Crop production in a rotation trial at Tarlee, South Australia

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Summary. A crop rotation trial was established in 1977 on a hard-setting red-brown earth at Tarlee, South Australia, to monitor the long-term effect of intensive and traditional rotations on soil properties and crop production. The rotations involve wheat alternating with cereals, grain legumes, pasture, and fallow. There are 3 stubble + tillage treatments: remove stubble + cultivate, retain stubble + cultivate, retain stubble + no tillage. Three rates of nitrogen (0, 40, 80 kg N/ha as ammonium nitrate) are applied to the wheat.

Grain yield varied with seasonal conditions, and water use efficiencies were up to 10 kg/ha.mm. In the more productive rotations, wheat grain yields expressed as a percentage of potential yield tended to increase over time. The best wheat yields were always in rotations that included a grain legume or legume pasture, with additional yield increases in all rotations coming from the use of N fertiliser. By comparison with rotation and N fertiliser effects, there was little effect of the stubble + tillage treatments on grain yield. Most of the yield variations were related to differences in tiller density or grains per ear, with grain weight remaining relatively constant over all seasons.

There was a tendency for grain legume yields to decrease over the latter years of the trial, and this was attributed to the build-up of plant diseases through growing the same species on the same plot every second year. Overall, faba beans were the highest yielding grain legume, and the wheat–beans rotation, with 80 kg N/ha on the wheat, gave highest total grain production.

Data for residue remaining after harvest indicate that in some years there is less than the desired minimum levels to give adequate protection against erosion, so any grazing of the residues must be carefully managed.

Introduction

Early wheat production in southern Australia was in a monocultural rotation, and this soon led to nutrient exhaustion and declining yields. The use of superphosphate, new varieties, and bare fallowing increased yields, but the continued use of the fallow–wheat rotation depleted soil organic matter and caused a loss of soil structure. Widespread land degradation resulted and crop yields stabilised at about the level recorded when cropping began, meaning no net yield increase after 80 years of farming. These trends in wheat yields on an Australia-wide basis were reviewed by Donald (1963), who also noted increases in yield from about 1950 and predicted further increases following the widespread adoption of crop–pasture rotations. This 'ley farming' system became a relatively stable pattern of land use and restored both the productivity of previously degraded soils and the profitability of farming. Donald (1982) considered that the advance in wheat yields from 1950 onwards was due mainly to improved soil fertility, but by 1980 Australian wheat yields had plateaued again.

By this time, cropping intensity had increased on many farms as a result of economic pressures that required increases in farm output and favoured grain over livestock production (Finlayson 1979). Farmers were asking about the possible consequences of a change to more intensive cropping rotations (e.g. Wickes 1983). Clarke and Russell (1977) recommended long-term sequential experiments to obtain information on the effect of alternative farming systems on crop yields and soil properties. Clearly, the challenge then existed to devise systems that allow intensive cropping while still maintaining soil fertility, soil structure, and crop yields.

Against this background, I established the Tarlee rotation trial in 1977, to monitor the long-term effects of intensive and traditional rotations on soil properties and crop production. Continuous cropping systems with cereals and grain legumes are compared with pasture–wheat and fallow–wheat rotations. Stubble treatments and nitrogen (N) fertiliser treatments were included in the design because they were seen as important components of the new farming systems and likely to interact with rotational effects.

This paper describes the trial design and practices, and summarises data on crop production from 1978 to 1993.

Materials and methods

Site and environment

The trial is located at Tarlee, 80 km north of Adelaide, on a hard-setting red-brown earth soil with a sandy loam texture (Dr2.13, Northcote 1979; fine, mixed, thermic Calcic Palexeralf, Soil Taxonomy classification). Before the trial, the site had been farmed on a cereal–pasture rotation to restore fertility and reverse structure degradation caused by earlier intensive cropping in a cereal–fallow rotation. Some soil properties at the start of the trial are given in Table 1.

The long-term mean annual rainfall is 475 mm and the growing season (April–October) rainfall is 355 mm. Rainfall data are given in Table 2, and class A pan evaporation data and maximum and minimum air temperatures in Table 3.

Experimental design and treatments

The experiment comprises eight 2-year rotations in factorial combination with 3 stubble + tillage treatments, and these plots (6 by 40 m) are split for 3 rates of N fertiliser. There are 2 phases, so that each crop is grown each year, and 2 replicates.

The 8 rotations are continuous wheat (*Triticum aestivum*); wheat–barley (*Hordeum vulgare*); wheat–field peas (*Pisum sativum*); wheat–lupins (*Lupinus angustifolius*); wheat–field beans (*Vicia faba*); wheat–volunteer annual pasture (grasses and broadleaf weeds plus medics, *Medicago* sp.); wheat–sown legume pasture (medics and subterranean clover, *Trifolium* sp.); and wheat–fallow. The 3 stubble + tillage treatments over 1978–87 were stubble burned; stubble incorporated into the soil; and stubble chopped and retained as a surface mulch. All of these were cultivated for weed control and seed-bed preparation. In 1988, treatment management was modified to eliminate burning and to include no tillage. The treatments became stubble removed + cultivation; stubble retained + cultivation; and stubble retained + no tillage. The changes were made to keep treatments relevant to contemporary farm practices whilst maintaining treatment effects in the trial. Stubble burning on commercial properties has been discouraged, but stubble harvesting (partial removal) will be an option for many farmers if a proposed pulp mill to process wheat straw is built in the lower north of South Australia; and other trials and farmer experience have shown that no tillage is successful on red-brown earths and gradually improves soil structure. The 3 rates of N fertiliser are 0, 40, and 80 kg/ha of N as ammonium nitrate applied to wheat and barley plots only and incorporated by sowing.

Table 1. Soil characteristics at the start of the experiment in 1977

Soil depth (cm):	0–10	10–30	30–60
Organic carbon (%)	1.00	0.75	0.39
Total nitrogen (%)	0.10	0.09	0.05
Total phosphorus (%)	310	250	200
$NaHCO_3$ extractable P (μg/g)	54	15	2
$NaHCO_3$ extractable K (μg/g)	430	340	200
pH (1 :5 soil : water)	6.8	8.5	9.2
EC (1:5 extract; mS/cm)	0.25	0.60	0.87
Clay (%)	14	41	37
Silt (%)	8	9	16
Sand (%)	78	50	47

Agronomic management

Pre-sowing preparation of the plots commenced after the opening rains in autumn, except in the fallow plots, where initial tillage was done at the end of winter (August–September) in the year before cropping. Volunteer pasture growth on these plots was cut with a rotary slasher before mould-board or offset disc ploughing to 8–10 cm followed by 0–3 (average 1.3) workings with a tined cultivator to control weeds in spring and summer. From 1988, the initial tillage was also done with a tined cultivator. After the break of the season, the fallow plots were cultivated at the same times as the initial tillage and subsequent cultivations of the other (non-fallow) plots.

Summer weeds postharvest were generally not a problem, but in most years judiciously managed grazing by sheep over the whole trial area removed spilled grain and controlled wireweed (*Polygonum aviculare*).

The stubble + tillage treatments began with stubble burning in April when weather conditions were suitable. Some raking was necessary on plots with light wheat stubbles and on the grain legume stubbles to achieve a complete burn. At about the same time as burning, stubble on the stubble retention plots was chopped to about 10 cm, using a rotary slasher, to facilitate later cultivation of these plots. After 1990, the stubble treatments were carried out as soon as practical after grain harvest. A mulcher was used to chop stubble on the retention plots. The same machine was adapted to harvest stubble by setting the cutting height lower and using a sheet-metal cowling to direct chopped stubble into a trailer for removal from the plots.

Initial tillage treatments were done after sufficient rainfall to make soil conditions suitable, and allowing a short period for weed germination and emergence. The plots where stubble had been removed (burned, or later harvested) were tilled with a tined cultivator to a depth of about 8 cm. Until 1987, the stubble incorporation plots were tilled with a rotary hoe to a similar depth. Careful setting of the various adjustments on the rotary hoe and choice of a suitable forward speed enabled the standing stubble and early weed growth on these plots to be thoroughly incorporated into the surface soil whilst leaving a satisfactory soil tilth. The stubble retention plots (with slashed stubble on the soil surface) were tilled with a tined cultivator fitted with sweep shares

Table 2. Monthly rainfall (mm) at the trial site and for 1881–1977 (long-term mean, LTM) at Tarlee

	LTM	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	16-year mean
Jan.	22	9	9	0	20	18	10	42	6	7	41	16	2	5	31	1	68	18
Feb.	21	5	27	1	15	4	5	2	0	3	12	3	0	11	0	7	9	6
Mar.	21	6	2	1	10	39	47	15	73	0	25	28	19	0	5	61	17	22
Apr.	39	42	30	70	11	78	86	52	44	28	20	16	9	8	38	57	4	37
May	55	53	41	28	37	36	55	26	33	24	73	75	70	7	5	67	25	41
June	54	87	9	71	129	40	24	31	35	30	46	75	48	76	98	49	45	56
July	53	101	42	50	87	11	62	89	32	94	79	50	73	75	58	54	34	62
Aug.	59	69	73	21	90	8	63	94	88	85	39	28	81	80	76	123	30	66
Sept.	51	95	143	24	28	42	56	59	81	72	18	49	44	42	47	128	63	62
Oct.	44	23	87	110	30	19	47	47	52	83	48	29	35	29	5	80	71	50
Nov.	31	41	42	32	25	4	42	33	12	27	4	58	46	14	41	80	27	33
Dec.	25	17	58	13	7	4	16	5	33	20	28	14	20	37	5	103	31	26
Total	475	548	563	421	489	303	513	495	489	473	433	441	447	384	409	810	424	479
Decile	6	8	8	4	6	1	7	7	7	6	5	5	5	3	4	10	5	6
Apr.–Oct. total	355	470	425	374	412	234	393	398	365	416	323	322	360	317	327	558	272	374
Apr.–Oct. decile	6	9	8	7	8	1	7	7	7	8	5	5	6	5	5	10	3	7

Table 3. Mean (range in parentheses) monthly class A pan evaporation and maximum and minimum air temperature at the site, 1978–93

	Class A pan evaporation (mm)	Temperature (°C) Maximum	Minimum
Jan.	305 (188–383)	31.0 (28.0–35.8)	15.8 (12.3–20.9)
Feb.	266 (184–360)	31.3 (28.8–35.0)	16.2 (12.9–19.8)
Mar.	214 (171–268)	28.3 (26.0–30.4)	14.8 (12.3–17.5)
Apr.	138 (96–172)	23.6 (20.2–27.9)	11.8 (9.9–14.1)
May	79 (63–117)	19.0 (16.2–21.6)	9.5 (6.1–11.2)
June	53 (30–82)	15.5 (13.6–19.2)	7.1 (4.6–10.6)
July	62 (50–74)	14.5 (12.7–16.8)	6.5 (4.2–8.0)
Aug.	74 (55–113)	15.8 (13.8–20.6)	6.8 (5.2–10.1)
Sept.	102 (83–134)	18.5 (15.5–21.9)	7.7 (3.8–9.7)
Oct.	153 (110–220)	22.3 (18.4–25.3)	9.4 (7.3–11.5)
Nov.	217 (161–259)	26.5 (23.4–29.4)	12.4 (9.8–14.0)
Dec.	271 (164–338)	28.9 (26.0–31.8)	14.8 (12.4–16.6)

(300-mm points) so that most residues remained on the soil surface.

Following initial tillage, timing of cultivation of all plots (including fallow) was governed by weed growth on the worst-affected plots. The number of cultivations required decreased during the 16 years as herbicides that were more effective became available (e.g. Glean, for control of soursobs). The total number of cultivations on non-fallow plots decreased from 6 to 2 cultivations/year for cereals and from 5 to 2 cultivations/year for grain legumes. The total number of cultivations on the fallow plots decreased from 10 to 4 cultivations/year. After 1988, when no tillage was introduced, weed growth on these plots was controlled with a knockdown herbicide (glyphosate, Roundup), generally twice before sowing.

The plots were sown when seedbed moisture was sufficient, after weeds were controlled. Sowing dates for all crops tended to be earlier as the trial progressed, with the mean sowing dates being in the last week of May for pasture and grain legumes and in the third week of June for wheat and barley. Both dry soil and excessively wet soil caused late sowing in different years.

A 10-row, 3-point linkage tined drill (or combine) was used to sow all plots and apply fertiliser. Normal (150-mm) points were used on cultivated plots and narrow (10-mm) points for no-tillage plots. Ammonium nitrate (at 0, 40, or 80 kg N/ha) was spread on the soil surface and incorporated by sowing, and single superphosphate was applied at 120 kg/ha with the seed in the drill row. All cereal and grain legume crops were sown at normal commercial rates recommended for the area. The combine was fitted with mulch treaders (helical harrows) to level the soil and to spread the straw evenly on stubble retention treatments. This equipment was adequate for all amounts of stubble encountered.

The legume pasture was sown at 20 kg/ha, a rate higher than the normal farm practice, to obtain a dense stand of legume-dominant pasture. The pasture seed and 120 kg/ha of superphosphate was spread over the soil surface and covered lightly by using the mulch treaders. The volunteer pasture plots were topdressed at the same rate of superphosphate.

The pasture plots were not grazed during the growing season because of the difficulty of managing sheep in a complex rotation trial design. However, these plots were mown (using a mulching machine) twice in each season, to simulate grazing. The cut material was left on the plots to return nutrients to the soil.

The crop and pasture cultivars grown in the trial have been selected from those recommended for the district, and a change was made only to obtain advantages such as improved disease resistance and, hence, higher potential yield. During the 16 years, cultivars used were as follows: wheat (Condor 1978–84, Warigal 1985–87, Machete 1988–92, Janz 1993); barley (Clipper 1978–83, Galleon 1984–93); peas (Early Dun 1978–85, Alma 1986–93); lupins (Unicrop 1978–82, Illyarrie 1983–90, Gungurru 1991–93); beans (Ostlers 1978, Fiord 1979–93); legume pasture (Jemalong medic + Daliak subterranean clover 1978–85, Paraggio medic + Clare and Seaton Park subterranean clovers 1986–90, Paraggio medic + Clare, Seaton Park, and Trikkala subterranean clovers + Paradana balansa clover 1991–93).

The main weeds at the trial site were annual ryegrass (*Lolium rigidum*), wild oats (*Avena fatua*), soursobs (*Oxalis pes-caprae*), and wireweed (*Polygonum aviculare*), and a variety of herbicides were used at different times to counter them. Treflan (1.0 L/ha) was used pre-sowing for all crops in the establishment year (1977) and for peas and legume pasture in 4 of the first 10 years. Hoegrass, applied to the wheat phase in 8 of the 10 years at 1.0–2.0 L/ha, was the main post-emergent herbicide used against annual ryegrass and wild oats. It was also used on wheat and barley in the alternate crop phase in 9 of the 10 years; on peas in 5 of the 10 years; and on lupins, beans, and sown legume pasture in 4 of the 10 years. Other herbicides used on the cereals were Glean (15 g/ha), Ally (7 g/ha), Buctril (2.1 L/ha), and Stomp (2.0 L/ha). Others used at different times on grain legumes and sown pasture were Fusilade (0.6–1.0 L/ha), Sencor (300 g/ha on peas), and Simazine (2.0–4.0 L/ha) on lupins and beans.

Herbicide applications gave effective weed control until 1987, when herbicide-resistant ryegrass was observed. The whole site was cut for hay in 1988 and again in 1989, to prevent the ryegrass from setting seed. This control strategy was effective. Since 1990, a wider range of grass control herbicides has been used. Full details of the weed control program, annual ryegrass densities resulting from herbicide resistance, control strategies, and hay production will be presented.

Recommended pesticides were applied at commercial rates as required to control redlegged earth mite (*Halotydeus destructor*) and lucerne flea (*Sminthurus viridis*) in newly emerged grain legume crops and legume pasture and for the control of native budworm (*Helicoverpa punctigera*) in grain legumes post-flowering. A fungicide was used on faba beans in 1987 to control chocolate spot disease (*Botrytis fabae*).

Crop and pasture measurements

The following measurements (except crop establishment and root diseases) were made annually on wheat plots from 1978 to 1987, but after the 2 years of hay cutting (1988 and 1989) not all measurements were made in all years (i.e. 1990–93). Most measurements were confined to only 2 of the 3 N fertiliser treatments (i.e. 0 and 80 kg N/ha).

Crop establishment. Following crop emergence in some years, plant counts (10 counts/plot, each of 1 m by 2 rows) were carried out to determine the density of crop establishment.

Root diseases. From 1978 to 1981, 10 wheat plants were removed from each plot at flowering and the roots were examined for the incidence of take-all (*Gaeumannomyces graminis* var. *tritici*), cereal cyst nematode (CCN, *Heterodera avenae*), and rhizoctonia (*Rhizoctonia solani*), using the techniques described by King (1984). Measurements from 1985 to 1987 were similar but included counting the white female cysts of CCN. A commercially available CCN bioassay was done on soil collected in late summer 1985–1987 and 1992. In all other years, observations were made of root diseases but detailed assessments were not undertaken.

Dry matter at flowering. The amount of dry matter at midflowering was measured by cutting quadrats (4 per plot, each 1 m by 2 rows), oven-drying, and weighing.

Dry matter at maturity. At crop maturity, dry matter was again measured by cutting 4 quadrats (each 1 m by 2 rows) per plot, oven-drying, and weighing.

Harvest index. The quadrat cuts were threshed in a stationary threshing machine and the grain from each quadrat was weighed. The harvest index (ratio of grain weight to total dry matter weight) was recorded.

Tiller density. Tiller density (no. of ears/m^2) was assessed from the quadrat samples by counting the number of ear-bearing tillers.

Grain yield. The grain yield on each plot was measured by harvesting the whole plot with a plot harvester and weighing the grain collected. A subsample of grain was kept from each plot.

Thousand-grain weight. Grain weight was measured by counting (with a laboratory seed counter) 1000 grains from the sample taken at harvest, and weighing.

Grains per ear. The number of grains per ear for each treatment was calculated from data for grain yield, 1000-grain weight, and tiller density.

Crop residue. The amount of residue remaining after harvest and therefore available to be returned to the soil, unless burned or removed, was calculated from the total dry matter at maturity less the grain yield.

For crops in the alternate phase (i.e. wheat, barley, peas, lupins, beans), grain yields were measured in all years except 1988 and 1989, using the plot harvester. Total dry matter at maturity (from quadrat cuts) and the weight of residue remaining after grain harvest were recorded until 1987. Dry matter at flowering and 1000-grain weights for barley and the grain legume crops were measured in some years.

Dry matter production of pastures (both volunteer and sown legume pasture) was recorded at the time of maximum production in spring by cutting quadrats (4 per plot, each 1 by 0.5 m), oven drying, and weighing.

Plant samples at flowering and maturity from the various crops and pastures, and grain samples from all crops, were analysed for a range of elements (J. E. Schultz unpublished data).

Results and discussion

Before the mid-1980s, almost all crops on red-brown earths in southern Australia were established with conventional cultivation and up to 6 passes were made before sowing, especially in areas where soursob was prevalent. As a result, soils were bare with a fine tilth at the completion of crop sowing and were vulnerable to degradation by heavy rain, with consequent poor crop emergence.

The assessment of crop establishment was particularly relevant in 1978, when July rainfall was high (101 mm) before and after sowing, and crop emergence was affected by soil surface sealing and/or soil slumping and waterlogging. Plant counts showed that crop rotation (previous crop) had an effect on crop establishment, even though 1978 was the first year of the trial, but stubble treatment did not. The effect of N fertiliser was very apparent (Table 4). A value of 180–200 plants/m^2 is desirable for wheat crop establishment in the 450–500 mm rainfall zone. This was achieved in 1979 (Table 4) and thereafter.

Table 4. Wheat plant establishment (no. of plants/m^2) in 1978 and 1979, showing effect of previous crop and N fertiliser

Previous crop	1978		1979	
N rate (kg/ha):	0	80	0	80
Wheat	62	93	183	200
Barley	84	129	164	188
Peas	76	132	182	200
Lupins	72	141	163	194
Beans	74	110	161	188
Volunteer pasture	49	102	165	190
Sown pasture	43	103	175	194
Fallow	85	120	186	206
Mean	68	116	172	195

Table 5. Annual values for sowing day; derived April–October rainfall (mm); wheat yield (kg/ha) and water use efficiency (WUE, kg/ha.mm) for the mean of all treatments, a low-yielding treatment, and a high-yielding treatment; and wheat yields for stubble + tillage (averaged for previous crop and N) and N fertiliser (averaged for previous crop and stubble + tillage)

Rm, stubble removed; Rt, stubble retained; C, cultivation; NT, no tillage

	Sowing day of year	Derived Apr.–Oct. rainfall[A]	Mean yield	WUE	Wheat–wheat (nil N)		Wheat–beans (80 kg N/ha)		Wheat yield					
									Stubble + tillage treatment[B]			N fertiliser rate (kg/ha)		
					Yield	WUE	Yield	WUE	Rm + C	Rt + C	Rt + NT	0	40	80
1978	199	470	1830	3.9	780	1.7	2130	4.5	2070	1660	1750	1360	1960	2160
1979	172	425	2350	5.5	1600	3.8	2610	6.1	2450	2370	2240	1760	2440	2860
1980	198	374	1170	3.1	500	1.3	1480	4.0	1210	1130	1160	1030	1230	1240
1981	197	412	2510	6.1	1680	4.1	2640	6.4	2500	2450	2580	2320	2660	2560
1982	158	244	670	2.8	500	2.1	1060	4.3	770	610	630	660	670	680
1983	155	407	2970	7.3	1920	4.7	3460	8.5	2880	2970	3050	2670	3170	3060
1984	178	398	2210	5.6	1160	2.9	3030	7.6	2270	2090	2260	1890	2270	2460
1985	162	392	3230	8.2	1090	2.8	3890	9.9	3300	3160	3230	2760	3400	3520
1986	202	416	2310	5.6	1030	2.5	2780	6.6	2280	2290	2370	2040	2370	2530
1987	153	326	2070	6.4	760	2.3	2730	8.4	2200	2040	1970	1710	2120	2370
1988	175	325	—	—	—	—	—	—	—	—	—	—	—	—
1989	157	360	—	—	—	—	—	—	—	—	—	—	—	—
1990	204	318	1670	5.3	1190	3.7	1820	5.7	1730	1690	1590	1600	1730	1680
1991	177	327	2960	9.1	1830	5.6	3270	10.0	2880	2980	3020	2670	3120	3090
1992	153	578	2470	4.3	1030	1.8	2800	4.8	2490	2420	2510	2000	2590	2820
1993	175	309	2070	6.7	690	2.2	2720	8.8	2120	2010	2100	1570	2260	2400
Mean	176	380	2180	5.7	1120	3.0	2600	6.8	2220	2130	2170	1860	2280	2390
l.s.d. (P = 0.05)														
W/i year	—	—	—	—	—	—	—	—		170			90	
Any comparison		—	490	—	440	—	670	—		500			490	

[A] (Apr.–Oct.) + 0.33 x (summer rainfall above average) + 0.5 x (March rainfall above average).
[B] From 1988 (see text for details of treatments from 1978 to 1987).

From 1978 to 1981, the day of sowing (day of the year) averaged 192; from 1982 to 1993 (omitting 1986 and 1990 when late breaks were followed by wet conditions that delayed sowing) the day of sowing averaged 164, that is, 28 days earlier than for the first 4 years (Table 5). The difference can be attributed to the release of Glean, the herbicide effective against soursobs. This was a major advance for farmers on the red-brown earths as it meant reduced cultivation, which decreased soil erosion, allowed more timely sowing, and hastened the acceptance of conservation farming practices.

Wheat yield and corresponding water use efficiency (WUE) varied from season to season and between low- and high-yielding treatments (Table 5). WUE is here defined as production per mm of 'derived' April–October rainfall: (April–October) + 0.33 x (summer rainfall above average) + 0.5 x (March rainfall above average). The highest WUE was 10.0 kg/ha.mm (wheat in wheat–beans rotation with 80 kg N/ha in 1991), identical to the mean of a high-yielding group of crops reported by French and Schultz (1984), who summarised data from 61 sites x seasons in South Australia. Their most efficient crop produced 12.3 kg/ha.mm. The average WUE of the high-yielding treatment in the present trial (6.8 kg/ha.mm) was close to the average of all sites (6.7 kg/ha.mm) in the comprehensive South Australian study.

Efficiency of production can also be expressed in terms of potential wheat yield (French and Schultz 1984), in which the potential yield is related to crop water use (or derived April–October rainfall as an estimate of water use) after allowing for water lost directly from the soil or crop canopy by evaporation. The potential yield can be calculated for each year, and the actual yield expressed as a percentage of the potential yield. Figure 1 shows the yields of the low- and high-yielding treatments expressed thus. In the wheat–bean rotation N_{80} treatment, wheat yield as a percentage of potential increased over time compared with the wheat–wheat N_0 treatment, showing the benefits of legumes in the rotation and N fertiliser. Potential yields were calculated using a value of 170 mm for the loss of water by evaporation. This value was identified by French and Schultz (1984) as appropriate for hard-setting soils and compares with a loss of 110 mm on the more friable red-brown earths. The higher value is due to poor infiltration, surface ponding, and runoff, and

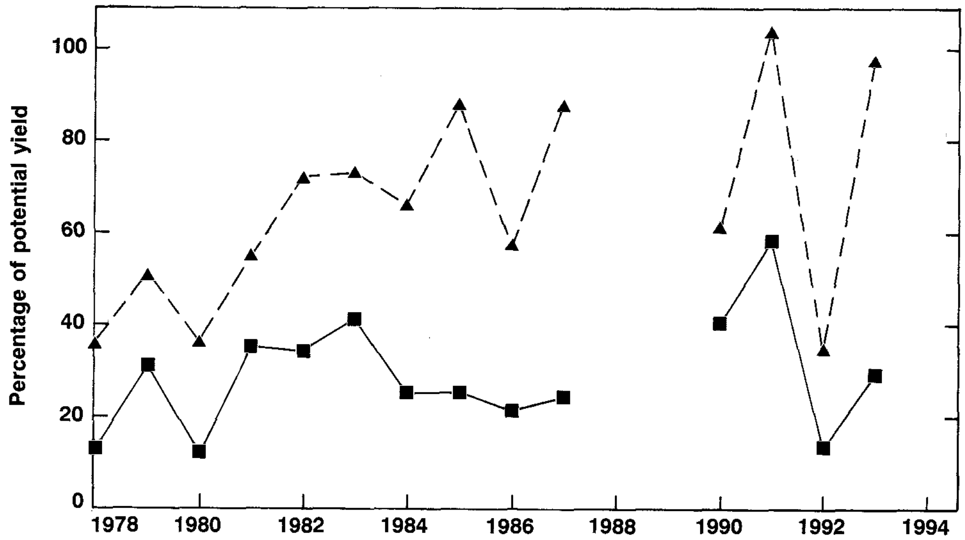

Figure 1. Changes in the percentage of potential wheat yield over time for wheat–beans, 0 kg N/ha (■) and wheat–wheat, 80 kg N/ha (▲).

emphasises a yield-limiting feature of the hard-setting soils that may gradually improve as soil organic matter content increases through the use of sound rotations and conservation farming practices.

The stubble + tillage treatments had only small, inconsistent effects on wheat yield (Table 5), with the biggest effect in the first year (1978) when stubble removal + cultivation gave a significantly higher yield of wheat. Overall, there was a small, non-significant advantage to the stubble removal + cultivation treatment (stubble removed by burning 1978–1987). This is despite evidence of some benefit, at least in later years, to the soil organic carbon and total N contents where stubbles were retained (J. E. Schultz unpublished data). Heenan *et al.* (1994) also reported that burning stubble resulted in higher yields than retaining stubble. They considered that yield improvement through burning may be associated with better disease control [e.g. take-all and eyespot lodging (*Pseudocercosporella herpotrichoides*), Murray *et al.* 1991; yellow leaf spot of wheat

Table 6. Effects on wheat yield (kg/ha) of previous crop, stubble + tillage (averaged over years and N), and N fertiliser (averaged over years and stubble + tillage)

1980 and 1985 were low and high yield years, respectively
Rm, stubble removed; Rt, stubble retained; C, cultivation; NT, no tillage

Previous crop	Mean	1980	1985	Stubble + tillage treatment[A]			N fertiliser (kg/ha)		
				Rm + C	Rt + C	Rt + NT	0	40	80
Wheat	1610	780	2200	1680	1530	1630	1120	1760	1960
Barley	1730	730	2360	1740	1720	1730	1220	1830	2140
Peas	2330	1230	3750	2420	2350	2210	2030	2490	2470
Lupins	2470	1440	3840	2410	2400	2590	2270	2540	2580
Beans	2460	1490	3780	2440	2460	2480	2230	2540	2600
Volunteer pasture	2100	1000	2890	2240	1980	2100	1790	2190	2330
Sown pasture	2300	1360	3670	2390	2290	2220	2080	2410	2410
Fallow	2420	1300	3340	2490	2320	2440	2140	2520	2600
Mean	2180	1170	3230	2220	2130	2170	1860	2280	2390
l.s.d. (P = 0.05)									
Same previous crop	—	—	—		—			70	
Any comparison	70	270	270		130			90	

n.s, not significant. [A] From 1988 (see text for details of treatments from 1978 to 1987).

(*Pyrenophora tritici-repentis*) and leaf scald of barley (*Rhynchosporium secalis*), Herrmann 1989]; better weed control [e.g. brome grass (*Bromus* spp.), Heenan *et al.* 1990]; or other phenomena related to stubble retention such as nutrient immobilisation, release of toxins, or biological activity restricting root growth. Similar factors may be involved in the Tarlee trial.

Nitrogen fertiliser significantly affected wheat yields (Table 5). In all years but 1982 (a severe drought year) there was a significant response to the first increment of 40 kg N/ha; and in 8 of the 14 years there was a significant response up to 80 kg N/ha. Table 6 shows that this response was measured across all rotations, but only the non-legume rotations (wheat–wheat, wheat–barley, wheat–volunteer pasture, wheat–fallow) responded to the second increment of N fertiliser. The responses were greatest in the continuous cereal rotations. Researchers in various parts of Australia (e.g. Strong *et al.* 1986; Rowland *et al.* 1988; Silsbury 1990; Evans *et al.* 1991; Rowland *et al.* 1994) have examined wheat responses after grain legumes and the effect of applied N. Cereal yields were generally increased by previous grain legume crops compared with continuous cereal rotations, with the yield improvement often attributed to improved soil N status. In this trial, yield differences between wheat following grain legumes (and sown legume pasture) and wheat in continuous cereals were not completely eliminated by N fertiliser at 80 kg N/ha annually (Table 6), indicating that other factors (probably disease control) were involved.

Table 7. Dry matter of wheat at flowering and maturity, harvest index, and yield components of wheat, showing the effect of year, previous crop, stubble + tillage treatment, and N fertiliser

	Dry matter (kg/ha) Flowering	Dry matter (kg/ha) Maturity	Harvest index	Tiller density (no. of ears/m^2)	1000-grain weight (g)	No. of grains per ear
Year						
1978	4410	3730	0.478	350	32.6	30.7
1979	5010	5870	0.396	278	32.3	25.0
1980	2420	2810	0.411	504	30.4	11.4
1981	4060	5080	0.484	356	30.8	24.1
1982	1580	1490	0.445	185	32.2	15.0
1983	7620	7200	0.402	392	34.8	26.3
1984	4610	5820	0.383	287	33.5	21.0
1985	5860	7710	0.409	284	36.0	27.2
1986	4570	5920	0.389	265	35.8	23.4
1987	3980	5140	0.399	248	31.7	24.9
Mean	4410	5080	0.420	315	33.0	22.9
l.s.d. (P = 0.05)	1200	1290	0.017	65	2.2	1.9
Previous crop						
Wheat	3360	3840	0.411	269	32.2	21.3
Barley	3500	4020	0.417	270	32.8	21.1
Peas	4780	5520	0.413	332	32.8	22.6
Lupins	5090	5850	0.418	350	33.0	24.1
Beans	5170	5850	0.425	350	33.1	24.1
Volunteer pasture	3960	4630	0.430	293	34.2	23.1
Sown pasture	4810	5310	0.415	330	32.1	22.7
Fallow	4630	5600	0.429	324	33.8	24.4
l.s.d. (P = 0.05)	220	210	0.008	12	0.4	0.9
Stubble + tillage						
Remove + cultivate	4490	5140	0.426	316	33.2	23.3
Retain + cultivate	4350	4990	0.416	313	32.7	22.5
Retain + no tillage	4400	5100	0.417	316	33.1	22.8
l.s.d. (P = 0.05)	n.s.	n.s.	0.005	n.s.	0.2	0.6
N fertiliser (kg/ha)						
0	3510	4240	0.437	279	33.8	22.2
40	n.d.	n.d.	n.d.	n.d.	33.1	n.d.
80	5320	5910	0.402	351	32.1	23.6
l.s.d. (P = 0.05)	100	80	0.003	6	0.2	0.4

n.s., not significant; n.d., not determined.

Table 8. Annual yield (kg/ha) of the alternate crops (averaged over stubble + tillage and N fertiliser treatments) and dry matter production (kg/ha) of pasture (averaged over stubble + tillage and 80 kg N/ha treatments)

	Wheat	Barley	Peas	Lupins	Beans	Volunteer pasture	Sown pasture
1978	1360	1710	830	1690	1900	5850	7270
1979	1830	2580	1370	860	1640	1290	4980
1980	1020	870	290	560	580	1220	2200
1981	1690	1990	1240	910	2340	2840	3140
1982	600	950	1310	1020	1460	2120	2910
1983	1860	2140	1740	480	2990	5340	6910
1984	1820	2920	2060	1760	2710	6070	4460
1985	1660	3660	1900	1480	2930	4740	4010
1986	1480	2730	2020	1470	2850	3650	4130
1987	710	1570	1520	710	1610	2450	5490
1988	—	—	—	—	—	2520	2590
1989	—	—	—	—	—	3660	5300
1990	1510	2170	750	90	890	1470	1650
1991	2080	2670	830	1210	1260	4480	4200
1992	1130	2100	1020	2360	1350	5090	6800
1993	830	1640	1420	1090	1060	4820	5220
Mean	1400	2120	1310	1120	1830	3600	4450
l.s.d. (P = 0.05)							
Same year			190				—
Any comparison			260			710	

The root disease assessments did show rotation effects, and the mean data for wheat after wheat *v.* wheat after grain legumes (average of 3 species) were 5 *v.* 2% for roots infected with take-all, 3 *v.* 2% for roots infected with *Rhizoctonia*, 9 *v.* 4% for roots infected with CCN, 6 *v.* 3 for number of white CCN cysts per plant, and 1.5 *v.* 0.7 for CCN bioassay (0–5 scale).

Wheat after barley and after volunteer pasture gave values similar to wheat after wheat, but CCN in wheat after barley was reduced to about half after the introduction of the CCN-resistant barley cultivar Galleon in 1984. Wheat after sown pasture and wheat on fallow gave values similar to wheat after grain legumes. In general, the disease levels were lower than those reported by King (1984) on a red-brown earth in the South East of South Australia.

The effects of year, previous crop, stubble + tillage, and N fertiliser on dry matter at flowering and maturity, harvest index, and yield components (tiller density, grain weight, grains per ear) are presented in Table 7. There were significant (P<0.05) effects on all of these factors due to year, previous crop, and N fertiliser, with fewer differences due to stubble + tillage treatments. Of interest is the different response pattern in the yield components in the 2 low-yielding years, 1980 and 1982. In 1980, April–October rainfall was in decile 7, and 110 mm fell in October. This was the highest October rainfall of the trial, with 83 mm in the first 13 days. These conditions stimulated extra tiller development, and many tillers carried a small ear at crop maturity, giving rise to a tiller density of 504 ears/m^2 with an

Table 9. Total grain and pasture dry matter production (t/ha) over 14 years (1978–87; 1990–93) of eight rotations, with 0 or 80 kg N/ha applied to the wheat phase and to wheat and barley in the alternate crop phase

Rotation and N fertiliser (kg/ha)	Wheat (7 years)	Alternate (7 years)	Total (14 years)
Wheat–wheat			
0	7.5	7.5	15.0
80	12.9	12.9	25.8
Wheat–barley			
0	8.5	10.6	19.1
80	15.0	18.2	33.2
Wheat–peas			
0	14.2	9.0	23.2
80	17.3	9.1	26.4
Wheat–lupins			
0	15.9	7.8	23.7
80	18.1	8.0	26.1
Wheat–beans			
0	15.6	12.8	28.4
80	18.2	12.7	30.9
Wheat–volunteer pasture			
0	12.5	n.d.	
80	16.3	25.7	
Wheat–sown pasture			
0	14.6	n.d.	
80	16.9	31.7	
Wheat–fallow			
0	15.0	—	15.0
80	18.2	—	18.2

n.d., not determined.

average of only 11.4 grains/ear (Table 7). In 1982, with April–October rainfall in decile 1 and low October rainfall (19 mm), tiller density was the lowest of all years at 185 ears/m^2, combined with a relatively low 15.0 grains/ear. Of the yield components, grain weight seems least affected by seasonal conditions.

The annual yields of the alternate crops and dry matter production of pasture are given in Table 8. The stubble + tillage treatments had only small, variable effects on the yields of the grain legumes (data not shown), and none of peas, lupins, or beans showed any response to residual N (applied to the wheat phase only). Seasonal variations in yield are quite evident (Table 8). Barley outyielded wheat, and the highest yielding grain legume was beans. Some lupin crops showed excellent early promise and produced a high yield of dry matter but failed to give the expected grain yield. Variation in growth along the plots suggested that the problem may occur when the lupin roots reach the relatively high pH subsoil at about 15 cm depth. This was the apparent cause of the low lupin yield in 1983, a year with favourable growing conditions throughout the season. In 1990 the soil was dry until the last week of June when it became very wet. Grain legumes could not be sown until 16 July (day of sowing, 197), limiting the yield. The lupins failed completely. The mean day of sowing for grain legumes over 1978–93 (omitting 1990) was 148 (28 May).

Yields of peas and beans were lower from 1990 to 1993 than during the 1980s. A possible explanation is the growing of the same species every second year, allowing a build-up of yield-limiting disease.

Pasture production data (Table 8) were obtained by cutting quadrats at maximum growth in spring, and since the pastures were not grazed, the values may underestimate the total production that could be achieved in a well-managed, grazed pasture. Careful grazing is also a means of controlling pasture composition. In the Tarlee trial, the sown legume pastures remained legume-dominant because of annual resowing and occasional use of grass-control herbicides. In the volunteer pasture, however, grasses and weeds became major components and desirable legume species tended to be suppressed. Typical pasture

Table 10. Effect of year and previous crop on dry weight of wheat residue (kg/ha)

Rm, stubble removed; Rt, stubble retained; C, cultivation; NT, no tillage

	Mean	Stubble + tillage treatment			N fertiliser (kg/ha)	
		Rm + C	Rt + C	Rt + NT	0	80
Year						
1978	1970	2280	1770	1870	1420	2530
1979	3560	3650	3610	3410	2620	4500
1980	1680	1720	1650	1660	1380	1980
1981	2640	2600	2590	2730	2250	3030
1982	810	850	780	820	750	870
1983	4350	4080	4560	4400	3580	5110
1984	3650	3700	3540	3710	2820	4480
1985	4570	4630	4470	4600	3880	5250
1986	3640	3460	3560	3890	2990	4280
1987	3100	3090	3160	3060	2510	3690
Mean	3000	3010	2970	3010	2420	3570
l.s.d. (P = 0.05)						
Same year	—		270		180	
Any comparison	740		770		750	
Previous crop						
Wheat	2310	2280	2320	2330	1460	3160
Barley	2390	2460	2410	2310	1530	3260
Peas	3290	3210	3450	3210	2760	3820
Lupins	3460	3420	3330	3630	3020	3900
Beans	3430	3350	3410	3520	2950	3910
Volunteer pasture	2680	2770	2500	2770	2180	3180
Sown pasture	3150	3210	3180	3070	2700	3610
Fallow	3250	3360	3150	3260	2770	3740
l.s.d. (P = 0.05)						
Same previous crop	—		n.s.		160	
Any comparison	140		240		180	

n.s., not significant. [A] From 1988 (see text for details of treatments from 1978 to 1987).

Table 11. Annual values for dry weight of residue (kg/ha) remaining after harvest of alternate crops

N_0, N_{80}: N fertiliser applied at 0, 80 kg N/ha

	Barley, N_0	Barley, N_{80}	Peas, N_{80}	Lupins, N_{80}	Beans, N_{80}
1978	2170	3470	2980	3190	3740
1979	1910	4520	3210	3480	3750
1980	1350	2900	1850	1250	1620
1981	1670	3700	1640	1570	2080
1982	1440	2140	1180	1440	1320
1983	2400	3990	2720	6340	5420
1984	2310	4400	4260	3420	4220
1985	1900	4160	3540	2850	3930
1986	1340	3870	2980	3660	3570
1987	1130	3250	4500	3160	2980
Mean	1760	3640	2890	3030	3260
l.s.d. (P = 0.05)					
Same year			720		
Any comparison			1070		

compositions were (sown legume pasture) 70% medic, 20% subterranean clover, 10% ryegrass and other weed species; (volunteer pasture) 20% medic, 30% capeweed, 30% ryegrass, 20% other weed species.

In commercial farming, high annual yields are desirable but total production over a number of years is important, because the farming system must be sustainable. Table 9 summarises total grain and pasture production in the Tarlee rotation trial over 1978–87 and 1990–93 (the 2 missing years are hay production, J. E. Schultz unpublished data). Wheat production (7 crops) was highest in the grain legume rotations and fallow rotation, both with the high rate of applied N. While wheat in wheat–fallow performed well, the lack of production in the alternate year (minimal grazing is available before the initial fallow preparation) made total production in that rotation lower than in all others, including the continuous cereals. The highest alternate crop production was beans, giving highest total grain production in the wheat–beans rotation.

It is a prerequisite of a sustainable farming system that soil organic matter be maintained or increased. In practice, this means that organic material grown *in situ* must be returned to the soil. Data on the dry weight of wheat residue are given in Table 10, which shows the effect of year and previous crop on overall mean residue levels and the interaction with stubble + tillage treatments and N fertiliser. The amounts of wheat residue available for return to the soil ranged from <1000 to >5000 kg/ha, depending on year and treatment. Residues of 2000–3000 kg/ha (giving 60–75% groundcover) are considered necessary to reduce to acceptable levels the risk of water erosion on sloping red-brown earths (Herrmann 1992). Therefore, in some instances the wheat residue remaining after harvest is insufficient to provide adequate protection against erosion, and extra care is needed with summer grazing and soil preparation for the next crop.

The dry weight of residues remaining after harvest of the alternate crops varies with the season (Table 11). Special care should be taken with management of the grain legume residues, as the soil surface cover provided is often less than the desirable minimum.

Overall, the crop production data from the Tarlee rotation trial show that grain yields can be maintained in continuous cropping rotations that include grain legumes. Many farmers in southern Australia are now cropping continuously, using cereals, grain legumes, and oilseed crops, and are finding this more profitable than returns from a pasture phase. They are using a variety of techniques to avoid herbicide resistance or are learning to manage it where it has already developed. The impact of the treatments in the trial on soil fertility and the influence of conservation farming practices (stubble retention and no tillage) on long-term sustainability will form the basis of another paper.

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