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Validating economic and environmental sustainability of a short-term summer forage legume in dryland wheat cropping systems in south-west Queensland

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Abstract. The present study set out to test the hypothesis through field and simulation studies that the incorporation of short-term summer legumes, particularly annual legume lablab (*Lablab purpureus* cv. Highworth), in a fallow–wheat cropping system will improve the overall economic and environmental benefits in south-west Queensland. Replicated, large plot experiments were established at five commercial properties by using their machineries, and two smaller plot experiments were established at two intensively researched sites (Roma and St George). A detailed study on various other biennial and perennial summer forage legumes in rotation with wheat and influenced by phosphorus (P) supply (10 and 40 kg P/ha) was also carried out at the two research sites. The other legumes were lucerne (*Medicago sativa*), butterfly pea (*Clitoria ternatea*) and burgundy bean (*Macroptilium bracteatum*). After legumes, spring wheat (*Triticum aestivum*) was sown into the legume stubble. The annual lablab produced the highest forage yield, whereas germination, establishment and production of other biennial and perennial legumes were poor, particularly in the red soil at St George. At the commercial sites, only lablab–wheat rotations were experimented, with an increased supply of P in subsurface soil (20 kg P/ha). The lablab grown at the commercial sites yielded between 3 and 6 t/ha forage yield over 2–3 month periods, whereas the following wheat crop with no applied fertiliser yielded between 0.5 to 2.5 t/ha. The wheat following lablab yielded 30% less, on average, than the wheat in a fallow plot, and the profitability of wheat following lablab was slightly higher than that of the wheat following fallow because of greater costs associated with fallow management. The profitability of the lablab–wheat phase was determined after accounting for the input costs and additional costs associated with the management of fallow and in-crop herbicide applications for a fallow–wheat system. The economic and environmental benefits of forage lablab and wheat cropping were also assessed through simulations over a long-term climatic pattern by using economic (PreCAPS) and biophysical (Agricultural Production Systems Simulation, APSIM) decision support models. Analysis of the long-term rainfall pattern (70% in summer and 30% in winter) and simulation studies indicated that ~50% time a wheat crop would not be planted or would fail to produce a profitable crop (grain yield less than 1 t/ha) because of less and unreliable rainfall in winter. Whereas forage lablab in summer would produce a profitable crop, with a forage yield of more than 3 t/ha, ~90% times. Only 14 wheat crops (of 26 growing seasons, i.e. 54%) were profitable, compared with 22 forage lablab (of 25 seasons, i.e. 90%). An opportunistic double-cropping of lablab in summer and wheat in winter is also viable and profitable in 50% of the years. Simulation studies also indicated that an opportunistic lablab–wheat cropping can reduce the potential runoff + drainage by more than 40% in the Roma region, leading to improved economic and environmental benefits.

Additional keywords: deep placement, phosphorus, short-term summer forage legume, sustainability, wheat.

Introduction

The fallow–wheat cropping system in the south-west Queensland relies mostly on the stored summer rainfall water in the soil profile and in-crop rainfall in winter. The storage of summer rainfall is achieved by maintaining a weed-free fallow by using herbicides and minimum tillage. This system leads to poor annual rainfall use efficiency and significant runoff and soil erosion losses during episodic rainfall events (Silburn *et al*. 1992).

Incorporation of ley-pastures in rotation with crops have been suggested to minimise the soil erosion, maintain the soil organic matter and improve the soil structure (Dalal *et al*. 1995), as well as reduce the weed density (Teasdale *et al*. 1991). However, uncertainties in economic and environmental benefits from the existing medium- to long-term (3–5 years) use of ley-pastures have resulted in poor adoption, particularly in the cropping paddocks. The biophysical, economic and social constraints,

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such as poor and erratic rainfall events, shallow soil with subsoil constraints, increased cost of livestock management, the loss of cash crop production during the interchange phase, higher grain prices and complex decision-making processes during the changeover from crop to ley-pasture and *vice versa* have primarily limited the confidence of growers in the ley-pasture technology (McCowan *et al.* 1988; McGuckian 2008; Singh *et al.* 2009). However, greater livestock prices in comparison to grain prices are more likely to favour the adoption of ley-pasture and proportion of years for livestock enterprises in a mixed farming system; livestock production would be more profitable when grain prices are low and *vice versa* (Bell *et al.* 2008).

Advantages of growing a short-term annual forage legume in summer may include providing a better ground cover than with either a bare fallow or a stubble cover in the marginal cropping areas of south-west Queensland. Additionally, a forage legume can be used as a good-quality feed for intensive livestock production and a medium to fix atmospheric N into the soil. Furthermore, greater ease of decision making and a less labour-intensive technology, such as incorporation of a short-term summer forage legume, may favour a more rapid adoption of the ley-pasture technology in the cropping paddocks (Armstrong *et al.* 1999; Singh *et al.* 2009). On the other hand, disadvantages of using the summer rainfall by the legumes might include concerns about less soil water being stored in the profile before the sowing of the wheat crop. However, it can be argued that the use of fallow does not greatly influence the quantity of water stored in the soil for use by the subsequent wheat crop because its growth primarily depends on growing-season rainfall in semiarid regions. For example, areas where fallowing is practiced, the efficiency of precipitation storage is often low, in the order of 10–25%, because of soil-surface evaporation, particularly if the soil surface is disturbed to control weeds (Freebairn *et al.* 1993; Fengrui *et al.* 2000; Hatfield *et al.* 2001). Obviously, a combination of both stored water during the fallow period and in-crop rainfall would result in a successful wheat crop in the fallow–wheat system.

Nevertheless, changes to the current fallow–wheat system are required not only to address the environmental concerns, but also to utilise the benefits of short-term summer forage legume in rotation with grain cropping. In considering such changes, proper trialling and experimenting and demonstrations of various economic and environmental benefits are also required before any change can be considered by growers. The present paper will test through field and simulation studies the hypothesis that the incorporation of short-term summer legumes will improve the overall economic and environmental benefits of cropping systems in south-west Queensland.

Materials and methods

Field site description and growing-season rainfall

The study sites were spread from Goondiwindi (28.52°S, 150.3°E) to Condamine (26.92°S, 150.1°E), Roma (26.54°S, 148.8°E) and St George (28.04°S, 148.6°E) in south-west Queensland. These sites in the same order represent the following four primary land and soil types: flood plains grey vertosols (highly productive), brigalow/belah grey vertosols gilgai (moderately productive), open downs grey/brown vertosols (lower productive) and red kandosols (marginal lands for cropping) (Table 1).

Treatments and experimental design

The experiments at the commercial sites (2 at Goondiwindi, 1 Meandarra, 1 Roma, and 1 Condamine) were laid out as a randomised block design in four replicated blocks. Treatment included plots of lablab and fallow, followed by planting wheat in the subsequent season in both lablab and fallow plots. The management of weeds in the fallow plots at the Goondiwindi and Meandarra sites was carried out by spraying a broad-spectrum systemic herbicide glyphosate at the end of the legume phase. No application of herbicide was carried out in the legume plots because of significant alleleophathic effect of lablab on weed growth, which reduced by more than 80% in the lablab plots. Whereas, commercials sites at Roma and Condamine were grazed and, therefore, no application of herbicide was carried out for management of the weeds in the fallow plots.

The experiment at the Roma Research Station was laid out as a split-plot design in four replicated blocks, with a factorial combination of two rates of P application as main plots and four legumes + one fallow treatment as subplots. The two P treatments were low (10 kg P/ha) and high (40 kg P/ha), placed at a depth of 10–15 cm. The legume treatments were lucerne (*Medicago sativa* cv. superseven), butterfly pea (*Clitoria ternatea* cv. Milgarra), burgundy bean (*Macroptilium bracteatum*) and forage lablab (*Lablab purpureus* cv. Highworth). These represented a summer-active annual (lablab), biennial (burgundy bean) and perennials (butterfly pea and lucerne). Similar experimental set up was carried out at St George, with an additional treatment of a shallower placement of P at a depth of 5–7 cm, than the deeper depth of 10–15 cm above (Singh *et al.* 2005).

Table 1. Description of the land system, soil type, long-term mean annual rainfall and growing-season rainfall for the major sites in the study area of south-west Queensland

Site	Land system	Soil type	Mean rainfall	Growing-season rainfall (mm) (Oct.–Mar. 2003/ Apr.–Sept. 2004)	Growing-season rainfall (mm) (Oct.–Mar. 2004/ Apr.–Sept. 2005)
Goondiwindi	Flood plains	Grey vertosols	620	623/185	343/246
Condamine	Brigalow/belah gilgai	Grey vertosols	610	509/150	318/188
Roma	Open downs	Sodosol	600	579/137	189/193
St George	Mulga	Red kandosols	520	443/105	331/190

Management practices

All sites including research stations had a row spacing between 25 and 36 cm for lablab and a seeding rate between 18 and 20 kg/ha, except the site at the Condamine, which had a row spacing of 100 cm and a seed rate of 8 kg/ha. All sites started with a legume phase then followed by a wheat phase, except the research site at St George. The first crop at the St George site was wheat, followed by legumes. Findings on the performance of wheat at the St George site have been discussed previously (Singh *et al*. 2005). During the legume phase, only lablab produced any substantial yield at this site; all other legumes failed to germinate and/or establish. All sites received P only (triphos), except the sites at the Roma Research Station, which had applications of mono-ammonium phosphate (MAP) and urea.

The P at the Roma site was banded at 10–15 cm depth in 33 cm wide row spacing, in the form of MAP on 14 October 2002, 4 months before the scheduled planting of legumes. Urea was also applied to the low-P treatments to match the additional N added from the increased rate of MAP for the high-P treatment. The forage legumes were planted at twice the recommended seeding rates in 33 cm wide row spacing at the sites in both research stations. Lucerne was planted at 8 kg seeds/ha, butterfly pea at 20 kg seeds/ha, burgundy bean at 20 kg seeds/ha and forage lablab at 40 kg seeds/ha, after inoculating legumes with their respective rhizobia. Each plot was 2.5–5.0 m wide and 15–20 m long at the research station sites, whereas commercial sites had one planter width 11–16 m wide and the plots were 50–200 m long.

Roma Research Station

A detailed study on soil water use during legume–wheat rotation in response to P was carried out at this site. At the time of the legume harvest in Roma, the soil was very moist because of 120 mm of rain that fell 1 week before the legume harvesting in April 2003. However, we could not plant wheat immediately after the legume harvest, and had to delay the planting. Then wheat (*Triticum aestivum* cv. Kennedy) was planted into the legume stubbles and fallow plots on 8 May 2003, and 30 mm of irrigation water was also provided through overhead irrigator for the rapidly drying surface soil. Two strips of wheat, each 1.2 m wide with six rows of wheat in 20 cm spacing, were planted into legume and fallow plots, leaving a 2.4 m wide space between the two wheat strips. This gap between the two wheat strips in each plot was used to monitor weed growth and soil water use, particularly from a previous lablab and fallow plots during the wheat phase. The wheat cv. Kennedy was sown at a rate of 60 kg seeds/ha which is twice the recommended rate of 30–40 kg seeds/ha for the region, and the row spacing of 20 cm is ~40% narrower than the recommended practice of 33 cm. The recommended seeding rate and row spacing in the region (30–40 kg seeds/ha, row spacing between 30 and 50 cm) appeared not to be optimum for (1) providing a good ground cover, (2) reducing the water loss through surface evaporation and improving the crop water use efficiency and (3) providing the maximum plant density to utilise the surface water and additional P in the soil. That is why doubling the seeding rate and reducing the row spacing was considered, similar to the practices in northern NSW and southern states in Australia.

No fertiliser or herbicide applications were undertaken during the wheat phase. The wheat crop matured in early October. After harvesting the wheat crop, forage legumes were replanted in their respective plots on 14 October 2003, because there was some moisture available from a 25 mm rainfall event, just 5 days before the wheat harvest. The second phase of legumes was harvested in March 2004, followed by planting of wheat in early May 2004, with very little in-crop rainfall. This wheat crop in 2004 was compromised for grain yield because of severe bird damage; however, shoot dry matter yield at the time of heading was recorded.

Harvested legumes were removed from the commercial sites as hay before the planting of wheat, except from one commercial site in Roma. Lablab forage at this site was grazed by sheep until the end of July 2004, and sorghum, as the second phase crop, was planted in late October at this site.

Measurements

Dry matter (DM) sampling of legume shoots involved cutting the shoots in a 1 m^2 quadrat at a height of 5 cm. The wheat DM cuts at crop physiological maturity involved removing three 1 m row-lengths (equating to 1 m^2 sampling area) from the middle rows from each plot and cut at a height of 5 cm above the ground. Three and one set of quadrats per plot were used for larger and smaller field plots, respectively. Dry weights were determined after drying in an oven at 75°C for 48 h. The wheat was harvested at maturity with a small plot harvester at the research stations and at one commercial site. Harvesting at other commercial sites was carried out by commercial machines equipped with yield monitors. Weighing bin was also used to quantify grain yield harvested from commercial machines. At the Meandarra and one of the sites at the Goondiwindi, grain yield data were collected by cutting three 1 m row-lengths of the crops.

Soil water

Soil cores were collected with a hydraulic-powered corer at the time of lablab and wheat planting to a depth of 90–150 cm, depending on the soil profiles for field sites. There were no significant differences in plant available water capacity (PAWC) between lablab and fallow plots at the time of wheat planting for commercial sites (data not presented). However, a detailed soil water measurement, including field capacity and PAWC, has been described for the Roma Research Station. Each soil core at the Roma Station was divided into 0–10, 10–30, 30–60, 60–90 cm sections and weighed into paper bags immediately after coring. The soil samples were dried in the oven at 105°C for 24 h to determine the gravimetric soil water content (GWC), which was then converted to volumetric water content as the product of GWC and bulk density (previously determined for various depths). The PAWC were also determined from the wettest (February 2003) and driest (October 2003, after a wheat crop) soil profiles at Roma. The wettest profile occurred on 24 and 25 February, just 10 days after planting; soil sampling on 24 and 25 February was carried out manually with hand-held augers.

Simulation studies

The PreCaps (Lloyd 2006) and the APSIM (Keating *et al.* 2003) decision support models were used to understand likely economic and biophysical/environmental benefits of a short-term legume and wheat cropping simulated over a long-term climatic pattern from 1980 to 2005 for Roma. The PreCaps, based on excel worksheets, is a steady-state interactive model enabling whole-farm analysis of crop pasture rotations (Lloyd 2006). The input parameters in PreCaps were the actual input costs, interests and insurance costs and depreciations of the machinery used on the commercial farms.

The profitability ($GM, gross margin) of a system was calculated from the difference between the benefits and the cost of production. For example, the cost associated with forage lablab production included seed, fertiliser, field preparation, harvesting and baling costs. Whereas a fallow–wheat system would have additional costs of fallow management and in-crop weed management, as well as seed, fertiliser, field preparation, harvesting costs. The costs of production for forage lablab and wheat at the current prices were almost similar, about $300/ha. The prices of wheat grain and forage lablab (hay) used for this simulation were $300/t grain and $100/t hay, respectively.

The APSIM is a modular modelling framework to simulate biophysical processes in farming systems for production and ecological outcomes (Keating *et al.* 2003). APSIM–wheat model was used following parameterisation of modules SOILN2 and SOILWAT2 for Roma Research Station; the soil parameters are given in Table 2. Sowing and harvesting rules for forage lablab included cv. Highworth, sowing between 15 October and 1 February when rainfall during a 3 day period is 20 mm or more, planting density 15 plants/m^2, fertiliser rate 20 kg P/ha and harvest by 31 March. For wheat, the sowing and harvesting rules included cv. Kennedy, sowing between 1 May and 30 June when rainfall during a 3 day period is 20 mm or more, planting density 100 plants/m^2, fertiliser rate 100 kg urea/ha and harvest at the crop maturity. Historical climate data between 1980 and 2005 for the Roma Airport were obtained from the Silo Patched Point Data Set (http://www.bom.gov.au/silo, verified 17 October 2008).

Statistical analysis

The data were subjected to an analysis of variance after examining the residuals for normal distribution to check for homogeneity of variances, using GENSTAT Release 6.1. No data transformations were required. Significant means were identified with Duncan's multiple range test.

Table 2. Soil parameters used for initialisation in the Agricultural Production Systems Simulation (APSIM) for Roma Research Station

Soil parameter	Soil layer number 1	 2	 3	 4
Depth of soil layer (mm)	0–150	150–300	300–600	600–900
Water content at air dry (mm/mm)	0.12	0.20	0.25	0.24
Crop lower limit (mm/mm)	0.22	0.23	0.25	0.24
Saturated water content (mm/mm)	0.49	0.46	0.43	0.39
Bulk density (g/cm^3)	1.21	1.39	1.41	1.49
NO_3-N (µg/g)	11.8	4.4	8.9	7.6

Results

Seasonal rainfall and PAWC

The average annual rainfall for these regions has been 620 mm, 610 mm, 600 mm and 520 mm for Goondiwindi, Condamine, Roma and St George, respectively, with the PAWC (calculated as the difference between the soil water at the field capacity and permanent wilting point) ranging from >200 mm (highly productive) to <100 mm (for the marginal lands) (data not presented). The growing-season rainfall for summer (October–March) and winter (April–September) cropping during 2003–2004 and 2004–2005 is presented in Table 1. The experiment at the Roma Research Station was conducted between 2002–2003 and 2003–2004, with a growing-season in-crop rainfall of 330 mm during the legume phase, and 147 mm during the wheat phase. For 2003–2004, the growing-season rainfall was 579 mm (October–March) and 137 mm (April–September) (Table 1).

Legume forage and wheat grain yield

Commercial sites

The legume forage DM yields were, on average, between 3.0 and 5.5 t/ha, except at Condamine (2.25 t/ha) where lablab was planted at a wider row spacing and a very low seed rate (Table 3). Whereas wheat grain yield was between 0.5 and 2.25 t/ha. The grain yields may have been compromised at the Goondiwindi and Meandarra sites because of delays in sowing or because of planting too deep in an attempt to sow into the moist

Table 3. Lablab forage and wheat grain sequences over a 2-year period (2003–2004) and the mean (±s.e.) yields at different sites in south-west Queensland

Site	Lablab forage (t/ha)	Wheat following lablab (t/ha)	Wheat without lablab (t/ha)
1. Goondiwindi[A]	3.25 (±0.28)	2.25 (±0.18)	2.84 (±0.21)
2. Goondiwindi[B]	3.85 (±0.21)	0.7 (±0.104)	1.25 (±0.14)
3. Meandarra[C]	2.95 (±0.19)	0.5 (±0.098)	0.95 (±0.11)
4. Roma[D]	3.15 (±0.32)	1.20 (±0.11)	1.75 (±0.15)
5. Roma[E]	5.5 (±0.45)	2.45 (±0.25)	2.40 (±0.19)
6. St George[F]	2.8 (±0.23)	2.25 (±0.17)	–
7. Condamine[G]	2.25 (±0.12)	–	–

[A] Following lablab, wheat was sown on time just after rainfall in May.

[B] Wheat following lablab was sown quite late in June because of machinery failure.

[C] Wheat was sown late because of heavy rain in late April delaying the removal of hay from the paddock; also, wheat was sown very deep at the moisture seeking depths.

[D] Forage lablab was grazed until the end of July, then the field was sown with sorghum in dry soil.

[E] A Roma Research Station site where wheat sowing was done on time.

[F] The soil at this site was deep red earth and lablab was sown after wheat. The second crop of wheat following lablab yielded 0.5 t/ha shoot DM compared with 1.2 t/ha shoot DM for the fallow plots at the time of anthesis. The grain yield for the second crop of wheat was not recorded because of severe bird damage.

[G] Row spacing for this site was 1.0 m. No wheat sowing was done because of drier conditions.

layer of soil. On average, wheat following a lablab crop yielded ~30% less than wheat following fallow (Table 3).

Roma Research Station

A detailed study on various forage legumes indicated that lablab produced the highest shoot DM yields of between 5 and 6 t/ha in the 2.5 month growth period from mid-February to the end of April 2003 (Fig. 1*a*). Burgundy bean produced ~4 t of shoot DM/ha, whereas the second perennial legume, butterfly pea, produced yields intermediate between those for lucerne and burgundy bean.

There was a slight P × legume interaction ($P = 0.06$) for shoot DM yield. The interaction resulted from the differential response to the high rate of 40 kg P/ha of deep P by the legumes. The two legumes that responded strongly to the deep P were the butterfly pea with a 55% response, and the lablab with a 24% response. The other two legumes produced smaller and non-significant responses to the higher rate of P, of 12 and 13% by the burgundy bean and lucerne, respectively.

The highest grain yield of 2.7 t/ha occurred with the fallow and lablab treatments, followed closely by the 2.6 t/ha yield for the butterfly pea treatment in response to a higher (40 kg/ha) supply of P (Fig. 1*b*). With lucerne, there was a considerable, although non-significant ($P > 0.05$), 22% reduction in wheat yield with the high rate of P. The only response to high-P treatment of 30% occurred with the butterfly pea, where the wheat yield with high P was significantly greater than that with the low P. Opposite responses to high-P treatment by lucerne and butterfly peas appeared to have contributed to the significant P × legume interaction ($P = 0.005$) for wheat grain yield (Fig. 1*b*).

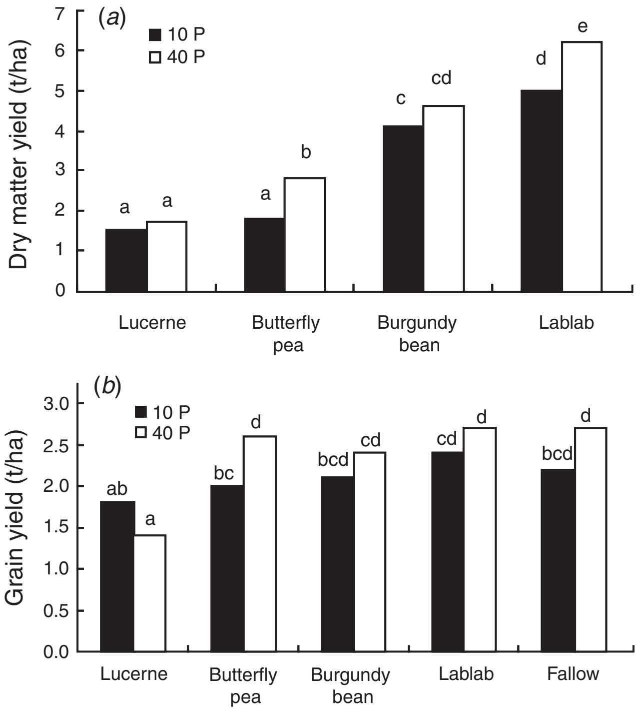

Fig. 1. (*a*) Effect of deep P applied at low (10 kg P/ha) and high (40 kg P/ha) rates on the shoot dry matter yield of legumes at the end of April 2003, and (*b*) wheat grain yield in respective legume plots. Same letters indicate no significant difference ($P > 0.05$) between the phosphorus × legume interaction means. The *F* probability (*P*-value) for the interaction was 0.039 and 0.002 for legume dry matter and wheat grain yields, respectively.

It should be noted that these responses to high P were in fact a residual effect to the P fertiliser applied 18 months earlier (in October 2003) for the first crop of legumes grown during February–April 2003. It is also important to note that lucerne plants were still alive in the lucerne plots planted to wheat. Lucerne plants in the high-P plots started to grow vigorously about the time of the late grain filling stage, although there was no significant difference in wheat shoot DM (data not presented), which was measured a couple of weeks earlier, before grain harvesting.

All the legumes, except lucerne, were resown into wheat stubble in their respective plots after the wheat harvest in October 2003, following a 25 mm rainfall event just before the harvest. Lablab produced a 100% emergence, compared with <5% emergence for other legumes. Furthermore, the lack of follow-up rain during early November resulted in complete seedling mortality for the newly planted legumes (burgundy bean and butterfly pea). More than 50% mortality also occurred for the established lucerne stands; only lablab survived and grew slowly.

The second crop of lablab forage, on an average, yielded 3.5 t/ha when harvested in March 2004, whereas the second wheat crop following the second lablab forage failed because of minimum in-crop rainfall (<50 mm) and bird damage at the time of grain filling and maturity. However, the shoot DM (sampled in early August, at the time of heading stage) for the second wheat crop, on an average, was ~2.0 t/ha (±0.08, s.e.m.). There was no significant difference in shoot DM between the second wheat following lablab and fallow plots (data not presented).

Soil water

At the time of legume and wheat plantings, soil water measurements for different depths were recorded and are presented in the Fig. 2. The soil profile (0–90 cm) was noted to be at the field capacity 10 days after the planting (during late February 2003), resulting from heavy and soaking rains on 24 and 25 February (the total February rainfall at the research station was more than 120 mm). The top 0–20 cm profile was saturated.

Soil water measurement at the end of the legume phase indicated no significant differences among legumes for water use, particularly for 0–10 cm and 10–30 cm depths, except that the fallow plot had significantly less volumetric water than did the legume plots in the top 0–10 cm profile (Fig. 2*a*). Lablab and lucerne extracted more water than did the other legumes, particularly from 30–60 cm and 60–90 cm profiles (Fig. 2*a*). The plots of fallow and butterfly pea had more plant-available water for the following wheat crop than did the lablab or lucerne plots. Lablab, in particular, used ~40 mm more water than did the fallow plot. However, the fallow plot lost more than 45% of plant-available water by the end of the legume phase, from a full profile of 156 mm down to 86 mm (Fig. 2*a*).

At the end of the wheat phase in October, soil water measurement indicated that wheat following lablab (lablab–wheat) had the driest profile, followed by fallow–wheat (Fig. 2*b*). Measurements from fallow–fallow and lablab–fallow

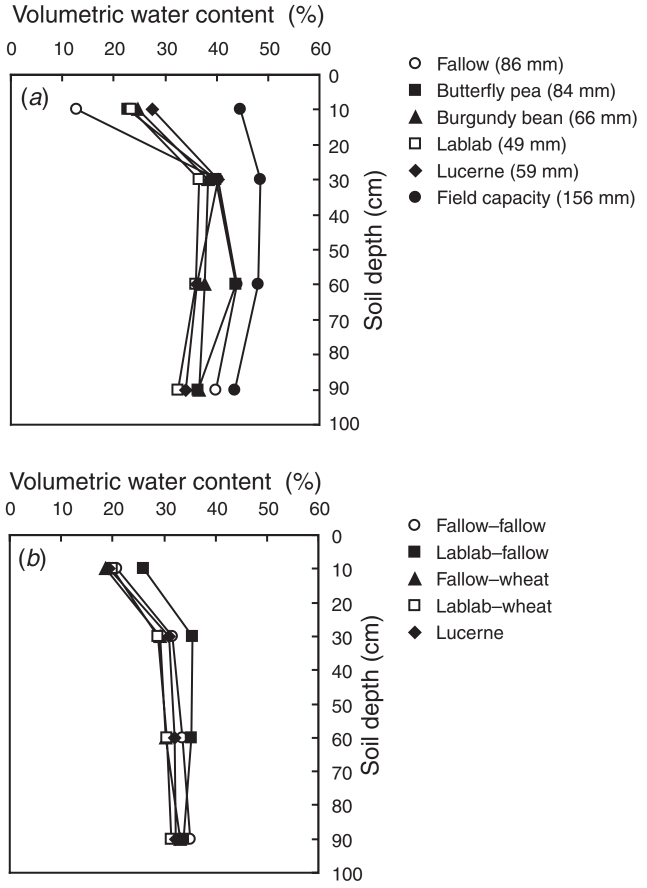

Fig. 2. (*a*) Volumetric water content in the soil profile (0–90 cm depth) at the end of the legume phase (plant available water capacity is also given in parentheses), and (*b*) volumetric water content in the soil profile (0–90 cm depth) at the end of the wheat phase, for the Roma Research Station. (*a*) Treatment × soil depth (P = 0.033; average l.s.d. = 7.37%). (*b*) Treatment × soil depth (P = 0.066; average l.s.d. = 2.61%).

plots indicated that lablab–fallow plots had significantly more plant-available water than did the fallow–fallow plots (Fig. 2*b*).

Economic benefits

APSIM simulations predicted that 14 wheat crops over 26 cropping seasons produced grain yields of 1 t/ha or more, whereas lablab produced 22 crops, yielding more than 3 t DM/ha over 25 seasons (Fig. 3*a*). A grain yield of more than 1.0 t/ha is required for a crop of wheat to be profitable at the current (2008) cost of production (i.e. about $300/ha) and at a farm gate price between $250 and $300/t grain. On average, estimated gross margin (by using PreCaps) for the wheat crop was $105/ha per year. On the other hand, the cost of forage lablab production (sowing to baling) is also ~$300/ha. Economic simulation showed, on an average, a gross margin of $190/ha per year for the forage lablab (forage lablab was priced @ $100/t at the farm gate) (Fig. 3*b*).

Environmental benefits

Simulation studies showed that continuous fallow–wheat cropping had a potential of ~4000 mm runoff + deep drainage compared with 2700 mm for continuous lablab cropping across a 25-year period (1980–2005) (Fig. 4*a*). On average, just by changing the cropping preference from winter to summer would potentially reduce the runoff + deep drainage losses by more than 30%, from 164 mm/year down to 109 mm/year. Furthermore, opportunistic double-cropping with lablab and wheat, which is feasible in 50% of the years, has the potential of reducing the runoff + deep drainage by more than 55%, from 164 mm/year to only 73 mm/year (Fig. 4*b*).

Discussion

Analysis of the long-term rainfall pattern in south-west Queensland indicated that a forage summer crop can be grown 90% of the years between September and February, and 50% of the time there will be more than adequate rainfall from March to June to refill the soil profile (up to at least 2/3rd) for the planting of a subsequent wheat crop (Fig. 3). However, success of a wheat crop would not only depend on the stored soil moisture but also on an adequate in-crop rainfall between June and September. Wheat often failed to produce a good crop, even after summer fallow when exposed to minimum in-crop rainfall and dry finishes, which are common in the region. Simulation study also indicated that more than 50% of the time a wheat crop failed to produce a profitable grain crop (>1.0 t grain/ha) because of the long-term rainfall pattern in the Roma region (Fig. 3*a*). Furthermore, economic analyses, on the basis of the long-term rainfall pattern, also indicated greater profitability, ~80% more ($190 *v.* $105/ha per year), from growing only lablab than from growing only wheat (Fig. 3*b*).

Similarly, at the commercial farms, a gross margin comparison at the 2004 wheat grain price and cost of production indicated a slightly greater gross margin for the wheat following lablab, between $140/ha and $230/ha, than for the wheat following fallow, between $130/ha and $220/ha, depending on whether the wheat crop was average or good (Singh and Mann 2008). Although, a fallow–wheat system had ~0.5 t/ha greater wheat grain yield than did the wheat following lablab, associated fallow management costs (4–6 herbicide sprays) reduced the gross margins for the fallow–wheat system. A reduced application of herbicide in a lablab–wheat system implicates not only an economic benefit, but also a significant benefit to the environment. In this context, Howden *et al.* (2008) also recommended consideration of sown legumes and P nutrition where appropriate for the farm-level adaptation to changing climatic conditions and managing agricultural productivity, particularly forage and animal productions.

The most productive legume in the present study was the large-seeded, summer-active annual forage lablab, followed by burgundy bean. Lablab also responded to increased supply of P by increasing the forage DM, whereas butterfly pea was the legume most responsive to P supply. In contrast, burgundy bean and lucerne had insignificant responses to P supply. Interestingly, the two legumes that responded to an increased P supply had roots with many lateral branches spreading from 5 to 20 cm depth on the primary root axis, which were observed while characterising root morphology earlier in the season (data not presented). It was particularly noticeable that the burgundy bean and lucerne had very prominent tap roots and

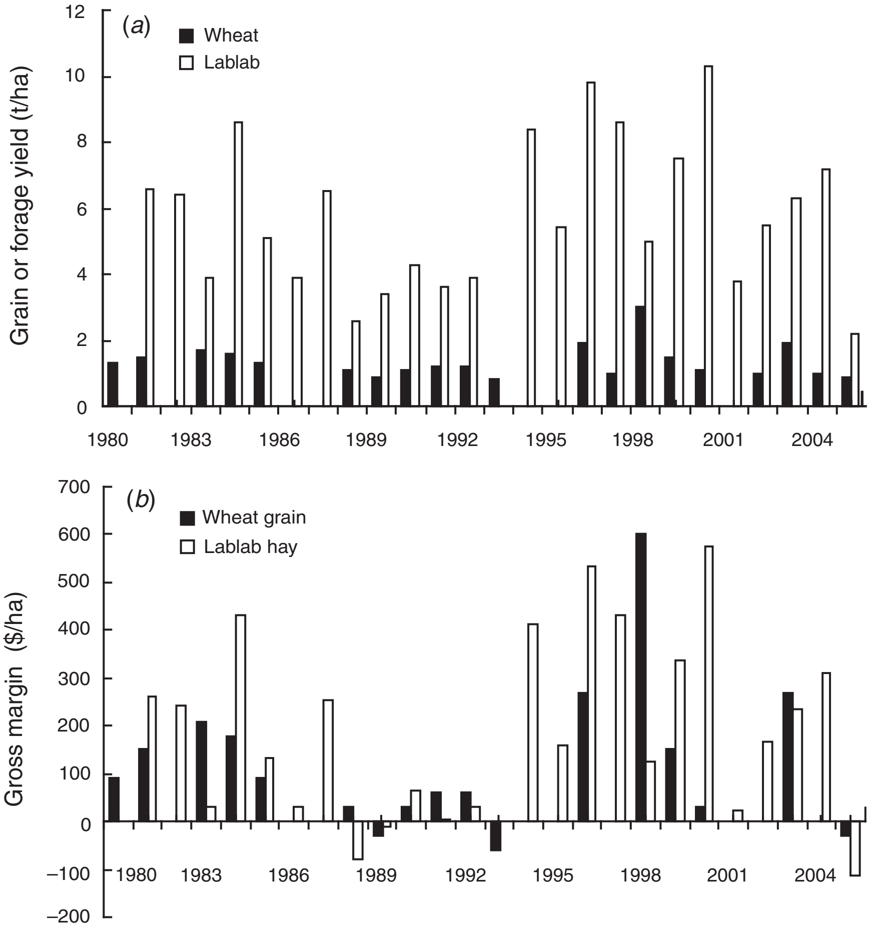

Fig. 3. (*a*) APSIM-simulated lablab forage dry matter and wheat grain yields, and (*b*) PreCaps-simulated economic profitability ($GM) for lablab hay and wheat grain over the period 1980–2005 at Roma.

only few lateral branches, and these legumes responded least to an increased P supply. However, the discussion will primarily focus on annual forage lablab, even though other legumes, such as burgundy bean (biennial), butterfly pea (perennial) and lucerne (perennial), are also productive species for specific medium- to long-term legumes (as ley-pastures) in grain cropping systems (Lloyd *et al.* 1991; Pengelly and Conway 2000).

The dependence of wheat and legume production on an increased supply of plant-available P in the subsurface soil, particularly in a semi arid region, has been indicated by several findings (Alston 1980; Jarvis and Bolland 1991; Singh *et al.* 2005; Fig. 1). In this context, Nuruzzaman *et al.* (2003, 2005) reported that wheat grew better after legumes, in particular when legumes had received P fertiliser, a result similar to our findings. Increasing the supply of P to a legume crop may lead to greater N fixation and therefore greater soil N supply to subsequent cereal crops. It should be noted that just one application of increased amount of P (40 kg P/ha) at deeper depth (10–20 cm deep) before lablab phase resulted in a substantial residual effect for the subsequent wheat crop in this region (Singh *et al.* 2005). Also, legume crops can enhance P uptake of subsequently grown wheat, even at relatively high concentrations of residual P, because they are able to mobilise residual P through root exudates, and thus increase their own growth, and potentially that of subsequent cereal crops (Nuruzzaman *et al.* 2005).

A further benefit from the use of large-seeded lablab in the cropping system comes from its ability to readily establish in soil that is subject to rapid drying. Land managers in the region have experienced many failures in establishing stands of small-seeded lucerne and other grasses (L. Ward, unpubl. data), resulting in poor adoption of ley-pastures in the semiarid regions of south-west Queensland (McCowan *et al.* 1988; Singh *et al.* 2009). A large-seeded lablab can be directly drilled deeper into the moist soil, with a high probability of successful germination and establishment, which meet the criteria of desirable pasture species characteristics as noted by Dear and Ewing (2008).

A very satisfying feature of the summer forage legume–wheat system is its ability to use *in situ* practically all of the water that falls as rain, compared with a fallow–wheat system. The ability to retain and use episodic rainfall *in situ* avoids the likelihood of soil erosion occurring from excessive surface runoff, and/or deep drainage (Fig. 4). Also the continuous crop cover promoted through lablab–wheat systems provides on-going protection to the soil. The cover would also protect against the risk of soil erosion from heavy rainfall events during summer, and minimise

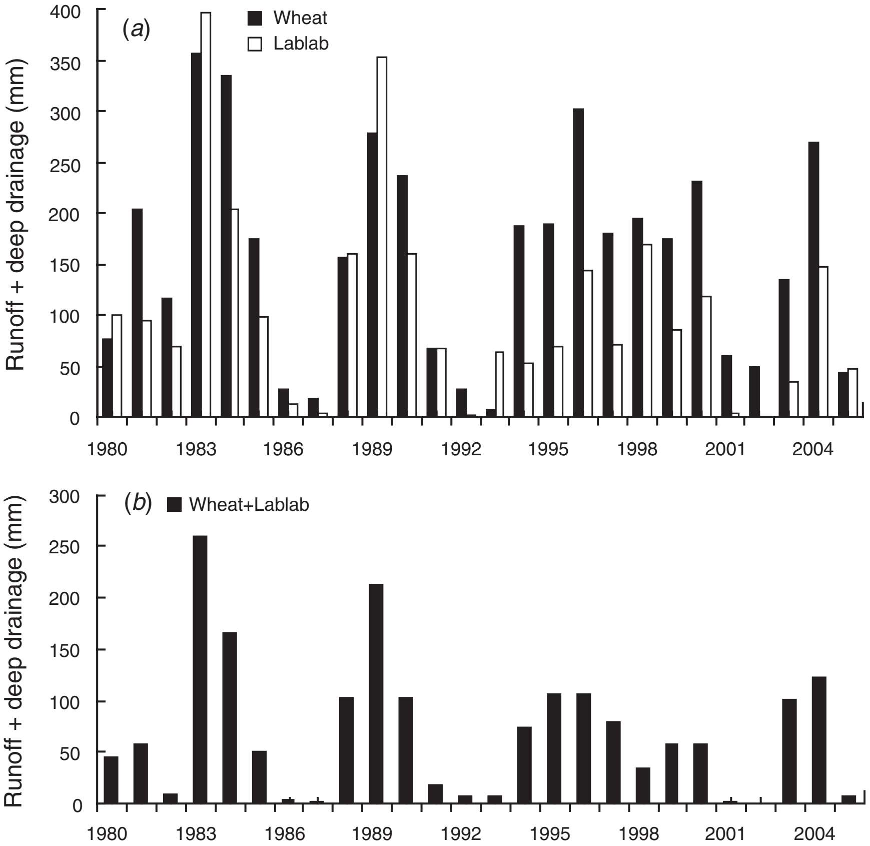

Fig. 4. (*a*) APSIM-simulated probabilities of runoff plus deep drainage from lablab and wheat cropping phases, and (*b*) a double-cropping of lablab + wheat (generally 50% of the years) over the period 1980–2005 at Roma.

high soil surface temperatures and wasteful evaporation of soil water from the soil surface. This benefit was observed in the present study when ~120 mm of episodic rainfall (14 April 2003) was able to generate significant runoff and eroded the fallow plots next to the experimental plots. Whereas legumes in experimental plots provided 100% ground cover and were able to minimise the runoff and erosion. The use of episodic rainfall water by crops will also minimise the chances for potential dryland salinity occurring from groundwater recharge, which could result from the deep drainage of water that is not used by plants even in the drier regions (Zhang *et al.* 1999).

It appears that although a short-term (2–3 months) summer forage lablab was able to produce substantial amount of forage DM, this occurred at a cost of 40 mm more water being used than with the fallow plot (Fig. 2*a*). The use of the summer rainfall by the legumes might raise concerns about less soil water being stored in the profile before the sowing of the wheat crop. Consequently, it is quite likely to have reductions in the wheat grain yields following a lablab crop because of lesser availability of stored soil water, as indicated from the commercial sites in the present study (Table 3). The extra subsoil moisture under the fallow system could provide more favourable conditions for grain filling. However, there was no reduction in the wheat grain yield at the Roma Research Station following a lablab crop fertilised with P (Fig. 1*b*). This result may indicate that a good crop of lablab with adequate P nutrition might have provided a better P and N nutrition to the subsequent wheat crop, leading to an improved water use efficiency, thus compensating for the reduced availability of water. Increasing N and P nutrition can increase the water use efficiency by 15–25%, through modifying physiological efficiency of the plant (Singh and Sale 1997; Hatfield *et al.* 2001).

It should be noted that some operational delays (as noted in the Table 3) might have also contributed to the observed reductions in the subsequent wheat grain yield at the commercial sites to some extent (Table 3). Also, Fengrui *et al.* (2000) found that the use of fallow crops did not greatly influence the quantity of water stored in the soil for use by the subsequent wheat crop because its growth primarily depended on the growing-season rainfall. In areas where fallowing is practiced, the efficiency of rainfall storage is often low, in the order of 10–15%, because of soil surface evaporation, particularly if the soil surface is disturbed to control weeds (Fengrui *et al.* 2000; Hatfield *et al.* 2001). Similarly, we also noted that the fallow plots lost ~45% of stored PAWC (from 156 mm to 86 mm) (Fig. 2).

An effective ground cover in legume plots may have also reduced the surface heating and loss of water from the top 0–10 cm profile, compared with the fallow plots, which had significantly drier soil in 0–10 cm profile (Fig. 2*a*). This may be due to a greater soil surface heating and evaporation from the fallow plots in summer (Singh *et al*. 2005). However, at the end of the wheat phase, the unplanted areas of lablab plots (between the two wheat strips, designated lablab–fallow plot), had more stored soil water, particularly in the 0–10 and 10–30 cm depths than did the fallow–fallow plot (Fig. 2*b*). This may have been due to a significant weed growth (naturalised burr medics, *Medicago* spp.) because no herbicide application was carried out for weed management in the fallow plots, whereas the lablab plots had minimal weed growth (data not presented). Cheruiyot *et al*. (2003) also noted that lablab showed outstanding positive effects on succeeding cereal crops by controlling weed population.

Nevertheless, growing a forage lablab in summer to its full potential, with a 90% probability of a successful forage crop, or limiting the production of forage, to leave more stored water in the soil profile for a subsequent wheat crop (with a probability of only 50% success), or practicing the old fallow–wheat system (with a poor economic return and being detrimental to the environment in long-term) would be the decision made by the land managers. The process of making this decision is very complex and many complicated factors interact, such as social, financial and environmental considerations (McGuckian 2008; Singh *et al*. 2009).

In conclusion, a field study over a period of 2 years apparently demonstrated that incorporation of a short-term summer forage legume, particularly annual lablab (cv. Highworth), with an additional P supply into a wheat cropping system would improve the economic and environmental benefits in south-west Queensland. A crop of forage lablab in summer would not only provide an effective ground cover and prevent likely soil erosion, runoff and deep drainage (which are the norms because of episodic rainfall events in summer), but it would also generate economically profitable quality forage 90% of the years (see Singh *et al*. 2009). In addition, an opportunistic double-cropping with wheat in 50% of the years would also add substantially to the economic and environmental benefits.

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