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Weed Suppression and Performance of Grain Legumes Following an Irrigated Rice Crop in Southern Australia

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Abstract: Post-rice irrigated soils offer several potential advantages for the growth of subsequent crops, but Australian producers have often been reluctant to grow grain legumes immediately following a rice crop due to physico-chemical constraints. A field experiment was thus conducted to explore the potential for producing grain legumes following rice in comparison to those following a fallow during 2012 and 2013. Two grain legumes, field pea and faba bean, were sown 5, 7 and 12 weeks after rice harvest in 2013 at Yanco, NSW, and plant growth indicators and grain yield were compared. Early sowing of field pea following rice gave the best outcome, with plants flowering three weeks earlier and yielding 1330 kg·ha^{-1} more grain than after fallow. In contrast, faba bean yield was 35 kg·ha^{-1} less after rice than after fallow across the three sowing dates. Higher pea yield was consistent with the early emergence of seedlings, higher light interception and overall greater plant growth following rice. Post-rice crops also had 10-fold less weed infestation than crops in a similarly-established fallow treatment and, thus, required far less weed management. Legume crops sown at the later seeding date had significantly reduced (~50%–60%) yields compared to those of the first two sowings; this is most likely a reflection of reduced temperatures and day lengths experienced during vegetative and reproductive growth phases.

Keywords: post-rice; field pea; faba bean; flooded rice; pulse

1. Introduction

Rice is the staple food crop for at least half of the world's population [1]. Australia is currently the world leader in terms of yield per hectare for irrigated rice where it is grown in the southeast of the continent [2] and arguably the most efficient in terms of water usage [3]. During the last lengthy drought in Australia (2002–2009) [4], rice cultivation in this region dropped to less than 20,000 ha, but by 2013, production expanded again to 114,000 ha [5]. While there are clearly opportunities to sow a crop immediately following rice, producers in this region are often reluctant to do so, and existing data suggest that there may be physico-chemical constraints in post-rice soils that discourage them from attempting a subsequent crop [6].

In Australia, irrigated rice production occurs as an anaerobic culture, with fields inundated with 10–25 cm of standing water during the growing season [7,8]. In southern NSW, rice is normally grown on heavy clay alluvial soils [9], and each crop utilises approximately 10–12 mL of water ha^{-1}. The crop is commonly sown by direct seeding, and fields are subsequently flooded from the early vegetative stage until a few weeks before harvest in mid-autumn (April) [10].

Prior to harvest, all excess water is drained, and the soil transits from an anaerobic (rice) to an aerobic (post-rice) state, affecting both nutrient turnover and soil structure, which can influence the performance of subsequent crops, as well as the incidence of pest and diseases [11–13]. Dynamic changes in nutrient availability occur during the period of inundation, and this flux may continue for a considerable period following rice harvest. For example, higher concentrations of Mn^{2+} produced during anaerobic rice culture can be observed for up to four weeks after drainage [14] and may interfere with the germination of subsequent crops [15]. Soil physical factors are also affected during rice growth and often make cultivation in wet, post-rice soils difficult because of excessive cloddiness [16]. Hence, post-rice soils are not always suitable for immediate cultivation of aerobic crops following rice harvest [17]. However, it would be desirable to determine if a high value pulse crop could be grown following rice to improve profitability, weed management and soil properties for successive rotations and, hence, the sustainability of the cropping system [18]. Production of leguminous crops following rice offers numerous potential advantages, including more efficient use of irrigation water in contrast to post-fallow [19] and reduction of weed pressure [8,20].

Although wheat is the most commonly-produced cereal in Australia [5], its production following a rice crop may not be sustainable in the long term because of the high requirements for fertilizer inputs, e.g., 260 $kg \cdot ha^{-1}$ of urea [21], and successive cereal disease pressures. However, the literature suggests a beneficial effect of legumes on the soil N balance [22,23]; the inclusion of a pulse crop through its ability to fix atmospheric nitrogen (about 100 $kg \cdot N \cdot ha^{-1}$) [24] could supplement the N requirements of a subsequent rice crop. Recent work [25] has demonstrated that the optimal rice crop N requirement is approximately 100 $kg \cdot ha^{-1}$ for a crop in delayed permanent water culture; this requirement could logically be assisted by inputs provided by a healthy legume crop.

In Australia and other dryland production regions, residual soil moisture in post-rice soils could also be an economic resource for subsequent crops [21], with greater than 1 $mL \cdot ha^{-1}$ of available water that would otherwise drain into the water table [6]. Crops sown immediately after rice could access available water before soil drying [26] or drainage beyond the root zone. This is relevant to Australian irrigators, as significant reductions in water allocation in the Murray-Darling Basin have occurred, particularly during the recent millennium drought [27]. Future climatic trends indicate that river flows may be reduced by 25% by 2050 and up to 48% by 2100 [28]; resulting in further reductions in irrigation water access. Using a legume crop to capture residual soil water following rice could strategically enhance production efficiencies associated with the use of irrigation water.

Over the past forty years, pulse crops are of increasing importance in Australia for the improvement of soil tilth and fertility. Key pulses include field pea (*Pisum sativum* L.), faba bean (*Vicia faba* L.), chickpea (*Cicer arietinum* L.), lentil (*Lens culinaris*) and narrow-leafed lupin (*Lupinus angustifolius* L.) [29]. Only faba bean was reported to be successfully grown using excess soil moisture [30], while field pea and others legumes were suggested as suitable for drier soils and lower (160–230 mm) rainfall conditions [31]. Currently, Australia is the largest global exporter of faba beans [2], but faba bean is susceptible to the fungal disease chocolate spot (*Botrytis fabae* Sard.). The severity of this disease was reduced when cultivation was performed in rotation with cereals, such as rice, rather than other legumes [32]. Faba bean and field pea also performed well under controlled climatic conditions following rice produced in saturated soils [33], but faba bean emergence was reduced when sown immediately after rice [33]. Possible causes for reduced emergence include, but are not limited to: the toxic effects of soil Mn^{2+}, the influence of soil anaerobic microorganisms and/or the excess moisture content of the flooded rhizosphere. However, limited information on the fate of pulse crops following irrigated rice is available, and most reports have focused on wheat [20,34,35] or maize [36] rotations. This study was thus undertaken to compare the performance of field pea and faba bean sown at three different planting dates following a flooded rice crop in comparison with non-flooded fallow.

2. Materials and Methods

2.1. Experimental Site

Field experiments were conducted at the Leeton Rice Research Station of the NSW Department of Primary Industries in Yanco, NSW, Australia during 2012 and post-rice in 2013 (Supplementary Materials Figure S1). Detailed weather information during the study period was obtained from a meteorological station located at the Yanco Agricultural Institute and is presented in Figure 1. Local soils were self-mulching grey vertosols [37] with a pH of 7.0 (1:5 water) and approximately 1.7% organic matter in the upper 10 cm of the soil. Soil properties are presented in Table 1. The production site was previously levelled to maintain good drainability.

Table 1. Soil properties and nutrient content at a depth of 0–10 cm at the experimental field site.

Nutrient	Unit	Amount	Nutrient	Unit	Amount
Calcium [1]	$mg \cdot kg^{-1}$	2126	Zinc [5]	$mg \cdot kg^{-1}$	4.2
Magnesium [1]	$mg \cdot kg^{-1}$	606	Iron [5]	$mg \cdot kg^{-1}$	52
Potassium [1]	$mg \cdot kg^{-1}$	95	Copper [5]	$mg \cdot kg^{-1}$	2.0
Sodium [1]	$mg \cdot kg^{-1}$	130	Manganese DTPA [5]	$mg \cdot kg^{-1}$	13
Phosphorus [1]	$mg \cdot kg^{-1}$	1.5	Manganese (ER) [6]	$mg \cdot kg^{-1}$	234
Nitrate Nitrogen [2]	$mg \cdot kg^{-1}$	31.3	Total Manganese [7]	$mg \cdot kg^{-1}$	476
NH_4^+ Nitrogen [2]	$mg \cdot kg^{-1}$	5.4	Boron [8]	$mg \cdot kg^{-1}$	0.72
Sulphur [2]	$mg \cdot kg^{-1}$	9.7	Silicon [8]	$mg \cdot kg^{-1}$	25
pH [3]	Units	7.70	Total Carbon [9]	%	0.95
Conductivity [3]	$dS \cdot m^{-1}$	0.139	Total Nitrogen [10]	%	0.10
Organic Matter [4]	% OM	1.7	Aluminium [2]	$mg \cdot kg^{-1}$	8
			Effective CEC [11]	$cmol(+) \cdot kg^{-1}$	31.06

The prefix number indicates the method of analysis, i.e., 1 = Morgan 1; 2 = KCl; 3 = 1:5 water; 4 = calculation; 5 = Diethylenetriaminepentaacetic acid (DTPA)-extractable; 6 = easily reducible Mn, HYD-Q; 7 = hydroquinone digestion method; 8 = $CaCl_2$; 9 = LECO IR Analyser; 10 = analyser; 11 = Effective Cation Exchange Capacity (CEC) is the sum of the exchangeable Mg, Ca, Na, K, H and Al; All results reported as dry weight, 40 °C oven dried soil lightly crushed. Organic matter = (% total carbon) × 1.75. Sample digested with Aqua Regia acid for total nutrients/salts and metals. The analysis was undertaken at a National Association of Testing Authorities Australia (NATA) accredited Environmental Analysis Laboratory (Accreditation No: 14960).

2.2. Rice and Legume Cultivation

Rice (*Oryza sativa* cv. Sherpa) was dry sown on 16 October 2012 using a drill seeder (Stubble King seeder, PHM Private Limited, Bacchus Marsh, Australia) at a rate of 150 $kg \cdot ha^{-1}$ and a row spacing of 18 cm. A standard water management strategy was applied throughout the season as described in Ricecheck [38]. The first irrigation was applied on the day of sowing, followed by a second irrigation one week after sowing. Urea (120 $kg \cdot N \cdot ha^{-1}$) was spread onto dry soil on the 6th week after sowing, after which the field was flooded to a 10-cm depth. The plots were sprayed a week after sowing (before the rice crop emerged) with herbicides for weed management at standard labelled rates including glyphosate containing diquat (Roundup Attack, Monsanto Co., Melbourne, Australia) (1 $L \cdot ha^{-1}$), bensulfuron methyl (Magister) at 0.4 $L \cdot ha^{-1}$ and 2.5 $L \cdot ha^{-1}$ of pendimethalin (Stomp). On the 6th week after the field was flooded, the crop was further sprayed with herbicides at standard labelled rates including Molinate 960 (Molinate, Nufarm Australia Limited, Laverton, Australia) at 3.75 $L \cdot ha^{-1}$, bensulfuron (Londax DF, Dupont, North Ryde, Australia) at 85 $g \cdot ha^{-1}$ and chlorpyrifos (Nufarm Australia Limited) at 100 $mL \cdot ha^{-1}$ using a gun applicator. At 21 weeks after sowing, irrigation water was drained from the rice bay. The crop was harvested 23 weeks after sowing using a combine harvester, and all yields were recorded. Yield from the entire experiment averaged 12.7 $t \cdot ha^{-1}$ (14% moisture). Remaining rice stubble was chopped, mulched and burned before preparing the site for seeding of the successive legume crop. An adjacent fallow plot was also selected for comparative purposes; this site had previously been maintained in the absence of rice as a fallow field with standard weed management practices during the 2012–2013 cropping season. A detailed description of crop management practices is reported in Supplementary Materials Table S1.

Cultivation of legumes following rice: Field pea (cv. Aura) and faba bean (cv. Nura) were evaluated as post-rice legume crops. A preliminary analysis of germination and establishment of both the crops in simulated irrigated rice soils is presented (Supplementary Materials Table S2). Seed was sown using a disc drill seeder with 10 rows at a standard 18-cm row spacing. Rice and fallow field bays were each approximately 2500 m^2 and were divided into 48 individual plots (1.8 m × 30 m) with a spacing of 0.2 m between plots. Three separate sowing times were investigated: (sowing S1) 5 weeks following rice harvest, which is the earliest possible sowing time, (S2) 7 weeks following rice harvest, which was coincidently after a major rainfall event (Figure S1), and (sowing S3) 12 weeks after rice harvest (Supplementary Materials Figure S1). The sowing dates were identical for both the post-fallow and post-rice plots.

Legume seed was inoculated using a seed-coating adhesive (Seed Sticker, Becker Underwood, 50 $g{\cdot}L^{-1}$) heated to 70 °C and stirred until smooth. The adhesive was cooled (<30 °C) and then spread over the seeds by rotation (in a small concrete mixer) until all seeds were observed to have a shiny coating. Nodulaid (Group E inoculant, Becker Underwood) was then added (3 $g{\cdot}kg^{-1}$ seed) and mixed with seed until the inoculant was thoroughly dispersed. The inoculated seeds were then air-dried for 2 h prior to sowing.

The seed drill (Stubble King Seeder) was calibrated to deliver seeds at 135 $kg{\cdot}ha^{-1}$ (60 $seeds{\cdot}m^{-2}$) for field pea and at 210 $kg{\cdot}ha^{-1}$ (40 $seeds{\cdot}m^{-2}$) for faba bean. At the time of planting MAP (monoammonium phosphate) was applied at a rate of 100 $kg{\cdot}ha^{-1}$ (10 $kg{\cdot}N{\cdot}ha^{-1}$ and 21.9 $kg{\cdot}P{\cdot}ha^{-1}$).

2.3. Crop Management

Immediately after the S1 sowing (30 April 2013), 10 mm of irrigation were applied to both the field pea and faba bean plots to support germination. A flood irrigation (100 mm) was performed in all plots at 20 weeks after rice harvest. To control grass weeds, both the legume crops (before flowering) were sprayed with 20 $g{\cdot}L^{-1}$ haloxyfop present as haloxyfop-R methyl ester (Verdict 520) at the rate of 38 $mL{\cdot}ha^{-1}$. An oil adjuvant (Uptake) was used for mixing the herbicide at the rate of 1 $L{\cdot}ha^{-1}$. Broadleaf weeds were hand-weeded within 7 days following herbicide application to avoid reduced yields and interference with crop growth. A 5-m section of each plot was maintained without herbicide treatment throughout the experiment for comparative purposes.

2.4. Plant and Weed Growth and Phenology

Seedling crop emergence (number of emerged plants m^{-2}) was evaluated at Weeks 1 and 3 after sowing of field peas and at Weeks 2 and 4 after sowing of faba bean. A quadrat (1 m^2) was used to count the number of plants emerging, as hypocotyl hooks were clearly visible well above the soil surface. The emergence (Stage Code 09) of seedlings was recorded as described by Meier [39] for both legumes. Six sub plots of 1 m^2 each were randomly selected per replicate for assessment of seedling emergence.

Flowering was assessed in each plot and was considered to be the time when more than half of the plant population had reached the flowering stage (Stage 65 for field pea and faba bean, as described by Meier [39]). Plant height was measured from the base of the plant to the tip of the central stem. Harvested plant samples were dried at 70 °C for 72 h, after which the dry weights were recorded.

During the flowering stage (Code 65 for field pea and faba bean), light interception was recorded above and below the canopy by a Sunfleck Ceptometer (Decagon, Pullman, Washington, DC, USA). To assess photosynthetically-active radiation (PAR), a 1 m-long light quantum sensor was used around midday. The PAR at the top of the canopy (Io) and beneath the canopy near the soil surface (I) were taken in three rows, comprising a total of 6 readings, and light interception (LI) was calculated by the Formula (1):

$$LI\ (\%) = 100 - (\frac{I}{Io} \times 100) \quad (1)$$

In each case, the sensor was kept at right angles to the row direction and parallel to the soil surface.

At the time of yield measurement, plots were highly populated with weeds, and these weeds in plots from the S3 sowing date were therefore removed by hand from each plot to avoid interference with crop harvest. The collected weeds from four randomly-selected sub-plots of 1 m^2 from each replication were dried at 70 °C for 3 days and the dry weights determined, following uprooting.

Plants were harvested once they reached maturation. For faba bean, harvesting was performed when the hilum of the seed turned black in colour. The peas were harvested once the seed coat turned a straw colour. A one-meter square quadrat was used to facilitate this hand-harvested operation. Six randomly-selected sub-plots (1 m^2 each) of plants were harvested separately from each plot. Separate sub-plots were also harvested from the unweeded area of each plot. Plant samples were dried in a dehydrator for 3 days at a temperature of 70 °C. The dried samples were removed from the dehydrator on the day before threshing. The total harvested plants for each treatment were weighed to determine total dry matter. The samples were then threshed, and the grain was weighed and the moisture content measured. Grain yield was calculated by adjusting the grain moisture content to 14%. The harvest index was calculated using the following Formula (2):

$$\text{Harvest index} = \frac{\text{Economic yield } \left(\text{kg ha}^{-1}\right)}{\text{Biological yield } \left(\text{kg ha}^{-1}\right)} \quad (2)$$

A subsample of 200 seeds was selected by equally dividing the samples until the correct number of seeds was obtained, and these were then weighed to obtain seed weight/100 seed. A seed sorting board with the capacity of 100 seeds was used to record the proportion of disease-infested seeds. The yield loss due to weed growth was measured by subtracting the grain yield in unweeded plots from the yield obtained in weeded plots, and the difference calculated as a percentage.

The calculation of potential N fixation by a crop, based on the total dry matter produced in each sowing dates was used with the reported N fixation rate in Australian conditions for faba bean (at a rate of 120 $kg \cdot N \cdot ha^{-1}$) [40] and field pea (N fixation of 100 $kg \cdot N \cdot ha^{-1}$) [41].

2.5. Experimental Design and Statistical Analysis

The experiment was conducted as a split plot with four replications. The main plots included post-rice crops and the post-fallow crops, and the sub-plots included the three sowing dates. All data were analysed by a two-way ANOVA using Genstat v16 (VSN International Ltd., Hemel Hempstead, UK), for field peas and faba beans separately. The Least Significant Differences (LSD) test was performed using the 5% level of significance.

3. Results

The weather conditions encountered at this study site (Figure 1) were close to the long-term average, with maximum and minimum temperatures ranging from 44.8 °C–8.8 °C. Minimum daily temperatures fell below 1 °C on four occasions during June, July and August. Annual total rainfall at the experimental site over the course of the study was 380 mm, which was close to the long-term average (394 mm) for this location (Supplementary Materials, Figure S2).

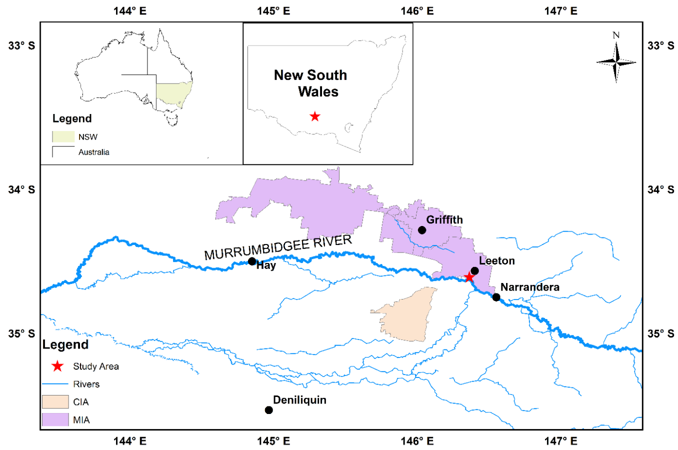

Figure 1. Map of study site of Leeton, New South Wales, Australia. CIA (Coleambally Irrigation Area) and MIA (Murrumbidgee Irrigation Area) refer to locally important irrigation areas.

3.1. Growth of Crops in Post-Rice Soils

Plant emergence of field pea and faba bean was higher at the second count than first count ($p < 0.05$) (Figure 2), and greater emergence was observed following rice compared to post-fallow.

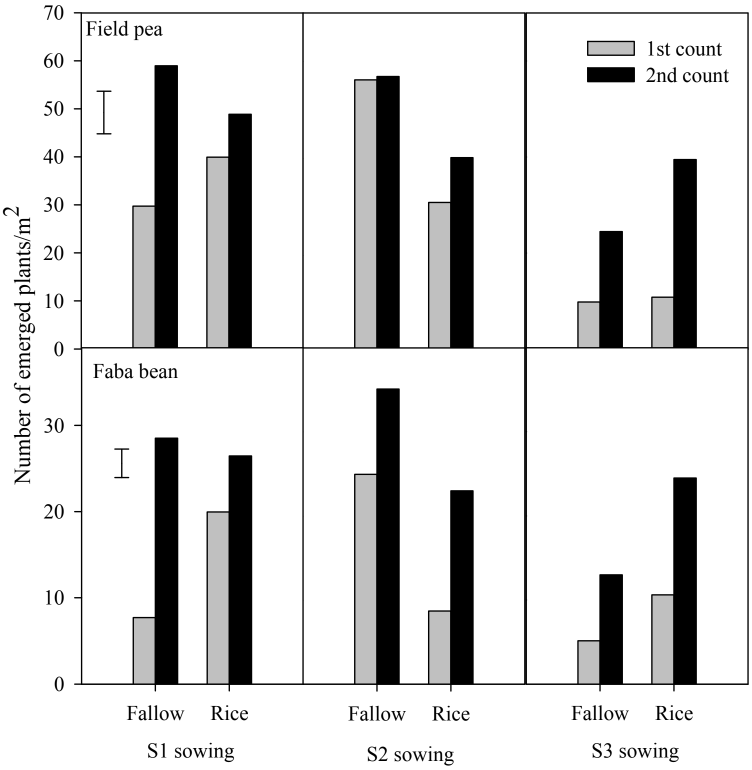

Figure 2. Seedling emergence per square meter for field pea and faba bean in post-fallow and post-rice conditions (fallow and rice, respectively) and at three sowing dates (S1, S2 and S3 sowings, respectively). Seedling counts were taken at one (grey bars) and three (black bars) weeks after sowing for field pea, and two (grey bars) and four (black bars) weeks after sowing for faba bean. Vertical error bars represent Least Significant Difference (LSD) values at the 0.05 level of significance for three sowing dates in both counts.

Initial plant height varied among treatments, but plant height was similar among the post-rice and post-fallow plants at flowering (Figure 3). Light interception at flowering varied significantly with sowing date ($p < 0.001$), with similar trends observed in both legumes (Figure 4). A dramatic reduction (70%–80%) in light interception at Sowing Date 3 (S3) was noted, likely due to the presence of weed and pathogen infestation in crops sown at later sowing dates. Interactions between the pre-treatment and sowing date were not statistically significant. The first sowing (S1) of field pea grown after fallow produced plants that intercepted 99% of available light during the flowering stage, while the S1 sowing after rice intercepted 96% of available light. A similar trend occurred within the faba bean crops (Figure 3).

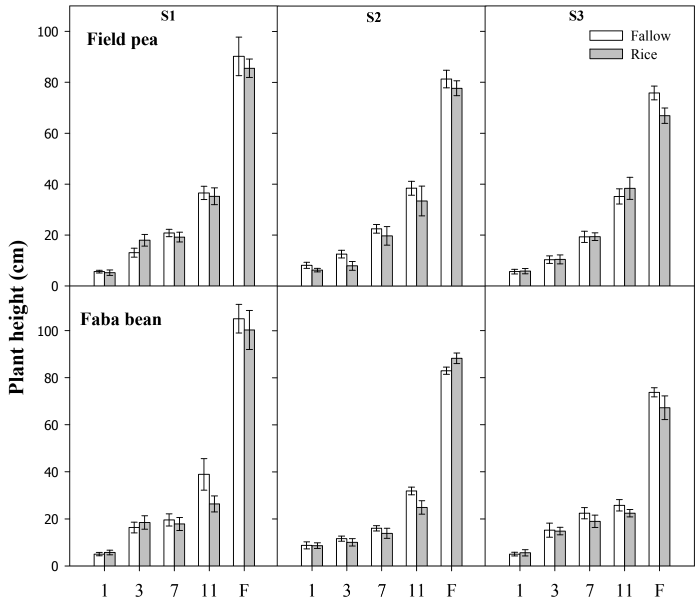

Figure 3. Plant height of field pea and faba bean grown in post-fallow and post-rice soils and at three sowing dates. Plant height was measured at 1, 3, 7 and 11 weeks after sowing and at flowering (F). The vertical error bars represent standard deviations of the means ($n = 40$).

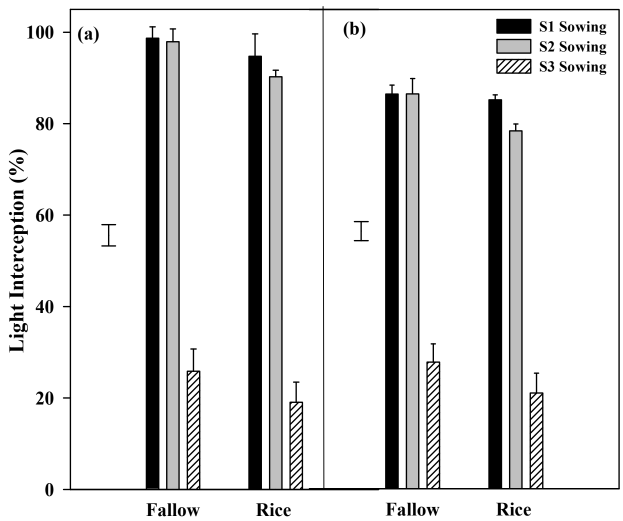

Figure 4. Light interception of (**a**) field pea and (**b**) faba bean crops measured at crop flowering in post-rice and post-fallow conditions, at three sowing dates. Error bars at the tops of columns represent standard deviations of means ($n = 12$), and error bars at the left of the filled black bars represent LSD values at the 0.05 level of significance.

Later sowing dates were associated with more rapid maturity in the crop (Figure 5). Plants from the S3 sowing treatment exhibited no difference in flowering time between post-rice and post-fallow treatments. However, the S1 and S2 sowings showed greater variation between treatments, where plants flowered earlier in the post-rice (~10 days, $p < 0.05$) than the post-fallow treatment. The largest differences were observed in S1 sowing of field pea (17 days; Figure 5A), and this crop matured approximately 21 days earlier than the corresponding fallow crop.

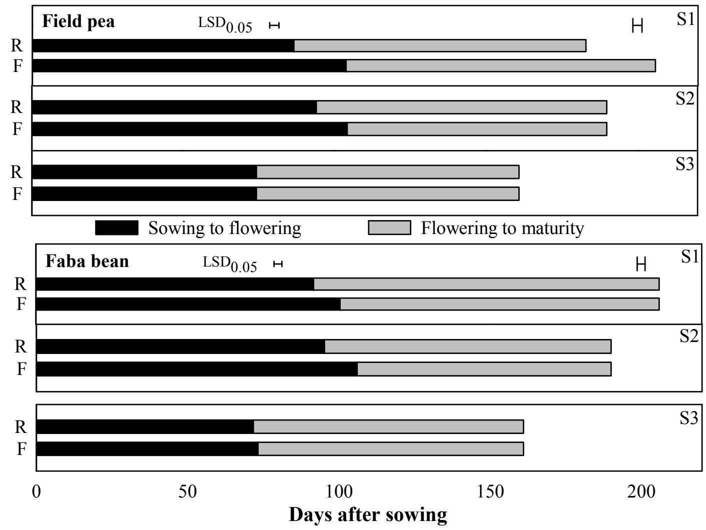

Figure 5. Duration from sowing to flowering (black) and flowering to maturity (grey) in field pea (**A**) and faba bean (**B**) crops grown in post-rice (R) and post-fallow (F) soils, at three different sowing dates (S1, S2 and S3). The horizontal error bars (smaller capped bar for flowering time and larger capped bar for maturity time) represent LSD values at the 0.05% level of significance.

Total Dry Matter (TDM) varied significantly ($p < 0.05$) between pre-treatments and sowing dates in both crops (Figure 6). TDM trends were well correlated with trends in grain yield ($R^2 = 0.88$, $n = 288$). In field pea, the highest TDM was recorded in crops from the S1 sowing date in the post-rice treatment (1147 $g \cdot m^{-2}$) and was significantly higher (30% more) than that of the post-fallow treatment. Both legumes from the S1 and S2 sowing dates exhibited higher TDM than those from the S3 sowing date. Faba bean crops from the S1 and S2 sowings produced significantly higher TDMs, while the S3 sowing date comparisons showed more dry matter in plants grown in post-rice soils than post-fallow soils.

3.2. Grain Yield and Quality

Grain yield and Harvest Index (HI) decreased in crops sown at later sowing dates (Figure 6). Crops from the S3 sowing were most affected, with yields and HI values often less than half that of the S1 sowing. The clearest difference observed between soil pre-treatments related to the yield of field pea, where the S1 sown crop gave a significantly ($p < 0.05$) higher grain yield (474 $kg \cdot ha^{-1}$) in post-rice soils compared to post-fallow plots (Figure 6). Later sowings (S2 and S3) of field pea did not display an effect of soil pre-treatment on yield. Faba bean yields were lower in post-rice plots than the post-fallow plots in both the S1 and S2 sowings, but in the S3 sowing, yield increased (30%) in post-rice treatments compared to post-fallow treatments.

Post-rice soil treatment had a significant and beneficial influence on weed infestation ($p < 0.05$) in contrast to post-fallow soil and consequent crop yield for both faba bean and field pea (Figure 7). Weed infestation was reduced at the S1 sowing date, with weed numbers increasing in subsequent plantings. The contrast between post-rice and post-fallow was most evident in crops from the S3 sowing date. In post-rice soils, weed dry weight was 14 $g \cdot m^{-2}$ in field pea and 21 $g \cdot m^{-2}$ for faba bean, but this increased 10-fold in post-fallow plots (Figure 7). In post-fallow soil, plots with faba bean had 35%

more weed biomass than field pea. Significant differences in grain yield were observed between the weeded and unweeded plots for both crops ($p < 0.05$). Regardless of crop type, post-rice soils were less impacted by weed infestation than post-fallow soils, at all sowing dates, and this effect was maximal at the S3 sowing date. The grain yield lost in unweeded plots in field peas from the S1 sowing date was 145 g·m^{-2} (post-fallow) and 27 g·m^{-2} (post-rice) as compared to weeded plots.

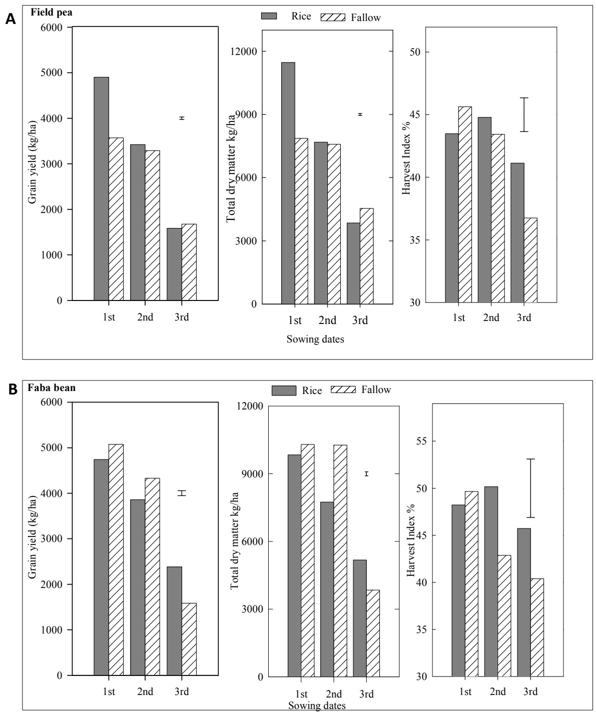

Figure 6. Grain yield, total dry matter and harvest index for field pea (**A**) and faba bean (**B**) grown after rice and after fallow soils at three sowing dates (S1 sowing) S1, (S2 sowing) S2 and (S3 sowing) S3. The harvest index is the ratio between grain yield and total dry matter. Vertical error bars represent LSD values at the 0.05% level of significance.

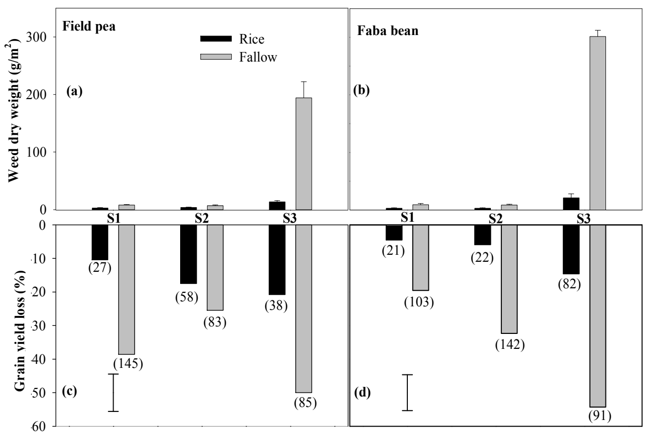

Figure 7. Weed dry weight (**a**,**b**) and grain yield loss (**c**,**d**) in post-rice and post-fallow pea (**a**,**c**) and faba bean (**b**,**d**) at three sowing dates (S1, S2 and S3). Error bars projecting from shaded vertical bars represent the standard deviation of the mean (n = 4). Error bars in the lower left corners of Panels (**c**) and (**d**) indicate LSD values at the 5% level of significance. The values in parentheses represent grain yield losses in non-weeded plots ($LSD_{0.05}$ = 25 for field pea and 92 for faba bean).

Chocolate spot (*Botrytis fabae*) and Ascochyta blight (*Ascochyta fabae*) were detected in crops sown at the S1 sowing date and in the post-fallow soil (Figure 8). Within two weeks, infestation spread through post-rice fields and affected the majority of faba bean plants. Infection was more pronounced in plants from the S3 sowing in contrast to plants of the earlier sowing dates (Figure 8). Discoloration of beans may also have been enhanced by tannin leaching from damp pods and by non-pathogenic saprophytes. The post-rice soil had a positive effect on grain yield loss for both field pea and faba bean (Table 2). Greater weed infestation in the S3 sowing was associated with higher yield loss in both crops.

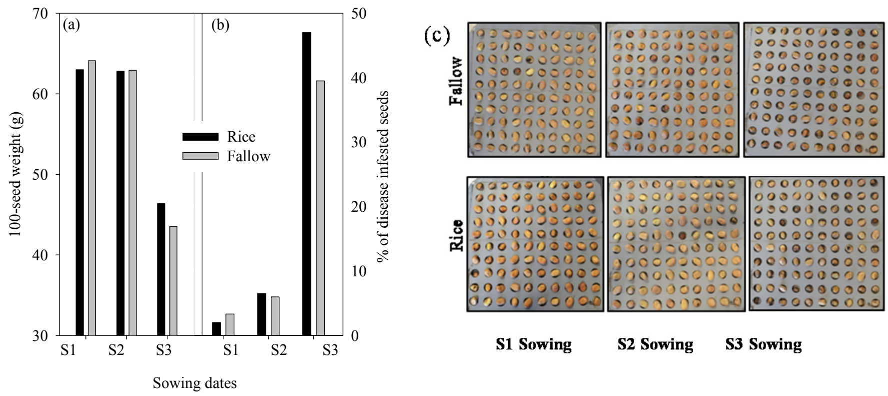

Figure 8. 100-seed weight (**a**) and the percentage of disease-infested seeds for faba bean (**b**) at three sowing dates in post-rice and post-fallow plots. Appearance of faba bean seed grown in post-fallow and post-rice plots on different sowing dates (**c**).

Table 2. Comparative analysis of the weeds' biomass and yield loss due to weeds present in post-rice and post-fallow treatments at three different sowing dates (S1, S2 and S3).

Parameter	Sowing	Post-Fallow Soil		Post Rice Soil	
		Field Pea	Faba Bean	Field Pea	Faba Bean
Weed dry matter (g·m^{-2})	S1	80 b	27 b	91 b	32 b
	S2	68 b	38 b	86 b	30 b
	S3	1942 a	136 a	3015 a	213 a
Yield loss (kg·ha^{-1}) due to the presence of weeds	S1	145 a	103 a	52 a	21 a
	S2	83 b	142 b	62 a	22 a
	S3	85 b	92 c	33 b	37 b

Values with different letters within each parameter differed significantly at $p < 0.05$.

4. Discussion

Growth and Yield of Grain Legumes in Post-Rice Soil

As seed germination does not always correlate with field emergence, seedling emergence is widely used to predict stand establishment [42]. Early-emerging plants can generally better utilize available resources, including soil moisture in the soil profile [43], and can also successfully compete with weeds. In related experiments under laboratory conditions, field pea required eight full days to emerge while faba bean required ~15 days. In the field experiment, initial emergence at the S1 sowing date was higher for field pea (60%) than for faba bean (30%), suggesting that differential rates of emergence exist among legume spp. and may be related to the ability to withdraw moisture or regulate enzyme activity for stored carbohydrate metabolism. Differences in seed size and shape (field pea is spherical, while faba bean is flat) are also likely to alter the relative seed-soil interface, thus affecting emergence values.

The presence of decomposing rice roots and their associated microflora in post-rice soils and differential soil textural properties are factors associated with variation in crop emergence of faba bean, in contrast to soils under a fallow rotation with no rice roots present [44]. Faba bean is generally successfully produced in loamy to clay soils with neutral to alkaline pH, but typically performs poorly in acid soils [30].

The long-term average rainfall in the month of April in Yanco NSW is ~30 mm, which could induce waterlogging in legumes such as faba bean if heavy rainfall is experienced directly after sowing; a situation more likely to occur in a post-rice soil [45]. In 2013, heavy rainfall was not experienced during seeding; a total of 246, 221 and 145 mm of water (sum of irrigation and rainfall) was received in 2013 by seedlings of S1, S2 and S3 sowing dates, respectively. In the early sown field pea crop following rice, seedling emergence was higher than the S2 sowing date, which is likely associated with the improved moisture availability in the post-rice soil to field pea, which thrives under high soil moisture availability. The extensive remaining rice root system and residues in an existing rice field could potentially act to retain soil moisture more than in a fallow soil, possibly resulting in greater subsequent seedling emergence. Rice plants produce up to 4 $t \cdot ha^{-1}$ of roots in Australian conditions, and about 90% of these roots are located in the top 10 cm of the soil profile [7], which can alter and significantly enrich soil physico-chemical properties. It has been reported that the majority (80%–90%) of roots of field pea are located within the top 20 cm of soil depth [46], as would be expected for faba bean.

Optimum soil conditions for faba bean emergence were experienced approximately seven weeks after rice harvest. Interestingly, emergence values for faba bean were lower in rice plots than in post-fallow plots for S1 and S2 sowing dates, while plant emergence was higher in the rice plots of the last sowing date when less rainfall was reported than during S1 and S2 dates. This suggests that in contrast to field pea, faba bean prefers a moderate amount of soil moisture. Rahman and Chikushi [47] reported the presence of significant residual soil moisture after rice harvest because of the presence of the mat of rice roots. Others have also observed that post-rice soils could be enriched by higher concentrations of toxic metals (particularly Mn^{2+}) [48,49], which could potentially inhibit the growth of succeeding crops. In this field study, legumes were sown at approximately six weeks after rice harvest, which may have diminished the possibility of Mn^{2+} toxicity due to anaerobic soil conditions. However, the presence of the mat of rice roots in soils following rice would allow for considerable soil moisture retention from the ample rainfall received in 2013 (Figure S2). Evidently, the emergence of faba bean was adversely affected by these conditions, while field pea emergence was not.

Plants sown during the S3 sowing date were seriously and negatively affected by excessive weed growth, but this was legume species dependent. In the S3 sowing treatment, at least 50% more plants emerged per m^2 in field pea treatments than for faba beans. This resulted in greater penetration of the canopy by sunlight in the faba bean plots, allowing sunlight to reach the soil surface, and this likely stimulated weed seed germination in contrast to field pea treatments. In addition, faba bean plants were slower growing and required more time to reach full canopy cover than did field pea plants, so rapid emergence and growth of field pea resulted in greater weed suppression in this treatment in contrast to faba bean (Figure 8). Faba bean proved to be less competitive with weeds, especially at the later sowing date treatment. This may be associated with its ability to successfully compete for resources, such as space, light and nutrients, in the presence of actively-growing weeds. In addition, under conditions of reasonable rainfall (in 2013, ~30 mm of rainfall was obtained in early July), the input of fertilizer after the S3 sowing date also likely resulted in enhanced weed growth in faba bean treatments. An additional ~5 mm of rain after the S3 sowing also supported further weed and crop growth (Figure 2).

The strong relationship between grain yield and total dry matter accumulation in a legume crop reflects the influence of dry matter in partitioning into grain over time [50]. Lower light interception at the soil surface due to significant weed presence and substantial competition for resources including space experienced by the S3 crop led to reduced production of biomass and inefficient partitioning into the grain. The highest yields achieved for field pea and faba bean in this experiment (~5000 $kg \cdot ha^{-1}$, in the S1 sowing date) were above the higher limits of the Australian national average yield of 3000–4000 kg·ha^{-1} [40,51]. This could be due to favourable growth conditions experienced and the intensive crop management of this research site.

The influence of weeds was far greater in fallow soil treatments than in post-rice treatments. Weeds were also noted to flourish in post-rice treatments during crop maturation, when the leaves of crop plants began to senesce. Available moisture and nutrients, due to rainfall and topdressing plus the fixation of nitrogen by legumes also likely impacted the growth and emergence of weeds over time. Plants in unweeded plots incurred a substantial reduction in grain yield (Figure 8 and Table 2) in comparison to hand-weeded plots, but the exact effect of weed removal was not able to be determined (Figure 6), as all plots experienced herbicide application, which was moderately successful in weed eradication initially in experimental sites. The observed and significantly reduced weed growth in post-rice treatments versus fallow treatments is well supported by the findings of Seal and Pratley [52] in Australian rice, who suggested that the allelopathic activity of rice and its root system may also suppress weeds over time. In this case, the decomposing mat of rice roots is likely to have altered soil microbial communities compared to the fallow treatments [53], and it is difficult to speculate whether allelopathy or altered microbial communities or other conditions may have contributed to reduce weed seed emergence and growth in post-rice soils. However, the physical presence of water in rice production systems leading to anaerobic soil conditions may also influence the viability of weed seed propagules in post-rice soils.

Fungal infestation in faba bean varied among the sowing date treatments and can likely be explained by the prevailing soil moisture and weather conditions experienced during crop growth. The monthly rainfall in July and September was reported as >30 mm, and pathogen infestations were noted over that period. Faba bean is most susceptible to chocolate spot disease if grown in waterlogged soils [30], likely due to excess moisture. The developmental stage of the legume pod also influenced disease severity; for example, faba bean plants sown at the S3 date were more severely affected than plants of the S1 or S2 sowing dates (Figure 8). Although the crop seeded at S3 took less time to mature than crops from the earlier sowing dates (Figure 5), the reduced yields of S3 sown crops were clearly undesirable. It is not possible to predict the potential for disease development across all climatic zones in the region, and further experimentation is needed to evaluate the potential for pathogens adversely impacting on legume crop growth and yield in post-rice soils. It has been suggested previously that the inclusion of faba bean in cereal rotations could minimize the extent and severity of chocolate spot infestation in faba bean [32].

The present study suggested that the inclusion of field pea and faba bean as possible legume crops post-rice could likely prove successful in existing rice-based rotations in southern Australia if sowing date is carefully optimized. According to the winter crop variety sowing guide [54], the grain legumes suitable within the feasible sowing period include chickpea (mid-May–mid-June), lupin (early April–early May), field pea (May–early June) and faba bean (mid-April–mid-May). As irrigated rice is harvested in late March–mid-April in southern Australia and preparation for the next crop can take two to three weeks (depending on weather), the suitable legume options remaining include field pea and faba bean, in terms of timing for optimal production. Improved use of available soil moisture profiles after irrigation of a rice crop could be an additional way to increase water use efficiency for the rice or irrigated farming system. Inclusion of field pea or faba bean, as shown in this field, study could be a valuable component of this system and may help to reduce the possibility of increased salinity over time associated with a rising water table [6].

The early sowing of field pea led to considerable production of dry matter or crop biomass, which may also be beneficial if growers are interested in a green manuring or hay crop [54]. Optimum growth of faba bean occurs in well-watered conditions with adequate soil temperatures [55]. The sowing options for faba bean include; sowing soon after rice harvest, reliance on natural rainfall or the use of supplemental irrigation. However, the availability of adequate supplies of irrigation water is less predictable in southern Australia [56]. Sowing during mid-May could likely provide reasonable yields, and it is therefore suggested that sowing be done as soon as possible after rice harvest. This is likely due to a combination of soil conditions, including moisture and nutrient availability, soil temperature and exposure to pathogens. The current study indicates that the maximum window for sowing a post-rice grain legume is less than 70 days following rice harvest. Cooler soil conditions and air temperatures during the initial crop growth led to reduced seed size (Figure 8) and a lower harvest index (Figure 6).

The major benefit obtained from legume production is generally associated with the added N to the soil through symbiosis. However, soil nitrogen (N) supplementation by legume production varies with legume crop, soil mineral N content, sowing time and the growth rate of the plant. Plant biomass has been shown to correlate strongly with plant N release to the ecosystem [41,57]. Using the method of Matthews and Marcellos [40] to estimate the levels of N added to the soil by faba bean, the S1, S2 and S3 sowing dates in the present study are likely to have fixed 200, 180 and 90 $kg{\cdot}N{\cdot}ha^{-1}$, respectively for faba bean. Similar estimates have been calculated for field pea [41], and in the present study, we estimate these values at 170, 135 and 75 $kg{\cdot}N{\cdot}ha^{-1}$ fixed by S1, S2 and S3 field pea crops, respectively. These represent significant inputs to soil N that could be used by cereal crops following legumes as a rotation [18].

5. Conclusions

This field study was conducted in a post-rice vertosol and demonstrated the ability to grow grain legumes (field pea and faba bean) in post-rice soils. Field pea reached maturity at least three weeks earlier in post-rice soils than in post-fallow soils, with a yield benefit of 1330 $kg{\cdot}ha^{-1}$. In comparison, the growth of faba bean was similar in post-rice soil and post-fallow soils. Faba beans were unfortunately affected by fungal diseases, including chocolate spot; however, the infestation had rather limited effects on the grain yield of the earliest sown crops (S1). Legume crops produced in post-rice soils experienced greatly reduced levels of weed infestation in comparison to those produced in neighbouring post-fallow soils. This may be due to the increased competition in crops grown in post-rice soils with greater moisture availability or direct declines in weed seedbank numbers associated with rice production and flooding over time. The incorporation of grain legumes in post-rice soil could potentially improve soil fertility and overall productivity of the rice-based cropping systems in southern Australia, as well as other agricultural regions of the world with similar soils and climates. Early sowing was most beneficial in terms of optimal maturity and grain yield for field pea, particularly when planning for another summer crop after pea harvest. A delay in sowing of faba bean would be effective in irrigated post-rice soils to potentially minimize waterlogged soils. Further research is suggested to validate the potential for growing field pea and faba bean in post-rice soil, including the study of the effects of stubble burning following harvest, the use of legume inoculants, the timing of water drainage in rice crops, the depth of legume sowing and the inclusion of different legume cultivars.

Supplementary Materials: The following are available online at www.mdpi.com/2073-4395/6/4/47/s1, Figure S1: Daily temperature (**upper** panel) and rainfall (**lower** panel) records for the experimental field during rice and post-rice pulse crop growth. Rice harvest time and the crop sowing dates are indicated by downward pointing arrows. Long-term average of total rainfall (**solid black** line) and the average total rainfall for the previous 5 years (2007–2011, dashed line) are presented in the lower panel, Table S1: Timing of experimental activities performed before, during and after crop establishment, Table S2: Assessment of of seed germination and purity analysis in seed utilised for field establishment of crops.

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