat/canola stage is below 75 kg N ha^{-1}.

4. Discussion

Grain legumes have the potential to improve soil N availability in following crop growing seasons, but more knowledge is needed to understand their role in legume cereal-based crop rotations (Chalk, 1998; Peoples et al., 2009; Preissel et al., 2015). In this study, we linked field experimental data with the APSIM model to present three propositions relating to the benefits of grain legumes in rotations: (1) simulations of the net input of legume-fixed N_2; (2) N contribution of grain legumes to subsequent crops; and (3) economic profitability of incorporating grain legumes in crop sequences.

4.1. Simulations of the net input of legume-fixed N with APSIM

Nitrogen is the primary soil nutrient limiting agricultural productivity in Australia (McNeill and Penfold, 2009; Nichols et al., 2007) and elsewhere (FAO Joint, 1998). Understanding the processes of N accumulation (demand, uptake and translocation of N) in response to climate variables, soil water and N supply, and their effects on crop yields, is an important research issue for crop production. The role of symbiotic N_2 fixation by grain legumes to improve soil N fertility in agricultural systems has been the subject of numerous studies (Jensen et al., 2006; McCallum et al., 2000; Peoples et al., 2009; Preissel et al., 2015).

In the present study, we calibrated and validated the APSIM model with three years of experimental data. APSIM performed well in simulating phenology (flowering and maturity), above-ground biomass, grain yield, and biological N_2 fixation for field pea and lupin. Our results showed that this model captured the crop-environment interactions processes well, similar to previous studies (Anderson et al., 1998; Chen et al., 2016; Farre et al., 2004). In addition, N concentrations in crop residues and grain enabled us to further evaluate the model's performance to estimate net N input of legume to fix biological N_2 to the subsequent crops (Figs. 1 and 2), estimated by the difference between the total biological N_2 fixation in total plant biomass and removed biological N_2 fixation in grain (Beckie et al., 1997; Espinoza et al., 2012). This meant APSIM could be used to evaluate a broader range of farming systems and environmental conditions.

Our study revealed that average annual biological N_2 fixation by field pea and lupin in above-ground biomass was 160–175 kg N ha^{-1} y^{-1} without N fertilizer inputs in legume cereal-based crop rotations (Fig. 4). These values were within the range (100–216 kg N ha^{-1} y^{-1}) reported in Australia (Anderson et al., 1998; Evans et al., 1989; McCallum et al., 2000; Peoples et al., 2009) and other dryland environments (Peoples et al., 2009; Preissel et al., 2015). Simulated BNF from the total plant biomass was 25–40% higher than simulated BNF from the above-ground biomass (Fig. 4). This is consistent with Russell and Fillery (1996) and McCallum et al. (2000) who used the ^{15}N technique to find that biological N_2 fixation in above-ground biomass and roots was 20–40% higher than in above-ground biomass alone. This indicated that the simulated values of biological N_2

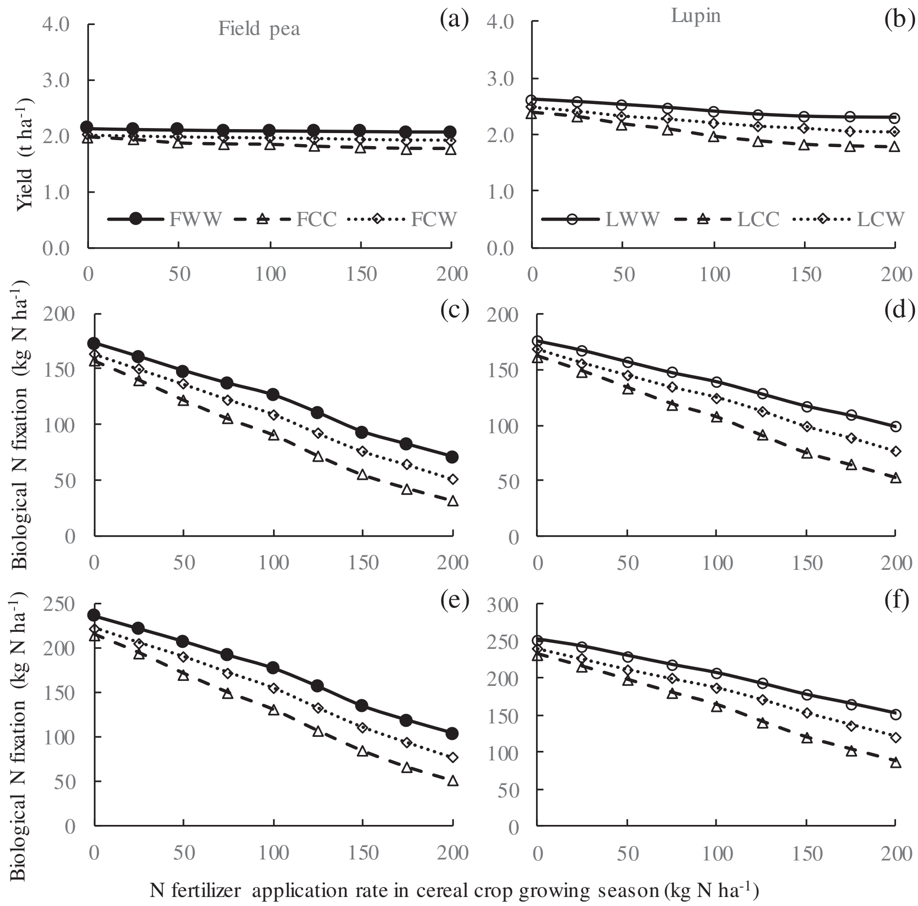

Fig. 4. Response of yields (a, b), biological N_2 fixation in above-ground biomass (c, d) and whole plant (e, f) of field pea and lupin to N inputs in wheat/canola growing seasons and rotation systems in rainfed cropping systems at Wagga Wagga, NSW, Australia. FCC, FWW, FCW represent field pea-canola-canola rotations, field pea-wheat-wheat rotations and field pea-canola-wheat rotations, respectively; LCC, LWW and LCW represent lupin-canola-canola rotations, lupin-wheat-wheat rotations, and lupin-canola-wheat rotations, respectively.

fixation in total plant biomass in this study were acceptable and further confirmed the capability of APSIM to estimate the net input of fixed N_2 to subsequent crops, N contributions of grain legumes to subsequent crops, and the productivity benefit of wheat/canola planted after grain legumes caused by legume-fixed N. However, this applies only to the pure nitrogen effect; the full nitrogen plus break-crop effect of grain legumes is not estimated by APSIM, which needs further model development.

4.2. Nitrogen contribution of grain legumes at crop and rotation levels

The direct N contribution of grain legumes to subsequent crops was explored at both crop and rotation levels in this study. Our simulation results showed that, without N fertilization, grain legumes contributed 25–60 kg N ha^{-1} of fixed N to subsequent crops (Fig. 6c–d), which agreed with results from previous studies (Anderson et al., 1998; Beckie et al., 1997; Chalk et al., 1993; Evans et al., 1991; Evans et al., 1989; McCallum et al., 2000). However, legume N, as an organic material, has the notable feature of mineralization, and N release follows the exponential decay function and can take years (Davidson et al., 1991; Ladd and Amato, 1986; Ladd et al., 1983). Nevertheless, 60–80% of organic material decomposes in the first two years (Davidson et al., 1991; Ladd and Amato, 1986; Ladd et al., 1983). Our simulations also showed that 30–55% and 60–85% of net N input of legume-fixed N

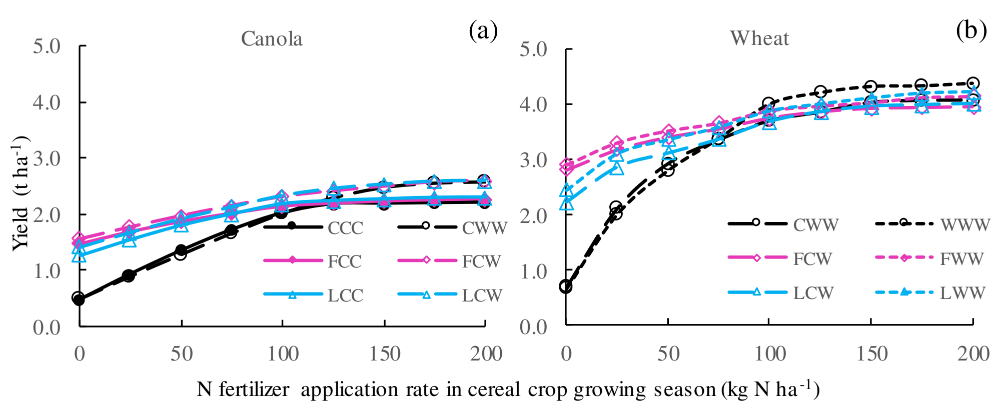

Fig. 5. Impact of N inputs in wheat/canola growing seasons on yields of wheat and canola in legume cereal-based and non-legume crop rotations in rainfed cropping system at Wagga Wagga, NSW, Australia.

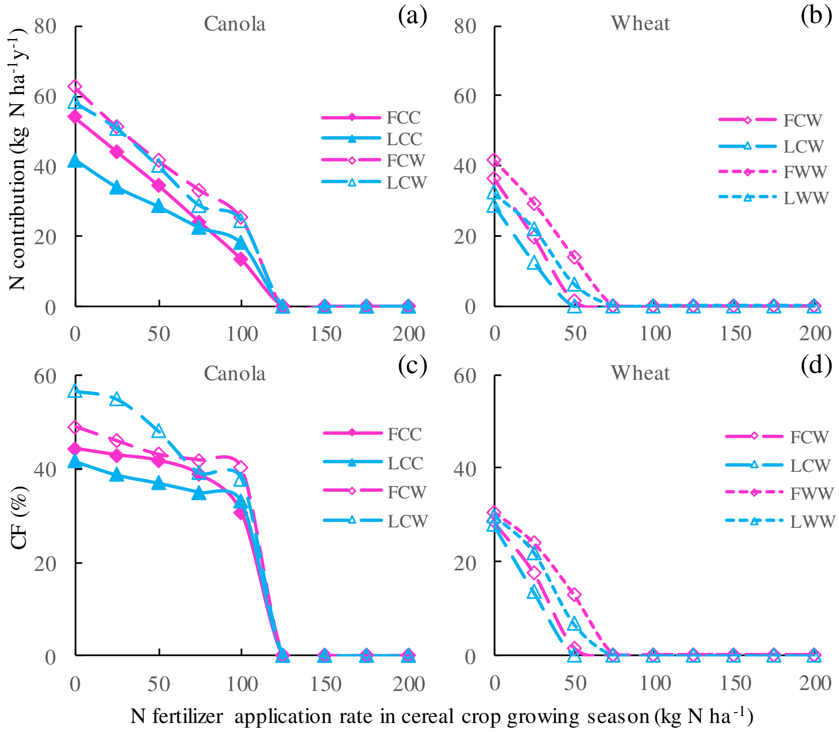

Fig. 6. Response of N contribution of grain legumes to canola (a) and wheat (b), and the fraction of N contribution to the net N input of legume-fixed N (CF, canola: c, wheat: d) to the N fertilizer inputs in wheat/canola stages at Wagga Wagga, NSW, Australia.

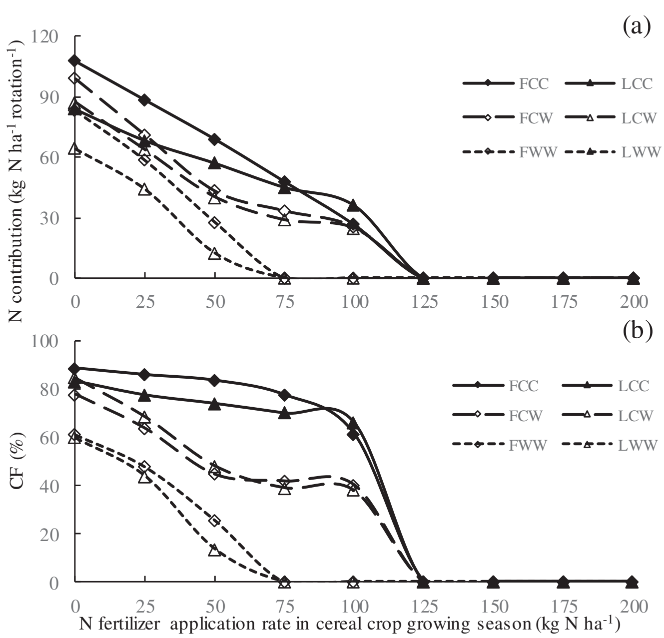

Fig. 7. Response of N contribution of grain legumes to wheat/canola (a) and the fraction of N contribution to the net N input of legume-fixed N (CF, b) at rotation level to N fertilizer inputs in wheat/canola stages at Wagga Wagga, NSW, Australia.

would contribute to the succeeding crop and to two crops respectively, corresponding to a total 60–110 kg N ha^{-1} in the two years after the legume crop (Figs. 6 and 7). This indicated that the N benefit to crops should be measured over two years to fully evaluate the N contribution of grain legumes.

To further explore the profitability of incorporating legume crops in the study region, we investigated the response of legume N contribution to N fertilizer applied in wheat/canola in legume cereal-based crop rotations (Figs. 6 and 7). Our results showed that as N inputs in subsequent crop growing seasons increased, legume N contributions reduced, similar to findings reported by Peoples et al. (1995), Peoples et al. (2009) and Preissel et al. (2015). Additionally, we confirmed that, in this region, the direct N benefit of grain legumes to subsequent crops would be invisible when N fertilizer was applied over the optimal level. In our studies, the optimal rate of N fertilizer was 125 and 75 kg N ha^{-1} y^{-1} for canola and wheat respectively. The typical N fertilizer application rate in the study region is about 50 kg N ha^{-1} y^{-1} to canola and 40 kg N ha^{-1} y^{-1} to wheat. At these application rates, the addition of grain legumes in crop sequences could provide up to 40 kg N ha^{-1} of average annual N benefit to the next crop and up to70 kg N ha^{-1} to crops over two years.

4.3. Economic profitability

Our simulated results showed that individual legume crops were uneconomic compared with wheat and canola (Fig. 8c–d) as previous studies have reported (Lehmann et al., 2013; Li et al., 2010; Preissel et al., 2015). This is one of the major reasons for the decline of legume production, especially in Australian rainfed cropping systems (Seymour et al., 2012), because profit-motivated farmers seek and adopt cropping systems that provide higher net economic benefit (Zentner et al., 2002). The decline of legume production in Australian cropping systems can be attributed to insignificant N benefit from individual legume crops, higher economic risk in using grain legumes as break crops in comparison to cereal crops (Seymour et al., 2012), and the significant increase in more profitable canola production (ABARES, 2016; Li et al., 2016), since canola was introduced into Australia in the late 1980s (ABARES, 2016; Seymour et al., 2012).

However, our simulations indicate that the profitability of incorporating legume crops into crop sequences may be underestimated, as may estimates of N benefit from grain legumes. We observed that legume crops provided additional N to subsequent crops (Fig. 6), resulting in a yield benefit to the subsequent crop (Fig. 4) and higher farm profitability of subsequent crops in legume cereal-based crop rotations (Fig. 8a–b). This resulted in a higher gross margin from legume

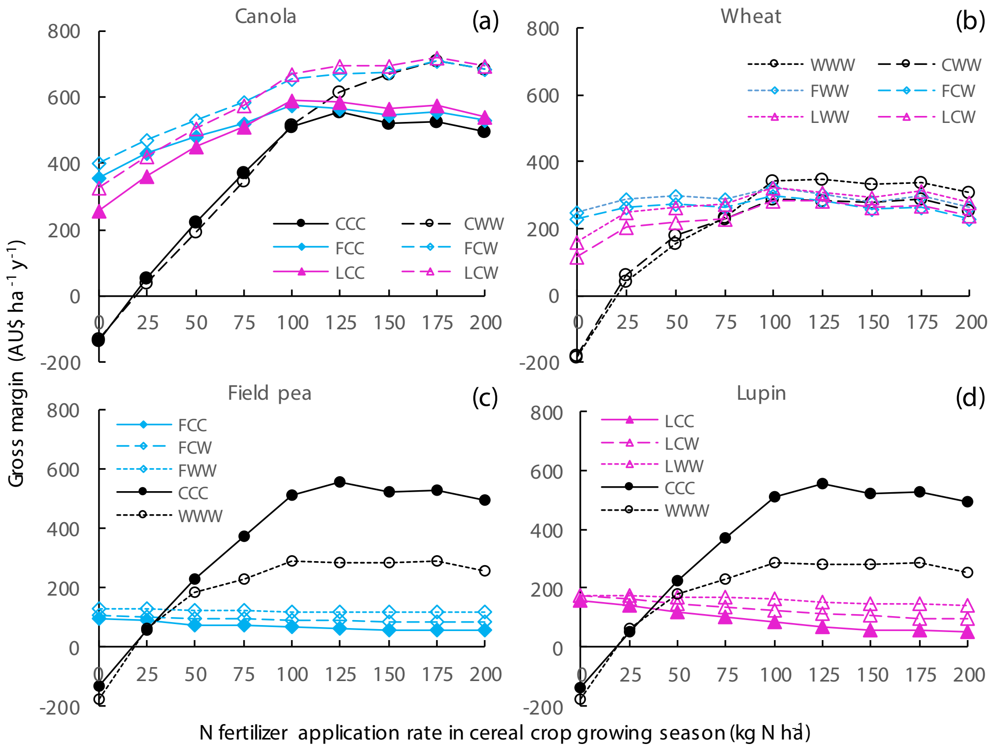

Fig. 8. Response of gross margins gained by sowing canola (a), wheat (b), field pea (c) and lupin (d) to N inputs in wheat/canola growing seasons in non-legume crop and legume cereal-based crop rotations at Wagga Wagga, NSW, Australia. FCC, FWW, FCW represent field pea-canola-canola rotations, field pea-wheat-wheat rotations and field pea-canola-wheat rotations, respectively; LCC, LWW and LCW represent lupin-canola-canola rotations, lupin-wheat-wheat rotations, and lupin-canola-wheat rotations, respectively; CCC and WWW represent continuous canola and wheat cropping systems, respectively; CWW represents canola and wheat crop rotations.

cereal-based crop rotations in comparison with non-legume crop rotations when N fertilizer inputs in the canola/wheat crop growing seasons were lower than optimal N input levels (Fig. 9). The gross margins of legume rotations would be even higher, when break crop benefits were considered. Our results, supported by Sánchez-Girón et al. (2004) and Preissel et al. (2015), demonstrate that addition of grain legumes into crop sequences could lead to an economic benefit to farmers, and that benefits of grain legumes need to be considered at the rotation level rather than the individual crop level. Moreover, our study confirmed an upper limit of 75 kg N ha^{-1} of N fertilizer input in the wheat/canola growing season if inclusion of grain legumes in crop sequences is to be profitable. This provides useful information for farmers in the region looking to gain optimal profit under different N inputs.

Additional benefits of legume crops in rotations, including the break crop benefit and reduced greenhouse gas emissions, were not considered in this study. By acting as a break crop, grain legumes have potential to reduce pests and diseases in following crops, thereby reducing control costs and increasing net profit. In fixing nitrogen, legumes potentially reduce nitrous oxide emissions (Reckling et al., 2016). The break crop benefits of canola to wheat productivity were also not considered in this study. Further research should incorporate break crop and emissions benefits to fully evaluate the profitability of retaining or adding legume crops in crop rotations.

5. Conclusion

Our simulation study confirmed that APSIM is a reliable tool to estimate the pure N contribution of grain legumes to subsequent crops after careful validation against observed data relating to growth, above-

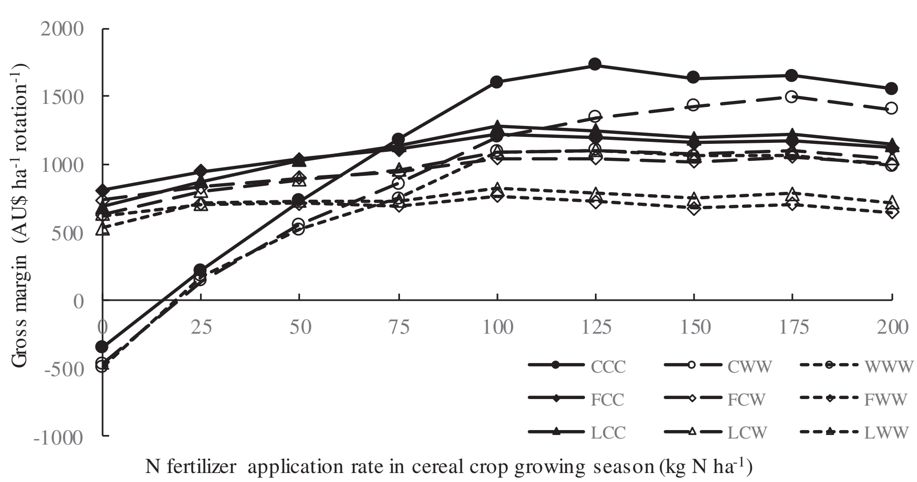

Fig. 9. Response of gross margins gained from non-legume crop and legume cereal-based crop rotations to N inputs in wheat/canola growing seasons at Wagga Wagga, NSW, Australia.

ground biomass, yield, N concentrations in plant parts and biological N_2 fixation. It is crucial to evaluate the N benefit and farm-economic profit of legume crops in the full rotation rather than as an individual crop. There is a fertilizer threshold applied in wheat/canola growing season if the grain legumes are able to provide a fertilizer benefit and farm-economic profit. In southern NSW, this threshold is 100–125 kg N ha^{-1} for N benefit and 75 kg N ha^{-1} for farm-profitability.

Acknowledgements

This work was funded by the New South Wales Department of Primary Industries and collaboration with University of Technology, Sydney (RM8: CONT16/573).

References

ABARES, 2016. Agricultural commodity statistics 2016. In: Wright, A. (Ed.), Australian Commodities, . http://www.agriculture.gov.au/abares/display?url=http://143.188.17.20/anrdl/DAFFService/display.php?fid=pb_agcstd9abcc0022016_Sn9Dg.xml.
Anderson, G.C., Fillery, I.R.P., Dolling, P.J., Asseng, S., 1998. Nitrogen and water flows under pasture-wheat and lupin-wheat rotations in deep sands in Western Australia - 1. Nitrogen fixation in legumes, net N mineralisation, and utilisation of soil-derived nitrogen. Aust. J. Agric. Res. 49, 329–343.
AOAC, 2012. AOAC Official Method 990.03 Protein (Crude) in Animal Feed - Combustion Method, Official Methods of Analysis of AOAC International, 19th ed. Association of Official Analytical Chemists International, Arlington, VA.
Archontoulis, S.V., Miguez, F.E., Moore, K.J., 2014. Evaluating APSIM maize, soil water, soil nitrogen, manure, and soil temperature modules in the Midwestern United States. Agron. J. 106, 1025–1040.
Asseng, S., Turner, N.C., Keating, B.A., 2001. Analysis of water- and nitrogen-use efficiency of wheat in a Mediterranean climate. Plant Soil 233, 127–143.
Beckie, H.J., Brandt, S.A., Schoenau, J.J., Campbell, C.A., Henry, J.L., Janzen, H.H., 1997. Nitrogen contribution of field pea in annual cropping systems. 2. Total nitrogen benefit. Can. J. Plant Sci. 77, 323–331.
Chalk, P.M., 1998. Dynamics of biologically fixed N in legume-cereal rotations: a review. Aust. J. Agric. Res. 49, 303–316.
Chalk, P.M., Smith, C.J., Hamilton, S.D., Hopmans, P., 1993. Characterization of the N benefit of a grain legume (*Lupinus angustifolius* L.) to a cereal (*Hordeum vulgare* L.) by an in situ ^{15}N isotope dilution technique. Biol. Fertil. Soils 15, 39–44.
Chen, C., Lawes, R., Fletcher, A., Oliver, Y., Robertson, M., Bell, M., Wang, E., 2016. How well can APSIM simulate nitrogen uptake and nitrogen fixation of legume crops? Field Crop Res. 187, 35–48.
Chen, C., Wang, E.L., Yu, Q., 2010. Modeling wheat and maize productivity as affected by climate variation and irrigation supply in North China Plain. Agron. J. 102, 1037–1049.
Davidson, E.A., Hart, S.C., Shanks, C.A., Firestone, M.K., 1991. Measuring gross nitrogen mineralization, and nitrification by 15N isotopic pool dilution in intact soil cores. J. Soil Sci. 42, 335–349.
Espinoza, S., Ovalle, C., Zagal, E., Matus, I., Tay, J., Peoples, M.B., del Pozo, A., 2012. Contribution of legumes to wheat productivity in Mediterranean environments of central Chile. Field Crop Res. 133, 150–159.
Evans, J., Fettell, N., Coventry, D., O'Connor, G., Walsgott, D., Mahoney, J., Armstrong, E., 1991. Wheat response after temperate crop legumes in south-eastern Australia. Aust. J. Agric. Res. 42, 31–43.
Evans, J., O'Connor, G.E., Coventry, D.R., Walsgott, D.N., Mahoney, J., Turner, G.L., Fettell, N., Armstrong, E.L., 1989. N_2 fixation and its value to soil N increase in lupin, field pea and other legumes in south-eastern Australia. Aust. J. Agric. Res. 40, 791–805.
Ewing, M., Bathgate, A., French, R., Revell, C., 1992. The role of crop and pasture legumes in rotations on duplex soils. Aust. J. Exp. Agric. 32, 971–979.
Fang, Q.X., Ma, L., Green, T.R., Yu, Q., Wang, T.D., Ahuja, L.R., 2010. Water resources and water use efficiency in the North China Plain: current status and agronomic management options. Agric. Water Manag. 97, 1102–1116.
FAO Joint, 1998. Improving yield and nitrogen fixation of grain legumes in the tropics and sub-tropics of Asia. Results of a co-ordinated research programme. In: Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture, .
FAO STAT, 2016. Production—Crops. Grain Legume Production Areas EU Countries and Switzerland. (Available online at: http://faostat3.fao.org/home/E) Food and Agriculture Organization of The United Nations Statistics Division.
Farre, I., Robertson, M.J., Asseng, S., French, R.J., Dracup, M., 2004. Simulating lupin development, growth, and yield in a Mediterranean environment. Aust. J. Agric. Res. 55, 863–877.
Gabrielle, B., Roche, R., Angas, P., Cantero-Martinez, C., Cosentino, L., Mantineo, M., Langensiepen, M., Henault, C., Laville, P., Nicoullaud, B., Gosse, G., 2002. A priori parameterisation of the CERES soil-crop models and tests against several European data sets. Agronomie 22, 119–132.
Heenan, D.P., 1995. Effects of broad-leaf crops and their sowing time on subsequent wheat production. Field Crop Res. 43, 19–29.
Herridge, D.F., 2008. Inoculation technology for legumes. In: Dilworth, M.J., James, E.K., Sprent, J.I., Newton, W.E. (Eds.), Nitrogen-fixing Leguminous Symbioses. Springer Netherlands, Dordrecht, pp. 77–115.
Holzworth, D.P., Huth, N.I., deVoil, P.G., Zurcher, E.J., Herrmann, N.I., McLean, G., Chenu, K., van Oosterom, E.J., Snow, V., Murphy, C., Moore, A.D., Brown, H., Whish, J.P.M., Verrall, S., Fainges, J., Bell, L.W., Peake, A.S., Poulton, P.L., Hochman, Z., Thorburn, P.J., Gaydon, D.S., Dalgliesh, N.P., Rodriguez, D., Cox, H., Chapman, S., Doherty, A., Teixeira, E., Sharp, J., Cichota, R., Vogeler, I., Li, F.Y., Wang, E., Hammer, G.L., Robertson, M.J., Dimes, J.P., Whitbread, A.M., Hunt, J., van Rees, H., McClelland, T., Carberry, P.S., Hargreaves, J.N.G., MacLeod, N., McDonald, C., Harsdorf, J., Wedgwood, S., Keating, B.A., 2014. APSIM – evolution towards a new generation of agricultural systems simulation. Environ. Model. Softw. 62, 327–350.
Isbell, R.F., 1996. The Australian Soil Classification. CSIRO Publishing, Collingwood, Victoria, Australia.
Solutions, J.C.S., 2014. Australian feed grain supply and demand report 2013/14. In: Spragg, J. (Ed.), Australian Feed Grain Supply and Demand Report 2013/14, (Berwick Vic, Australia).
Jensen, E.S., 1997. The Role of Grain Legume N_2 Fixation in the Nitrogen Cycling of Temperate Cropping Systems. Roskilde, Risoe National Laboratory.
Jensen, E.S., Ambus, P., Bellostas, N., Boisen, S., Brisson, N., Corre-Hellou, G., Crozat, Y., Dahlmann, C., Dibet, A., von Fragstein, P., Gooding, M., Hauggaard-Nielsen, H., Kasyanova, E., Launay, M., Monti, M., Pristeri, A., 2006. Intercropping of Cereals and Grain Legumes for Increased Production, Weed Control, Improved Product Quality and Prevention of N-losses in European Organic Farming Systems. Joint Organic Congress, Odense, Denmark.
Kirkegaard, J., Christen, O., Krupinsky, J., Layzell, D., 2008. Break crop benefits in temperate wheat production. Field Crop Res. 107, 185–195.
Kollas, C., Kersebaum, K.C., Nendel, C., Manevski, K., Müller, C., Palosuo, T., Armas-Herrera, C.M., Beaudoin, N., Bindi, M., Charfeddine, M., Conradt, T., Constantin, J., Eitzinger, J., Ewert, F., Ferrise, R., Gaiser, T., Cortazar-Atauri, I.G.D., Giglio, L., Hlavinka, P., Hoffmann, H., Hoffmann, M.P., Launay, M., Manderscheid, R., Mary, B., Mirschel, W., Moriondo, M., Olesen, J.E., Öztürk, I., Pacholski, A., Ripoche-Wachter, D., Roggero, P.P., Roncossek, S., Rötter, R.P., Ruget, F., Sharif, B., Trnka, M., Ventrella, D., Waha, K., Wegehenkel, M., Weigel, H.-J., Wu, L., 2015. Crop rotation modelling—a European model intercomparison. Eur. J. Agron. 70, 98–111.
Köpke, U., Nemecek, T., 2010. Ecological services of faba bean. Field Crop Res. 115, 217–233.
Ladd, J.N., Amato, M., 1986. The fate of nitrogen from legume and fertilizer sources in soils successively cropped with wheat under field conditions. Soil Biol. Biochem. 18, 417–425.
Ladd, J.N., Amato, M., Jackson, R.B., Butler, J.H.A., 1983. Utilization by wheat crops of nitrogen from legume residues decomposing in soils in the field. Soil Biol. Biochem. 15, 231–238.
Lecoeur, J., Sinclair, T.R., 2001. Harvest index increase during seed growth of field pea. Eur. J. Agron. 14, 173–180.
Lehmann, N., Finger, R., Klein, T., Calanca, P., Walter, A., 2013. Adapting crop management practices to climate change: modeling optimal solutions at the field scale. Agric. Syst. 117, 55–65.
Li, G., Peoples, M., Lowrie, R., Lowrie, A., Swan, T., Goward, L., 2015. Using Broadleaf Crops to Improve Wheat Grain Yield and on Farm Profitability .
Li, G.D., Conyers, M.K., Schwenke, G.D., Hayes, R.C., Liu, D.L., Lowrie, A.J., Poile, G.J., Oates, A.A., Lowrie, R.J., 2016. Tillage does not increase nitrous oxide emissions under dryland canola (*Brassica napus* L.) in a semiarid environment of south-eastern Australia. Soil Res. 54 (5), 512–522.
Li, G.D., Singh, R.P., Brennan, J.P., Helyar, K.R., 2010. A financial analysis of lime application in a long-term agronomic experiment on the south-western slopes of New South Wales. Crop Pasture Sci. 61, 12–23.
Liu, D.L., O'Leary, G.J., Ma, Y., Cowie, A., Li, F.Y., McCaskill, M., Conyers, M., Dalal, R., Robertson, F., Dougherty, W., 2016. Modelling soil organic carbon 2. Changes under a range of cropping and grazing farming systems in eastern Australia. Geoderma 265, 164–175.
Liu, Y.Y., Wu, L., Watson, C.A., Baddeley, J.A., Pan, X.B., Zhang, L.Z., 2013. Modeling biological dinitrogen fixation of field pea with a process-based simulation model. Agron. J. 105, 670–678.
Liu, Y.Y., Wu, L.H., Baddeley, J.A., Watson, C.A., 2011. Models of biological nitrogen fixation of legumes. A review. Agron. Sustain. Dev. 31, 155–172.
Luo, Z.K., Wang, E.L., Sun, O.J., Smith, C.J., Probert, M.E., 2011. Modeling long-term soil carbon dynamics and sequestration potential in semi-arid agro-ecosystems. Agric. For. Meteorol. 151, 1529–1544.
McCallum, M.H., Peoples, M.B., Connor, D.J., 2000. Contributions of nitrogen by field pea (*Pisum sativum* L.) in a continuous cropping sequence compared with a lucerne (*Medicago sativa* L.)-based pasture ley in the Victorian Wimmera. Aust. J. Agric. Res. 51, 13–22.
McNeill, A.M., Penfold, C.M., 2009. Agronomic management options for phosphorus in Australian dryland organic and low-input cropping systems. Crop Pasture Sci. 60, 163–182.
Nichols, P.G.H., Loi, A., Nutt, B.J., Evans, P.M., Craig, A.D., Pengelly, B.C., Dear, B.S., Lloyd, D.L., Revell, C.K., Nair, R.M., Ewing, M.A., Howieson, J.G., Auricht, G.A., Howie, J.H., Sandral, G.A., Carr, S.J., de Koning, C.T., Hackney, B.F., Crocker, G.J., Snowball, R., Hughes, E.J., Hall, E.J., Foster, K.J., Skinner, P.W., Barbetti, M.J., You, M.P., 2007. New annual and short-lived perennial pasture legumes for Australian agriculture – 15 years of revolution. Field Crop Res. 104, 10–23.
O'Leary, G.J., Liu, D., Ma, Y.C., Li, F.Y.H., McCaskill, M., Conyers, M., Dalal, R., Reeves, S., Page, K., Dang, Y.P., Robertson, F., 2016. Modelling soil organic carbon 1. Performance of APSIM crop and pasture modules against long-term experimental data. Geoderma 264, 227–237.
Peoples, M.B., Brockwell, J., Herridge, D.F., Rochester, I.J., Alves, B.J.R., Urquiaga, S., Boddey, R.M., Dakora, F.D., Bhattarai, S., Maskey, S.L., Sampet, C., Rerkasem, B., Khan, D.F., Hauggaard-Nielsen, H., Jensen, E.S., 2009. The contributions of nitrogen-

fixing crop legumes to the productivity of agricultural systems. Symbiosis 48, 1–17.
Peoples, M.B., Herridge, D.F., Ladha, J.K., 1995. Biological nitrogen fixation: an efficient source of nitrogen for sustainable agricultural production? Plant Soil 174, 3–28.
Power, J.F., 1987. Legumes: their potential role in agricultural production. Am. J. Altern. Agric. 2, 69–73.
Preissel, S., Reckling, M., Schläfke, N., Zander, P., 2015. Magnitude and farm-economic value of grain legume pre-crop benefits in Europe: a review. Field Crop Res. 175, 64–79.
Probert, M.E., Keating, B.A., Thompson, J.P., Parton, W.J., 1994. Modelling water, nitrogen, and crop yield for a long-term fallow management experiment. In: National Workshop on Long-term Experiments. C S I R O Publications, Canberra, Australia, pp. 941–950.
Reckling, M., Bergkvist, G., Watson, C.A., Stoddard, F.L., Zander, P.M., Walker, R., Pristeri, A., Toncea, I., Bachinger, J., 2016. Trade-offs between economic and environmental impacts of introducing legumes into cropping systems. Front. Plant Sci. 7.
Robertson, M.J., Carberry, P.S., Huth, N.I., Turpin, J.E., Probert, M.E., Poulton, P.L., Bell, M., Wright, G.C., Yeates, S.J., Brinsmead, R.B., 2002. Simulation of growth and development of diverse legume species in APSIM. Aust. J. Agric. Res. 53, 429–446.
Robertson, M.J., Holland, J.F., 2004. Production risk of canola in the semi-arid subtropics of Australia. Aust. J. Agric. Res. 55, 525–538.
Robertson, M.J., Lawes, R.A., Bathgate, A., Byrne, F., White, P., Sands, R., 2010. Determinants of the proportion of break crops on Western Australian broadacre farms. Crop and Pasture Science 61, 203–213.
Robertson, M.J., Silim, S., Chauhan, Y.S., Ranganathan, R., 2001. Predicting growth and development of pigeonpea: biomass accumulation and partitioning. Field Crop Res. 70, 89–100.
Rochester, I., Peoples, M., 2005. Growing vetches (*Vicia villosa* Roth) in irrigated cotton systems: inputs of fixed N, N fertiliser savings and cotton productivity. Plant Soil 271, 251–264.
Russell, C.A., Fillery, I.R.P., 1996. Estimates of lupin below-ground biomass nitrogen, dry matter, and nitrogen turnover to wheat. Aust. J. Agric. Res. 47, 1047–1059.
Sánchez-Girón, V., Serrano, A., Hernanz, J.L., Navarrete, L., 2004. Economic assessment of three long-term tillage systems for rainfed cereal and legume production in semiarid central Spain. Soil Tillage Res. 78, 35–44.
Schwenke, G.D., Felton, W.L., Herridge, D., Khan, D.F., Peoples, M.B., 2002. Relating particulate organic matter-nitrogen (POM-N) and non-POM-N with pulse crop residues, residue management and cereal N uptake. Agronomie 22, 777–787.
Seymour, M., Kirkegaard, J.A., Peoples, M.B., White, P.F., French, R.J., 2012. Break-crop benefits to wheat in Western Australia – insights from over three decades of research. Crop and Pasture Science 63, 1–16.
Siddique, K.H.M., Erskine, W., Hobson, K., Knights, E.J., Leonforte, A., Khan, T.N., Paull, J.G., Redden, R., Materne, M., 2013. Cool-season grain legume improvement in Australia-use of genetic resources. Crop Pasture Sci. 64, 347–360.
Siddique, K.H.M., Sykes, J., 1997. Pulse production in Australia past, present and future. Aust. J. Exp. Agric. 37, 103–111.
Soltani, A., Galeshi, S., Attarbashi, M.R., Taheri, A.H., 2004. Comparison of two methods for estimating parameters of harvest index increase during seed growth. Field Crop Res. 89, 369–378.
Soltani, A., Torabi, B., Zarei, H., 2005. Modeling crop yield using a modified harvest index-based approach: application in chickpea. Field Crop Res. 91, 273–285.
Stevenson, F.C., van Kessel, C., 1997. Nitrogen contribution of pea residue in a hummocky terrain. Soil Sci. Soc. Am. J. 61, 494–503.
Thorburn, P.J., Probert, M.E., Robertson, F.A., 2001. Modelling decomposition of sugar cane surface residues with APSIM-residue. Field Crop Res. 70, 223–232.
Unkovich, M., Herridge, D., Peoples, M., Cadisch, G., Boddey, B., Giller, K., Alves, B., Chalk, P., 2008. Measuring Plant-Associated Nitrogen Fixation in Agricultural Systems. ACIAR, Canberra, ACT.
van Diepen, C.A., Wolf, J., van Keulen, H., Rappoldt, C., 1989. WOFOST - a simulation-model of crop production. Soil Use Manag. 5, 16–24.
Verburg, K., Bond, W.J., Hunt, J.R., 2012. Fallow management in dryland agriculture: explaining soil water accumulation using a pulse paradigm. Field Crop Res. 130, 68–79.
Wang, E., Robertson, M.J., Hammer, G.L., Carberry, P.S., Holzworth, D., Meinke, H., Chapman, S.C., Hargreaves, J.N.G., Huth, N.I., McLean, G., 2002. Development of a generic crop model template in the cropping system model APSIM. Eur. J. Agron. 18, 121–140.
Wang, E.L., Smith, C.J., Bond, W.J., Verburg, K., 2004. Estimations of vapour pressure deficit and crop water demand in APSIM and their implications for prediction of crop yield, water use, and deep drainage. Aust. J. Agric. Res. 55, 1227–1240.
Zentner, R.P., Wall, D.D., Nagy, C.N., Smith, E.G., Young, D.L., Miller, P.R., Campbell, C.A., McConkey, B.G., Brandt, S.A., Lafond, G.P., Johnston, A.M., Derksen, D.A., 2002. Economics of crop diversification and soil tillage opportunities in the Canadian Prairies. Agron. J. 94, 216–230.