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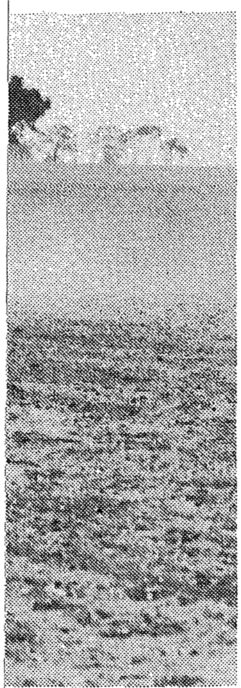


Abstract

In 1977, a ten year series of continuous cropping trials was commenced to compare the effect of four farm tillage systems.

This bulletin reports the grain yield results for the first six years of these trials.

Three of the tillage systems involved direct-drilling, with an initial weed control by the bipyridyl herbicide, Spray. Seed®
followed by:

- seeding with a triple-disc drill; or
- seeding with a combine-drill with scarifying points; or
- one shallow cultivation with a scarifier followed by seeding with a triple-disc drill;

The fourth tillage system was:

- the conventional district practice current at the inception of the trials. This was normally a scarifying (or disc-ploughing), followed by one working with a scarifier and seeding with a combine drill.

The results for the first six years are presented at this stage as the area under direct drilling has increased since 1977 from 25 000 ha to over 1 000 000 ha in Western Australia in 1983.

No one tillage method gave consistently higher yields at all sites. As the sites ranged from 31° to 34°S latitude and from 290 to 650 mm average annual rainfall, different conditions had significant interactions with tillage systems. At the more northerly sites, where water stress dominates the latter part of the growing season, the temporal pattern of water use varies with tillage. On the sandy soils this is related

to slower growth of direct-drilled crops and less water use up to anthesis. Post-anthesis water use can be more for the slower maturing crops, but frequently the potential for yield in the form of kernel numbers per unit area is less and grain yields are lower. On finer textured soils, structural decline was observed after three years continuous cropping. Before that, yields from conventional cultivation were as good or better than direct drilling. However, in succeeding years yields were successively lower, especially in drier seasons, when less water infiltrated the cultivated soil, more being lost through surface evaporation and run-off. Direct-drilling is possibly the only safe tillage method for continuous cropping in these circumstances. At the wetter, more southerly sites, average yields were most influenced by diseases and weeds. The main disease affecting the trial sites at Esperance and Mt Barker was take-all (*Gaeumannomyces graminis* var. *tritici*). The interaction of disease with tillage was significant in some seasons when the triple-disc drilled treatment was less severely affected. However, *Rhizoctonia* root rot was greater at Esperance in direct-drilled treatments.

At the wetter sites, adequate weed control was not achieved solely with the pre-sowing contact herbicide despite increasing the herbicide rate at Mt Barker to 3 L/ha including 500 mL/ha Dicamba ® in the mix. Post-emergent herbicides were used at every site each year; Hoegrass ® for control of grasses, especially ryegrass (*Lolium rigidum*), and Brominil M ® for broad-leaved weeds. Nevertheless, there was an interaction of weeds with tillage at the southern sites, where lower grass-weed numbers occurred in the undisturbed, triple-disc drilled treatment. This may explain the relatively lower incidence and severity of take-all in this treatment. At Mt Barker, where take-all infestation affected 99% of all wheat plants by the fourth year, a lupin-wheat rotation was introduced on half the plot area to be compared with the continuous wheat sequence in which two different sources of nitrogenous fertilizer were tested. Reduction in take-all incidence was dramatic after one year of lupins. Only 20% of plants were infected as compared with 86% in the acidifying fertilizer $[(NH_4)_2SO_4]$ treatment and 95% in the control plots. Triple-disc drilled lupins yielded less than in the other three treatments where there was some ground disturbance.

Four nitrogen levels were superimposed as subplots across each tillage treatment on every trial each year. Nitrogen responses increased with number of years of cropping except at the driest and most clayey site, which is not normally nitrogen responsive. The nitrogen levels initially applied were computed as zero, half, standard and twice standard Departmental recommended rates for each location, but the actual amounts applied were varied to take residual effects and increasing responsiveness into consideration. Nitrogen response interacted with tillage on the sandier soils and in wetter seasons at most sites. Conventionally cultivated treatments have yielded better than direct-drilled and particularly zero tilled treatments at zero applied nitrogen. At the twice standard rate however, the reverse frequently occurs. Thus, the nitrogen response curves are steeper for triple-disc drilled, and direct drilling with a combine seeder than for the conventionally cultivated treatments. The frequently observed slower early growth of cereals with direct-drilled crops, as reported in other parts of Australia, (Cornish and McNeill, 1982), may partially be due to the slower release of mineralized soil nitrogen in non-tilled or minimally disturbed soils. At low levels of applied nitrogen this has a pronounced effect in soils of relatively high levels of readily mineralized organic matter content.

Yields from direct drilling can equal or exceed the grain yields achieved with conventional cultivation. This is provided good weed control is achieved with both contact and post-emergent herbicides, and relatively high rates of nitrogen are supplied. It is probably the only safe tillage system available for continuous cropping of structually unstable or easily-eroded soils.

However, comparative yield reductions persist on some sandy soils which develop high mechanical strength unless periodically loosened.

Recommendations.

- Cultivations should be reduced on fine textured soils to avoid further degradation of soil structure. Direct drilling will result in better grain yield in the long term provided weeds can be controlled with available herbicides.

- Direct drilling is desirable on coarse sandy soils to reduce the risk of wind erosion. However, yields are lower from direct drilling with currently available (1984) machinery. Seeding machines which cultivate deeper than the seed placement are required to maximise grain yield. On sands with acid subsoils, tillage method has little effect because of the severe root growth limitation imposed by acidity.

- Well structured soils can be maintained under a direct drilling system. Lack of cultivation of these soils does not reduce yield, and reduces the risk of erosion from wind and water.

- Most direct drilling in Western Australia is carried out with combines or cultivator bars connected to air seeders. With this degree of ground disturbance seed and fertilizer rates need not be increased above those recommended when normal cultivation is used.

Introduction

Minimum tillage; conservation tillage; reduced cultivation and direct drilling are frequently used terms to describe the trend towards fewer cultivations for crop establishment, with the replacement of mechanical weed control by chemicals. (Johnston, D.A. ed. 1983). The first trials using this technique in Western Australia were initiated by G. A. Pearce in 1964 under the name of chemical ploughing.

However, earlier work by H. Fisher in 1958 was aimed at proving the effect of weed competition on yield (Fisher, 1962). In these trials, Shell Weedkiller Q (pentachlorophenol) and dieselene was used to kill weeds before seeding. With a direct drilling system a five fold yield response was obtained when weedicides were used, although this was still less than yields obtained from various pre-seeding cultivation methods.

In 1970, a minimum tillage system was introduced to Western Australia by Imperial Chemical Industries (ICI Australia Operations Pty Ltd) who marketed the bipyridyl herbicides as a mixture called Spray.Seed® (paraquat 125 g/L, diquat 75 g/L, surfactant 98 g/L), in a combined 'one-pass' system of contact herbicide application followed by seeding. Western Australian climatic conditions and rotational practices were considered particularly suited to this system, as the marked winter-season rainfall and coarse-textured soils made complexities such as fallowing, long rotations and heavy weed burdens uncommon. The direct-drilled area remained small until the late 1970s (<100 000 ha/a), because of difficulties in achieving effective in-crop grass weed control, and unfamiliarity with spray technology as an alternative to cultivation.

Many short term—one year—experiments were conducted on direct drilling by the Western Australian Department of Agriculture to test the efficiency of this system (G. A. Pearce, M. G. Mason, M. L. Poole, unpublished data, 1970 - 1980). These indicated that wheat yields from direct drilled crops, following Spray.Seed® application to kill weeds, could equal those obtained from crops sown after cultivation, once operators were familiar with

the technique (G. A. Pearce, personal communication). However, minimum tillage failed to produce yields equal to those obtained following cultivation in situations of low available nitrogen, on some soil types and where grass weeds in the crop could not be controlled by herbicides.

Nevertheless, direct drilling was shown to be an extremely effective measure in controlling wind erosion on sandy soils (Marsh, 1981). Many innovative farmers claimed improvements in soil structure, in the long term, by reducing soil-damaging cultivation. The introduction of Hoegrass® (diclofop-methyl 375 g/L) in 1978 for the in-crop control of annual ryegrass (*Lolium rigidum*), one of the main problem weeds in direct drilled crops, greatly improved the prospect of successfully reducing cultivation.

In 1977, G. A. Pearce and D. Tennant began trials to compare long-term yield trends with alternative tillage systems on a range of soil types (Tennant, 1977). The nitrogen status of these soils varied due to soil type and the amount of applied nitrogen. At the same time, the area sown with reduced tillage methods began to increase and there was more public debate on soil structural deterioration. The trend to ever-shorter rotations and continuous cropping focused much farmer interest on direct-drilling and of 5.5 million hectares sown to crops in the South-West Province of Western Australia in 1983 an estimated 1.4 million hectares were sown in a one-pass system.

The aim of our trial programme is to compare the effect of four different tillage systems with four rates of applied nitrogen, over time on:

- The establishment, growth, total vegatative production and grain yield of cereals.
- Weed population dynamics.
- Interaction with disease.
- Changes in the soil chemical and physical properties.

The long term tillage trials are to continue for ten years. It is because of the substantial adoption by farmers of minimum tillage, the needs of the cereal industry and a growing interest by researchers, that the crop and soil responses for the first six years of these trials are reported in this bulletin. The data on soil chemical and physical properties are not included.

In 1980, the authors assumed responsiblity for the research begun by Pearce and Tennant after several years of involvement in the programme. The scope of the research has been modified, particularly in response to the effect of disease.

Materials and methods

Site selection

Sites were selected to cover the main climate and soil types within the central and southern cereal growing areas of Western Australia. Trials were located on Department of Agriculture research stations at Avondale, Esperance Downs, Merredin, Mt Barker and Wongan Hills (figure 1). Two trials were located at each site, one to compare systems in a continuous cropping programme, the other to compare the same systems in a crop/pasture rotation. The latter trials will not be discussed in this publication. Some climatic details at each site are summarised in table 1.

While the two southernmost sites at Esperance and Mt Barker had growing season rainfalls near the long-term average, the three more northerly sites, which more closely typify the 'wheatbelt' had drier than average seasons during the period of the trials.

The soils represented in the trial sites are vertically heterogeneous with finer textured subsoils than topsoils (table 2). The yellow earth at Wongan Hills is representative of large tracts of sandplain soils in the north and eastern wheatbelt, but many of these sandplains are more acid at depth than at Wongan Hills (Bettenay and Hingston 1961). An additional long-term tillage trial was therefore established at Merredin Research Station in 1978 on one such acid yellow earth locally known as 'wodgil' from a vegetation association complex dominated by *Acacia signata* and *A. beauverdiana*. This trial has had very low yields because of severe nutritional problems, which has necessitated additional fertilizer. These additional treatments did not make any substantial improvement in yield and, as a separate acid-soils programme is now being undertaken at Merredin, this paper contains only an abbreviated account of this trial.

All sites had been cleared for cultivation for at least 20 years and at Avondale and Merredin for over 50 years. The paddocks previously had a subterranean clover (*Trifolium subterraneum*) based ley-rotation with cereal cropping and adequate superphosphate histories.

Trial design and operation

Trials were laid out to a common design with four main tillage treatments replicated six times in randomised blocks except at Avondale and Mt Barker where space limitation reduced the trials to five replications. At the Avondale and Wongan Hills Research Stations two direct drilling treatments were added, but at a different time of planting. These two

Table 1. May to October (growing season) mean values of climate at the trial sites.

Site	Latitude S	Average annual rainfall mm		Average rainfall May - Oct. mm		Average daily min. temp. °C	Average daily max. temp. °C	Average daily solar radiation MJ/M^2
		A	B	A	B			
Merredin	31°29′	289	275	196	173	6.3	19.0	14.1
Wongan Hills	31°50′	345	302	262	222	7.6	19.6	14.0
Avondale	32°06′	389	327	295	273	6.2	18.8	13.1
Esperance	33°36′	494	478	336	344	7.4	18.1	13.4
Mt Barker	34°38′	645	677	482	484	7.3	16.5	12.1

A-long term average for Research Stations   B-1977 - 1982 season average

Table 2. Soil characteristics of the trial sites

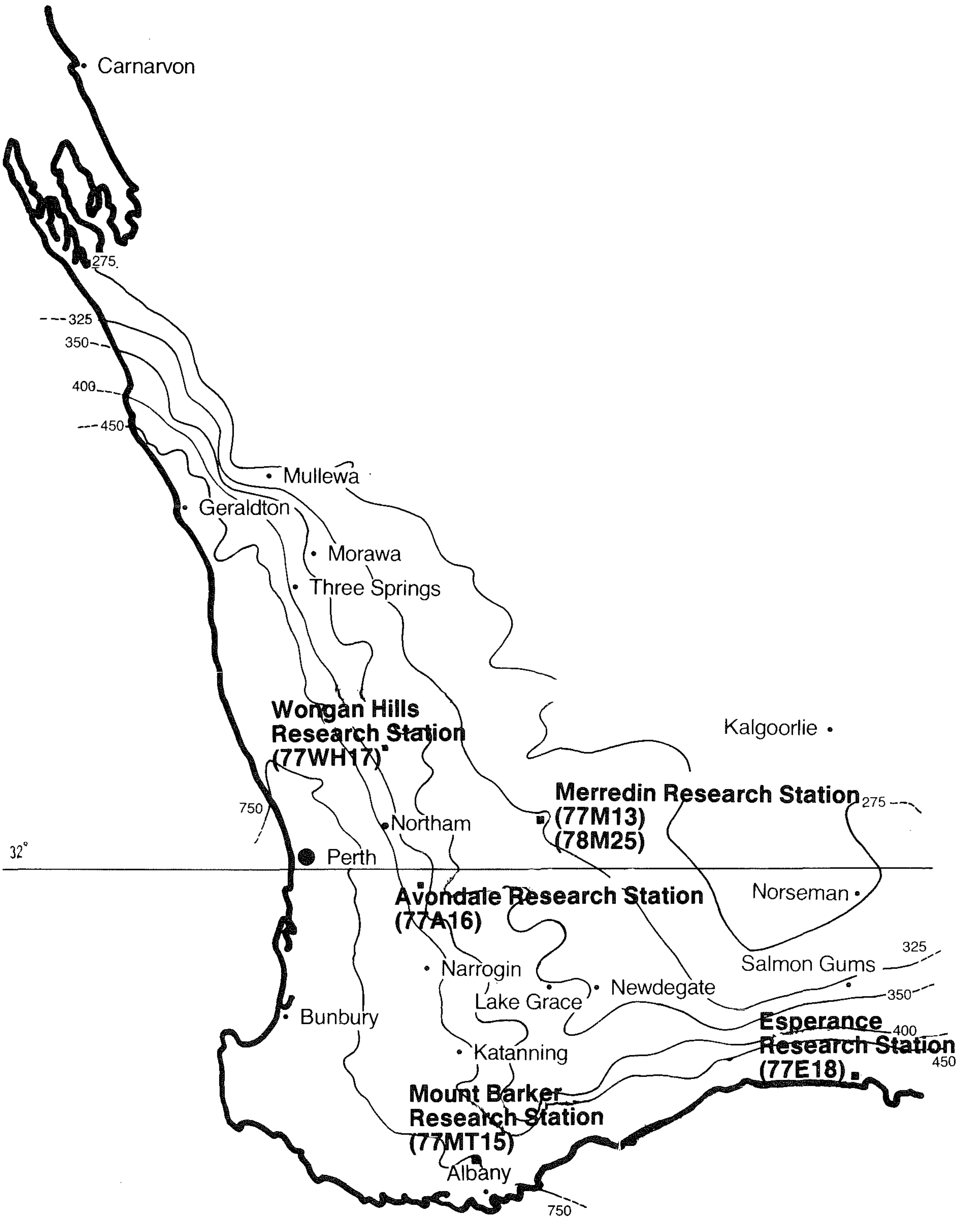
Site	Slope	Soil group*	Northcote** classification	Texture (a) 0 -10 cm (b) subsoil	pH (1:5 water) (a) 0 -10 cm (b) subsoil	Organic Carbon 1977 0 -10 cm %	Clay (< 2 μm) 0 -10 cm %	Clay (< 2 μm) at 40 cm %
Mt Barker	5°	Brown podzolic	Dy 3.61	(a) SY-G (b) CY-G	(a) 5.5 (b) 6.0	3.0	5.5	23.0
Esperance	1°	Duplex yellow podzolic	Dy 5.81	(a) S (b) SYCG	(a) 5.8 (b) 6.0	1.05	2.5	30.0
Avondale	7- 12°	Non calcic brown earth	Dr 2.12	(a) SYL (b) CL	(a) 5.7 (b) 6.1	1.73	16.0	33.0
Wongan Hills	3 - 4°	Yellow earthy sand	Uc 5.22	(a) LYS (b) SYL	(a) 5.6 (b) 6.0	0.78	10.0	19.0
Merredin (i)	1°	Calcic red brown earth	Dr 3.23	(a) SYCL (b) CL	(a) 6.5 (b) 9.0	1.03	20.0	45.0
Merredin (ii)	3 - 4°	Acid yellow earth	Gn 2.21	(a) LYS (b) SY-G	(a) 5.1 (b) 4.3	0.78	15.0	23.0

* Stace *et al*, 1968, A Handbook of Australian Soils.

** Northcote 1974, A factual key for the recognition of Australian Soils.

SY=sandy; CY=clayey; L=loam; G=gravel.

Figure 1.
The South-West Province of Western Australia. Area of predominately winter rainfall above 275 mm per year showing selected rainfall isohyets. Map shows Research Stations where research located.



treatments at Wongan Hills were later modified by subsoiling (or deep ripping) the subplots within each treatment. Most of the sites were known to be nitrogen responsive (Mason 1975) and tillage by nitrogen interactions had been reported in other nitrogen-responsive environments (Pollard 1974, Dowdell and Cannell 1975). Because of this, four nitrogen subtreatments were applied to each cultivation treatment. Nitrogen was applied as 0, 0.5, 1 and 2 times the 'standard' nitrogen fertilizer rate recommended for the district (Mason 1975).

Main treatments were 60 m x 4 drill widths, the drill widths being 2.1 m for the 12 run combine-seeder, and 2.5 m for the 15 run triple-disc seeder. Nitrogen subtreatments were applied to each drill width, and randomised within main plots. The tillage treatments were:

1. Direct drill with a triple-disc drill (TDD)

One spray of a paraquat-diquat mixture (Spray.Seed®) at 2 L/ha at one or two leaf weed stage, then sown with a triple disc drill [Bettinson 15-row seeder, (18 cm between rows) at all sites except at Merredin and Esperance where a Walker 12-row seeder (18 cm between rows) was used]. The ground was disturbed from 2 to 4 cm depth only in the rows. Where larger weeds were present (mainly at the higher rainfall sites) a higher rate of Spray.Seed® applied as a split application was necessary in some seasons.

2. Cultivated, sown with triple-disc drill (C/TDD)

One cultivation with a scarifier at the break of the season, followed by one spray of Spray.Seed® and then seeded with the triple-disc drill. The ground was disturbed to 5 cm depth, and the seedbed left rough. This treatment was developed as a means of controlling grass weeds by an initial cultivation to encourage weed seed germination, so that the following Spray.Seed® treatment would be more effective. The subsequent introduction of selective in-crop herbicides such as Hoegrasss® has made this treatment somewhat obsolete.

3. Direct drill with combine seeder (DDC)

One spray of Spray.Seed® at 2 L/ha as in (1) followed by seeding with an unmodified 12-row combine seeder, with 5 cm scarifying points, disturbing the ground to an average depth of 4 cm.

4. District practice (DP)

'District practice' was taken as the most common conventional practice for each area. When the trials started this was commonly based on disc ploughing. Disc ploughs are now, in 1984, less frequently used by farmers, and scarifiers with 12 cm points have replaced ploughs on most medium and coarse textured soils. Plots were cultivated either with a disc plough or scarifier, worked back with a scarifier one or more times to control weeds and seeded with the standard 12-row (18 cm spacing) combine seeder. The ground was disturbed to between 8 and 10 cm depth.

Spring wheat (*Triticum aestivum*) cvv. Gamenya, Miling, Halberd and Egret have been grown on all the trials, except at Mt Barker where barley (*Hordeum vulgare*) cv. Clipper was grown in 1977, oats (*Avena sativa*) cv. West in 1978 and since 1980, wheat and lupins (*Lupinus angustifolius*) cv. Yandee have both been grown. At Esperance, Clipper barley was grown in 1978. Sowing rates were 50 kg/ha for cereals and 118 kg/ha for lupins. Initially, trials were sown according to the optimum time for each system. However, under these conditions simultaneous growth comparisons between treatments were not valid and from and including 1979 treatments at a site have been sown on the same day. For details of varieties sown see appendix A, table A-1.

In-crop weeds were controlled on all treatments by cross spraying the trial area. Brominil M® (bromoxynil 200 g/L MCPA 200 g/L) at 1.0-1.4 L/ha has been used throughout for broad-leaved weeds. Hoegrass® at 1.0-1.5 L/ha has been used to control annual ryegrass (*Lolium rigidum*), and wild oats (*Avena barbata*). Banex® (dicamba 200 g/L) at 0.5-1.0 L/ha was used in the first two years to control clover (*Trifolium subterraneum*) and broad-leaved weeds. Simazine (500 g/L) at 1.5 L/ha has been used after seeding the lupins.

Occasional infestations of red legged earth-mite (*Halotydeus destructor*) and webworm (*Hednota* spp.), present in early years, were controlled by spraying 1 L/ha DDT when Spray.Seed® was applied.

Nitrogen was applied as ammonium nitrate, topdressed by hand, one to four weeks after seeding. Nitrogen rates have not been changed substantially except in 1978 when one-third the normal rates were applied to all trials. All trials receive annual dressings of single

superphosphate at seeding (drilled with the seed) at 60 kg/ha at Merredin (red brown earth), 70 kg/ha at Avondale, 85 kg/ha at Wongan Hills, 120 kg/ha at Merredin (acid yellow earth) and Esperance, and 150 kg/ha at Mt Barker. In addition, the Merredin acid yellow earth received potassium chloride at 100 kg/ha, and Mo, Cu, Zn trace elements in 1979. Full details are in table A-2, appendix A.

Harvesting was carried out with 10-row (1.8 m) commercial headers over the full length of plots and adjusted for quadrat cuts as required. Stubbles were grazed in most instances and burnt where necessary for trash clearance.

During the course of the trials' histories, responses have occurred which necessitated changes in individual site management. Thus, the barley and oat crops were sown at the southern sites in an attempt to control the development of the root rot, take-all (*Gaeumannomyces graminis* var. *tritici*). At Mt Barker the take-all incidence became so high by 1979 (99% of all plants of all treatments affected) that a major change in crop rotation was necessary.

Field measurements

The number of wheat and weed plants were counted by rows and quadrats at about the two leaf growth stage of the wheat. Other measurements varied from site to site. At Wongan Hills, Merredin and Avondale, leaf and root diseases assessed in 1977 and 1978 were of very low incidence with no significant differences between treatments (G. C. MacNish, personal communication). Disease monitoring was therefore concentrated at the two southern sites, Mt Barker and Esperance. The three more northerly sites showed differences in dry matter production and grain yield which were related to soil physical conditions and patterns of water uptake. These sites were monitored for various aspects of crop water balance.

Statistical procedures

Analyses of variance, with linear and quadratic regressions were performed on the grain yields at each site.

A combined analysis was carried out in which relative treatment grain yields (absolute treatment mean yield as a percentage of the maximum treatment mean yield) for each year were fitted as a function of year, N, N^2, tillage, N x tillage and N^2 x tillage. Terms were added to the model in the above order and the significance of each term tested. A model was then fitted which included only those terms which were statistically significant ($P < 0.05$).

A 'normalising' procedure on the combined analysis was used to remove between year effects of seasonality. Data for the combined analysis was 'normalised' within years for each site by using maximum treatment mean yield as the 100% yield for that site and season with other treatment yields being expressed as a comparative percentage (appendix B). This gives each year's yield an equal weighting, whereas averaging has the effect of giving a greater weighting to the years of better yield.

Response curves for each tillage system adjusted for years (normalising the years effects) were plotted for the full model and for the reduced model which included only significant effects. The analysis was repeated excluding the 1978 results when nitrogen applications were only one-third of the normal. Nitrogen levels have been designated 0, 0.5, 1 and 2 (not actual nitrogen rates) on the assumption that our management tried to achieve the same labile nitrogen pool each year.

Table 3(a). Merredin — red brown earth: wheat grain yields (kg/ha) for four nitrogen levels (1977-1982).

Year	Amount of N applied at "standard" recommended rate kg/ha	Nitrogen level**				LSD (P < 0.05)
		0	0.5	1	2	
1977	25	265	260	263	270	N.S.
1978	8	1775	1742	1785	1837	63
1979	25	1665	1644	1709	1644	N.S.
1980	17	No yield because of severe drought				
1981	17	1085	971	925	949	86
1982	15*	850	856	837	926	31
Average	18	922	922	931	938	

*In 1982 only the 1 N level of nitrogen plots received nitrogen fertilizer, thus yield differences result from residual N, in other subtreatments.

**Nitrogen level as a proportion of the "standard" rate.

Table 3(b). Merredin — red brown earth: wheat grain yields (kg/ha) with tillage as the main effect.

Year	Tillage method				LSD (P <0.05)
	TDD *	C/TDD **	DDC ***	DP ****	
1977	296	257	306	199	53
1978	1049	2300	1691	2100	247
1979	1555	1703	1777	1647	N.S.
1980	No yield because of severe drought				
1981	977	1195	1190	568	334
1982	1026	858	1002	582	136
Average	817	1052	994	849	

N.S. Not significant

* Direct drill with triple disc drill

** Cultivated, sown with triple disc drill

*** Direct drill with combine seeder

**** District practice

Results and discussion

Results are presented for each site from the driest to wettest as in table 1. The main treatment effects are examined first for nitrogen levels, and then for tillage intensities. Soil structural aspects relating to water use are discussed as main effects produced by tillage. Weeds and diseases are discussed separately for each site. Nitrogen responses have varied between sites principally because of differences in climate and soil type. Responses to cultivation treatments have also varied because of soil type differences.

1. MERREDIN—Calcic red brown earth (77M13)*

Main effects

This site has the lowest and most variable rainfall. In 1980, the drought was so severe that no grain was harvested. Mean grain yields for each year by nitrogen level and cultivation treatment are shown in table 3. In 1978, the DP treatment was sown three weeks later than the other treatments to ensure adequate weed control. Stubble remaining from the 1978, 1981 and 1982 crops was burnt in the following autumn.

The soil at this site is structurally weak with low hydraulic conductivity (Hamblin 1982). In the first three years of the trial, tillage operations which broke up the hard, summer-set surface improved infiltration and reduced soil strength so that the two cultivated treatments yielded better than the other treatments even when the DP treatment was planted later in 1978. The growing season is shorter in this eastern, drier area of the wheatbelt than in western areas and any delay in seeding after mid May reduces yield by about 9 - 12 kg/ha.d (Smith and Perry 1980), so that the three week delay in seeding would otherwise have reduced the yield of DP relative to the other treatments.

*Trial site index number of the Western Australian Department of Agriculture.

However, by the fifth and sixth years of the trial, repeated cultivation of the DP soil led to a marked decline in aggregate stability and hydraulic conductivity. Both plant establishment and crop-water relations were adversely affected and yields of the DP crops were reduced to half that of the direct drilled treatments.

The nitrogen response was generally not significant until the fifth season when there was a strong negative response through 'haying off' ($P < 0.001$). No nitrogen was therefore applied in 1982 except to the 1N level subplots which had been more frequently sampled. The nitrogen response in 1982, which was significant at $P < 0.001$, was associated solely with a residual effect from the 2N level plots, while the fertilized 1N level plots showed a small yield depression.

Table 4 shows the soil properties for 1981, the first year in which they showed a marked decline with cultivation.

Table 4. Soil and crop responses after five years continuous wheat: Merredin, red-brown earth, 1981.

Tillage method	Grain yield kg/ha N kg/ha 0	8.5	17	34	Soil properties MOR* (Aug.)	W.S.A** (Aug.)	Ko† (Aug.)	Wheat dry matter kg/ha (Oct.)
TDD,	1165	1035	883	825	220 c	8.19 a	1.27 c	5296 a
C/TDD	1258	1173	1215	1133	354 ab	2.71 c	—	4756 ab
DDC	1414	1160	1115	1071	246 bc	4.58 b	0.84 b	5988 a
DP	503	515	487	767	463 a	2.93 c	0.09 a	3383 b

Cultivation/nitrogen

LSD within cultivations: 172 ($P < 0.05$)

LSD between cultivations: 350 ($P < 0.05$)

* MOR = modules of rupture (Richards 1953)

** W.S.A. = % water stable aggregates retained on 2 mm sieve (Yoder 1936)

† Ko = hydraulic conductivity at $\psi = 0$ cm, (x10^{-7} m/s)

DM = dry matter

Means with a common lower case letter are not significantly different at $P < 0.05$ (Duncan's multiple range test)

Yield responses in 1981 showed a very significant ($P < 0.001$) linear interaction between cultivation and nitrogen with much smaller differences in yield between N levels in the two 'minimum' cultivation treatments, a strong negative response curve with TDD and a positive response with DP.

The 1981 season was very wet at seeding, whereas in 1982 it was dry (73 mm rainfall as compared with 18 mm in May). In both years the cultivated treatments yielded very poorly as a result of the pronounced structural decline in the surface soil. This soil type has a structural stability which falls into Emerson's (1967) category 3, that is, it slakes when aggregates are immersed dry into water, but disperses after remoulding and subsequent immersion. Repeated mechanical working of wet soil rapidly leads to slaking and dispersion of the surface which then tends to pond water. This results in lower soil water storage at planting and less water available during the season. Also, there are deleterious effects of cloddy and crusted seedbeds on depth of seeding and emergence. The direct-drilled soils however, have maintained their structural condition or even slightly improved it, probably because of the retention of organic matter at the soil surface (Hamblin 1984). The water balance relations on the TDD, DDC and DP treatments (1N level) for 1982 are given in table 5.

Table 5. Water balance (mm) in 1982 for plots receiving 15kg N/ha

	Tillage method TDD	DDC	DP
Total soil water (0 - 130 cm) at seeding (mm)	270	303	215
Wettest minus driest profiles (mm) during growing season	115	131	62
Computed soil evaporation* (mm)	59	72	75
Depth to wetting front at seeding (cm)	27	23	20

* Using Fischer's (1979) analysis where 'water use' is regressed against dry matter over the linear growth phase.

At Merredin the changes in soil structural condition invalidated the use of a combined normalised analysis over the six years as the soil could not be assumed unchanging through time. An attempt to analyse the significance of tillage systems over years (appendix B, figure 1(a) and 1(b)) was made on year groups 1977 to 1979 and 1981 and 1982. However, the analyses still showed year effects to be significant in both groups. The normalising procedure was not successful in

removing seasonal influence. Nitrogen and N-interactions were non-significant in both groups, as anticipated at a low rainfall, high-clay site, but in the 1981-82 group 'cultivation' accounted for 71% of the variation.

Weeds and diseases

In common with many dry Australian cereal growing areas, the disease levels at this site were negligible. Weeds were surveyed in most years, but numbers were generally low and differences between treatments not significant. The post-emergent herbicide Hoegrass® for the control of ryegrass was applied to all treatments in 1977, 1978, 1980, and 1982. Full details are in table A-3(a) to (c) in appendix A.

2. MERREDIN 2—Acid yellow earth (78 M 25)

Main effects

Mean cereal grain yields are given in tables 6(a) and (b) for nitrogen levels and tillage treatments. All yields have been very low (generally <1 t/ha) reflecting the combination of low subsoil pH and low rainfall. Soil pH (1:5 in water) is 5.1 at 0 - 10 cm, 4.5 at 10 - 20 cm and 4.3 from 30 - 100 cm depth. Nitrogen responses have been significant ($P < 0.001$) even in drier years. Responses to tillage have not been consistent, with direct-drilling yielding best in some years and DP in other. However, DDC has been consistently better than TDD.

Table 6(a). Merredin—acid yellow earth: wheat grain yield (kg/ha) for four nitrogen levels (1978 - 1982).

Year	Amount of N applied at "standard" recommended rate kg/ha	Nitrogen level 0	0.5	1	2	LSD (P < 0.05)
1978	8	691	729	767	820	31
1979	31	660	833	877	1009	51
1980	24	402	454	463	493	27
1981	24	599	797	927	1013	48
1982	35	797	937	980	1020	29
Average	24	630	750	803	871	

Table 6(b). Merredin—acid yellow earth: wheat grain yields (kg/ha) with tillage as the main effect.

Year	Tillage method TDD	C TDD	DDC	DP	LSD (P < 0.05)	Level of significance of nitrogen x tillage interaction
1978	579	776	785	868	81	*
1979	860	802	948	769	93	*
1980	469	459	483	401	N.S.	N.S.
1981	761	871	804	901	50	N.S.
1982	980	876	997	881	78	***
Average	730	757	803	764		

* P<0.05, ***P<0.001

Grain yield responses to nitrogen showed significant interaction with tillage in three years; 1978, 1979 and 1982. In 1982, the TDD treatment required significantly less N to reach maximum yield ($P < 0.001$), and the DP and DDC treatments had steeper curves. These results could be, in part, explained in terms of the faster hydraulic conductivities of the tilled surface soil leaching topdressed NH_4NO_3 more rapidly from this layer, together with overall restriction to root growth in the acid subsoils. A similar difference in hydraulic conductivity occurs on the other deep sandy site at Wongan Hills. However, the pronounced subsoil acidity at Merredin has led to a reversal of the nitrogen response curves with tillage method between the two sites.

Weed numbers were low throughout the history of the trial and there were few significant differences other than in the first year (1978) when significantly more broad-leaved weeds were found in the C/TDD and DP treatments, (35 plants/m^2 compared with 4 plants/m^2 in the two direct drill treatments), (tables A-4(a) to (c), appendix A). All treatments received post-emergence weed control sprays following wheat and weed counts.

3. WONGAN HILLS—Yellow earthy sand (77WH17)

Main effects

As described, the trials at Wongan Hills and Avondale included two additional treatments of TDD (L) and DDC (L), the two direct

drilled treatments sown, on average, three weeks later than the first sowing date. At Wongan Hills, the significance of early sowing date was very rapidly demonstrated for all treatments. The identification of a traffic pan at about 20 — 30 cm on this site (Hamblin and Tennant 1979) led to the later redesign of these treatments to incorporate a deep tillage or 'ripping' pre-treatment.

Only the four main treatments (1 to 4) have been used in the statistical analyses for comparative purposes. In 1977 and 1978, yields were lower on the DP treatment because it was planted late on the same date as TDD (L) and DDC (L), both of which it out-yielded. When treatments are planted on the same day there is a consistent and significant advantage in favour of cultivation, and of deep cultivation over normal depth (10 cm) cultivation for this soil type (table 7).

Table 7(a). Wongan Hills: wheat grain yield (kg/ha) for four nitrogen levels (1977 — 1982).

Year	Amount of N applied at "standard" recommended rate (kg/ha)	Nitrogen level				LSD ($P < 0.05$)
		0	0.5	1	2	
1977	45	456	682	650	545	91
1978	15	1656	1734	1778	1824	134
1979	40	1277	1414	1483	1522	96
1980	40	905	1048	1159	1217	48
1981	40	907	1566	1838	2150	45
1982	50	1219	1805	2018	2224	108
Average	38	1100	1375	1488	1580	

Table 7(b). Wongan Hills: wheat grain yield (kg/ha) with tillage as the main effect.

Year	Tillage method				($P < 0.05$) LSD	Level of significance of nitrogen x tillage interaction
	TDD	C TDD	DDC	DP		
1977	687	465	780	582	151	N.S.
1978	1655	1805	1746	1786	N.S.	*
1979	1299	1323	1465	1609	222	*
1980	928	1215	984	1203	89	*
1981	1369	1487	1690	1916	114	N.S.
1982	1593	1995	1779	1900	130	N.S.
Average	1255	1382	1407	1499		

* $P < 0.05$

Table 7(c). Grain yield responses (kg/ha) to deep ripping at Wongan Hills in 1981* (1981 - 1982).

Year	Tillage method						Overall increase from ripping %
	TDD		DDC		DP		
	No-rip	Rip	No-rip	Rip	No-rip	Rip	
1981	1516	2171	1881	2543	2041	2648	34.2
1982	1766	1974	1998	2154	2075	2089	6.5

*1982 responses are residual effects of the 1981 ripping treatment. All treatments had the "standard" rate of N applied (40 kg/ha in 1981, 50 kg/ha in 1982)

1977 was unusually dry (178 mm in the growing season) and as the trial was located on a paddock which had grown lupins in 1976 no significant nitrogen response was expected in the first year. Under these dry conditions a negative yield response occurred at the 2N rate. However, these sandy soils have high unsaturated hydraulic conductivites, ranging from 1 to 10 cm/week for steady state values at —0.1 bar potential. The wetting front advances at a rate of 20 cm/week as the profile fills in autumn. These soils leach nitrate substantially in rainy seasons. In later years the response to nitrogen has been highly significant, with curves becoming steeper with time as total soil nitrogen levels have declined.

Significant ($P < 0.05$) tillage x nitrogen interactions occurred in 1978, 1979 and 1980, but the response curve was flatter with increasing tillage disturbance. Plant growth rates were higher in the cultivated treatments and nitrogen uptake greater. In 1981, the May-June rainfall was 130% of the long term average and all treatments showed a steeper response curve than for previous years. The tillage x nitrogen interaction was not significant in 1981 and 1982.

The combined analysis on normalised data (figure 3 appendix B) demonstrates the need for tillage on these yellow earths. The tillage x nitrogen interaction was not significant when tested on the normalised data. Soil physical conditions have been monitored in detail in this trial by Hamblin and Tennant (1979, 1981). In summary, cultivated surfaces have higher macro and total porosities, and conduct water faster than untilled soils. Soil strengths are significantly higher in the untilled seedbeds. There has been no evidence of a change in soil structure (in terms of proportion of macropores or structural stability) with time at this site

(Hamblin and Tennant 1981) and the effects of surface disturbance by tillage do not last longer than one season because of mechanical action from rain and traffic.

Traffic pans

The sandy earths at Wongan Hills tend to form naturally hardened and massive structures on drying, with a strong functional dependence of soil strength on water content and soil matric potential (Hamblin *et al.* 1982). Traffic pans develop after only a few wheelings if the soil is wet (J. W. Bowden, personal communication) and their existence on this soil type is very widespread (Jarvis 1983a and b). Crops sown by direct drilling techniques may thus suffer a double check in terms of root impedance both in the surface soil and at the traffic pan, which is expressed as reduced early vigour. Water use by the direct drilled crops is lower in the pre-anthesis part of the season, but may be greater in the grain filling stage, provided there is sufficient stored water. More frequently however, the total volume of soil exploited by crop roots is reduced in direct drilled crops and the result is reflected directly in the yield (Hamblin *et al.* 1982).

When the traffic pans were broken up by deep-ripping, root extension rate was greater with maximum root depths recorded at 60 cm at six weeks compared with 30 cm in unripped treatments (D. Tennant, personal communication). The yield increases ascribed to deep ripping were 43% (TDD), 35% (DDC) and 30% (DP) over the adjacent unripped standard N subplots. In 1982, the residual effects of the 1981 ripping gave a 12% (TDD) and 8% (DDC) improvement over the unripped subplots, but no difference in the DP treatment. Penetrometer and root measurements indicated that the rip effects had persisted, but late season water stress was greater than in 1981, reducing the significance of the better growth of the plants on grain production.

Weeds and diseases

Before the annual application of post-emergence herbicides, weeds were monitored in the first four years of the trial and are shown in table A-5, appendix A.

Annual ryegrass numbers averaged 100 - 200 plants/m^2 in the first year, but declined thereafter as a result of annual Hoegrass® applications at the two to four leaf stage of the crop. Other grasses were present in small amounts, and broad-leafed weeds were adequately controlled each year with post-emergence herbicide. There were no significant differences in wheat plant emergence numbers which could be attributed to seedbed differences and which would have affected dry matter production significantly, whereas the difference in early vigour and resultant dry matter accumulation is strongly related to differences in soil mechanical strength and pore geometry (Hamblin *et al.* 1982).

Root and leaf diseases were assessed in the first two years of the trial (G. C. MacNish, personal communication), but there were very low occurrences, mainly of glume blotch (*Septoria nodorum*). In subsequent years the disease level has remained low and has not necessitated evaluation.

4. AVONDALE—Non calcic brown earth; (77A16)

The Avondale site represents a contrast to the previous three in both climate and topography. It has a wetter and cooler climate with a lower potential evaporation. It is a sloping site with a shallow, loamy soil over granitic rocks on which run-off is a contributing factor to yield variation in some years. On average, yields at Avondale are 1.0 - 1.5 t/ha greater than at Wongan Hills or Merredin, but large variations still occur from year to year depending on the rainfall, particularly during September.

Main effects

As at Wongan Hills, the design at Avondale included two additional late-sown treatments DDC(L) and TDD(L). In 1977 and 1978, the DP was also sown on that later date, three weeks after the other direct-drilled treatments. In subsequent years, the DP treatment was sown at the same time as the other three main treatments. Tables 8(a) and (b) show the mean yields for each nitrogen and tillage level over the six years. Tillage treatments were significantly different in four years out of six, and nitrogen levels significantly different in all years except the first two. The initial 1977 crop followed lupins in 1976 and the 1977 and 1978 nitrogen responses were therefore low. Tillage x nitrogen interactions were not significant until 1980 after which the response curve for DP maintained a shallower slope than the TDD (table 9 and figure 2). This difference in shape of the N response curve, also seen at Wongan Hills,

has been reported from other tillage comparisons in Britain (Coutts *et al.*, 1975) and the United States of America (Moschler *et al.*, 1972). To test whether differences in nitrogen availability were responsible for the differences in response curves at Avondale, soil nitrate levels and N concentration in plant herbage were measured in 1981 on the zero N plots.

Table 8(a). Avondale: wheat grain yield responses (kg/ha) for four nitrogen levels (1977 - 1982). Late planting treatments not included in the averages.

Year	Amount of N applied at "standard" recommended rate (kg/ha)	Nitrogen level 0	0.5	1	2	LSD (P < 0.05)
1977	58	1732	1728	1692	1699	N.S.
1978	19	3081	3199	3132	3215	N.S.
1979	61	2284	2504	2604	2502	118
1980	70	1404	1728	1814	1846	71
1981	58	1660	2263	2552	2904	161
1982	60	2929	3230	3272	3377	155
Average	54	2182	2442	2511	2590	

Table 8(b). Avondale: wheat grain yield responses (kg/ha) with tillage as the main effect (1977 - 1982).

Year	Tillage method TDD	C TDD	DDC	DP	DDC (L)	TDD (L)	LSD (P < 0.05)
1977	1740	1611	1872	1628	1728	1795	N.S.
1978	3168	2936	3084	3439	3217	3002	238
1979	2486	2299	2668	2441	2565	2281	158
1980	1802	1757	1805	1429	1406	1430	118
1981	2235	2218	2303	2624	2533	2371	189
1982	3331	3116	3122	3238	3098	3389	N.S.
Average	2460	2323	2476	2466	2424	2378	

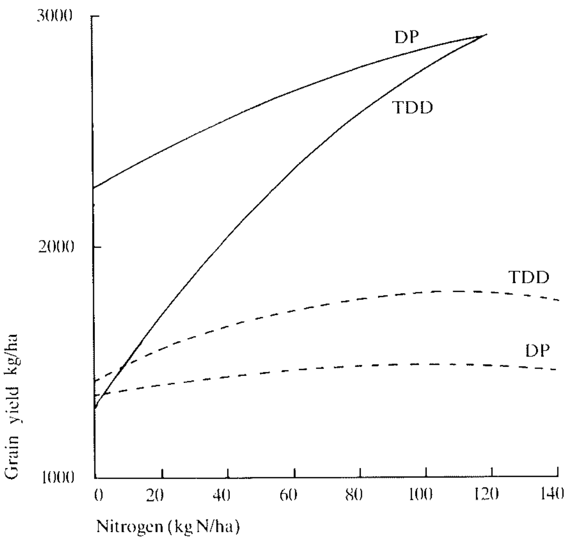
Table 9. Wheat grain yields (kg/ha) at Avondale: interaction between nitrogen and tillage level averaged for 1979 - 1982

Tillage method	Nitrogen level 0	0.5	1*	2
TDD	1957	2424	2696	2777
C/TDD	1942	2316	2556	2576
DDC	2162	2479	2544	2713
DP	2217	2506	2445	2564

* "Standard" N = 62 kg/ha

The cultivation x nitrogen interaction in table 9 was significant in 1980, 1981 and 1982.

Figure 2
Avondale: wheat grain yields in 1980 (---) and 1981 (—) for tillage treatments TDD and DP.



Figures 2 and 3 show the wheat grain yield responses x N level for 1980, a drier than average year, and 1981, a wetter than average year, together with the soil and plant nitrogen status in the 1981 growing season. Taking the yield evidence first, we noted that the 1980 DP yields were much lower than the other treatments because less water penetrated the profile (A. P. Hamblin and D. Tennant, unpublished data) with a subsequent difference in depth of wetted profile of 70 cm compared with 100 cm. Thus, residual soil nitrogen in the DP should have been higher in 1981, but it was not. Although soil NO_3 was higher in the 0 - 10 cm zone of the TDD treatment until early August, the nitrogen concentration in the plant herbage confirms the greater uptake from the DP treatment (figure 3). Over 100 mm more rain fell in the 1981 growing season than in 1980 and differences because of water stress were less significant in 1981. Higher nitrogen levels gave higher yields, with the DP treatment higher than the direct drilled treatments except at the 2N rate.

The combined analysis for the six years (appendix B, figure 4) gave a significant F ratio for a linear and quadratic curve fit to N levels, which accounted for only 23% of the variance. All other parameters accounted for even smaller percentages of the variance,

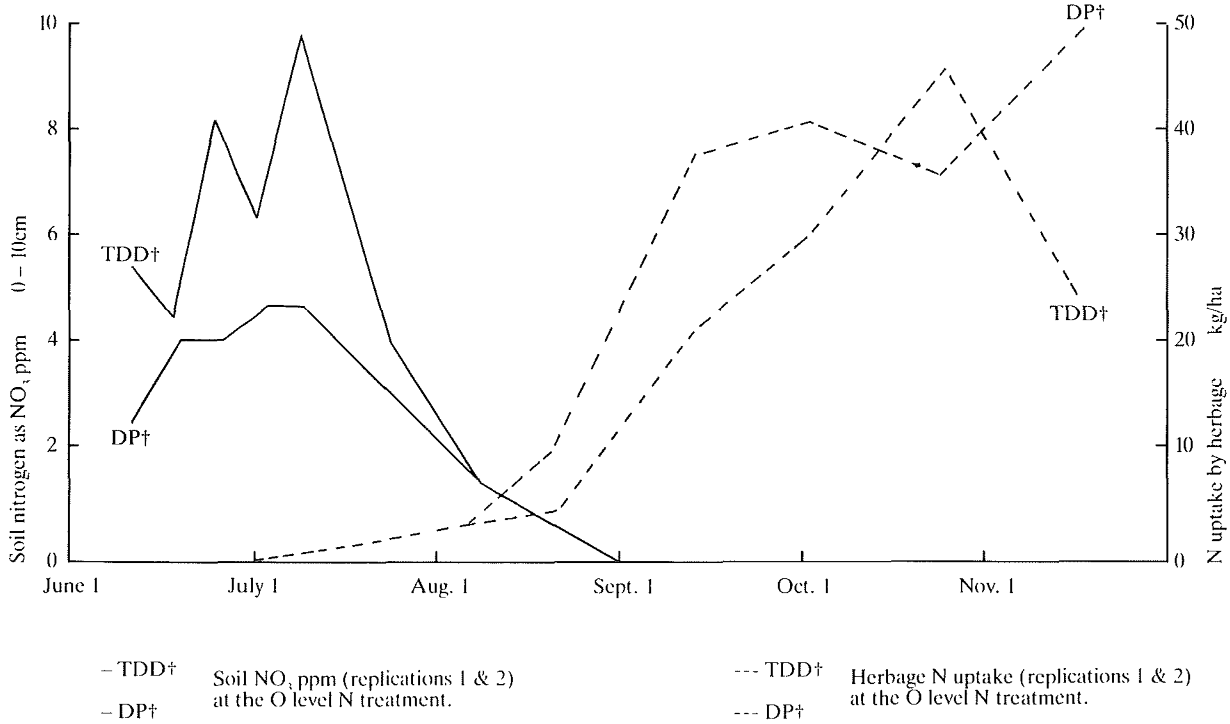
although the year effect was also significant. As at the Merredin red-brown earth site however, a combined analysis for the total period was invalid because changes in soil structural condition were found after three years (Hamblin 1982) and patterns of water use varied between treatments thereafter (Bligh 1982); (A. P. Hamblin and D. Tennant, unpublished data). Infiltration capacity was lower and surface-detention excess greater on the DP and TDD treatments than on the DDC, with the DP treatment having the lowest total infiltration. For example, 76% of winter rainfall infiltrated in 1981 and 85% in 1982. A combined analysis was done on the 1977 to 1979 and 1980 to 1982 years as two groups, (appendix B, figure 4(a) and (b)). A big shift in steepness of all the curves between the two groups is noticeable, resulting from a much-increased responsiveness to nitrogen on this soil type after four years cropping. The difference in the TDD treatment for the 1980 to 1982 period suggests that at standard N rates or higher, this form of direct drilling is providing more efficient use of nitrogen than conventional tillage, probably because of a real improvement in water use by the crop.

Weeds and diseases

The Avondale site was weedy in the first year of the trial (1977) with grass numbers ranging from 180 to 460 plants/m² although the dicotyledon weed burden only averaged 11 plants/m² (appendix A, table A-6(b)). Hoegrass® and Brominil M® have been used at rates of 1.5 and 1.0 L/ha respectively every year, with the result that weed numbers have declined and grass weeds remained at totals of less than 50 plants/m² in the cultivation treatments for the past four years (1979 - 1982). This situation contrasts with that at Esperance where there was a considerable ryegrass problem and where Hoegrass® applications were 1.0 L/ha. Ryegrass numbers at Esperance increased in 1981 and 1982 and in 1982 two applications of Hoegrass® at 1.0 L/ha, plus a wetting agent, failed to give effective control (table 11).

Figure — 3
Avondale: soil nitrate status and plant uptake of N for the continuous tillage trial 77A16 in the 1981 growing season. (Data from Summary of Experimental Results 1981. J. W. Bowden)

Seeded June 4
Nitrogen topdressed June 15



† See explanation
– Table 3b

Diseases were monitored in the early years of the trial, but the only one noticeable was take-all which was rated as of low incidence and severity (G. C. MacNish, personal communication). There were no significant differences between treatments and ratings were discontinued in later years.

Late sown treatments

Seeding treatments TDD and DDC had two times of planting in 1977-1981. The later treatments were sown an average of 20 d later than their counterparts. Appendix A, table A-7 shows the yield differential between the two planting dates. Late sown treatments have not always yielded less, but overall there has been an 84 kg/ha yield reduction from late seeding, or 4 kg/ha.d.

5. ESPERANCE DOWNS—Duplex yellow podzolic (77E18)

At latitude 33°36'S, Esperance has a different climate from the more northerly sites. The rainfall is more evenly distributed throughout the year, only the months of December and January having less than 5% of the annual total. With nearly 500 mm per year, mild winters and relatively high levels of growing-season radiation (similar to Avondale), the potential for high yields along the southern coast is greater than in the main wheat growing areas. As in all wetter environments however, the problems associated with diseases, weeds and pests are greater, and selection of suitable varieties for this relatively recently developed area is still in progress. At the trial site, wheat cv. Madden was grown in 1977, barley cv. Clipper in 1978, and wheat cv. Egret from 1979 to 1982. Before the trial commenced, the areas had been in clover pasture for three years followed by a barley crop in 1976. Except in the first year, cereal grain yields have averaged less than 2 t/ha. In general, the very wet years have averaged lower yields than the drier years, and the later years of the trial have averaged lower yields than earlier years of equivalent rainfall as seen in the yield data for 1977 and 1981.

Main effects

Tables 10(a) and (b) give the nitrogen and tillage level main effect grain yields. The TDD and C/TDD treatments outyielded the DP and DDC treatments significantly in 1979, 1981 (TDD only) and 1982. In the other three years tillage differences were not significant. Grain yield response to nitrogen level was highly significant at $P < 0.001$ every year; in 1979 and 1982 the difference between the zero and twice standard rate being three and five-fold.

Table 10(a). Esperance: Grain yield responses (kg/ha) for four nitrogen levels (1977 - 1982).

Year	Amount of N applied at "standard" recommended rate (kg/ha)	Nitrogen level 0	0.5	1	2	LSD (P < 0.05)
1977	55	2281	2564	2527	2490	83
1978*	19	1612	1885	1978	2249	107
1979	51	556	775	1122	1851	70
1980	58	1530	1737	1954	2230	104
1981	60	1009	1505	1688	1654	82
1982	60	387	964	1562	2007	89
Average	50	1229	1572	1805	2080	

* Barley; wheat all other years.

Table 10(b). Esperance: Grain yield responses (kg/ha) with tillage as the main effect (1977 - 1982.)

Year	Tillage method TDD	C TDD	DDC	DP	LSD (P < 0.05)	Level of significance of nitrogen x tillage interaction
1977	2470	2431	2492	2468	N.S.	N.S.
1978	1950	1906	2016	1852	N.S.	*
1979	1376	1372	886	669	176	***
1980	1810	1864	1804	1973	N.S.	***
1981	1643	1465	1451	1295	161	***
1982	1463	1338	1069	1051	141	*
Average	1785	1729	1620	1551		

* $P < 0.05$, <*** $P < 0.001$

Waterlogging, and loss of nitrogen by denitrification or leaching, were the causes of the steep nitrogen response curve in 1979, a very wet year. In 1982, there was no exceptionally wet period, and the steepness of the nitrogen response must be due to increasing loss of total nitrogen from the site after several years of cropping.

Soil physical conditions were not monitored in detail, but limited data suggest that similar tillage differences occur as at other sandy sites. Penetrometer measurements of soil strength (Hamblin and Tennant 1981) showed similar lower values for cultivated surface soils. Air permeability measurements are lower for uncultivated soils which have

fewer macropores. These differences have not significantly affected plant growth and yield as they have done at the drier sites because of the dominance of weeds, disease and a shortage of nitrogen. Also, there is not the same requirement for rapid growth and maturation as in drier parts of the wheatbelt because of the longer growing season. On this white A-horizon, duplex soil site with poor subsoil drainage, excess water rather than a water deficit is the most severe water problem. Seedbed conditions did not differ sufficiently between treatments to affect plant establishment in any year (table A-8, appendix A).

Interaction of tillage method x nitrogen rates gave the following responses:

1977 no interaction

1978 * TDD flatter response curve than other treatments

1979 *** TDD steeper response curve than other treatments

1980 *** TDD steeper response curve than other treatments

1981 *** TDD flatter response curve than other treatments

1982 * TDD yield better at the low N rates with a flatter response curve

* $P < 0.05$,*** $P < 0.001$

The combined years' analysis (appendix B, figure 5) gave a significant yield advantage to the TDD treatment at $P < 0.05$, but the normalisation procedure was not sufficient to reduce the yearly variation to a non-significant level. Both linear and quadratic fits to the N response curves were significant. There was no significant tillage x nitrogen interaction in the combined analysis.

Weeds and diseases

Weed numbers were not high in the early years of the trial, but nevertheless, the TDD treatment had the lowest number of ryegrass plants. In later years, ryegrass levels rose despite Hoegrass® applications in most years. It is probable that the ryegrass seed population was not sufficiently suppressed in the early years. Late Hoegrass® application in wet years has reduced effectiveness and contributed to persistence of ryegrass in the crop. Table 11 summarises the ryegrass numbers and Hoegrass® applications.

Table 11. Annual ryegrass numbers/m^2 in relation to application rates of Hoegrass® (L/ha) for each tillage treatment at Esperance.

	Tillage method							
Year	TDD		C/TDD		DDC		DP	
	AR	H	AR	H	AR	H	AR	H
1977	67	0	94	0	90	0	76	0
1978	10	1.0	33	1.0	34	1.0	37	1.0
1979	6	0	10	0	39	1.0*	64	1.0*
1980	nd	1.0	nd	1.0	nd	1.0	nd	1.0
1981	60^b	1.0	139^a	1.0	120^{ab}	1.0	111^{ab}	1.0
1982†	1.90^a	2.0	2.96^b	2.0	2.80^b	2.0	2.75^b	2.0

AR = annual ryegrass H = Hoegrass®

*—late application (August 28, 1979) because of severe waterlogging in July and August

nd—no data

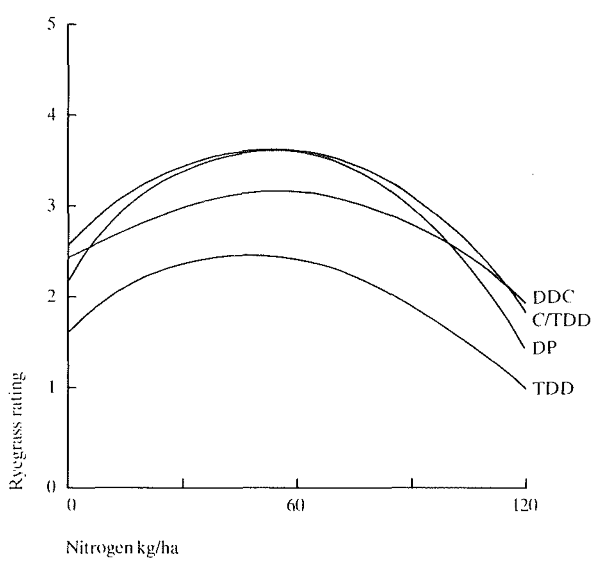
†ryegrass visually rated on a score 0 = 100% control, 5 = no control, (ie: heavy infestation) following two sprays of

Means within any year with a common letter are not significantly different ($P < 0.05$).

The ryegrass population density was significantly lower in the TDD treatment than in the C/TDD treatment in 1981 and all other treatments in 1982. There was a relationship between ryegrass ratings and N level in 1982 which is shown in figure 4 (J. Holmes, unpublished data). The parabolic

Figure 4. Fitted curves of ryegrass ratings $r^2 = 0.79$

Esperance Downs Research Station continuous tillage trials
Ryegrass ratings Oct. 14, 1982. 0 = Total control
5 = No control



response is explained by severe nitrogen deficiency, in both wheat and ryegrass, at zero N level and by a more vigourous growth of wheat than ryegrass at 2N level.

The lower ryegrass numbers in the TDD treatment were probably due to the lack of soil disturbance. Surface disturbance stimulates ryegrass germination (Pearce and Quinlivan 1971). The cultivation component of the C/TDD treatment was originally designed to provide deliberate stimulation of ryegrass which was then killed by Spray.Seed®. This was to be followed by the TDD seeding method to prevent further germinations. However, this system has not been successful and has largely been replaced by the use of Hoegrass® in commercial management.

Disease incidence at Esperance has been monitored each year by G. MacNish (unpublished data 1977 to 1982). A summary of his results is as follows:

Until 1980, only the standard N treatments were sampled for root rot. In 1981 and 1982 all N treatments were assessed.

There is a trend to increasing take-all incidence and severity with time on all treatments. In 1977, there were no significant differences between treatments. In 1978, TDD had significantly less take-all than the other three treatments. This trend continued in 1979, with TDD and C/TDD having significantly less take-all than DDC and DP and with TDD having slightly less than C/TDD. In 1980, the treatments had no significant effect on severity of take-all, but TDD had less infection. The 1981 and 1982 results were similar (slightly more take-all in 1982) and indicate that there is less take-all incidence in the TDD treatment, although C/TDD had the lowest severity in these two years.

Increasing rates of Agran 34-0 (34% N as NH_4NO_3) reduced take-all incidence and severity. This could be explained by the annual use of this fertilizer, which at the higher rates of application (0, 30, 60 and 120 kg N/ha) has reduced pH levels and may have suppressed the growth of the fungus. The 1983 soil data showed pH reductions in the top 10 cm of soil of standard N treatments, compared to the O level N treatments, of 0.33 of a pH unit in the TDD and 0.11 of a pH unit in the DP treatment.

Monitoring of *Rhizoctonia* root rot commenced in 1981. There was significantly more *Rhizoctonia* in the direct-drilled treatments than the cultivated treatments (C/TDD and DP) in 1982. Similar results have been reported by Neate *et al.* (1981) in South Australia, Jarvis (1984), and MacNish (1985) in Western Australia (end of summary).

It is evident that there are significant tillage treatment differences in weeds and disease incidence which help to explain the yield results. The TDD treatment has some yield advantage because of better ryegrass control. Yield depression from ryegrass averaged over many Western Australian trial sites is about 10% per 100 plants/m^2 (M.L. Poole, personal communication). However, ryegrass control with Hoegrass® was ineffective at this site in 1981 and 1982. The very large yield reduction of the combine-sown treatments in 1979 was the result of higher ryegrass numbers and a correlated, higher take-all severity. Because of the very wet conditions following seeding in that year, Hoegrass® application was delayed until nine weeks after seeding. This was too late to prevent a substantial reduction in yield from the two treatments (DDC and DP) which had the highest ryegrass densities. Both of these treatments had a lower yield in 1982. In that year, the two TDD sown treatments had significantly less take-all and DD/TDD had less ryegrass.

6. MT BARKER—Brown podzolic (77MT15)

Mt Barker is the most southerly and wettest site, located in dissected and well-timbered country. Take-all incidence is always high in this area and by the fourth consecutive year of cereals on this site the incidence was 99% of all plants, the infection level being severe in most cases. This necessitated a change in design of the trial in 1981. In all treatments, the main plots were divided into two parallel sets of subtreatments:

1. Continuous wheat with either ammonium sulphate, $(NH_4)_2SO_4$, or sodium nitrate, $NaNO_3$, at 100 kg N/ha. This design permits monitoring of levels of take-all decline, should it occur, with an acidifying source of N, $(NH_4)_2 SO_4$, compared with a less acidifying N source (MacNish and Speijers 1982).

2. Lupin-wheat rotation on a year-in year-out basis to study the effect of a break crop on the progress of the disease. The lupins were *L. angustifolius* cv. Yandee, sown at 118 kg/ha. Wheat plots in the lupin-wheat rotation were topdressed with ammonium nitrate at 100 kg N/ha in 1981. In 1982, the wheat following lupins received no nitrogen.

Before 1981, alternative cereal species had been used in an attempt to mitigate the effect of take-all. In 1977 Clipper barley was sown, in 1978 West oats, and in 1979 and 1980 Egret wheat. Table 12 gives the mean grain yields for nitrogen levels, nitrogen sources, and tillage treatments.

Main effects

Differences which could be ascribed to tillage in the first two years were small, whereas the continuous cereal effect on take-all disease was marked. Similarly, in the 1980 to 1982 period, variations in the severity of take-all infection per plant were related to tillage, with less severity associated wth the TDD treatment. Grain yield response to nitrogen was significant in each year ($P < 0.001$) until the change of trial design in 1980. There was no significant nitrogen x tillage interaction over the six years. There was a significant grain yield advantage of $(NH_4)_2SO_4$ over $NaNO_3$ fertilizer in 1981 and 1982.

A most striking increase in wheat yield occurred in 1982 in those plots which had grown lupins in 1981. The 1982 wheat yield (after lupins in 1981) averaged 2871 kg/ha as compared with the average wheat after wheat yield of 1516 kg/ha. Nitrogen was only applied to the continuous wheat plots.

Table 12(d) shows yields of lupins over two years. The TDD treatment gave the lowest yield in both years.

No combined-years analysis was possible at Mt Barker because of the change in trial design.

Table 12(a). Mt Barker: Grain yield responses (kg/ha) for four nitrogen levels (1977 - 1980).

Year	Amount of N applied at "standard" recommended rate (kg/ha)	Nitrogen level 0	0.5	1	2	LSD (P < 0.05)
1977	45	3491	3706	3748	3646	111
1978	15	2157	2214	2292	2433	71
1979	51	2256	2619	2898	2790	130
1980	68	797	886	1011	1119	154
Average	45	2175	2356	2487	2497	

Table 12(b). Mt Barker: Wheat grain yields (kg/ha) with different nitrogen fertilizers applied at 100 kg N/ha (1981 - 1982).

Year	$(NH_4)_2SO_4$	$NaNO_3$	NH_4NO_3	Nil	LSD ($P < 0.05$)
1981	1627	1211	1432		165
1982	1631	1402		2871†	145

†This treatment is wheat following lupins, with zero N applied

Table 12(c). Mt Barker: Cereal grain yields (kg/ha) with tillage as the main effect (1977 - 1982).

Year	Tillage method TDD	C TDD*	DDC	DP	LSD ($P < 0.05$)
1977†	3707	3545	3808	3531	179
1978	2376	2269	2218	2233	N.S.
1979	**1730	**2408	3217	3208	462
1980	1228	1033	834	718	212
1981	1761	1259	1413	1260	322
1982	2018	1896	1989	1969	N.S.
Average	2137	2068	2246	2153	

*1980 to 1982 this treatment was cultivated and sown with a standard combine (c/c)

**Sown at half the correct rate

†DP treatment sown two weeks later

Table 12(d). Mt Barker: Lupin seed yields (kg/ha) with tillage as the main effect.

Year	Tillage method TDD	C/C	DDC	DP	LSD ($P < 0.05$)
1981	2 425	2 675	2 751	2 596	N.S
1982	1,881	2 201	2 260	2 025	179
Average	2 153	2 438	2 506	2 310	

The TDD lupin yields were compared with C/C and DDC and were significantly less in both years. This was related to lower plant establishment in the TDD treatment despite the density being greater than that generally accepted to achieve maximum yield.

Weeds and diseases

The Spray. Seed® levels were increased at Mt Barker in some years to 3 L/ha to counteract the larger weed size and numbers. Ryegrass and silver grass (*Vulpia* spp.) still occurred at sufficiently high levels after Spray. Seed® application to affect yields in 1977 and 1978. Some clover re-growth also persisted each year, despite 500 mL/ha

dicamba (200 g/L) being included in the Spray. Seed® in 1977 and 1978 and also used as a post-emergence spray. Broad-leaved weeds included capeweed (*Arctotheca calendula*), sorrel (*Rumex acetosella*), chickweek (*Stellaria media*) and erodium (*Erodium botrys*). By 1980, ryegrass numbers had been reduced below 10 plants/m^2. In 1981 the total number of grass weeds were double in the wheat half of each treatment, because of better control achieved with the use of simazine on the lupin plots. Post-seeding applied simazine appeared to be less effective on the two cultivated treatments. Table A-9 (b), appendix A gives the full details for grasses and broad-leaved weeds.

Take-all has dominated the yield responses at Mt Barker. There was some influence of tillage treatments on the incidence and severity of the disease. With increasing number of years of cereal cropping, disease levels over the whole trial became so high that yields were reduced to a third of those achieved in the first year. Once the continuous wheat programme was established the TDD treatment tended to have less take-all incidence and less severity than the other treatments. These results are the opposite of those reported by Rovira (1981 b) for tillage trials at Avon in South Australia, where take-all incidence and severity have both been higher in direct-drilled treatments, and "take-all decline" occurred after three years continuous cropping in ploughed treatments, but not in direct-drilled treatments. Differences in the South and Western Australian results may occur because of the more pronounced vertical differentiation of organic A horizons of acid reaction in the undisturbed soils in Western Australia.

After the change in design in 1981, there was a significant reduction in the level of take-all associated with the acidifying nature of the $(NH_4)_2SO_4$ fertilizer, which had been anticipated from earlier work by MacNish and Speijers (1982). In addition, there was a reduction in severity of the disease with zero tillage (TDD). Both these effects were small however, in comparison with the very dramatic reduction in both incidence and severity of the disease in wheat following lupins.

Similar dramatic reductions in levels of take-all incidence with legume-cereal rotations have been reported for wheat-pea and wheat-medic rotations in South Australia (Rovira 1981a) across different tillage systems.

Conclusions

No single tillage method has consistently given higher yields at all sites, nor was such a result anticipated. However, this lack of clear-cut dominance by any system is in itself reassuring in that yields from direct drilling can equal or better yields of former traditional tillage and seeding operations once farmers are familiar with the newer systems.

Spread as they are over a distance of some 500 km, and from 290 to 650 mm annual average rainfall (table 1), the trials inevitably displayed a considerable range of grain yield responses to tillage and to fertilizer interactions. In addition, changes through time have confirmed the common observations that continuous cereal cropping leads to reduced organic matter, soil structural decline, and increased nitrogen requirement.

A division may be drawn between sites north and south of latitude 32°S. The more northerly sites experience predictable drought stress in all seasons, whereas the wetter southerly sites have less severe drought stress, but much higher disease levels and a tendency to higher weed burdens.

The interaction of tillage system with rainfall and water use has widespread significance for non-irrigated semi-arid agricultural areas. There is an initial tendency for direct drilled

crops to grow more slowly. In areas where rapid maturation is imperative because of low rainfall at or after anthesis, especially on soils of poor water storage capacity, direct drilling tends to reduce yields. This is because lower maximum leaf areas and smaller numbers of kernels per unit area are produced. This situation is typified by the consistently lower yields of direct drilled crops at Wongan Hills.

In semi-arid environments where water storage is better, where late season rain is probable and where early maturation is less crucial, direct drilled crops may balance their water use more favourably than conventionally sown crops (which grow more rapidly and may produce a higher proportion of vegetative growth than grain). This situation is seen in some seasons at Avondale.

At Merredin the constraints of structurally unstable, fine-textured soil and low rainfall represent an extreme Australian cereal cropping situation. Infiltration capacity is the most important single factor affecting yield. Under these conditions, direct drilling may be the only safe tillage system for continuous cropping, or long crop rotations, without serious soil structural deterioration.

Nevertheless, direct drilling cannot by itself restore or improve degraded, eroded or compacted soils. Soil amelioration practices such as gypsum application on slaking soils, deep ripping of compacted soils, contour banks and stubble retention in erosion prone areas are necessary adjuncts to improving land capability in many semi-arid farm environments. Direct drilling may then be seen as a suitable system for stabilising and maintaining these improvements.

Disease and nitrogen interactions have dominated the two southern tillage trial sites. The relationship between disease and tillage from these trials is in agreement with South Australian experience for *Rhizoctonia*, but in the case of take-all disease the evidence is inconclusive. Take-all is the most serious root disease of cereals in the southern part of the wheatbelt in Western Australia. In common with experience in south-eastern Australia, the most effective treatment for reducing levels of this disease is a crop-legume break in the cropping rotation. This affords a chance to eradicate most graminaceous species which serve as alternate hosts even in relatively clean cereal crops or good clover pastures. Control of weeds by direct-drill spray techniques was effective in these trials at Mt Barker. It would have been less so if considerable reliance had not been placed on the use of post-emergent herbicides, particularly Hoegrass® and Brominil M®.

The interactions of tillage system with nitrogen on the nitrogen responsive sites showed significant interactions between the TDD and DP tillage extremes with the TDD response curve steeper in most cases than the DP curve which is significantly flatter. At high nitrogen levels, the TDD treatment has sometimes outyielded the DP treatment whereas, at low nitrogen fertilizer levels TDD yields are generally substantially lower, especially on the sandier soil types. After a total of seven years cropping on most sites, the nitrogen response curves are steeper on all treatments than in the early years, further emphasising the risks involved in continuous cereal production.

Where correct spray technology is applied, direct drilling should give as high or higher yields as cultivation on most soils.

Lower yields from direct drilling (with currently available machines) are common on yellow loamy sands where high soil strength reduces early vigour and total dry matter production.

Under continuous cropping, direct drilling may provide the only safe system in environments prone to erosion and soil degradation. However, continuous cereal production with direct drilling will incur greater risks of some diseases, and higher costs of both nitrogen fertilizers and weed control than where legume-cereal crop rotations are practised.

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Appendix A

Table A-1. Cereal and lupin cultivars for each site and year

	Pre-trial 1976	1977	1978	1979	1980	1981	1982
Esperance	Barley	W Madden	B Clipper	W Egret	W Egret	W Egret	W Egret
Avondale	Lupins	W Gamenya	W Gamenya	W Gamenya	W Gamenya	W Gamenya	W Gamenya
Wongan Hills	Lupins	W Gamenya	W Gamenya	W Gamenya	W Gamenya	W Gamenya	W Gamenya
Merredin (fine textured)	Wheat	W Gamenya	W Gamenya	W Gamenya	W Gamenya	W Gamenya	W Halberd
Merredin (coarse textured)	Pasture	Pre-Trial Wheat	W Gamenya	W Gamenya	W Gamenya	W Gamenya	W Gamenya
Mt Barker	Rapeseed	B Clipper	O West	W Egret	W Egret	W-L Egret-Yandee	W-L Egret-Yandee

W = wheat

B = barley

O = oats

L = lupins

Table A-2. Phosphorus rates applied as kg/ha superphosphate (9 % elemental P)

Location	1977	1978	Year 1979	1980	1981	1982
Esperance	112	140	120	120	120	120
Avondale	64	70	70	70	70	70
Wongan Hills	100	70	70	70	95	100
Merredin—fine soil	64	60	63	60	60	60
Merredin—coarse soil	—	98	130†	120	110	120
Mt Barker	120	144	150	150	150	160

†Cu, Zn, Mo, super and also 100 kg KCl/ha applied.

Table A-3 (a). Wheat plant establishment counts (plants/m row)—Merredin: (77M13)

Year	Tillage method †			
	TDD	C/TDD	DDC	DP
1977	10	12	14	10
1978	21	22	21	18
1979	19	18	13	13
1980	18	20	15	14
1981	22	24	21	17
1982 nd	—	—	—	—

1982. Very patchy germination in DP estimated at 50% of the other three treatments

†See explanation—table 3b

nd—not determined

Table A-3 (b). Grasses (plants/m²)—annual ryegrass: Merredin (77M13)

Year	Tillage method			
	TDD	C/TDD	DDC	DP
1977	20	38	32	21
1978	84	42	134	42
1979	8	7	15	4
1980	22	26	46	17
1981	5	1	8	0
1982 nd				

Table A-3 (c). Broad-leaved (plants/m²) mainly doublegees (*Emex australis*) *Cruciferacae* and *Medicago* spp.: Merredin (77M13)

Year	Tillage method			
	TDD	C/TDD	DDC	DP
1977				
1978	15	2	2	0
1979	8	5	6	1
1980	14	4	16	9
1981	16	17	21	13
1982 nd				

Table A-4 (a). Wheat plant establishment counts (plants/m row)—Merredin: acid yellow earth (78M25)

Year	Tillage method			
	TDD	C/TDD	DDC	DP
1978	26	28	19	21
1979	14	16	12	11
1980	20	20	18	16
1981	19	22	16	18
1982 nd				

Table A-4 (b). Grasses (plants/m²) at Merredin: (78M25)

Year	Tillage method			
	TDD	C/TDD	DDC	DP
1978	10	9	5	7
1979	7	8	11	21
1980	2	7	9	37
1981	1	1	0	2
1982 nd				

Table A-4 (c). Broad-leaved weeds (plants/m^2)—capeweed, crucifiers, doublegee: (78M25)

Year	Tillage method			
	TDD	C/TDD	DDC	DP
1978	3	33	4	34
1979	8	6	8	13
1980	5	5	22	23
1981	8	10	12	19
1982 nd				

Table A-5. Wongan Hills; Weeds and wheat plants/m^2 : counts were made on the standard N level treatments (77WH17)

Year	Tillage method											
	TDD			C/TDD			DDC			DP		
	R	D	W	R	D	W	R	D	W	R	D	W
1977	200	63	89	153	79	95	214	133	112	101	62	101
1978	23	18	96	49	19	108	32	27	112	16	5	114
1979	65	31	114	82	10	118	44	7	103	10	28	108
1980	47	13	90	21	6	96	16	60	84	3	117	79
1981	3	17	115	2	10	110	2	12	115	2	11	122
1982	nd	nd	111	nd	nd	144	nd	nd	128	nd	nd	139

R = annual ryegrass (*Lolium rigidum*)

D = dicotyledons : capeweed (*Arctotheca calendula*), turnip (*Brassica* spp.), doublegee (*Emex australis*), and radish (*Raphanus raphonistrum*)

W = wheat

nd = not determined. Weed numbers were very low

Table A-6(a). Wheat plant establishment densities (plants/m row)*: Avondale (77A16)

Year	Tillage method					
	TDD	C/TDD	DDC	DP	TDD(L)	DDC(L)
1977	15	14	15	18	15	18
1978	29	26	48†	23	23	26
1979	18	18	18	18	18	17
1980	18	18	19	19	18	18
1981	25	23	25	25	26	30
1982	24	27	23	22	27	25

*from standard N plots, means from all five replicates

†1978—greater seeding rate

Table A-6(b). Weed numbers (plants/m²) at Avondale (77A16)

Year	Tillage method											
	TDD		C/TDD		DDC		DP		TDD(L)		DDC(L)	
	G*	B†	G	B	G	B	G	B	G	B	G	B
1977	437	16	466	15	424	10	238	16	253	3	185	7
1978	61	3	85	6	63	1	65	31	70	10	61	9
1979	22	4	49	9	18	1	17	2	19	4	11	3
1980	19	3	34	10	12	5	14	5	24	0	42	0
1981	29	12	50	16	36	2	37	5	0	0	0	0
1982 nd	—	—	—	—	—	—	—	—	—	—	—	—

* G = Grasses, mainly annual ryegrass and wild oats.

† B = Broad-leaved weeds : doublegees, turnip, dock and radish.

1982 — Patchy wild oats not corresponding to treatments. Counts not determined.

Table A-7. Difference in yield (kg/ha) for two planting times under two planting methods at Avondale (77A16)

Year	Planting delay (days)	Tillage method	
		TDD	DDC
1977	26	55 N.S.	— 145 N.S.
1978	20	— 166 N.S.	133 N.S.
1979	14	— 205 *	— 103 N.S.
1980	20	— 372 ***	— 399 ***
1981	19	136 N.S.	230 *
Mean	20	— 110	— 57
Mean of planting methods		— 84	

A negative figure means that there has been a yield reduction in the late planted treatment.

N.S.—not significant

* $P < 0.05$ *** $P < 0.001$

Table A-8. Cereal crop plant establishment densities (plants/m row): Esperance (77E18)

Year	Tillage method			
	TDD	C/TDD	DDC	DP
1977	18	18	19	20
1978	15	16	15	14
1979	20	21	21	20
1980	20	21	21	20
1981	22	21	24	21

Table A-9(a). Cereal crop plant establishment densities (plants/m row); Mt Barker, (77MT15)

Year	Tillage method			
	TDD	C/TDD (C/C)†	DDC	DP
1977	14	12	18	18
1978	16	16	19	18
1979	12*	13*	23	24
1980	14	13	13	14
1981	26	23	26	25
1982	21	21	23	22

* A fault in the triple disc drill resulted in a very low seeding rate which was reflected in the yields.

†Combine sown after cultivation, 1980 - 1982.

Table A-9(b). Grasses (G) (ryegrass, poa, brome) and broad-leaved (B) (dock, sorrel, clover, chickweed, capeweed) weeds at Mt Barker: plants/m^2

Year	Tillage method							
	TDD		C/TDD (C/C)		DDC		DP	
	G	B	G	B	G	B	G	B
1977	173	51	183	65	158	46	42	18
1978	111	16	54	20	88	23	102	36
1979	6	29	6	7	16	3	15	3
1980	11	7	12	17	17	13	11	19
1981	46	19	44	34	39	18	63	7
1981 (in lupins)	12	26	30	15	9	12	46	14
1982 nd								

nd—not determined, very low weed density.

Appendix B

Part 1. Normalising procedure

The normalising procedure used for the combined analysis, (see materials and methods), did not overcome effects between years. The point at which the maximum yield occurs each year in response to nitrogen applied is taken as the base value for normalising that years' yields. It is dependent principally on: (a) leaching effects as a function of soil physical properties, rainfall amount and intensity and (b) water availability, especially at the end of the season when a potentially good crop may dessicate too rapidly to translocate accumulated photosynthates into the grain. The result of this in the combined analysis was that there was a significant year effect at all sites. This year effect resulted in interactions in the combined analysis being non significant even though the individual year analyses that went into the combined analysis showed the same interaction to be significant.

Part 2. Additional figures

The figures presented in appendix B are without statistical significance tests. They are given so that an overall average effect may be appreciated for the seasonal conditions experienced throughout the trial. In different seasonal conditions the shapes of these curves could change substantially.

Figure B – 1(a)
Combined analysis of grain yield curves at Merredin — (77M13). 1977-1979.

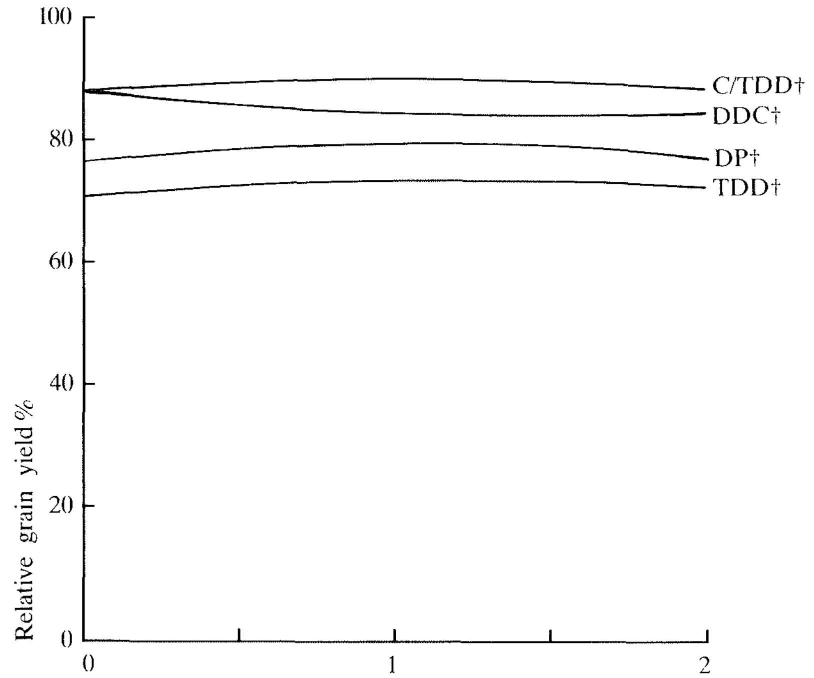
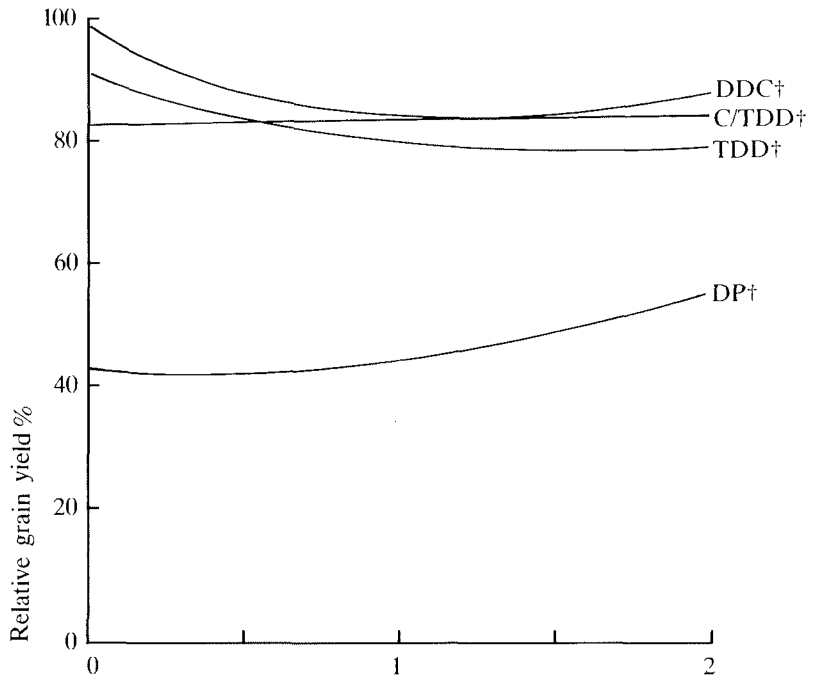


Figure B – 1(b)
Combined analysis of grain yield curves at Merredin — (77M13). 1981-1982.



† See explanation – Table 3b

Figure B – 2
Combined analysis of grain yield curves at Merredin — (78M25). 1978-1982.

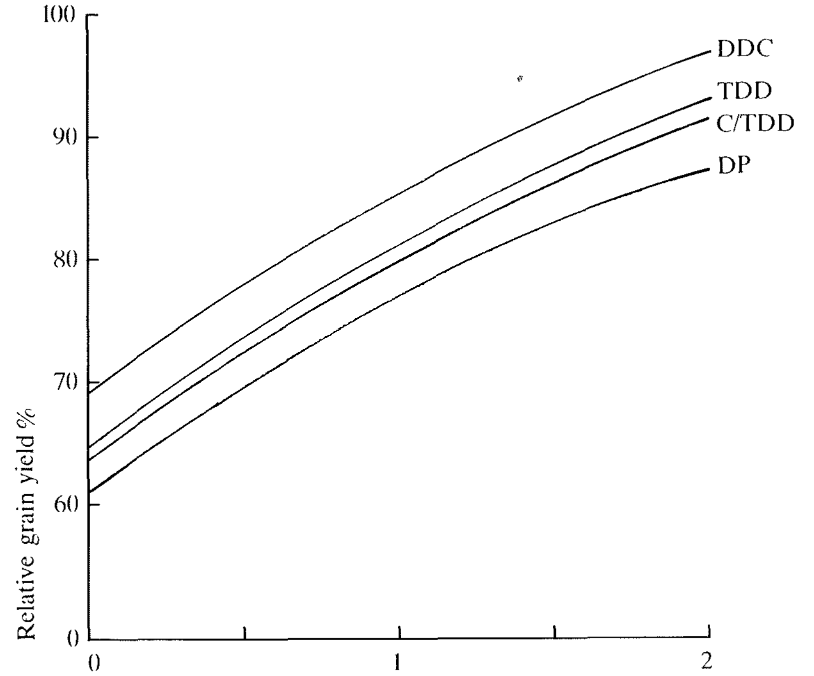


Figure B – 3
Combined analysis of grain yield curves at Wongan Hills. 1977 – 1982.

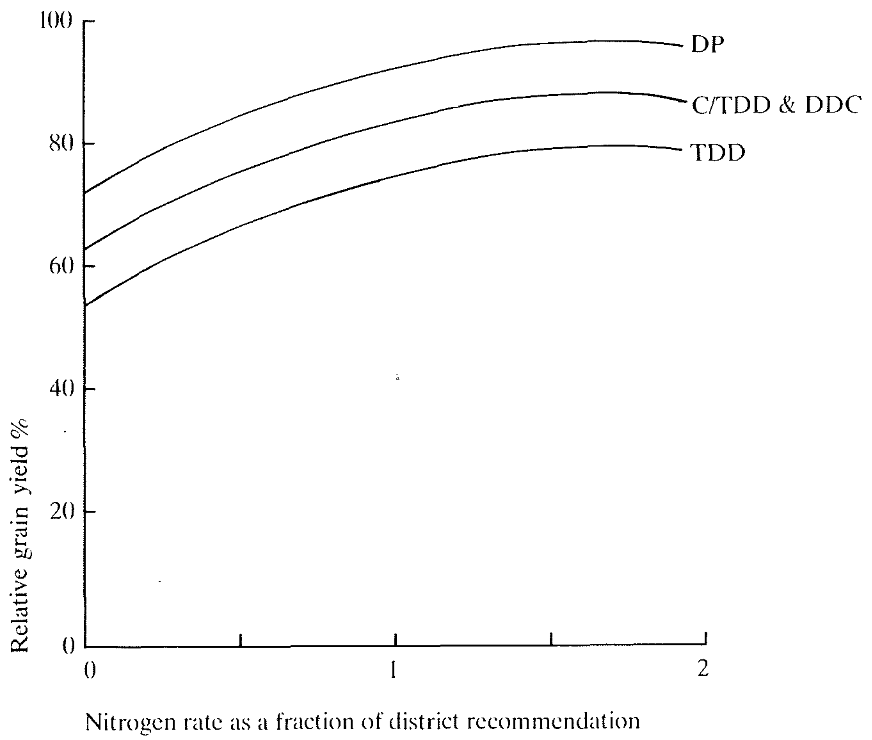


Figure B – 4(a)
Combined analysis of grain yield curves at Avondale. 1977 – 1979.

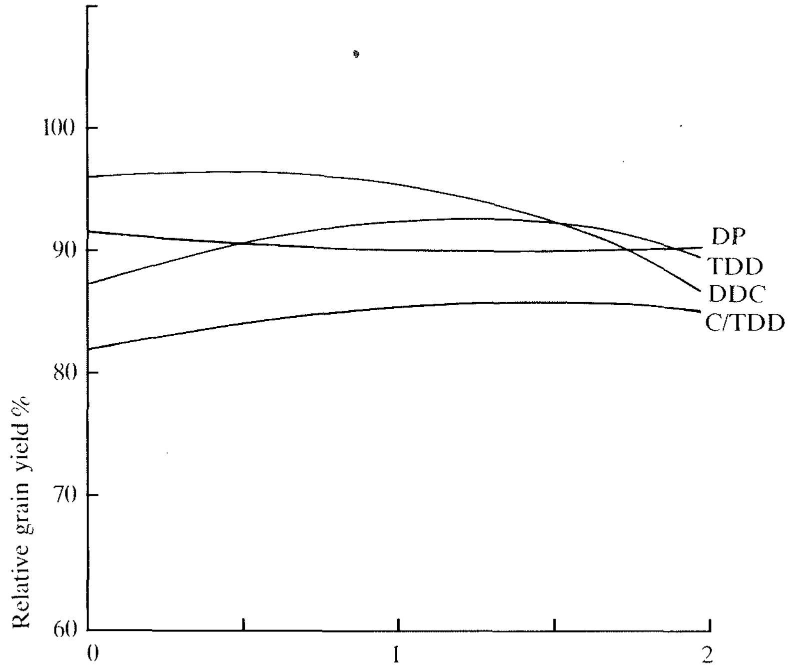


Figure B – 4(b)
Combined analysis of grain yield curves at Avondale. 1980 – 1982.

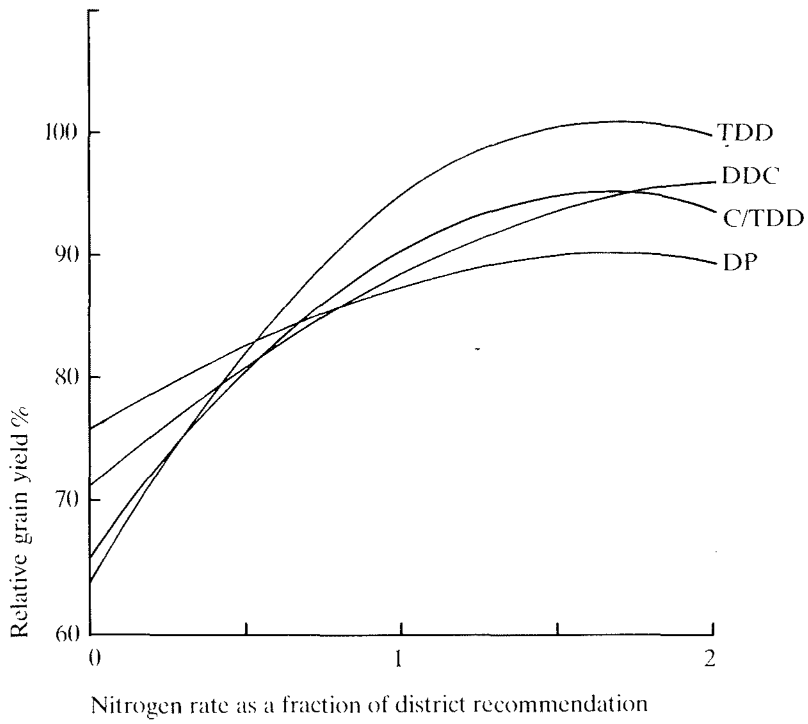
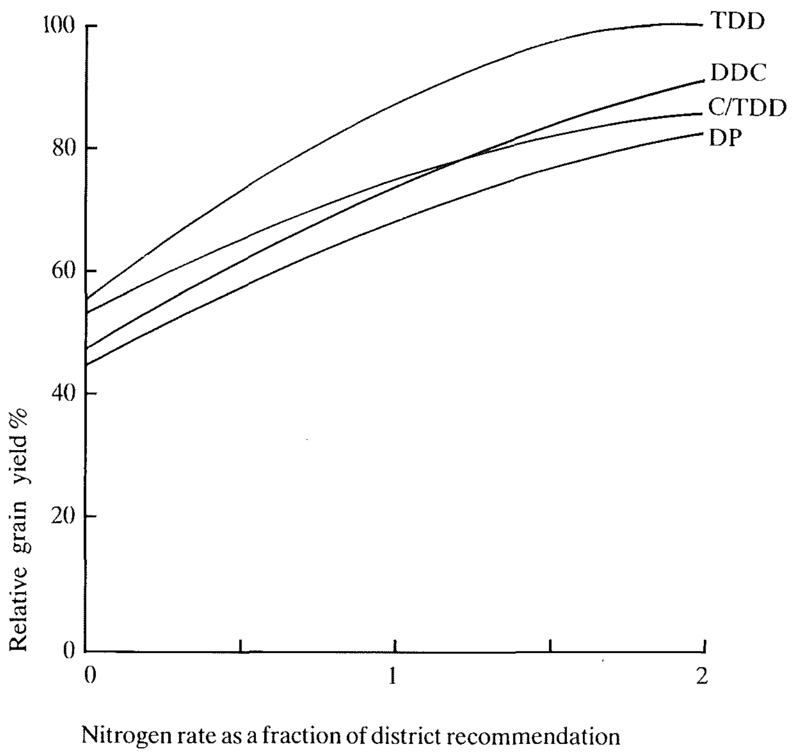


Figure B – 5
Combined analysis of grain yield curves at Esperance. 1977 – 1982



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