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Long Term Effects of Rotation, Tillage and Stubble Management on Wheat Production in Southern N.S.W.

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Abstract

A long term field experiment began in 1979 at Wagga Wagga, N.S.W., to compare the sustainability of a range of rotation, tillage and stubble management systems on a red earth. This paper reports yield, yield components and grain protein of wheat for 1979–90. Rotations considered were alternating lupin-wheat (LW), lupin-wheat-wheat (LWW), continuous wheat (WW) with and without N fertilizer (100 kg N/ha), and alternating sub-clover-wheat (CW).

Soil N supply at the start of the experiment was high following many years of sub-clover based pasture. From 1979 to 1983, there was a negative grain yield response to N fertilizer and no response to a legume in rotation except in the drought of 1982 when low yields were recorded from LW. Thereafter, a positive grain yield response was usually produced to N fertilizer in WW rotations, until 1989 and 1990, when these crops displayed aluminium toxicity symptoms. Overall, average grain yields from legume rotations were higher than WW with added N fertilizer. Since 1983, LW rotations consistently produced higher mean grain yields than CW, but mean grain protein and total N uptake were lower. Yields and N uptake by the second wheat crop in a LWW rotation indicated little carryover of benefits from the lupins. Slightly higher mean grain yield and harvest index, but lower mean grain protein, were produced by direct drilling, compared with cultivation before sowing, following lupins or sub-clover. However, retaining stubble rather than burning in autumn consistently reduced grain yields. There was no evidence that early burial of wheat stubble following summer rain, rather than incorporation in autumn, improved grain yield or total N uptake.

The build-up of giant brome grass and diseases, particularly where stubble was retained and crops direct-drilled, casts some doubt on the long term sustainability of these short term rotations in this environment.

Keywords: rotation, tillage, stubble, wheat yield.

Introduction

The recognition of biologically stable farming systems in which soil carbon and nitrogen (N), depleted by periods of cropping, are restored by leguminous pasture (Greenland 1971; Clarke and Russel 1977) set the basis of profitable mixed farming in much of southern Australia. The stability of such systems is only assured while the biological and economic constraints are in harmony. If, over an extended period, cropping proves more profitable than pasture-based enterprises and leguminous leys are abandoned, farmers may be able to maintain cereal yields only by applying fertilizer nitrogen. Continuous cereal cropping, however, can lead to a build-up of diseases and a yield decline (Glynne 1965).

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Alternatively, grain legumes, which can be expected to give high yields when grown on N deficient soil, may be grown.

Grain legumes should not be grown in successive years because of disease incidence (Stovold 1985). Ideally, they should be rotated with non-legumes, preferably cereals. A number of studies have shown a yield improvement in cereals following a lupin crop, compared with successive cereals (Reeves *et al.* 1984; Doyle *et al.* 1988; Rowland *et al.* 1988). Ellington *et al.* (1979) reported that narrow leaf lupin could maintain soil nitrogen and cereal yield in north-eastern Victoria as well as sub-clover. However, the potential benefits of both lupin and sub-clover can vary markedly from season to season (Watson *et al.* 1976; Evans *et al.* 1989), so it is important that these rotations be compared over the long term to assess their stability. Tillage and stubble management have been shown to influence crop yield and soil N supply in pasture-wheat and cereal-wheat rotations (Reeves and Ellington 1974), but there is little information on the long term effect of these management practices in a grain legume-wheat rotation.

Previous long term work at Wagga Wagga had found that grain yield and protein levels can be maintained and soil N used most efficiently by a cropping intensity of 50% and short rotations in a sub-clover-wheat system (Helyar pers. comm.) In designing this experiment, several hypotheses were established for testing: (i) that lupin and sub-clover were equally efficient at maintaining soil N supply and crop production; (ii) that in southern New South Wales, a cereal cropping intensity of 67% was exploitative and led to a decline in soil fertility and cereal yields; (iii) that a cropping intensity of 50% was exploitative unless conserving practices such as retaining stubble and reducing cultivation were employed; (iv) that early burial of residue as soon as possible after harvest would improve the chances of a 50:50 lupin-wheat rotation being stable; and (v) that mown and grazed sub-clover were equally efficient at maintaining soil nitrogen as reported by Watson and Lapins (1964).

This paper reports results obtained over a 12 year period, on growth, grain yield and grain protein of wheat, as influenced by rotation, tillage and stubble management treatments. Previous papers have presented results from this experiment on incidence of brome grass (Heenan *et al.* 1990), plant disease (Murray *et al.* 1991) and some soil properties (Chan *et al.* 1992; Heenan and Chan 1992).

Materials and Methods

Site

The experiment commenced in 1979 at the Agricultural Research Institute, Wagga Wagga (147° 20′ E., 35° 05′ S.), on a fertile red earth (Gn 2·12, Northcote 1979). According to FAO-UNESCO classification, the soil was a chromic luvisol. The site had been under pasture of sub-clover (*Trifolium subterraneum*) L., ryegrass (*Lolium*) spp. and barley grass (*Hordeum*) spp. for most of the previous 19 years, except with crops of lupins and oats in 1975 and 1976 respectively. The surface 0·1 m was a clay loam with 29% clay, 15% silt, 1·3% organic (Wakely-Black) carbon, 0·13% total N and 4·93 pH (1:5, soil:0·01 M $CaCl_2$) in 1979.

Treatments

The 13 treatments are listed in Table 1. Wheat (*Triticum aestivum* L.) cultivars used were WW33G (1979–84), Osprey (1985–6) and Dollarbird (1987–90) while the lupin (*Lupinus*

Table 1. Rotation number in the field including duplicates, distinct rotation number, treatment numbers used in the analysis and the text and details of rotation, stubble and tillage management

Field rotation no.	Distinct rotation no.	Treatment no.	Rotation[A]	Stubble management	Tillage
1, 15	1	1	W L W L W L	Mulch	Direct drilled
2	2	2	W L W L W L	Mulch	1 cultivation
3	3	3	W L W L W L	Mulch	3 cultivations
4	4	4	W L W L W L	Burn	Direct drilled
5	5	5	W L W L W L	Burn	1 cultivation
6, 14	6	6	W L W L W L	Burn	3 cultivations
7	7	7	W L W L W L	Early bury	1 cultivation
8	8_1	8	W_1 W_2 L W_1 W_2 L	Mulch	Direct drilled
8	8_2	9	W_1 W_2 L W_1 W_2 L	Mulch	Direct drilled
9	9	10	W W W W W W (zero N)	Burn	3 cultivations
10	10	11	W W W W W W (+N)	Burn	3 cultivations
11	11	12	W C W C W C (grazed)	Mulch	3 cultivations
12	12	13	W C W C W C (mown)	Mulch	Direct drilled
13, 16	13	14	W C W C W C (mown)	Mulch	3 cultivations

[A] W, wheat; L, Lupin; W_1, first wheat; W_2, second wheat; C, sub-clover pasture; 8_1, W_1 harvest; 8_2, W_2 harvest.

angustifolius L.) cultivars were Illyarrie (1979–86), Wandoo (1987), Danja (1988) and Gungurru (1989–90). The sub-clover cultivar was Seaton Park until 1986 and a 50/50 mix of Seaton Park and Junee from 1987. Both wheat and lupin were sown at 90 kg/ha, while sub-clover was undersown with wheat at 5 kg/ha until 1987, and also dropped onto wheat mulch at 10 kg/ha in autumn of the clover phase throughout the experiment. Treatment 11 received 100 kg N/ha as urea in a three-way split at sowing, mid-tillering and flowering. All crops including sub-clover received 20 kg P/ha as single super-phosphate with the seed at sowing. Lupin seed was treated with iprodione to assist in the control of the diseases brown leaf spot and pleiochaeta root rot, and wheat seed dusted with triadimefon. Recommended rates of rhizobia were applied to legume seed for the first 3 years of the experiment only.

Plot size for most treatments was 4·3 m by 50 m, but for grazed sub-clover was 60 m by 50 m. The minimum grazing intensity during the growing season was 10 d.s.e./ha. Treatment plots were separated by buffer plots measuring 4·3 m by 50 m. From 1979 to 1986, these were sown to wheat, but thereafter sub-clover was grown.

Management

Where stubble was to be retained, it was slashed between late December and early March. Burning of stubble occurred in the autumn as soon as fire control bans were lifted. Early burial of stubble with a one-way disc (Treatment 7) usually occurred when the first rainfall after harvest permitted the operation. Other cultivations were usually initiated in autumn after the soil had been wetted to 10 cm. Where stubble was retained in LW rotations, cultivation was done by offset disc harrows to 10 cm. A scarifier was used to a depth of 10 cm where stubble was burnt. The scarifier was also used in treatments 12 and 14. Until 1987, all sowing was done by a 24 run conventional combine. For 1987 and thereafter, a direct drilling undercarriage consisting of narrow tines attached to narrow high tensile strength shanks was employed.

Each treatment received at least one application of glyphosate during the summer fallow and/or just prior to sowing to control weeds. Wheat also received post-emergent applications of diclofop-methyl and bromoxynil. Simazine was applied to lupins immediately after sowing while post-emergent applications of fluazifop-p and diclofop-methyl were made as required. Post-emergent applications of paraquat or diclofop-methyl in the early years and carbetamide and fluazifop-p in more recent years were used on the sub-clover pastures.

Table 2. Time of sowing and anthesis time

	Sowing date	Anthesis date
1979	29/5	18/10
1980	13/5	14/10
1981	1/6	14/10
1982	3/6	25/10
1983	28/4	4/10
1984	9/5	17/10
1985	9/5	19/10
1986	13/5	22/10
1987	14/5	16/10
1988	24/6	27/10
1989	15/6	23/10
1990	4/6	11/10

Reports on the changes in weed flora have been given by Taylor and Lill (1986) and Heenan *et al.* (1990). Briefly, the main grass weeds encountered were ryegrass (*Lolium* spp.), wild oats (*Avena fatua*), giant brome (*Bromus diandrus*), barley grass (*Hordeum leporinum*) and silver grass (*Vulpia* spp.). The main broad leaf weeds were capeweed (*Arctotheca calendula*), wireweed (*Polygonum aviculare*), fumitory (*Fumaria* spp.), opium poppy (*Papaver somniferum*) and skeleton weed (*Chondrilla juncea*). Giant brome became a serious problem in 1985 and persisted until 1987. In 1988 and 1989, delayed sowing, combined with glyphosate use before sowing and hand weeding after sowing, successfully controlled this weed.

Use of post-emergent fungicides has been inconsistent and dependent on the severity of the disease and measures available for control. However, after 1986, wheat was regularly sprayed with benomyl at recommended time and rate to control eyespot lodging caused by *Tapesia yallundae*. This disease occurred in 1983, 1984, 1985 and again in 1986. Plants with take-all symptoms caused by *Gaeumannomyces graminis* were observed in 1979, 1983 and 1984 only. The absence of infection in other years before 1985 was mainly related to unfavourable weather conditions, while declining soil pH was the most likely cause of failure to develop after 1984 (Murray *et al*. 1991). Minor amounts of stripe rust (*Puccinia striformis*) and septoria tritici blotch (*Mycosphaerella graminicola*) occurred in a number of years. Barley yellow dwarf symptoms were observed on individual plants in some seasons and were most severe in 1979 (Murray *et al.* 1981).

Grain yield was measured by mechanically harvesting a 1·8 m strip in the centre of each plot. Subsamples (1 m^2) were taken from each plot at harvest for total dry matter production and ear number, while mechanically harvested grain was subsampled to determine grain size, grain protein and test weight.

Experimental Design

The experiment was laid out in six blocks, and within each block there were 16 plots. Treatments were randomly assigned to these plots within each block. Only 13 of the originally planned 16 treatments were instigated, resulting in treatments 1 and 6 appearing twice in each block in phase, and treatment 14 appearing twice but out of phase in each block. The term phase is used to describe the internal cropping-ley sequences of the rotations. Table 1 lists the 13 rotations along with the cropping-ley sequence. Rotations 1 to 7, and 11 to 13 have two phases (i.e. wheat or lupin, or wheat or sub-clover), rotation 8 has three phases (wheat 1, wheat 2 or lupin), and 9 and 10 have one phase. Thus, for the rotations with two phases, blocks 1, 3 and 5 were sown to wheat in 1979, whilst blocks 2, 4 and 6 were sown to lupins. For rotation 8, blocks 1 and 4, 2 and 5, and 3 and 6 are in the same phase.

This design is termed a phase confounded design (Patterson 1964), in which each phase of each rotation is represented at least once in each year, but in this case in different blocks. Thus, differences between blocks are necessarily confounded with year differences.

Statistical Analysis

The 13 rotations listed in Table 1 give rise to 14 'treatment' crops, the extra treatment arising from the second wheat crop in rotation 8, the WWL rotation. Given the design, the focal point of any analysis is the treatment × years table of means. Patterson (1964) developed procedures for modelling these means, in which he allowed for (overall) treatment effects and regressions on seasonal and trend variables [see equation 2·1·1 of Patterson (1964)]. Patterson (1964) states that this model is a natural choice, as the primary purpose of the analysis should be to identify how different rotations interact with different seasons, and hopefully then to extend the results to other circumstances. This analysis depends, therefore, on being able to identify key 'seasonal and trend' variates which essentially drive the farming systems in this environment. There are many variates which will influence the yield of wheat in this environment. However, it is clear that rainfall and sowing date are key variates. The analysis is further complicated by the need to adjust for several other concomitant variates, namely diseases, weeds and the change in wheat cultivar in 1985 and in 1988. Heenan *et al.* (1990) showed that there were significant populations of great brome densities present in 1985, 1986 and 1987. Close examination revealed that quite substantial variation existed both within and between rotations and this in turn resulted in substantial variation in wheat yield and yield component data. Similarly, Murray *et al.* (1991) recorded epidemics of takeall and eyespot in 1979, 1983 and 1984; the severity of the epidemics varied significantly between rotations. As for the great brome infestations, there was also substantial between-replicate variation in the level of takeall and eyespot.

Weed, disease and lodging (in 1985 and 1986) data were therefore not suitable for use as covariates in the classical sense; however, ignoring their effects would undoubtedly increase the errors of the experiment. Urquhart (1982) presents a method for constructing an analysis when covariates are affected by the treatments. The analysis consists of presenting the unadjusted treatment effects, but the residual error is estimated from the model which includes the covariates. It is arguable here, that although the covariates are affected by treatments, newer and better management practices may alleviate these problems in the future in these rotations. It is therefore of interest to examine the rotations with and without adjustment for these covariates.

The statistical model fitted for each variable is given by:

$$Y = X_1\beta_1 + X_2\beta_2 + Z_1u_1 + Z_2u_2 + e\,, \qquad (1)$$

where the X_i are matrices representing those design factors and covariates which are considered fixed, and the Z_i are matrices representing random effects. For these data, β_1 represents the

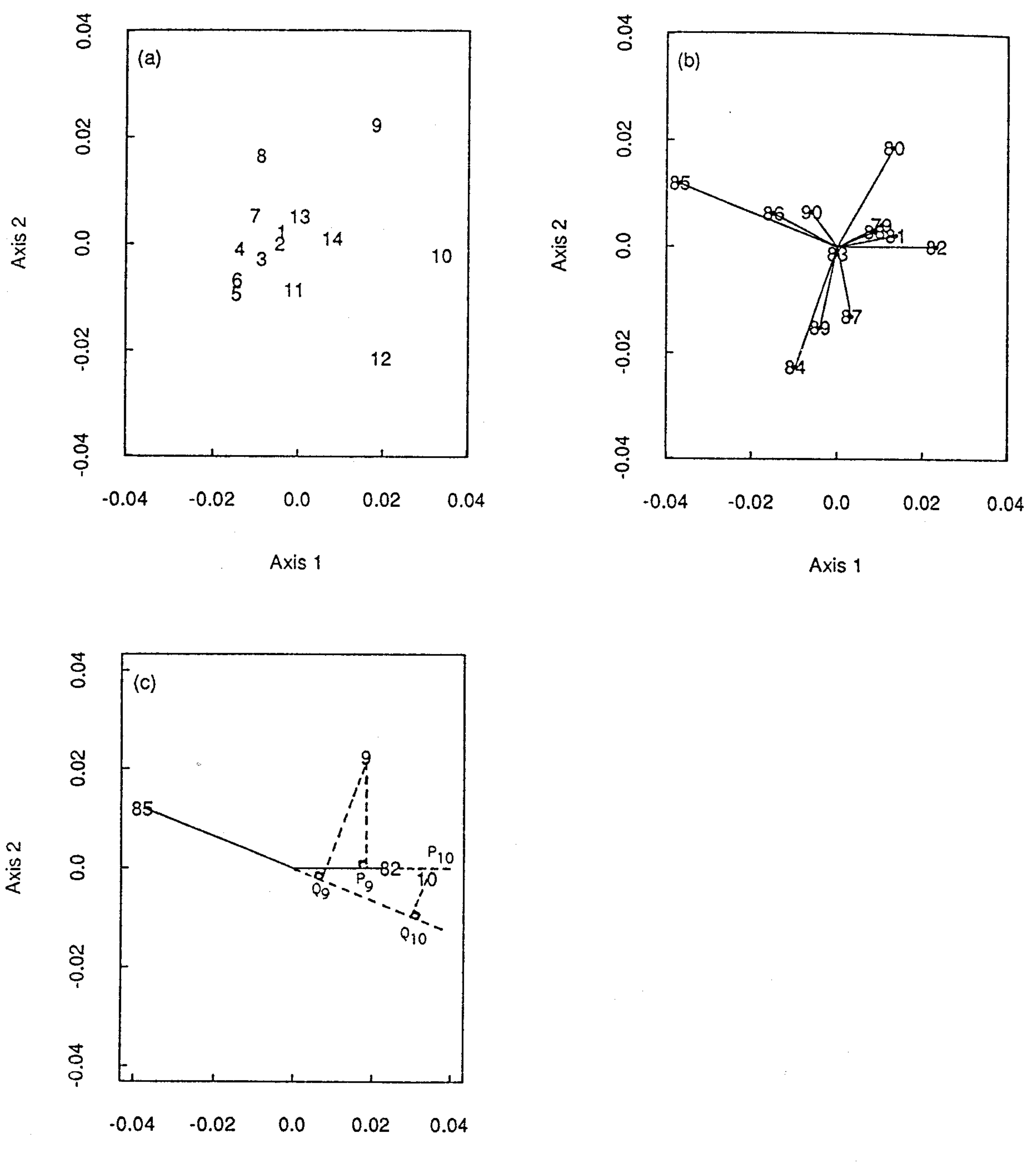

Fig. 1. Dismantled biplot of adjusted grain yield showing (a) points for treatment effects, (b) line segments for years, and (c) abbreviated biplot for treatments 9 and 10 in 1982 and 1985.

year and treatment effects and β_2 represents the covariate regression coefficients (allowed to vary for each year, if the same covariate is present in more than one year). The random effects that were included were year.treatment effects (u_1) and plot effects (u_2). The residual error term is denoted by e.

Equation (1) is an (unbalanced) mixed model and thus, assuming multivariate normality for the joint distribution of the u_i and e, leads to REML (Residual Maximum Likelihood, Patterson and Thompson 1971) estimation for the variance parameters. One can then obtain generalized least squares estimates of the treatment effects and best linear unbiased predictors of the (random) year treatment effects.

The assumption in this model is that the sequence of data recorded on each plot has equal variance (for each year) and the correlation is the same irrespective of the time lag. We examined these assumptions carefully by using, in the latter case, the semi-variogram (Diggle 1988) of the plot residuals.

To assist in the interpretation of the treatment $\times$ years table of interaction effects, we used the biplot technique of Gabriel (1971). This is a statistical device which determines the best rank 2 approximation to a two-way table of data (or means or effects). Kempton (1984) discusses the biplot and presents an application in the analysis of large genotype $\times$ environment tables. The biplot of the table of treatment $\times$ year effects, displays points for treatment and line segments for years from the best (rank 2) multiplicative model on the same graph. From a visual inspection, relationships between treatments, years, and the expected response of a treatment in a particular year can be derived.

Interpretation of the biplot follows the procedure in Fig. 1, which illustrates the biplot of grain yield adjusted for covariates for the 14 treatments. Fig. 1*a* shows what is essentially a form of principal component analysis, displaying the points for treatment effects. Treatments 1–7, 13 and 14 behave similarly for yield over the 12 years, with the remaining treatments clearly different.

Fig. 1*b* shows the line segments for years; the positive direction is indicated by the year symbol and the length of the line indicates the magnitude of the effect. The correlation between any pair of years (with respect to the treatment $\times$ year effects (in the 'best' two dimensions) is measured as a cosine of the angle between their axes. For example, 1980 and 1984 have a correlation ≈ -1 for the best rank 2 approximation of the table of year $\times$ treatment effects. The years 1979, 1981, 1982 and 1988 have similar effects on yield that are opposite to the effects of 1985, 1986 and 1990.

In Fig. 1*c*, only the points for treatments 9 and 10 and the lines for 1982 and 1985 are shown. The expected response in a year is derived by projecting a perpendicular line from the point to intersect the axis of the year line. The projected points P_9, P_{10}, Q_9 and Q_{10} show the relative ordering of treatment 9 and 10 in 1982 and 1985 respectively. In 1982, both treatments fall on the positive projection of the year line, with treatment 10 more positively affected than treatment 9. In 1985, the reverse occurs, and treatment 10 is negative compared with treatment 9.

The full biplot of adjusted yields is in Fig. 4. The reader is referred to Kempton (1984) for a more detailed exposition of the use and interpretation of biplots.

Results and Discussion

Seasonal Rainfall

Monthly rainfall totals for each year are shown in Table 3. Annual precipitation varied from a low of 311 mm in 1982 to a maximum of 709 mm in 1983.

Days to Emergence

The time to emerge varied from 9 days for Osprey sown on 28 April 1983 to 16 days for Dollarbird sown on 4 June 1990. Overall, there was no effect of treatment on the emergence time of wheat.

Early Plant Numbers

Early plant numbers, taken before tillering had commenced, were significantly affected by treatments (Table 4). There was no significant interaction between treatment (T) and year, so mean treatment effects only are presented. The use of covariates for weeds and diseases had no effect on these numbers.

Table 3. Monthly rainfall (mm) for the 1979–1990 period

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Total
1979	5	9	25	48	64	30	11	56	67	81	24	0	419
1980	23	7	26	30	39	37	37	60	24	46	9	76	415
1981	17	73	1	21	39	77	102	51	33	20	18	24	476
1982	33	0	118	29	49	22	5	6	29	11	0	9	311
1983	3	36	20	89	101	32	75	113	37	70	89	44	709
1984	191	34	15	70	17	7	90	98	39	39	19	15	631
1985	4	2	78	34	42	38	37	87	138	66	69	78	671
1986	35	4	2	20	48	20	103	52	61	91	73	34	543
1987	9	55	9	17	47	82	65	48	37	27	22	29	447
1988	17	18	36	13	164	47	68	29	57	16	36	130	631
1989	50	7	146	113	87	46	31	71	21	53	59	21	707
1990	46	65	9	84	76	28	64	78	48	48	10	9	564
						Mean							
1960/90	52	31	41	47	57	37	51	57	54	54	43	43	563

Relatively low establishment was generally recorded for T7, probably due to the rough seedbed conditions imposed by this treatment resulting in uneven sowing depth. The second wheat crop direct drilled into wheat stubble (T9) also produced slightly lower early plant numbers than wheat direct drilled into lupin stubble.

Ear Number

The mean annual number of ears per m^2 varied from a minimum of 314 in 1982 to 573 in 1984. Regression analysis showed that annual rainfall accounted for only 29% of the annual variation in ear numbers while sowing time had little effect.

Overall, minimum numbers were produced from continuous wheat (T10) and the second crop in the LWW rotation (T9) (Table 4). A significant interaction between year and treatment indicated variable treatment effects over time. Within the WW rotations, differences between T10 and T11 were not significant in the initial years, but, as symptoms of N deficiency appeared on T10, increased to a maximum of 242 by 1986; in the final 3 years, the response to N fertilizer declined, though was still significant (Fig. 2).

The overall benefit of adding a legume to the rotation (T10 *v.* T6) was significant (Table 4). This effect was not consistent over the duration of the experiment, but generally increased over time. This is shown in Fig. 2 where T10 is in the positive quadrant for the earlier years (1979, 1981, 1982) relative to T6.

Overall, similar numbers were recorded in LW (T3) and CW (T12 and T14). However, lupins did produce greater numbers than T12 in 1985, due mainly to herbicide damage to the latter, and T14 in 1984 and 1986. Within WC rotations,

Table 4. Effects of management system on mean ear number, mean early plant numbers, mean total dry matter and harvest index

Treatment	Ear no. (m^{-2})		Early plant no. (m^{-2})		Total dry matter (kg/ha)		Harvest index	
	Unadjusted	Adjusted[A]	Unadjusted	Adjusted	Unadjusted	Adjusted	Unadjusted	Adjusted
1	501	515	193	194	1056	1091	0·30	0·30
2	497	504	195	195	1075	1099	0·27	0·28
3	507	508	204	203	1076	1093	0·27	0·28
4	504	507	204	205	1120	1128	0·31	0·31
5	505	508	204	205	1093	1101	0·28	0·28
6	512	507	203	203	1110	1101	0·30	0·29
7	486	489	183	183	1068	1080	0·28	0·28
8	485	498	194	195	1022	1079	0·31	0·31
9	367	396	185	186	753	821	0·30	0·32
10	387	382	197	197	792	791	0·30	0·31
11	494	483	201	200	1030	1021	0·26	0·27
12	510	513	193	193	1112	1112	0·26	0·26
13	466	480	190	190	965	999	0·30	0·31
14	494	501	195	194	1023	1046	0·27	0·27
s.e.d.								
Min.	24	25	5·7	5·8	53	53	0·016	0·013
Max.	30	30	7·9	8·1	62	61	0·019	0·017
Mean	27	27	6·9	7·0	58	57	0·017	0·015

[A] Adjusted for covariates, disease and weeds.

grazing (T12) resulted in higher ear production than T14 in the majority of years; the difference was reversed in 1985 due to herbicide damage to T12. The higher numbers under grazing compared with mown may be partially due to a higher overall sub-clover content (77% cf. 70%) under grazing.

In LWW rotations, the second wheat crop (T9) consistently produced lower ear numbers than the first crop (T8). As indicated in Fig. 2, least differences occurred in 1980, 1982 and 1989.

Direct drilling in LW rotations produced slightly lower numbers than sowing into a cultivated seedbed on several occasions. However, the differences were inconsistent and the overall means revealed little long term difference between tillage treatments. Similarly, differences between stubble treatments were slight and inconsistent.

Where sub-clover was mown, direct drilling produced lower numbers than cultivation in the majority of years. Adjustment with the covariates indicated relatively greater effects of weeds on limiting tiller production with direct drilling in 1986 and 1987, but other factors were also probably involved including high soil strength impeding root extension, limiting nutrient supply, and biological agents inhibiting root growth (Chan *et al.* 1989; Cornish and Lymbery 1987).

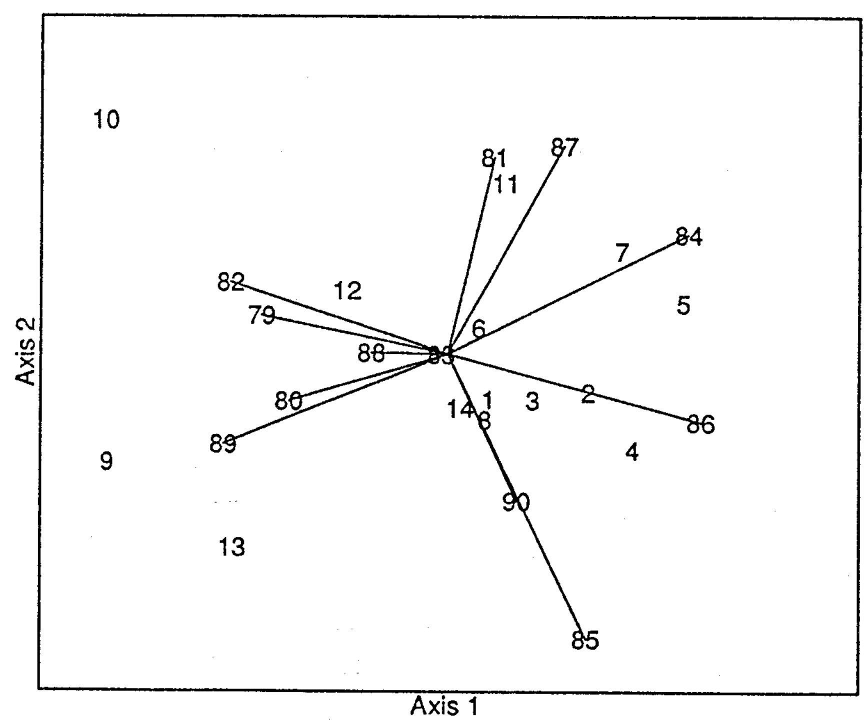

Fig. 2. Biplot for treatment×year interaction effects of unadjusted ear numbers. Points represent treatments and line segments indicate years.

Total Dry Matter

The annual mean total dry matter at maturity varied from 3·65 t/ha in 1982 to 11·41 t/ha in 1983. Rainfall during the April to October period explained 46% of the variation. The addition of sowing date to the regression increased the percentage variance accounted for (PVA) to 54%. This figure was further increased to 66% when only the maximum yielding treatment for the year was considered, thereby avoiding some of the agronomic limitations such as low soil N, diseases, and weeds. The latter relationship was best described by the equation:

$$\mathrm{TDM} = 11\cdot 91 + 0\cdot 028R_{\mathrm{A-O}} - 0\cdot 07\mathrm{SDT}\ (n = 12)\,,$$

where TDM = total dry matter (t/ha) from the maximum yielding treatment in each year, $R_{\mathrm{A-O}}$ = April to October rainfall, and SDT = sowing date (Julian days).

Over all years, direct drilling into burnt stubble in a LW rotation produced highest dry matter at harvest while continuous wheat cropping without N fertilizer produced the lowest (Table 4). The year × treatment variance component accounted for 43% of the variance, after removal of the main effects of treatment and year, indicative of the size of the interaction.

The WW crops not receiving N fertilizer (T10) consistently displayed N deficiency symptoms after 1983, and dry matter production was usually lower than other treatments after that year (Fig. 3). Addition of N fertilizer (T11) removed the symptoms and increased growth; the largest responses occurred from 1984 to 1987. The response to N fertilizer was reduced from 1988, and was associated with the appearance of aluminium toxicity symptoms. Fig. 3 shows the interaction of T10 and T11 with year, T10 in the negative quadrant and T11 in the positive quadrant from 1984 to 87, and the reverse occurring for the remaining years.

Adding lupins to the rotation (T6 *v.* T10) substantially increased TDM and removed N deficiency symptoms after 1983.

Wheat TDM from cultivated mown CW rotations (T14) was similar to or less than from LW with similar cultural management (T3), except in the drought

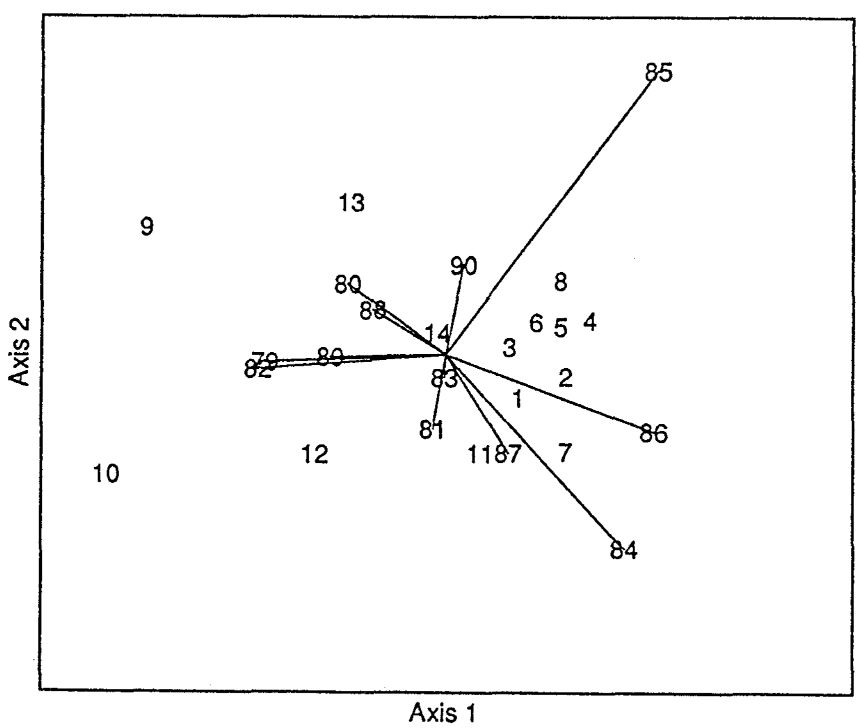

Fig. 3. Biplot for treatment×year interaction effects of unadjusted total dry matter. Points represent treatments and line segments indicate years.

year 1982 when the reverse occurred. Grazed CW (T12) produced more than T14 in most years except in 1985 when herbicide damage reduced growth.

Tillage, where stubble was burnt in WL rotations, had little effect except in 1986 when T4 produced 2 t/ha more than T6. Overall, T1 was lower than T3, though the difference was not significant ($P > 0 \cdot 05$), reflecting the inconsistency in the effect over time. Similarly, within mown CW, direct drilling (T13) usually produced less TDM than cultivation (T14), particularly in 1983, 1984, 1986, 1987 and 1989, but the differences were not large.

Overall stubble retention reduced TDM, the effect being greatest with direct drilling. Effects of stubble treatment varied considerably with time, being most apparent in direct drilled treatments in 1981, 1983, 1985, 1986, 1989 and 1990.

Brome grass incidence slightly reduced TDM in 1985, but had marked effects in 1986 and 1987, while take-all brought about changes in 1984 only. These effects were particularly obvious in treatments which were direct drilled and stubble retained. These management options were shown to have a large influence on the incidence of disease symptoms (Murray *et al.* 1992), and brome grass population (Heenan *et al.* 1990). After adjustment for these covariates, however, there was no change to the overall order of the treatments.

Grain Yield

Mean annual grain yields of wheat varied considerably with season from a maximum of 4·6 t/ha in 1983 to a minimum of 0·88 t/ha in 1982. Mean annual rainfall variation accounted for 35% of the variation in yield and this was increased to 49% when only the April to October falls were considered. The addition of sowing date to the regressions involving either annual or April to October rainfall increased the percentage variance accounted for to 55%. The accountability was further increased by considering only the maximum yielding treatment for the year, thereby avoiding at least some of the agronomic limitations such as low soil N, plant diseases, etc. April to October rainfall then accounted for 62% of the variability and the addition of sowing date increased this to 77%. The latter relationship was described by the equation:

$$Y = 4 \cdot 21 + 0 \cdot 0095 R_{\mathrm{A-O}} - 0 \cdot 028 \mathrm{SDT} \ (n = 12)\,,$$

where Y = grain yield (t/ha), $R_{\mathrm{A-O}}$ = April to October rainfall, and SDT = sowing date (Julian days).

The effect of delaying sowing date was largely influenced by rainfall during the growing season. However, the overall effect of delaying sowing after day 118 (28 April) was 0·19 t/ha for each week's delay. This compares with a reduction of 0·15 t/ha per week after day 114 (24 April) reported by Kohn and Storrier (1970). In terms of yields relative to the maximum yielding treatment obtained from the earliest sown crop, present studies show a reduction of 3·4% for each week's delay after day 118 while Kohn and Storrier found a reduction of 3·7% for each week after day 114. These similar results were obtained despite the use of different varieties and change of varieties in the present experiment.

The ability of the above regression to explain the annual variation in grain yields compares well with the water use efficiency model of Cornish and Murray

(1989). The estimated evapo-transpiration (ET) was based on rainfall, sowing and flowering times, pan evaporation, and estimated soil moisture at sowing and maturity, run off, and drainage beyond the root zone, for a red earth at Wagga Wagga. The ET estimate for post-anthesis explained more of annual variation in maximum treatment yield than ET for the whole growing season (74% cf. 47%). Cornish and Murray (1989) also found that post-anthesis ET was more closely related with grain yield than pre-anthesis ET.

Table 5. Effects of management system on mean grain yield, mean seed weight and mean grain protein

Treatment	Grain yield (t/ha)		1000 grain weight (g)		Grain protein (%)	
	Unadjusted	Adjusted[A]	Unadjusted	Adjusted	Unadjusted	Adjusted
1	3·18	3·28	29·8	29·8	12·0	11·9
2	2·87	3·04	28·8	29·0	12·9	12·8
3	2·95	3·17	28·7	29·0	12·6	12·5
4	3·48	3·49	30·0	30·0	11·9	11·7
5	3·22	3·23	29·5	29·5	12·5	12·5
6	3·34	3·29	29·2	29·2	12·4	12·3
7	2·98	3·03	28·3	28·4	13·2	13·1
8	3·25	3·36	30·3	30·3	11·5	11·4
9	2·40	2·63	31·0	31·1	11·3	11·2
10	2·44	2·50	31·7	31·8	10·8	10·7
11	2·71	2·79	28·1	28·4	13·7	13·4
12	2·92	2·87	28·4	28·2	12·9	12·9
13	2·94	3·09	30·3	30·3	12·2	12·3
14	2·74	2·88	28·5	28·6	12·6	12·5
s.e.d.						
Min.	0·21	0·14	0·74	0·74	0·45	0·45
Max.	0·25	0·17	0·90	0·90	0·56	0·56
Mean	0·23	0·16	0·83	0·83	0·52	0·52

[A] Adjusted for covariates, weed and disease.

The second crop of LWW (T9) and unfertilized continuous wheat (T10) produced lowest mean yields while T4 produced the highest (Table 5). Differences between treatments varied over time, with a large year × treatment variance component. In the first 4 years of WW, the addition of N fertilizer reduced grain yields (Fig. 4*a*, Table 6), obviously reflecting the initial high N fertility status of the soil and interaction with dry springs. From 1983 to 1990, positive yield responses to added N fertilizer were recorded on six occasions. The negative response in 1988 was related to a dry spring which resulted in premature wilting and senescence or 'haying off', and a low grain weight (Fig. 6) in the N fertilized crop. On the other hand, the absence of a response in 1990 was associated with the appearance of aluminium toxicity symptoms in patches throughout the T10 plots during tillering. These discrete patches were also noted in August 1989, and though they tended to recover with time, probably reduced the overall response to added N in that year. An analysis of the soil taken from these patches in August 1989 revealed Al concentrations of 14–18% of the total cation exchange capacity in the top 10 cm. These levels can limit yields of sensitive and tolerant plants (Fenton *et al.* 1993).

The LW rotations (T1–6) showed a strong positive interaction in 1985 and 1986 compared with T11, which was associated with a high incidence of eyespot lodging in the latter treatment. A visual assessment in 1985 recorded 81% lodging in the T11 compared with a mean 12% in LW. Application of the fungicide benomyl to all treatments after 1986 successfully controlled this problem.

Table 6. Grain yields (t/ha) for each treatment from 1979 to 1990

Treatment	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990
1	3·63	3·35	3·09	0·96	4·44	4·36	3·60	2·86	2·21	1·77	3·72	4·16
2	3·33	2·89	2·86	0·61	3·67	4·00	3·41	2·66	1·82	1·76	3·62	3·80
3	3·53	2·88	2·85	0·61	3·47	4·19	3·48	2·88	2·07	1·71	3·99	3·79
4	3·70	3·11	3·22	1·00	5·52	4·43	4·42	3·41	2·58	2·07	4·19	4·16
5	3·40	2·54	2·94	0·61	5·37	4·40	4·05	2·94	2·41	2·07	3·89	4·04
6	3·47	2·87	2·65	0·87	5·36	4·28	4·30	3·01	2·84	1·96	4·22	4·18
7	3·14	2·73	2·69	0·65	5·00	3·82	3·60	3·17	1·82	1·78	3·55	3·82
8	3·72	3·57	3·13	0·94	4·77	4·25	4·01	3·10	1·61	2·13	3·62	4·18
9	3·21	3·03	2·53	0·91	5·03	2·23	2·62	0·89	0·86	1·51	2·72	3·24
10	3·31	2·62	2·88	1·06	4·01	3·26	1·46	1·10	1·67	1·87	2·80	3·20
11	3·12	2·30	2·26	1·04	4·79	4·05	2·96	1·75	2·48	1·60	2·92	3·20
12	3·38	2·90	2·94	1·16	4·92	3·79	2·04	2·91	2·44	1·50	3·91	3·20
13	3·63	3·19	2·98	1·07	4·03	3·34	3·77	2·25	1·87	1·62	3·73	3·77
14	3·13	3·16	2·71	1·01	4·43	2·84	2·94	2·19	1·90	1·50	3·70	3·29
s.e.d.												
Min.	0·16	0·21	0·17	0·09	0·31	0·32	0·31	0·41	0·33	0·11	0·16	0·15
Max.	0·22	0·28	0·24	0·12	0·42	0·44	0·42	0·56	0·44	0·15	0·22	0·21
Mean	0·19	0·25	0·21	0·11	0·37	0·38	0·36	0·48	0·39	0·13	0·19	0·18

Grain yields from T3 LW rotations have been similar to T12 and higher than T14 CW in most years, except for the drought year of 1982 and again in 1983 when the reverse occurred. Similarly, direct drilling into lupins (T4) usually produced higher yields than direct drilling into sub-clover (T13), though differences did not appear until 1983. This interaction is evident in Fig. 4*a* where the relative positions of T13 and T14 are reversed for the years 1979–1982. Low yields from grazed CW rotations (T12) in 1985 were mainly due to herbicide damage. In 1990, and to a lesser extent 1989 and 1988, the lower yields from the CW rotations, particularly T12, were related to severe premature senescence in these treatments as a result of low rainfall periods after flowering. On the other hand, benefits to the soil N supply from the pasture phase before 1986 would have been lessened by low sub-clover levels in the early to mid term of this experiment (Watson *et al.* 1976).

Within CW rotations, there was only a marginal difference in overall mean yields, between grazed (T12) and mown (T14). Estimates of pasture productivity were not consistently taken. However, mean sub-clover content increased with time from 46% in 1979, to 65% in 1983, 80% in 1986 and 92% in 1990. Prominent grass weeds in the early years were barley grass and brome grass. Differences between treatments lessened over the later years but the overall means of sub-clover content are 77% for T12, 72% for T13 and 70% for T14 indicating slightly higher levels and reflecting the slightly higher wheat yields under grazing. Other work has shown that increasing grazing pressure can reduce the proportion of grass to sub-clover under similar conditions (Kohn 1974). The slightly higher yields from grazing (T12 *v.* T14) were also related to a lower incidence of disease and brome grass, as shown in the adjusted data following the covariate analysis. As with total dry matter production, the low yields from T12 in 1985, were mainly due to herbicide damage.

In all years except 1982 and 1983, the second wheat crop direct drilled into stubble (T9) was considerably lower than the first wheat crop (T8). The yield of T9 was extremely low in 1984 and 1986 as indicated by the strong negative projection of T9 onto 1984 and 1986 relative to T8. These differences were probably related to one or more factors including higher incidence of weeds (e.g. brome grass) (Heenan *et al.* 1990), diseases (Murray *et al.* 1991) (except 1983) and lower mineral N supply. It is likely that the low yields of the first crop in

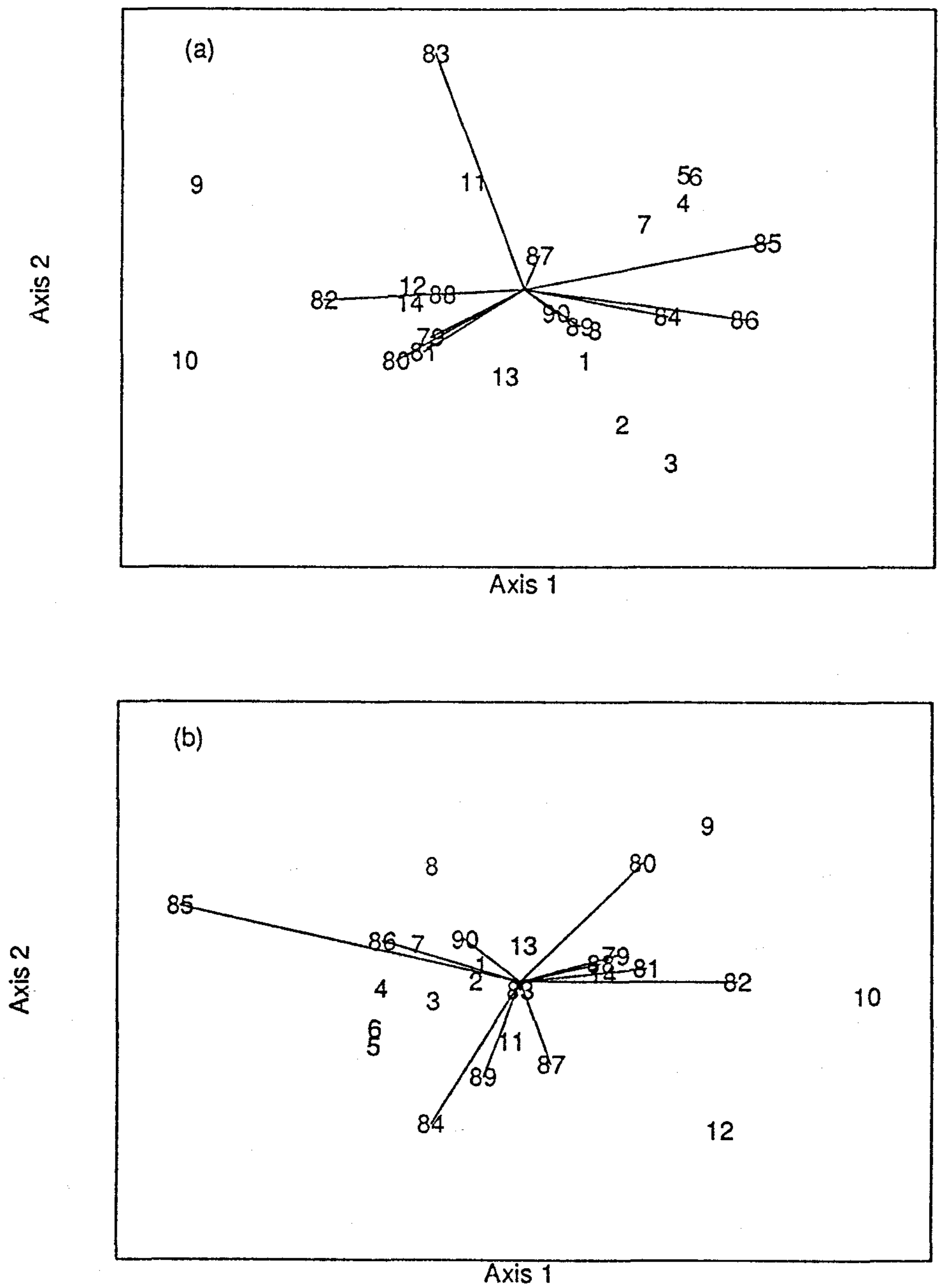

Fig. 4. Biplot for treatment×year interaction effects of (*a*) unadjusted and (*b*) adjusted grain yield. Points represent treatments and line segments indicate years.

1982 allowed for considerable carryover of available soil nitrogen for the second crop in 1983, while the poor lupin growth in 1982 provided little nitrogen for the following wheat. As well, the first wheat phase had a high incidence of take-all and eyespot in 1983. Murray *et al.* (1991) concluded that the diseases survived on wheat stubble through the lupin phase during the 1982 drought to infect wheat in 1983, but not through the lupin phase in the wet season of 1983 to infect wheat in 1984.

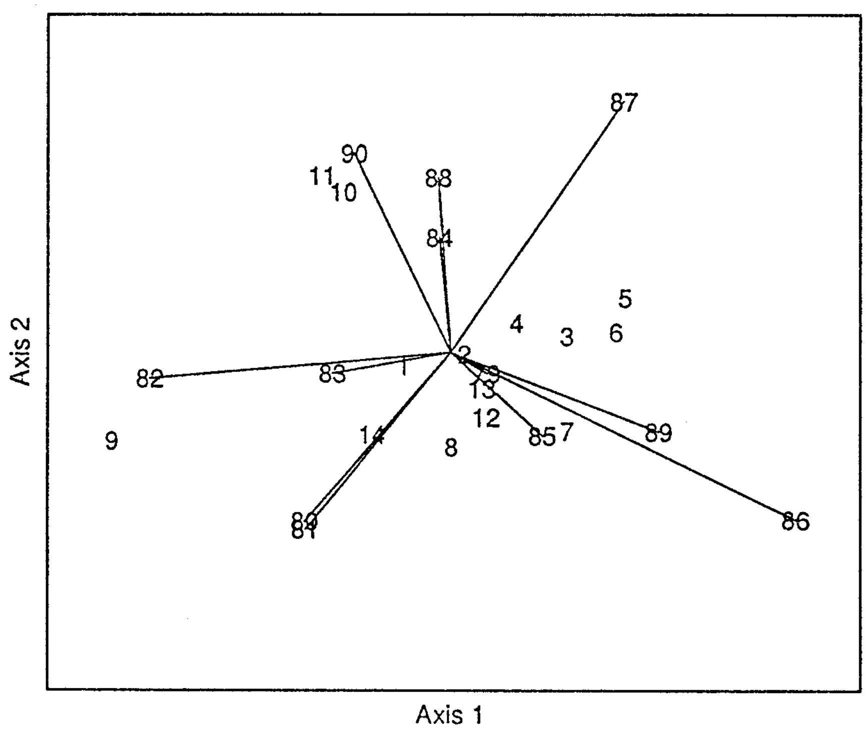

Fig. 5. Biplot for treatment×year interaction effects of unadjusted harvest index. Points represent treatments and lines indicate years.

Since 1982, burning stubble has resulted in slightly higher yields than retaining stubble in all years except 1983, 1985, and 1987, when the advantage to burning was substantial. This is shown in Fig. 4*a* with the burning treatments 4, 5 and 6 in the positive quadrant for the above years, and treatments 1, 2 and 3 in the negative quadrant. Between 1982 to 1986, these differences were associated with the diseases take-all and eyespot lodging which were more obvious where stubble was conserved (Murray *et al.* 1991). However, retention of stubble was also associated with greater incidence of weeds, particularly brome grass (Heenan *et al.* 1990). Fig. 4*b* shows that the interactive effects of the six LW treatments were very similar once the effects of weeds and diseases were removed. The positive interaction of the stubble retention relative to burning in 1979–82 is also indicated. Nevertheless, burning stubble still resulted in slightly higher yields towards the end of the experiment when disease and weeds were negligible. It is possible other phenomena related to stubble retention such as nutrient tie up, release of toxins or biological activity restricting root growth, may be involved. There was no evidence that the early burial of wheat stubble (T7), compared with autumn incorporation (T2), had a positive influence on grain yield.

Where stubble was retained in LW rotations, there was little interaction between the three tillage treatments and year, with direct drilling slightly higher yielding, except in 1983 and 1989. In 1983, take-all and eyespot were more severe on T3 than T1 or T2 while a higher supply of soil nitrogen in T3 than T1 (Heenan and Chan 1992) may have promoted slightly higher yields in 1989. This advantage of direct drilling over one or three cultivations was also evident where stubble was burnt, and there was no interaction between tillage and years. The higher yields from direct drilling were not due to lower weed infestation, as increasing tillage reduced brome grass population (Heenan *et al.* 1990), and higher yields were still achieved for direct drilling following covariate analysis. Reducing the number of tillage operations from three to one did not lessen the detrimental effects of tillage on grain yield.

Within mown CW rotations, higher mean yields were harvested from direct drilling compared with cultivation, despite the larger total dry matter produced from the latter. As with the lupin rotations, the higher yields were associated with higher grain size. The likelihood exists that direct drilling produced more efficient use of soil water by impeding early vegetative growth, resulting in a water saving which allowed for greater grain filling (Cornish and Lymbery 1987). This proposal is supported by the higher grain weights obtained from direct drilling. Over more recent years, a better soil structure developed under direct drilling (Chan *et al.* 1992; Chan and Heenan 1993), and could have improved early growth relative to initial results.

Grain Weight

The annual mean 1000 grain weight varied from 19·3 g in 1988 to 37·5 g in 1989 with rainfall during October–November accounting for 44% of the variation, confirming the importance of rainfall during grain filling to final grain size (Fischer and Kohn 1966). The addition of sowing date did not improve the PVA nor did use of the maximum 1000 grain weight. The resulting linear relationship was:

$$\mathrm{GRWT} = 22\cdot 2 + 0\cdot 08R_{\mathrm{O-N}}\ (n = 12)\,,$$

where GRWT = 1000 grain weight (g), and $R_{\mathrm{O-N}}$ = rainfall for the October and November months.

The treatment mean grain weight varied from 31·7 g for T10 to 28·1 g for T11 (Table 5). The two treatments with the lowest yields (T9 and T10) produced the largest grain weight. Consistent with TDM and grain yields there was a substantial year × treatment interaction.

In all years, the addition of N fertilizer to WW rotations reduced grain size, probably reflecting the higher demands for water and nutrients during vegetative growth and grain filling, under high N supply conditions (Fig. 6). Differences between T10 and T11 were least in 1982 and 1989 as indicated in Fig. 6 with T11 being in the positive quadrant for those years. There were substantial differences in grain weight between treatments in 1990 and 1981 as indicated by the lengths of the axes. These 2 years had rainfall patterns which were conducive to early growth (wet winter) and a dry finish, thus favouring low TDM producing treatments.

Of the rotations, T10 usually had the highest grain weight, followed by the second crop in LWW (T9) (Fig. 6). Both of these treatments by virtue of their relatively low total dry matter and ear numbers, probably resulted in a soil water saving during the growing season, and lower demand for soil water than other treatments during grain filling.

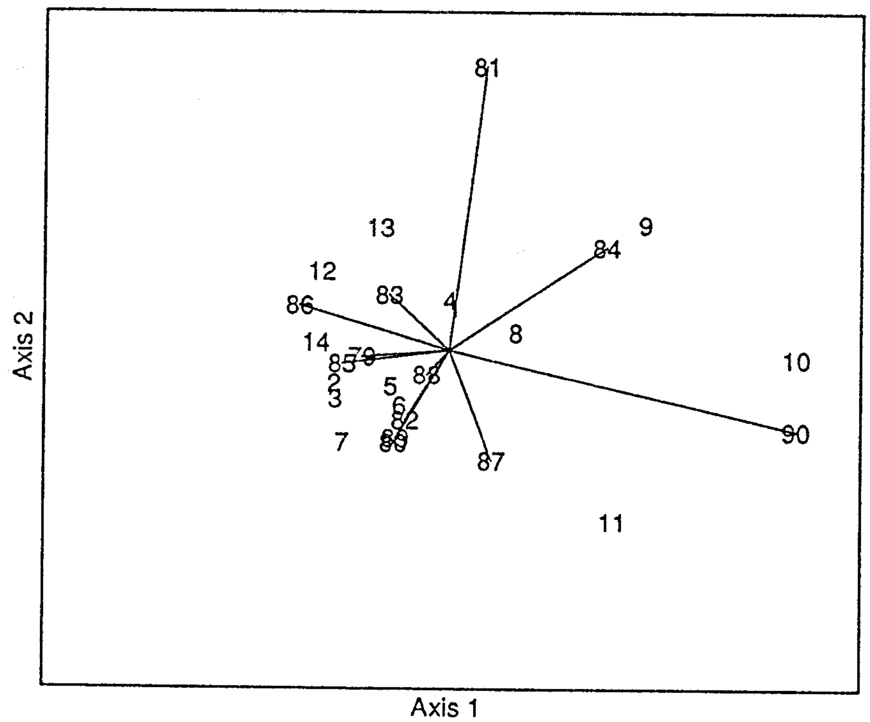

Fig. 6. Biplot for treatment×year interaction effects of unadjusted grain weight. Points represent treatments and lines indicate years.

Increasing tillage in LW rotations decreased grain size in most years, but the reverse was the case in 1986 and to a lesser extent in 1987. Tillage markedly reduced the population of brome grass in these years (Heenan *et al.* 1990), and the covariate analysis showed a significant effect of brome grass on grain size for 1986. As with LW rotations, direct drilling into mown sub-clover produced higher grain weights in 75% of years than cultivation. This was closely associated with lower ear numbers and to a lesser extent with lower total dry matter, from direct drilling.

Grain Protein

Annual mean grain protein varied from a low of 9·35% in 1983 to a maximum of 14·65% in 1982. The October–November rainfall accounted for 56% of the variation, but the April–November total increased this to 72%. The addition of sowing date did not significantly increase the PVA for either rainfall period. The relationship between grain protein and rainfall was:

$$\mathrm{GP} = 17\cdot083 - 0\cdot01138R_{\mathrm{A-N}}\ (n = 12)\,,$$

where GP = grain protein, and $R_{\mathrm{A-N}}$ = rainfall for the April–November period.

This result suggests that rainfall has a much greater influence on grain protein than sowing date, with the correlation between sowing date and GP being $r = 0\cdot56$. Kohn and Storrier (1970) found significant linear increases in grain protein within seasons as sowing was delayed, and Taylor (1965*a*), in a survey of commercial crops in southern N.S.W. in 1961 and 1965, found that GP increased by 0·17% for each week's delay in sowing after 1 April. It would seem that the marked seasonal differences in rainfall masked any effect of sowing date in the present experiment. The relationships between GP, rainfall and sowing date were not improved by considering maximum treatment grain protein levels.

The interaction between treatment and year was not as large as for grain yield or grain weight, but was still substantial, accounting for 31% of the total variance, after adjusting for the main effects of year and treatment.

Overall, incorporation of a legume into the rotation, or the addition of N fertilizer to continuous wheat, significantly increased grain protein (Table 5). The addition of N fertilizer produced a substantial increase, relative to all other treatments, in 1980, 1981 and 1983 (Fig. 7), obviously as a result of the high N levels available for this treatment during these early years. However, T10 quickly depleted soil N as shown by the positive interaction in 1979 only, and a strong negative interaction in 1987.

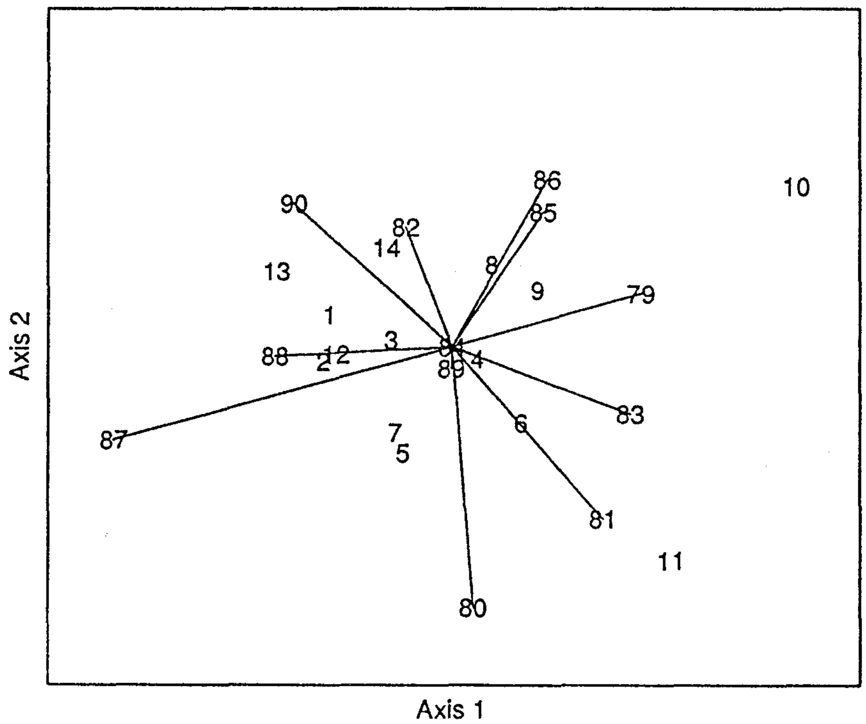

Fig. 7. Biplot for treatment×year interaction effects of unadjusted grain protein. Points represent treatments and lines indicate years.

The LW rotation (T3) was usually similar to ungrazed CW (T14), but both were generally lower than grazed CW (T12). There was a positive interaction for T14 relative to T3 and T12 in 1985 and 1986, and a negative interaction for T14 relative to T3 and T12 in 1980. Within CW rotations, grazing (T12) resulted in higher protein levels than mown sub-clover (T14) in several years. This effect was not due to dilution, but could be related to effects of grazing on sub-clover population as previously mentioned, or more N loss from mown sub-clover.

The second wheat crop (T9) in the LWW rotation typically recorded lower protein than the first crop (T8), though the reverse was the case in 1983. The latter result was probably related to the poor lupin growth in the drought of

1982 resulting in little N fixation and benefit to the soil N supply for the first wheat crop (Evans *et al.* 1987), as well as the low wheat plant uptake of soil N in the drought of 1982, allowing for more than usual carryover for the second crop.

Retention of stubble compared to burning reduced protein levels in 1980 and 1981, but thereafter levels were similar or greater with retention. Generally, there was less effect of stubble management with direct drilling than cultivation. Grain protein is largely influenced by soil N supply as well as other yield determining factors which can produce a dilution effect within the grain (Taylor 1965*a*, 1965*b*; McDonald 1992). Decomposition of wheat stubble has a relatively rapid initial rate, during which time there may be an immobilization of the soil mineral N supply (Strong *et al.* 1987), followed by a slow rate extending over a number of years (Amato *et al.* 1987). In the present experiment, supply of mineral N could have been reduced in the early years of stubble retention, but in later years, plants would have taken up not only N mineralized from the straw of the previous wheat crop, but increasing additional quantities mineralized from older residues. Studies during the wheat season in 1989 and 1990 found higher levels of soil mineral N where stubble was retained (Heenan and Chan 1992). Another consideration is that the higher grain yields produced from stubble burning resulted in dilution of protein, but the difference in grain yields was not consistent with differences in protein. Early incorporation of stubble compared with autumn incorporation (T2) resulted in slightly higher levels in only 3 years and were similar in others.

In LW rotations, cultivation produced similar or higher protein levels than direct drilling. The trend to higher levels following cultivation could be related to lower grain size and grain yield or increased mineralization of soil N following cultivation (Dowdell and Cannel 1975). Cultivation resulted in slightly higher protein levels than direct drilling in several years where the sub-clover was mown, but the trend was not consistent.

Total N Uptake at Maturity

Differences between rotations were recorded in years that estimates of N content of the above-ground dry matter were made (Table 7). Addition of N fertilizer to continuous wheat or incorporation of a legume in the rotation increased N uptake after 1982. Compared with legume rotations, N fertilization of WW resulted in similar or greater uptake, except over later years when it was lower. The latter effect was associated with the appearance of aluminium toxicity symptoms and reduced growth. Within the LWW systems, the second wheat crop invariably contained less N than the first crop.

Tillage and stubble had no consistent effect in a LW rotation. It is possible that the associated incidence of weeds and disease and effects on growth and yield of the previous lupin crop, confounded any long term trends, regardless of any effect of tillage and stubble on soil mineral N (Heenan and Chan 1992).

Grazing of sub-clover resulted in similar or greater uptake than mowing, except in 1986. As noted above, grazing increased the sub-clover component of the pasture which would have increased N benefit to the soil. Where sub-clover was mown, cultivation produced similar or greater uptake in most years except in 1990. Increased N content of wheat following cultivation rather than direct drilling in a sub-clover pasture-wheat rotation, has been noted elsewhere (Reeves and Ellington 1974).

General Discussion

This study clearly shows that farming systems need to be maintained and studied over a long time to assess their ability to sustain production. The time period must be long enough to cover the expected climatic variation, which in the present case is extensive, but also to allow the growing conditions to develop characteristics of that system. These characteristics will be dynamic and will change according to the inputs and outputs of the system. Thus, the grain yield response to added N fertilizer with continuous wheat was initially negative when soil N supply was high, then positive, though limited as diseases developed, and finally further limited with the appearance of aluminium toxicity symptoms.

Table 7. Total nitrogen uptake (kg N/ha) at maturity

Treatment	1982	1983	1986	1987	1988	1989	1990	Mean
1	45	110	125	82	93	85	122	95
2	28	133	125	73	92	96	137	98
3	32	136	118	69	77	101	134	95
4	48	137	128	67	67	100	135	100
5	39	137	92	75	88	97	127	94
6	40	137	92	82	90	108	135	98
7	38	134	129	78	94	87	140	100
8	44	120	117	61	100	83	127	93
9	38	78	26	31	61	65	102	57
10	49	82	40	29	51	60	61	57
11	50	216	114	95	89	89	90	106
12	66	213	99	74	84	120	162	117
13	50	98	76	61	79	96	149	87
14	49	105	132	82	94	93	128	98
s.e.d.								
Min.	1·3	12·3	5·7	2·9	3·5	2·1	3·6	
Max.	5·0	33·8	21·4	11·0	13·1	7·7	13·3	
Mean	3·7	23·6	15·7	8·1	9·6	5·6	9·8	

The effects of rotation, tillage and stubble management on wheat growth, grain yields and grain protein also interacted with time and seasonal conditions. Prior to 1983, the absence of any positive effect of a legume rotation was most likely related to the initial high soil N supply level and low disease incidence following a long period of sub-clover/grass pasture. Increased soil mineral nitrogen and the provision of a disease and weed break are the major benefits reported for growing lupins in rotation with wheat (Reeves *et al.* 1984; Rowland *et al.* 1988; Evans *et al.* 1989). Use of N fertilizer or a legume in rotation increased total N uptake and grain yields from 1983, suggesting N benefits from the legumes. The use of 100 kg N/ha fertilizer alone, however, was not a complete substitute for a legume rotation, initially reducing yield when soil N supply was high, incurring heavy eyespot lodging in 1985 and 1986, and inducing aluminium toxicity symptoms in 1989. Burning of stubble and cultivation in the continuous wheat cropping would have reduced disease and weed incidence, though take-all infection was not observed after 1985, when the soil pH was less than 4·8 (Murray *et al.* 1991).

Lupins were more effective as a disease break crop than sub-clover, at least until 1986, mainly due to the associated grass component of the pasture (Murray *et al.* 1991) and the availability of grass weed herbicides for lupins. In 1989 and 1990, when grass and weed control were excellent, grazed sub-clover produced highest total N uptake and grain protein, but low spring rainfall restricted grain filling and final grain yield. Wheat after lupins, therefore, produced a higher overall mean yield though lower grain protein than sub-clover-wheat. Nevertheless, it would seem that a sub-clover dominant pasture can produce higher levels of plant available N for a following wheat crop than lupins (Heenan and Chan 1992; Table 7). A major reason for this is probably the removal of the large proportion of the fixed N in the lupin grain (Evans *et al.* 1989).

The second wheat crop direct drilled into wheat stubble took up less N and produced relatively low yields and grain protein compared with the first crop. While it is possible that burning of stubble could have reduced disease and weed problems for the second crop, these results suggest that there is little carryover of benefits from a lupin break crop to the second wheat crop.

The lack of a positive effect of stubble retention in the LW rotations, on growth and yields, appears to conflict with the reported benefits of stubble on soil physical and chemical properties (Hamblin 1987; Dalal 1989; Rasmussen and Collins 1991). Work on this experiment in 1989 by Chan *et al.* (1992) found that burning stubble resulted in a greater decline in total organic carbon than where stubble was retained, but levels were apparently not low enough to have any adverse effect on wheat yields. Other work showed that higher levels of soil N were mineralized where stubble was retained in 1989 and 1990 (Heenan and Chan 1992). While the above effects may not have been present in the early years of the experiment, it is likely that the lower grain yields were mainly related to increased incidence of weeds and disease (Heenan *et al.* 1990; Murray *et al.* 1991). It was interesting to note that the level of disease and brome grass was usually higher where stubble was retained and direct drilled than in WW where stubble was burnt and soil cultivated, except in 1986 when eyespot lodging was more severe in WW than any LW rotations. As well, wheat varieties are selected for their ability to yield well over a range of soil conditions including on farm sites and so should be reasonably tolerant of different soil structural conditions. The potential benefits from stubble conservation therefore may not be easy to demonstrate and may well depend on removal of yield determining constraints as well as soil type.

There was no evidence in this experiment that early incorporation of the stubble was of any benefit to grain yields. Marginally higher grain protein (cf. T2) in 1981, 1983 and 1988 was associated with lower grain weights, suggesting limiting water supply during grain filling. This lack of any definite advantage of early incorporation of stubble confirms the practice of maintaining standing stubble over summer and early autumn. Besides providing some feed for stock, the stubble should also provide protection against wind erosion and water erosion from summer storms.

Similarly, advantages in soil structural maintenance have been widely reported with direct drilling (Hamblin 1987; Rasmussen and Collins 1991; Chan *et al.* 1992), but in the present experiment it has also been associated with a higher incidence of brome grass (Heenan *et al.* 1990). Nevertheless, direct drilling following lupins or sub-clover, increased grain yields in a number of years, or was similar to cultivated treatments in other years. The grain yield advantage of direct drilling was related to a lower number of ears, higher harvest index and grain size, suggesting more efficient use of rainfall.

The finding that grazing of the sub-clover pasture marginally increased mean total dry matter production, unadjusted grain yield and total N uptake, differs slightly from the conclusions of Watson and Lapins (1964). They found no significant difference between grazing and mowing of clover dominant pastures in grain yield and nitrogen uptake over four successive cereal crops following 3 pasture years. The slight difference in conclusions could be related to the different systems used and/or the higher clover levels produced under grazing in our experiment.

The successful adoption and entrenchment of the sheep pasture-wheat system, ensures its future role on most farms in the wheat belt of southern Australia. In times of economic returns favouring cropping, our results show that crop productivity can be maintained over extended periods, though grain protein may be slightly reduced, by alternating wheat with lupins. However, the major build-up of giant brome grass and diseases casts considerable doubt on the long term sustainability of the short term rotations used in this experiment, particularly where stubble was retained. In practice, therefore, farmers may need to change rotations to different crops and/or adopt rotations which include both legume pastures and grain legumes to help combat the spread of disease and troublesome weeds. Such crop and pasture rotations will be included for further studies in this experiment.

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