Winter cereal production on the Darling Downs—an 11 year study of fallowing practices

J. M. Marley[A] *and J. W. Littler*[B]

[A] Queensland Department of Primary Industries, Hermitage Research Station, via Warwick, Qld 4370, Australia.
[B] Present address: Toowoomba Road, Allora, Qld 4362, Australia.

Summary. A long term field experiment to compare 4 methods of fallowing for annual winter cereal production on a Darling Downs Vertisol was started in 1968 on the Hermitage Research Station near Warwick, Queensland. Fallowing systems being investigated are (i) tined tillage with stubble burnt (TcSb); (ii) tined tillage with stubble retained (TcSr); (iii) zero tillage with stubble burnt (TzSb); and (iv) zero tillage with stubble retained (TzSr); each at 3 rates of nitrogen (N) fertiliser application. This paper reports the effect of these treatments on fallow water accumulation, fallow N mineralisation, crop growth and yield, for the period 1968–79.

Average values for available soil water in the 0–150 cm zone at sowing were 195 mm for TcSb, 212 mm for TcSr, 225 mm for TzSb and 252 mm for TzSr, and for storage efficiency (percentage of fallow rainfall stored) were 18, 20, 25 and 27% respectively. The relatively greater water storage efficiency of Tz treatments occurred mainly in fallow seasons when initial storage was low.

Nitrogen mineralisation during fallows averaged 61 kg/ha and was depressed in some years by Sr. Carryover of available N in excess of crop requirements was shown at the higher rate of N fertilisation.

Grain yields averaged over 12 crops were similar for the 4 fallowing systems. The lack of grain yield response to the improved water storage under TzSr was probably caused by yellow spot disease (*Pyrenophora tritici-repentis*) and root lesion nematode (*Pratylenchus thornei*), which were most prevalent under this treatment in wheat crops. Poor early growth of barley under TzSr limited its water use and grain yield potential, however, the cause of the poor early growth of barley is not known. A reduction in grain yield of 232 kg/ha associated with Sr was overcome with the addition of 23 kg N/ha as urea.

Introduction

Wheat and barley growing on the Darling Downs Vertisols has long been based on a system of annual cropping with a period of bare fallow between crops. The 6-month tilled fallow is for storage of predominantly summer rainfall in the clay soils for growth of the winter crop (Waring *et al.* 1958*a*), nitrogen (N) mineralisation (Waring and Teakle 1960) and preparation of a fine seed-bed. After an initial ploughing to 12–15 cm with a disc scarifier or chisel plough, 4–5 progressively shallower tillage operations are usually performed during the fallow period to destroy weed growth and to prepare the seed-bed. Very often, especially on non-sloping land, farmers have burnt the stubble of the previous crop soon after harvest to allow easier operation of tillage and sowing machinery.

These fallowing procedures have been developed and accepted by Darling Downs grain farmers over a long period. However, during the 1960s interest developed in the possible use of stubble mulching as an aid to the control of soil erosion, especially on sloping cultivation (McGetrick 1968). Also, possible alternatives to repeated tillage operations for weed control were emerging as the broad-spectrum, non-residual herbicides diquat and paraquat became available in the mid 1960s.

For non-sloping lands, the benefits for erosion control of stubble mulching are less pronounced. Also, when our work was being planned in 1967, the only available information (Waring *et al.* 1958*a*) was that there was no water storage advantage in stubble mulching over stubble burning on Darling Downs Vertisols. At that time there was no published work reporting the effect of stubble mulching on N mineralisation on these soils, and the effects of reduced and zero tillage on fallow water storage, N mineralisation, crop establishment and growth were largely unexplored.

Therefore we established a long-term experiment on a non-sloping Vertisol to investigate the influence of stubble mulching and stubble burning, with either repeated cultivation or zero tillage, on fallow water storage, fallow N mineralisation and the growth and yield of winter cereals, as well as their effects on some of the longer-term indices of soil fertility.

This paper reports results for the first 11 years of the continuing trial, with emphasis on aspects of soil water storage, N mineralisation, crop growth and grain yield.

Table 1. Soil characteristics (0–10 cm) at the field site

Property	Value
pH (1 : 5)	7.3
Bicarbonate-extractable P (mg/kg)	>120
Replaceable K (cmol (+)/kg)	1.67
CEC (cmol (+)/kg)	65
Exchangeable Ca^{++} (cmol (+)/kg)	33
Exchangeable Mg^{++} (cmol (+)/kg)	26
Exchangeable Na^{+} (cmol (+)/kg)	3.4
Exchangeable K^{+} (cmol (+)/kg)	0.21
Total N (%)	0.10
Organic C (%)	1.7
Clay (%)	68
Wilting point (%)	29.0
Bulk density (g/cm^3)	1.1

Materials and methods

Experimental site

The experiment is being conducted at Hermitage Research Station (28°12' S., 152°06' E.), 8 km east of Warwick on the southern Darling Downs in Queensland. The soil is a deep, alluvial, black, montmorillonitic clay (Ug 5.17, Northcote 1974). Some properties of the surface soil are shown in Table 1. The pH gradually increases with depth to 8.6 at 90–120 cm. Organic carbon and clay content gradually decrease to 0.9% and 64% respectively at that depth. Between 10 and 180 cm depth, wilting point and bulk density remain relatively constant at approximately 29% and 1.2 g/cm^3 respectively.

The 34-year average annual rainfall is 717 mm, of which about 68% occurs from October through March. Mean monthly maximum temperature is 30°C in January and the mean monthly minimum is 1.5°C in July. Mean pan evaporation ranges from 6.8 mm/day for December to 2.0 mm/day for June.

We believe that the site was first ploughed in the early 1900s. From that time a range of annual winter and summer grain crops has been grown in rotation with periods of pasture. The 1968 crop, which preceded the establishment of this experiment, was wheat (cv. Timgalen).

Experimental design

Treatments comprise a factorial combination of 2 fallow tillage methods (Tc, mechanical tillage; Tz, zero tillage) x 2 stubble management strategies (Sb, stubble burnt after harvest; Sr, stubble retained) x 3 rates of N fertiliser, applied as urea before sowing (N0, no fertiliser; N1, 23 kg N/ha; and N2, 46 kg N/ha for the 1969–76 crops and 69 kg N/ha for succeeding crops). These 12 treatments are replicated 4 times in randomised blocks. The plots were split longitudinally in 1979 with both wheat and barley sown.

Plots are open-ended so that surface water can run off, but are separated laterally by low earth banks to prevent interplot movement of water. The site slopes gently down the plots with a fall of less than 1%. Sown and harvested plot widths vary slightly with the range of sowing machinery used but are approximately 5.5 and 4.8 m respectively. Harvested plot length is 60.7 m.

Agronomic procedures

The dates of all major agronomic measurements and treatment applications are shown in Table 2.

In each year stubble is burnt shortly after harvest and immediately before initial tillage. Stubble burning was not possible in the 1970–71 fallow period because stubble was sparse and wet weather after harvest promoted heavy weed growth.

Table 2. Dates of major agronomic measurements and treatment applications, 1969–79

Crop year	Postharvest soil sampling	Initial ploughing	Pre-sowing soil sampling	Nitrogen fertiliser application	Sowing	Crop measurements: Establishment	Crop measurements: Early tillering growth	Crop measurements: Dry matter at anthesis	Grain harvest
1969	12.xii.68	18.xii.68	2.vi.69	19.vi.69	19.vi.69	11.vii.69	—	16.ix.69	2.xii.69
1970	11.xii.69	19.xii.69	25.v.70	1.vi.70	26.ix.70	17.x.70	—	1.xii.70	8.i.71
1971	—[A]	1.iii.71	25.v.71	3.vi.71	28.vii.71	20.viii.71	—	18.x.71	13.xii.71
1972	17.xii.71	23.xii.71	22.v.72	30.v.72	21.viii.72	11.ix.72	—	1.xi.72	3.i.73
1973	8.i.73	22.i.73	28.v.73	1.vi.73	8.viii.73	30.viii.73	—	—	10.xii.73
1974	17.xii.73	19.xii.73	7.v.74	17.v.74	12.vi.74	10.vii.74	—	—	2.xii.74
1975	12.xii.74	22.xii.74	7.v.75	4.vi.75	23.vii75	15.viii.75	—	16.x.75	28.xi.75
1976	4.xii.75	10.xii.75	31.v.76	9.vi.76	4.viii.76	1.ix.76	9.ix.76	18.x.76	7.xii.76
1977	9.xii.76	14.xii.76	6.vi.77	9.vi.77	14.vi.77	18.vii.77	5.viii.77	14.ix.77	17.xi.77
1978	22.xi.77	29.xi.77	29.v.78	20.VI.78	23.vi.78	21.vii.78	7.viii.78	20.x.78	8.xii.78
1979	14.xii.78	19.xii.78	29.v.79	5.vi.79	10.vii.79	1.viii.79	20.viii.79	1.x.79[B] 12.x.79[C]	6.xii.79

[A] Not sampled. [B] Barley plots. [C] Wheat plots.

Tilled plots are chisel-ploughed shortly after harvest to a depth of 10–15 cm. The timing of subsequent tillage operations is determined by the need to control weed growth and prepare a seed-bed. All tillage operations, which average 5 per fallow season, are with tined implements.

Fallow weed growth under Tz is controlled by herbicides, supplemented as necessary by hand-weeding. Herbicides used during fallow periods include diquat, paraquat, 2,4-D, 2,2-DPA and glyphosate. The number of herbicide applications per fallow season approximates the number of tillage operations required for the Tc treatments.

Prolonged wet weather during the 1970–71 fallow delayed applying fallowing treatments until March 1971. This allowed barnyard grass (*Echinochloa crus-galli*) to seed and become the major weed of the fallow phase. Complete control of the grass was not possible with the non-residual herbicides then available so that with TzSr and, to a lesser extent, TzSb, it was only suppressed. Burning assisted with control in the latter treatment. Since 1976–77, glyphosate has provided excellent control of barnyard grass under these treatments.

In 1969, N fertiliser was applied as urea (46% N) at sowing through a tined combine. Subsequently the urea has been applied before sowing (Table 3) through a triple-disc drill.

Wheat (cv. Timgalen) was sown annually during 1969–74 and in 1978. Barley (cv. Clipper) was sown in 1975–77. In 1979 both wheat and barley were sown in split-plots so that the effect of treatments on growth and yield of each crop could be compared under the same seasonal conditions. Details of sowing machinery, sowing rates and row spacings are shown in Table 3.

Table 3. Details of sowing procedures and crop species, 1969–79

Year of Crop	Sowing machinery	Crop species	Sowing rate (kg/ha)	Row spacing (cm)
1969	Tined combine with 15 cm points (Tc)[A] or 5 cm points (Tz)[B]	Wheat	58	17.5
1970	Triple-disc seeder	Wheat	84	15.0
1971	Tined planter (Tc)	Wheat	58 (Tc)	15.0
	Triple-disc seeder (Tz)		58 + (Tz)	15.0
1972	Triple-disc seeder	Wheat	78	15.0
1973	Tined scarifier-seeder with press-wheels	Wheat	62	17.5
1974	Triple-disc seeder	Wheat	60	15.0
1975	Triple-disc seeder	Barley	72	20.0
1976	Rigid-tined seeder with narrow points and press-wheels	Barley	78	22.5
1977	Rigid-tined seeder with narrow points and press-wheels	Barley	62	22.5
1978	Rigid-tined seeder with narrow points and press-wheels	Wheat	51	22.5
1979	Rigid-tined seeder with narrow points and press-wheels	Wheat	67	22.5
		Barley	74	22.5

[A] Tc, mechanical cultivation. [B] Tz, zero tillage.

In most years broadleaf weeds were controlled during the cropping phase by applying bromoxynil/MCPA (300/300 g a.i./ha) during early tillering of the crop. The 1969 and 1977 crops were not treated. The most prevalent broadleaf species were climbing buckwheat (*Polygonum convolvulus*), wireweed (*Polygonum aviculare*) and dead nettle (*Lamium amplexicaule*). The grass species, wild oats (*Avena* spp.) and prairie grass (*Bromus unioloides*), were hand-weeded from the crops. We consider these control measures have prevented significant in-crop weed competition during the course of the experiment.

The plots were harvested with an autoheader in all years. Harvest dates are shown in Table 2.

Soil sampling (Loch and Coughlan 1984) had indicated above-normal concentrations of exchangeable sodium in the surface soil of the site. We considered this may have been differentially influencing the effect of treatments on water infiltration. Therefore in December 1974, after stubble burning but prior to initial ploughing, gypsum was applied at 7 t/ha over the trial area to reduce the concentration of exchangeable sodium in the surface soil.

Measurements

Plots were sampled for soil water content and nitrate-N status after harvest and shortly before anticipated sowing, but before N fertiliser application, in each year (Table 3). Soil samples were usually collected from depths of 0–15 cm, 15–30 cm and then in 30 cm increments to 180 cm. A composite sample was obtained from three 5 cm diameter cores per plot. Subsamples were taken for available water and nitrate-N determination. All treatments were sampled in the fallowing seasons 1968–69 to 1973–74 inclusive. In subsequent seasons N1 treatments were not sampled.

Mean bulk density of each soil depth increment was determined by taking a number of soil cores from the trial area for each increment when the profile was wet. Wilting point (pF = 4.2) of the soil for each depth increment was determined by means of Richard's pressure plate apparatus. Percentage soil moisture was determined by oven-drying the field samples at 105°C to a constant weight. Total soil water for each depth increment was calculated by taking account of bulk density. Available soil water for each depth increment was calculated by taking account of bulk density and wilting point. Bulk density values were not corrected for varying soil water content at different sampling times. The use of an average bulk density, derived for a wet profile, would have introduced maximum errors in estimating stored water of 8% for the 0–15 cm layer, and 6% for the rest of the profile (based on the range of water contents measured). For the bulk of the water storage calculations, errors would have been less than those maximum values, and are considered negligible for the purposes of this study.

In the field, samples for nitrate-N determination were stored in the shade in air-tight plastic bags, then transferred within 6 h to a forced-air dehydrator and dried at 42°C for 24 h. They were then ground and stored for analysis.

Measurements of soil temperature by soil thermographs were obtained in 1 replication for 2 treatments [zero tillage with stubble retained (3.6 t/ha) and zero tillage with stubble burnt] during the winter of 1977. The sensor probes were placed in the soil either 2 mm below the surface or at 5 cm depth, and the soil was moistened to remove air pockets.

Crop establishment was measured at the 2–3 leaf stage of crop growth in each year. Seedlings were counted from 10 or 15 randomly selected 1 or 1.5 m lengths of row in each plot.

In cropping years 1976–79, 20 plants were pulled at random from each plot during the early tillering growth stage. The top-growth was oven-dried at 82°C for 24 h prior to determining dry weight and N content.

At anthesis in each year (except 1974 and 1975), 2 adjacent rows, each 1 m long, were cut at ground level from 3 random positions in each plot. The material was dried at 82°C for 48 h and then weighed. In 1969 only, 1 position per plot was sampled. Nitrogen content of the dried samples was determined for the years 1975–79.

Grain yield at field moisture was measured at harvest. Prior to harvest, buffer areas of 2 rows at each side of the plots and 0.6 m at each end were discarded. Evapotranspiration or water use (WU) was calculated by subtracting the profile (0–150 cm) soil water at harvest from the soil water at the pre-sowing sampling and adding the rainfall for that period. As pre-sowing sampling preceded sowing by up to several months in some years (Table 2), the values reported are overestimations in most instances. Water use efficiency (WUE) for grain production values were calculated by dividing crop grain yield by evapotranspiration. Marginal water use efficiency (MWUE) for grain production was calculated as the grain yield increase per unit of extra water use. In each season the N content of the grain was determined.

Chemical analyses

The chemical analyses and particle size determinations for site characterisation (Table 1) used standard methods of the Agricultural Chemistry Branch, Queensland Department of Primary Industries [described by Bruce and Rayment (1982)].

Soil samples for nitrate analysis were extracted with 2 mol/L KCl, and nitrate determined in the extract using the method of Best (1976).

Nitrogen concentrations (%) in plant samples were determined by micro-Kjeldahl digestion and in grain samples by Method 46-12 of the AACC (1962).

Statistical analyses

A factorial analysis of variance was used to analyse the results of the experiment. In Tables 5–12 the l.s.d. values refer to the individual means in the tables. The model described in Fig. 4 was fitted by a general linear model procedure.

Results

Soil water accumulation

Pre-sowing levels. Pre-sowing available soil water to 150 cm, meaned over years and treatments, was 221 mm and ranged from 112 mm in 1970 to 313 mm in 1977 (Fig. 1). The means for the fallowing treatments were 252, 225, 212 and 195 mm for TzSr, TzSb, TcSr and TcSb respectively.

Tz and Sr treatments resulted in greater ($P<0.01$) pre-sowing water than did Tc and Sb respectively. Tz was the major factor operating to maximise soil water at sowing. It resulted in a statistically significant ($P<0.05$) main effect in 7 years and interacted positively with Sr in another year. In 4 years Sr operated independent of tillage and N fertiliser use in improving pre-sowing water. In another 2 years there was improved pre-sowing soil water associated with Sr only when no N fertiliser had been used with the previous crops.

Fig. 2 shows that the most marked fallow increases in water storage occur in the 0–120 cm zone of the soil profile. Although additions are not so marked at greater depths, the 120–180 cm zone does show evidence of water accumulation, for example, 1975–76 fallow. The superior moisture at pre-sowing associated with TzSr occurred regularly to a depth of 150 cm and occasionally to 180 cm.

Fallow water storage efficiency. Averaged over years and treatments, fallowing efficiency (expressed as a percentage of fallow rainfall stored) in this experiment was 22.4% (Table 4). Treatment means over all seasons and N rates of N0 and N2 were 27.4% for TzSr, 24.5% for TzSb, 20.3% for TcSr and 17.5% for TcSb. A segregation of the fallow periods into 'dry' and 'wet' starts (Table 4) shows the trend for Tz, especially with Sr, to have greater fallowing efficiency when the soil profile is relatively dry at the start of the fallow. With 'wet' starts the treatments had no consistent effects on fallowing efficiency. The 1978–79 treatment trends in fallowing efficiency were similar to those for 'dry' starts, possibly reflecting the below-average rainfall of that fallow period.

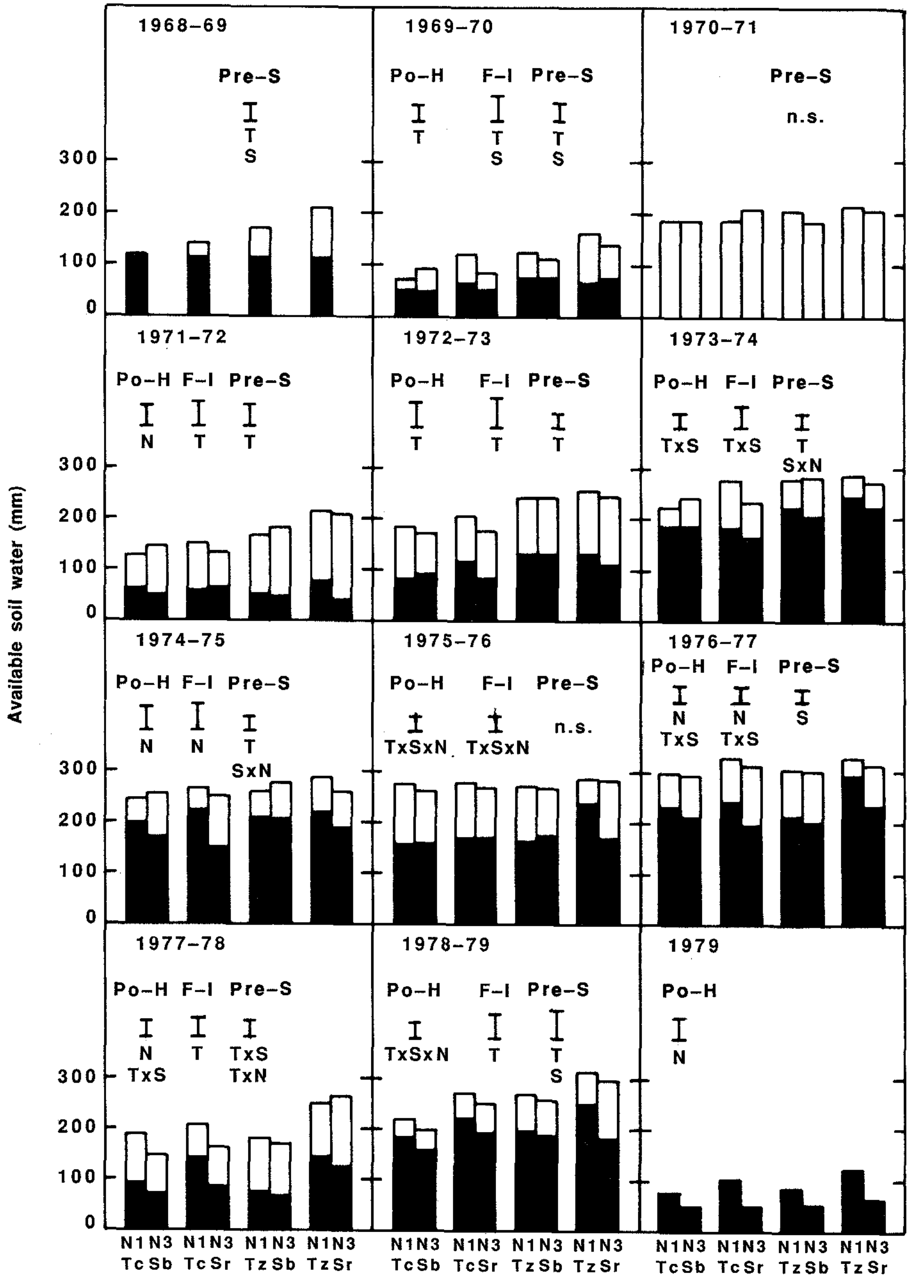

Fig. 1. Effect of 4 fallowing and 2 nitrogen fertiliser treatments on available soil water at 0–150 cm at postharvest (Po-H), increase during the fallow period (F-I), and total available soil water before sowing (Pre-S) for the fallow periods of 1968–69 to 1978–79 inclusive and for postharvest of the 1979 barley crop. The shaded segments of the bars indicate Po-H amounts, open segments indicate F-I. Vertical bars indicate l.s.d. (P=0.05) for comparisons between individual treatments for Po-H, F-I and Pre-S. Significant (P<0.05) factorial effects are indicated by treatment symbols. Site mean data, only, were determined Po-H for the 1968–69 period. Pre-S data, only, are available for the 1970–71 period.

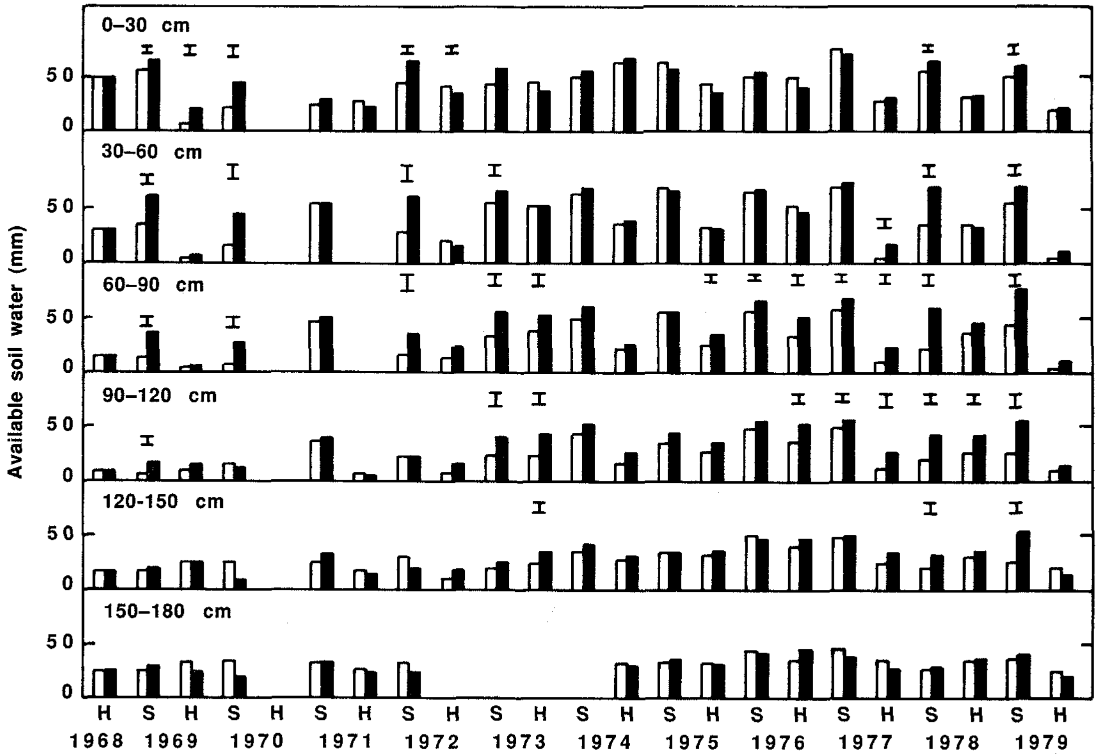

Fig. 2. Profile distribution of available soil water at harvest (H) and pre-sowing (S) for 2 fallowing treatments for the period 1968–79. (□) TcSbN2, (■) TzSrN2. Vertical bars indicate l.s.d. (P = 0.05) when the 2 treatments differ at that level of significance. Data are not available for the 1970 harvest or for the 150–180 cm zone for the samplings of 1972 harvest to 1974 pre-sowing inclusive.

Table 4. Percentage of fallow rainfall stored at 0–150 cm in the soil ('fallowing efficiency') under 4 fallow treatments in relation to postharvest soil water and fallow rainfall (mean of N0 and N2 treatments)

Fallow period	Postharvest available water (mm)	Fallow season rainfall[A] (mm)	Cultivated: Stubble burnt(%)	Cultivated: Stubble retained(%)	Zero tillage: Stubble burnt(%)	Zero tillage: Stubble retained(%)
		Initially 'dry' (post-harvest available water <130 mm)				
1968–69	121	243 (296)	4.1	10.3	25.1	36.6
1969–70	64	307 (419)	9.6	14.7	15.3	25.5
1971–72	57	311 (327)	25.1	25.8	39.8	48.2
1972–73	111	331 (294)	27.0	27.1	33.8	39.2
1977–78	101	308 (435)	28.0	23.2	32.6	39.1
Mean			18.8	20.2	29.3	37.7
		Initially 'wet' (postharvest available water >170 mm)				
1973–74	202	333 (336)	14.3	24.9	20.4	14.8
1974–75	197	426 (353)	16.2	16.2	14.1	16.9
1975–76	176	577 (406)	19.9	17.9	17.3	14.1
1976–77	230	418 (396)	18.1	24.6	22.8	13.6
1978–79	201	310 (371)	12.5	18.2	23.4	25.6
Mean			16.2	20.4	19.6	17.0
Overall means			17.5	20.3	24.5	27.4

[A] 34-year average for the equivalent period is in parentheses.

A model was fitted to the data in Table 4:

$$y = -154.3 + 84.3t - 0.7s + 51ts - 0.2257ph - 0.015tph + 1.045fr - 0.1657tfr - 0.000929fr^2$$
$$(R^2 = 56.5\%)$$

where y is fallow water accumulated (mm); $t = 0$ if Tc and 1 if Tz, $s = 0$ if Sb and 1 if Sr; ph is postharvest available water (mm); and fr is fallow rainfall (mm).

Using this model, a description of the effects of tillage, stubble, postharvest soil water and fallow rainfall is given in Fig. 3. The model indicates the greater fallowing efficiency of Tz over Tc for initially 'dry' fallows and suggests that Tz is superior to Tc over a range of post-harvest soil water values for low fallow rainfall. Fig. 3 also shows the interaction between tillage and stubble management, that is, the greater efficiency of Sr over that of Sb with Tz for initially 'dry' fallows.

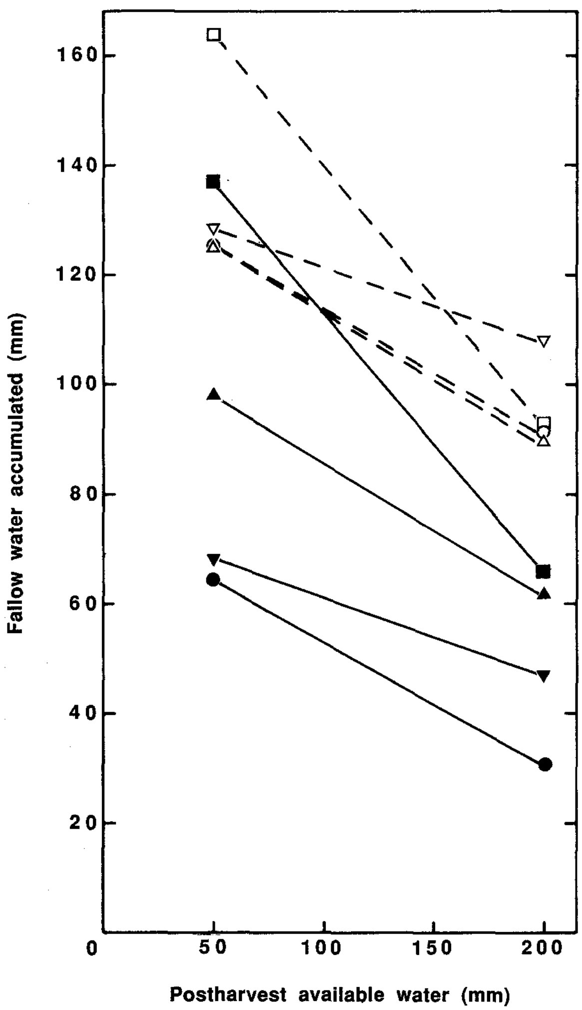

Fig. 3. Predictions from the model of fallow water accumulation for two values of fallow rain (300 mm, closed symbols and 500 mm, open symbols) and 4 fallow treatments (●○ TcSb, ▼▽ TcSr, ▲△ TzSb, ■□ TzSr) over a range of postharvest available water values (means of N0 and N2 fertiliser rates).

In the 1974–75 and 1976–77 fallows a greater increase in water storage occurred with N2 than with N0 (Fig. 1). This was associated with greater water storage at the start of these fallow periods in N0 plots.

Soil and crop water relations

Evapotranspiration. Crop evapotranspiration or water use (WU), averaged over all fallowing treatments, 2 N rates (N0 and N2) and all years, was 414 mm (Table 5). On average, WU with Tz (422 mm) significantly ($P<0.01$) exceeded that with Tc (406 mm) whilst with N2, WU (421 mm) significantly ($P<0.01$) exceeded that with N0 (408 mm). However, in 1976 and 1977 barley crops, TzSr resulted in lower WU ($P=0.052$) than did other treatments whilst in the crops from 1970 to 1975 inclusive there was no significant difference between treatments in WU.

Water use efficiency (WUE). Meaned over 11 crops, WUE for grain production (Table 5) was 6.7 kg/ha.mm and was greater ($P<0.01$) with Sb (6.8 kg/ha.mm) than with Sr (6.5 kg/ha.mm).

In 3 years (1973, 1974 and 1976), WUE was greater for Tc than for Tz. In 1977 Tz resulted in greater WUE than did Tc. A significant superiority of Sb over Sr occurred in 4 years (1969, 1973, 1974 and 1977). Nitrogen fertiliser application (N2) reduced WUE in 1974 and increased it in 1978 and 1979. TzSr was markedly more efficient than other treatments in 1970 but was less efficient than other treatments in 1972 and 1978. Application of N fertiliser increased efficiency when stubble was retained, but not when stubble was burnt, in 1970. In the 1975 barley crop, WUE of TzSr was improved by the addition of N2 whilst the other 3 fallowing treatments were reduced in WUE with N2.

Marginal water use efficiency (MWUE). The MWUE (expressed in kg grain/ha.mm) for the increased water use associated with Tz in 1969 was similar, at 3.8, to the overall WUE for Tz of 4.0. However MWUE associated with Tz in 1979 was greater at 9.6 than the average of 6.9 for the treatment.

The extra water use associated with Sr in 1969 was associated with lower yields than those attained with Sb and hence a negative MWUE. The increased water use associated with Sr in the 1979 barley crop was associated with a considerably lower MWUE of 0.5 than the overall WUE of the treatment of 6.6. In 1977, stubble burning resulted in increased water use and a large MWUE of 29.4 kg/ha.mm.

The extra water use by N2 over that of N0 resulted in MWUE of 10.9 versus the average WUE of N2 of 8.8 in 1976, and 17.7 versus the average of 7.2 in 1979.

Table 5. Effect of fallow and N fertiliser treatments on wheat (W) and barley (B) water use (mm) and water use efficiency (kg/ha.mm) at 0–150 cm for each of the eleven crops and overall mean

Fallow treatment	1969 W	1970[A] W	1971 W	1972 W	1973 W	1974 W	1975 B	1976 B	1977 B	1978 W	1979 B	Mean
					Water use (mm)							
TcSbN0	325	330	405	450	404	424	444	471	302	407	395	396
TcSbN2	358	335	415	459	393	469	446	479	325	391	401	406
TcSrN0	376	351	405	440	430	448	442	464	289	384	422	407
TcSrN2	366	326	428	458	417	476	432	499	329	369	460	416
TzSbN0	379	352	431	445	427	465	447	483	327	385	441	419
TzSbN2	373	364	416	456	443	472	451	493	332	376	461	424
TzSrN0	430	346	420	487	421	468	402	422	281	378	446	409
TzSrN2	394	342	442	505	429	481	438	474	288	481	489	436
l.s.d. (P=0.05)	61.4	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	40.6	41.3	42.0	51.5	14.2
Significance of factorial effects												
T	*										**	**
S	*								*		*	
N											*	**
T x S								*		**		
T x N								*		**		
S x N										*		
T x S x N										*		
					Water use efficiency (kg/ha.mm)							
TcSbN0	4.7	2.8	9.1	5.2	4.6	8.4	8.3	9.6	9.1	6.7	6.6	6.8
TcSbN2	4.1	2.7	9.3	5.1	4.5	7.7	7.4	9.1	9.4	8.0	7.4	6.8
TcSrN0	3.7	3.1	8.8	4.9	3.4	8.2	8.8	9.0	6.7	7.0	6.1	6.3
TcSrN2	3.8	4.2	8.7	5.7	4.0	7.5	8.2	8.8	7.6	8.3	6.8	6.7
TzSbN0	4.1	4.0	8.8	5.5	3.5	8.0	8.5	8.6	9.9	7.6	7.0	6.8
TzSbN2	4.2	3.8	8.8	5.5	3.8	7.8	7.2	8.6	10.0	8.7	7.3	6.9
TzSrN0	3.5	5.6	8.8	4.3	2.9	7.1	8.1	7.7	8.8	6.3	6.2	6.3
TzSrN2	4.1	6.3	8.4	4.7	3.0	6.6	9.2	8.6	9.1	6.7	7.2	6.7
l.s.d. (P=0.05)	0.79	0.87	n.s.	0.96	0.62	1.03	0.84	1.17	1.45	0.98	1.30	0.40
Significance of factorial effects												
T		**			**	*		*	**			
S	*	**			**	*	**		**	*		**
N						*				**	*	
T x S		*		*						**		
T x N												
S x N		*					**					
T x S x N							*					

* $P < 0.05$; ** $P < 0.01$.

[A] Soil water sampling postharvest of the 1970 crop was interrupted by rain. Data have been adjusted to the values of the first replicate which were obtained before rain.

Soil water at harvest. Meaned over years (including 1979 after barley, but omitting 1970), 4 fallowing treatments and 2 N fertiliser rates (N0 and N2), available soil water (0–150 cm) at harvest was 141 mm. The range was 57 mm in 1971 to 230 mm in 1976 (Fig. 1).

The relationship between growing period rainfall and the reduction in amount of stored water in the 0–180 cm profile during the growing period (meaned over treatments) is shown in Fig. 4. Reduction in stored water decreased linearly with increased growing season rainfall.

The greatest postharvest soil water values were recorded for the TzSr treatment in 1973, 1976 and 1977 when the stubble management x tillage treatment interactions were significant (Fig. 1). Use of N fertiliser resulted in reduced soil water at harvest, independent of fallowing treatment, in 5 years (1971, 1974, 1976, 1977 and 1979). In 1975 and 1978, higher soil water at harvest occurred under TzSrN0 but not under TzSrN2.

Extraction at depth. The major crop use of available soil water is from the 0–120 cm zone(Fig. 2). However, although crop use from greater depths is less, the 120–180 cm zone does show evidence of reductions in available water by some crops (i.e. the 1971, 1977 and 1979 crops).

Table 6. Effect of fallow and N fertiliser treatments on wheat (W) and barley (B) grain yield (kg/ha) for each of the 12 crops and overall mean

Treatment	1969 W	1970 W	1971 W	1972 W	1973 W	1974 W	1975 B	1976 B	1977 B	1978 W	1979 W	1979 B	Mean
TcSbN0	1452	1039	3689	2340	1870	3548	3660	4467	2754	2725	2061	2616	2685
TcSbN1	1468	1082	3735	2316	1753	3525	3410	4430	2928	3029	2163	2993	2736
TcSbN2	1438	1012	3835	2314	1763	3609	3267	4390	2978	3105	2042	2871	2718
TcSrN0	1309	1222	3574	2173	1456	3686	3863	4152	1926	2670	1770	2568	2531
TcSrN1	1374	1373	3739	2457	1717	3552	3809	4420	2290	3027	2428	3054	2770
TcSrN2	1317	1536	3725	2609	1652	3563	3509	4391	2492	3081	2210	3126	2768
TzSbN0	1529	1563	3781	2408	1484	3709	3777	4134	3185	2907	1989	3034	2792
TzSbN1	1504	1671	3702	2317	1676	3638	3622	4383	3287	3363	2280	3525	2914
TzSbN2	1505	1543	3650	2483	1699	3646	3247	4270	3320	3240	2040	3378	2835
TzSrN0	1505	2137	3691	2066	1225	3301	3239	3250	2463	2388	1776	2756	2483
TzSrN1	1471	2345	3517	2321	1349	3291	4019	3609	2683	2945	2208	3378	2769
TzSrN2	1549	2346	3691	2365	1300	3142	4014	4083	2530	3247	2236	3508	2834
l.s.d. (P=0.05)	100.2	283.4	157.9	304.4	183.7	204.3	292.4	314.9	249.6	216.6	274.7	334.3	119.0
Significance of factorial effects													
T	**	**			**	**		**	**			**	**
S	**	**	*		**	**	**	**	**	**			**
N				*	*		*	**	**	**	**	**	**
T x S	**	**				**		**		**			*
T x N			**				**	*					
S x N				*			**	*		*	**		**
T x S x N					*		**						

* $P < 0.05$; ** $P < 0.01$.

Grain yield

Mean grain yields for the 12 crops of the experiment (Table 6) show a significant (P<0.05) T x S interaction, with TzSb (2847 kg/ha) highest. The mean yield of the other 3 fallowing treatments was 5% lower. Stubble retention depressed yield by 8% when no N fertiliser was applied, but yielded similarly to stubble burnt plots with N fertiliser addition. There was no significant response to N fertiliser addition when stubble was burnt.

In 1969 there was a significant (P<0.01) T x S interaction with a yield reduction associated with Tc being greater with Sr than with Sb.

In 1970 there was again a significant (P<0.01) T x S interaction with marked differences in yield between the 4 fallowing treatments. There were large responses to both Tz and Sr with the response to Sr, being more pronounced with Tz than with Tc.

Treatments had little effect on grain yield in 1971. In 1972 grain yield was depressed by Sr by 254 kg/ha (11%) when no N fertiliser was applied.

A significant T x S x N interaction in 1973 was for fallowing treatments other than TcSb to respond to nitrogen fertiliser application (N1). TcSb was superior to TcSr and TzSb only when no nitrogen fetiliser was

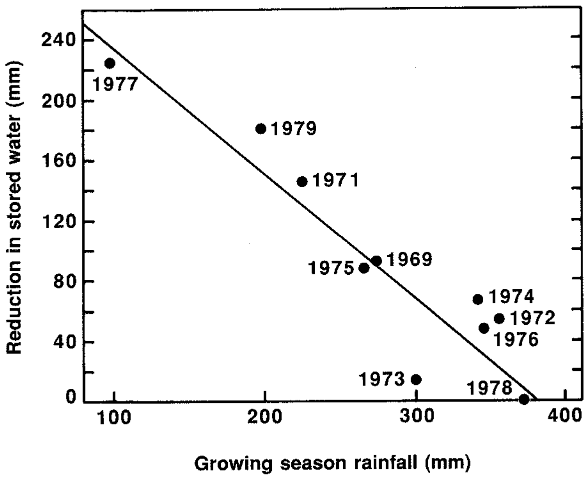

Fig. 4. Effect of growing season rainfall on reduction in stored water by 10 crops. Data points are superscripted by the year of the crop and are the means of the 4 fallowing treatments and N0 and N2 fertiliser rates. The equation of the line is:

$$Y = 319.63 - 0.84X \quad (R^2 = 0.87)$$

applied. TzSr was lower yielding (*P*=0.064) than the other fallowing treatments at all rates of N.

In 1974 the grain yield of TzSr (3245 kg/ha) was again inferior to that of the other fallowing treatments which were of similar yield and averaged 3608 kg/ha.

With the first barley crop (1975), N fertiliser application interacted markedly with tillage and stubble factors. At N0, TzSr yielded less than other treatments. However, the latter progressively declined in yield with increasing N fertiliser application whilst TzSr yield increased to be greater than that of the other treatments at the N1 and N2 levels.

The poorer yield of TzSr, relative to other treatments with the barley crop of 1976, was progressively improved with increasing rates of N fertiliser, but was still inferior to the other treatments at N2. The T x N and S x N interactions were both significant (*P*<0.05) with N application increasing yield with Tz and Sr, but not with Tc or Sb.

The grain yields of the 1977 barley crop responded to Tz, Sb and N fertiliser application, with no significant interaction between those factors. The major N response (215 kg/ha) occurred at the N1 level with no further significant response at N2. Mean grain yields for the 4 main treatments were 3264 kg/ha for TzSb; 2887 kg/ha for TcSb; 2559 kg/ha for TzSr; and 2236 kg/ha for TcSr.

In 1978, TzSb (3170 kg/ha) outyielded TcSb (2953 kg/ha), TcSr (2926 kg/ha) and TzSr (2860 kg/ha). Sb gave a higher yield than Sr at N0 and N1 but at N2 yields were not significantly different.

With the 1979 wheat crop, Sr depressed grain yields by 13%. However, for the N1 and N2 treatments, yields in stubble retained plots improved significantly to be greater than those of burnt plots. The responses in the barley crop of the same year were to the main effects of Tz (13% yield increase) and N fertiliser (14% increase with N1).

Grain nitrogen

In most years, TzSr produced grain of the lowest N concentration. Usually this was associated with significant main effect reductions for both Tz and Sr. However, the 1978 and 1979 wheat crops which followed 3 barley crops did not follow this pattern, but the 1979 barley crop did so as did barley in 1975, 1976 and 1977.

A significant (*P*<0.01) response to N fertiliser application was recorded in each crop from 1972 onwards. Before 1972 this response occurred only in TzSr in 1970. Percentage grain N did not appear to be related to either grain yield or time of sowing.

Soil nitrate-nitrogen

Soil nitrate concentration data are available for the 1975–76 and subsequent fallows only. The nitrate-N data for 0–90 cm profile for the 1975–76 to 1978–79 fallow periods are presented in Table 7. The mean increase of nitrate-N over the 4 fallow periods and all treatments was 61 kg/ha. The mean postharvest quantity was

Table 7. Effect of fallow and N fertiliser treatments on soil nitrate-N (kg/ha) at 0–90 cm for postharvest (Po-H), pre-sowing (Pre-S) and fallow period increase (F-I), 1975–76 to 1978–79

Treatment	1975–76			1976–77			1977–78			1978–79		
	Po-H	F-I	Pre-S	Po-H	F-I	Pre-S	Po-H	F-I	Pre-S	Po-H	F-I	Pre-S
TcSbN0	26	49	75	12	67	79	33	85	118	14	66	90
TcSbN2	74	33	107	18	76	97	72	98	170	69	58	126
TcSrN0	27	56	83	9	46	55	33	62	95	18	52	70
TcSrN2	31	61	91	19	77	96	70	67	137	69	67	136
TzSbN0	26	57	83	10	70	81	33	56	89	17	69	86
TzSbN2	48	61	109	19	82	101	77	63	140	81	56	137
TzSrN0	22	25	47	16	52	68	29	63	92	26	41	67
TzSrN2	18	41	59	8	67	75	80	69	148	53	52	105
l.s.d. (*P*=0.05)	18.8	21.4	21.6	n.s.	20.4	16.6	20.9	n.s.	32.0	14.9	23.5	20.9
Significance of factorial effects												
T	*		**									
S	**		**		*	**						*
N	**		**		**	**	**		**	**		**
T x S		**	**						*			*
T x N												
S x N	**										*	
T x S x N												

* $P < 0.05$; ** $P<0.01$.

36 kg/ha. Nitrogen fertiliser application consistently increased soil nitrate at both postharvest and pre-sowing samplings.

Stubble management was the major factor affecting soil nitrate increase during the 4 fallowing periods (Table 7) for which data are available. During the 1975–76 fallow period the increase in soil nitrate was greater for Sr than for Sb when the fallow was tilled, but greater for Sb than Sr when zero tillage was employed. During the 1976–77 period both Sr and lack of N fertilisation of the preceding crops resulted in decreased accumulation of nitrate. In the 1978–79 period, Sr resulted in decreased nitrate accumulation when N fertiliser (N2) had not been applied to the preceding crops.

Pre-sowing nitrate levels (Table 7) combine the treatment effects present at the previous harvests, which were largely residual effects from N fertiliser (N2) treatments, and the treatment effects produced during the preceding fallow periods, which were largely stubble management and N fertiliser effects. In 1976 and 1979, the TzSr plots had lower soil nitrate at pre-sowing than did those of the other 3 management treatments.

The distribution pattern of nitrate N under selected treatments is shown in Fig. 5. There was a marked seasonal carryover of nitrate-N in TcSb, particularly where N fertiliser had been applied, at depths below 90 cm. Greater quantities were present at depth with applied N fertiliser than with no fertiliser in that treatment. Much less carryover and accumulation of nitrate-N at depth is evident under TzSr even with applied N fertiliser.

Crop establishment and growth

Fallowing treatments significantly affected establishment of all crops (Table 8). Tz and Sr, acting either together or independently, resulted in the lowest crop establishment with TzSr in 8 out of 12 crops. In 1969, when the urea fertiliser was applied with the seed, there was a 9% depression in crop establishment at the highest rate of application in the Sb plots (data not shown). Nitrogen effects in other years were rare and minimal.

At early tillering, the TzSr plots for wheat (1979 crop) and barley (1976, 1977, 1979 crops) produced less dry matter than each of the other 3 fallowing treatments (Table 9). TcSr also produced significantly less dry matter than TcSb in each of the barley crops. The positive dry matter response to N fertiliser in the 1976 and 1979 barley crops was independent of fallowing treatment. The Sb treatments of the 1977 barley crop responded to N fertiliser whilst Sr treatments did not. The 4 fallowing treatments responded in dry weight to N1 but only TcSb gave an additional response to N2. The 1979 wheat crop did not respond to N application.

At early tillering, the N concentration of the top-growth (meaned over all treatments) was 6.4, 6.0, 5.9, 5.3 and 5.9% (w/w) in the 1976, 1977, 1978, 1979 (wheat) and 1979 (barley) crops respectively. There were no significant differences between treatments in 1976 and 1978. In the 1979 wheat crop, a slight, but

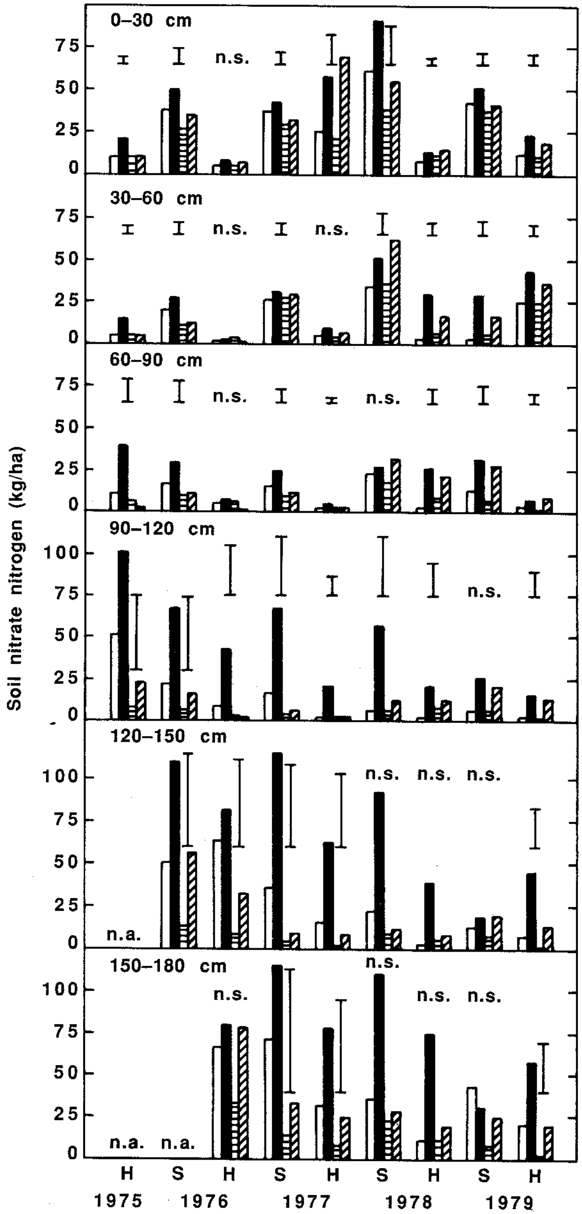

Fig. 5. Profile distribution of soil nitrate-N at harvest (H) and pre-sowing (S) for 4 treatments for the period 1975–79. (□) TcSbN0, (■) TcSbN2, (▤) TzSrN0, (▨) TzSrN2. Vertical bars indicate l.s.d. (P=0.05) for comparison between individual treatments. n.s., no significant difference (P>0.05) between treatments; n.a., data not available.

Table 8. Effect of fallow treatments on wheat (W) and barley (B) establishment (seedlings/m^2) for each of 12 crops
Data from the N fertiliser treatments are meaned

Treatment	1969 W	1970 W	1971 W	1972 W	1973 W	1974 W	1975 B	1976 B	1977 B	1978 W	1979 W	Mean
TcSb	120	150	165	174	116	148	129	123	66	99	121	112
TcSr	125	141	161	165	111	145	129	119	59	94	115	109
TzSb	112	145	194	154	112	138	127	104	61	100	102	100
TzSr	127	146	200	128	94	132	116	91	62	88	89	92
l.s.d. (P=0.05)	8.1	6.2	9.2	14.4	4.3	7.3	6.5	4.4	4.2	4.9	5.6	5.6
Significance of factorial effects												
T			**	**	**	**	**	**			**	**
S	**			**	**		*	**		**	**	*
T x S		*			**		*	**	*			

* P < 0.05; ** P < 0.01.

significant (P<0.05) depression in N concentration (from 5.35 to 5.20%, w/w) with Sr at N0 and N1 was overcome at N2. Some slight significant (P<0.05) differences between treatments in the 1977 and 1979 barley crops are considered of no practical significance.

With the 1969 wheat crop, dry matter production at anthesis increased in response to Tz (Table 10). A response to Tz occurred again in 1970 and was greater with Sr than with Sb. A significant S x N interaction with Sr, but not Sb, responding in anthesis dry matter production to N fertiliser application occurred with the 1970 and 1971 wheat crops and the 1975 barley crop. The same S x N interaction trend was recorded with the 1972 wheat crop (P=0.054) and the 1976 barley crop (P=0.077).

Table 9. Effect of fallow and N fertiliser treatments on dry weight (g DW/20 plants) of the above-ground parts of wheat (W) and barley (B) at early tillering in several years

Treatment	1976 B	1977 B	1978 W	1979 W	1979 B
TcSbN0	5.7	8.0	3.1	2.5	3.9
TcSbN1	6.5	8.4	3.5	2.7	4.4
TcSbN2	6.8	9.3	3.8	2.7	4.6
TcSrN0	5.7	7.0	3.2	2.5	3.6
TcSrN1	6.0	6.7	3.7	2.4	3.7
TcSrN2	6.0	7.0	3.4	2.5	4.3
TzSbN0	5.8	8.1	3.7	2.1	3.7
TzSbN1	6.1	8.8	4.2	2.3	4.3
TzSbN2	6.3	8.9	3.8	2.5	4.0
TzSrN0	3.9	5.7	3.2	2.1	2.8
TzSrN1	4.1	5.4	3.7	2.1	3.1
TzSrN2	4.7	5.4	3.8	2.1	3.0
l.s.d. (P=0.05)	0.49	0.90	0.36	0.29	0.50
Significance of factorial effects					
T	**	**	**	**	**
S	**	**	*	**	**
N	**		**		**
T x S	**	**			**
T x N					
S x N		*			
T x S x N			**		

P<0.05; ** P<0.01.

Barley crops grown from 1975 to 1977 produced less dry matter at anthesis for TzSr than for the other fallowing treatments. In the 1977 barley crop, TcSr was also inferior to TcSb and TzSb. The main effects of Tz and Sr combined in the 1979 barley crop to again result in poorest growth at anthesis in the TzSr treatment. A significant (P<0.01) T x N interaction in 1977 was for barley growth at anthesis to have responded to N fertiliser with Tc but not with Tz. A main effect of all fallowing treatments responding in growth similarly to N fertiliser was recorded at anthesis in the 1979 wheat and barley crops.

In the crops in which N concentration of the top-growth at anthesis was measured (1975–79 inclusive), the major treatment effect was for N fertiliser application. It increased N concentration similarly in crop plants from all 4 fallowing treatments at that sampling time in all but the 1976 barley and 1978 wheat crops. In the 1976 barley crop with N1 and N3, crop growth from TzSr had a significantly lower (P<0.01) N concentration than that for any other treatment. With N2 the N concentration of TzSr did not differ significantly from that of TcSr. In the 1978 wheat crop, the N concentration of top-growth with N3 was significantly greater (P<0.01) with Sr than with Sb but not with N1 or N2. In 1975, TzSr had a lower (P=0.03) N concentration than any other treatment.

Other factors affecting growth and yield

Time of sowing. The optimum sowing time for winter cereals for the area is June–July (Woodruff and Tonks

Table 10. Effect of fallow and N fertiliser treatments on wheat (W) and barley (B) dry weight (kg/ha) at anthesis in several years
Data were not collected for the 1973 and 1974 crops

Treatment	*1969* W	*1970* W	*1971* W	*1972* W	*1975* B	*1976* B	*1977* B	*1978* W	*1979* W	*1979* B
TcSbN0	4355	2424	5026	2442	7039	5497	2924	5320	4039	4795
TcSbN1	3891	2312	4419	2376	6978	5765	3722	6268	4225	5373
TcSbN2	4128	2280	4497	2538	7035	5594	3438	6117	4533	5264
TcSrN0	4288	2113	4488	2030	5949	5014	2464	5311	3691	4843
TcSrN1	4098	2913	4769	3131	6248	5607	2628	5998	4746	4839
TcSrN2	4175	3062	4829	3119	7286	5803	2891	5898	4330	5288
TzSbN0	4508	2983	4856	2538	6435	5831	3503	5417	3284	4752
TzSbN1	5291	3929	4787	2671	7124	5601	3354	5421	4083	4888
TzSbN2	4102	2672	4850	2305	6763	5599	3538	6086	3877	5217
TzSrN0	4589	4474	4479	2134	4501	3839	2539	4283	3248	4139
TzSrN1	4461	4353	4856	2815	4895	4360	2061	5217	3412	4384
TzSrN2	4999	5160	4945	2648	5805	4446	2220	6334	3877	4407
l.s.d. (P=0.05)	1008.6	891.0	443.4	n.s.	721.0	678.8	462.1	721.7	666.7	626.9
Significance of factorial effects										
T	*	**			**	**		*	**	**
S		**			**	**	**			**
N					**			**	**	*
T x S		**			**	**	*			
T x N							**	*		
S x N		*	**		**					
T x S x N										

* P<0.05; ** P<0.01.

1983). In 1970, 1972, 1973 and 1976 sowing was delayed beyond this optimum time (Table 2) owing to inadequate seed-bed moisture in most treatments. TzSr could have been sown during the optimum period in all years.

Crop diseases. A few plants infected with crown rot (*Fusarium graminearum*) were observed in 1971 and 1973. The disease was marked in the 1977 barley crop (Dodman and Wildermuth 1989) and was intensified with N2 and by Sr. Tillage had no effect on the severity of the disease.

The disease was again obvious in 1979, in both wheat and barley crops. In this year the only significant treatment effect in wheat was the lower disease intensity under TzSb (26% of tillers infected) compared with the other treatments (mean of 51% of tillers infected). A visual rating of the barley plots in 1979 indicated that the prevalence of the disease (i.e. identified by prematurely deadheads) was intensified by Tc and reduced with N fertiliser application.

Soil temperature. From 12 July to 14 September 1977, the diurnal soil temperature fluctuation 2 mm below the soil surface was less when a stubble cover was present (TzSr *v.* TzSb). Average maximum temperatures were 5.4°C lower with a stubble cover and minima were 0.7°C higher. As air temperatures increased in late-August and early September these treatment differences decreased. At a depth of 5 cm the diurnal fluctuation in soil temperatures was less pronounced but was again less with a stubble cover. The average maximum temperature of soil with stubble for the period was only 2.0°C lower, and the minimum was 0.4°C lower, than bare soil. However, the differences in soil temperatures between treatments were slight towards the end of this period.

Lodging. Within a week after anthesis, rain promoted lodging in both the 1975 and 1976 barley crops. In 1975, lodging in TzSr was minor compared with that in the other 3 treatments (Table 11). The degree of lodging increased with N fertiliser application under all 4 treatments but remained relatively minor under TzSr.

In 1976, burning of stubble resulted in increased crop lodging. Also the application of N fertiliser promoted more lodging with Tc than with Tz. No lodging occurred at any level of N with TzSr.

Average grain weight. The effect of fallow and N fertiliser treatments on average grain weight for the 1975 and 1976 barley crops are shown in Table 11. In 1975, average grain weight with TzSr (46.6 mg) was 13% higher than the mean of the other 3 treatments. Reduction in weight with the N2 treatment was 15% with Sb, and only 5% with Sr. In 1976, Sb resulted in decreased average grain weight, and the application of

Table 11. Effect of fallow and N fertiliser treatments on lodging and average grain weight (mg) of the 1975 and 1976 barley crops
Lodging rating scale was: 1, no lodging to 5, all plants lodged

Treatment	1975 crop		1976 crop	
	Lodging	Average grain weight	Lodging	Average grain weight
TcSbN0	3.3	45.5	2.0	48.3
TcSbN1	4.5	39.4	3.5	45.0
TcSbN2	4.3	37.0	4.5	43.6
TcSrN0	2.5	43.3	1.5	47.5
TcSrN1	2.8	44.6	2.0	45.5
TcSrN2	4.3	38.4	4.3	44.9
TzSbN0	3.0	43.0	1.5	47.8
TzSbN1	3.8	42.4	2.0	47.8
TzSbN2	4.5	38.0	3.3	45.4
TzSrN0	1.0	46.3	1.0	48.9
TzSrN1	1.0	47.1	1.0	49.4
TzSrN2	1.5	46.5	1.0	48.5
l.s.d. (P=0.05)	1.00	3.79	1.17	2.31
Significance of factorial effects				
T	**	**	**	**
S	**	**	**	*
N	**	**	**	**
T x S	**	*		
T x N			*	*
S x N		*		
T x S x N				

* P<0.05; ** P<0.01.

N2 resulted in a greater reduction in average grain weight with Tc (7%) than Tz (3%).

Discussion

Fallow water storage

Fallowing efficiency. An outstanding feature of this experiment has been the greater fallowing efficiency obtained with zero tillage plus stubble retention (27%) than that with conventional tillage by cultivation, with either stubble burnt (17%) or stubble retained (20%). Previous studies on cracking clays in the summer rainfall cereal areas of northern New South Wales (Fawcett 1978) and Queensland (Rawson *et al.* 1981) indicated relatively lesser water storage advantages for zero tillage fallows. However, Smika and Wicks (1968) obtained water storage efficiencies in a silt loam at Nebraska of 25% for bare cultivation, 32% for tillage with stubble retained and 44% for zero tillage with stubble retained.

Water intake recordings on vertisols are extremely variable and range from a rapid addition of 200 mm when dry (I. D. Barlow, unpublished data) to base infiltration rates of 4 mm/h or less when wet (Freebairn *et al.* 1984). This variation appears to be chiefly a result of the property of gross cracking of these soils when dry (Fox 1963). This gross cracking is, however, ineffective in accelerated water penetration unless it is open at the surface. Zero tillage ensures cracks remain open for rapid water entry and reduced runoff during high intensity rainfall and eliminates the successive rapid evaporative losses with exposure of moist soil with repeated tillage. When combined with surface stubble retention it also maximises the benefits afforded by a stubble mulch by promoting extended infiltration and in impeding runoff.

With fallows of medium to high antecedent water storage, cracks are closed due to swelling of the moist clay and the mechanisms of water entry will be similar in tilled and zero tillage systems. This, combined with the generally higher antecedent storage associated with TzSr when harvests were 'wet', could explain the reduced fallowing efficiency we recorded for the treatment in years of high antecedent water storage.

Waring *et al.* (1958*a*) found that on Darling Downs Vertisols available water at harvest was significantly correlated with available water at subsequent sowing. Therefore, the improved water storage efficiency of TzSr when antecedent water storage is low could be exploited most effectively when fallow periods are likely to finish with suboptimal water reserves. Following the 'dry' harvests of this experiment available water at sowing was 136 mm for TcSb, 151 mm for TcSr, 176 mm for TzSb and 215 mm for TzSr.

When the fallow was tilled, Sr increased storage efficiency by 2.9% over Sb. Other workers have recorded no advantage (Waring *et al.* 1985*a*), similar small advantages (Greb *et al.* 1967) or advantages of up to 7% (Smika and Wicks 1968) with stubble mulching in tilled systems. Stubble retention is thought to increase fallow efficiency primarily by reducing runoff, rather than by reducing evaporation (Felton *et al.* 1987). In our experiment an indication that retaining stubble in tilled situations may have improved fallowing efficiency when antecedent water storage was high confirms the possibility of an advantage of impedence of runoff by stubble leading to greater water infiltration.

The mean fallowing efficiency for all seasons and treatments in this study was 22%. Waring *et al.* (1985*a*) reported 17% for cultivated fallows on Darling Downs Vertisols. This corresponds closely with the average of 19% we recorded for the cultivated treatments. Possible reasons for the low value for mean storage efficiency for Darling Downs Vertisols include (i) the often high antecedent moisture following spring rains; (ii) low infiltration rates for montmorillonite clays when wet; (iii) runoff associated with high intensity summer rainfall; and (iv) significant evaporative losses from the upper soil layers (Waring *et al.* 1958*a*). The wide range of fallowing efficiency values that we recorded (3–58%)

are similar to those reported by other workers, for example, Waring *et al.* (1958*a*), –2–40% on the Darling Downs Vertisols; Greb *et al.* (1967), 16–34% on silt loams of the Great Plains; and Musick (1970), 0–50% on clay loams of Texas. Although differences in antecedent water content probably account for much of the variability, the importance of the other soil, climate and management factors operating have not been identified and quantified.

Pre-sowing levels. Available soil water levels at sowing combine postharvest soil water plus water accumulated during the fallow. Hence in fallow periods which were initially 'dry', treatment effects evident for pre-sowing water are similar to those for fallowing efficiency: TzSr>TzSb>TcSr>TcSb. However, in fallows that were initially 'wet', pre-sowing water contents under TzSr were also equal to or greater than other treatments, in spite of inferior fallowing efficiency in a number of years, for example, 1973–74, 1975–76 and 1976–77. This reflected the higher postharvest soil water levels under TzSr in those years.

Water storage at sowing was greater than had been recorded previously for cracking clays in Queensland. For cultivated fallows, over the 0–120 cm profile, Waring *et al.* (1985*a*) reported 122 mm for Darling Downs sites, Allen and George (1956) recorded 152 mm at Biloela whilst in our study cultivated treatments averaged 169 mm. This was probably a reflection of the greater postharvest soil water recorded in our experiment. Effective depth of accumulation on this site, which sometimes reached the 150–180 cm zone, also exceeded that of those previous studies.

Fallow nitrate-nitrogen accumulation

The several examples in this experiment of a reduced fallow period accumulation of soil nitrate when stubble was retained (1975–76, 1976–77 and 1978–79) agree with the findings of White *et al.* (1985) and Strong *et al.* (1987) for wheat–wheat sequences on Vertisol soils of this region. The low value for soil nitrate increase under TcSb during the 1975–76 period may have been due to relatively poorer soil water conditions under that treatment leading to lower N mineralisation. The low value for TzSr during the same period may have resulted from carbon leaching from stubble into the soil surface leading to immobilisation (Cochran *et al.* 1980) and/or uptake by fallow barnyard grass growth in that treatment in that season. The lack of a stubble effect on net N mineralisation during the 1977–78 fallow may have been due to low stubble quantities associated with the 1977 crop.

The N fertiliser (N2) effect of increasing net mineralisation under each of the 4 fallowing treatments in 1976–77 was not preceded by higher residual levels of nitrate at the start of that fallow period. Therefore the effect was presumably one of higher N concentration in the stubble and root residues and/or in the microbial biomass under the N2 treatments alleviating the immobilisation effect of the plant stubbles in those treatments. However, there was a significant carryover effect of fertiliser N (N2) present at the harvest of the 1978 crop and this may have been a significant factor in alleviating immobilisation effects of stubble retention which appear to have been associated with SrN0 in the 1978 season.

The results obtained by previous workers for the effect of fallow tillage on nitrate-N production have been variable. The laboratory work of Rovira and Graecen (1957) suggested that tillage increases N mineralisation through exposure to microorganisms of previously inaccessible organic matter and through the drying and rewetting processes commonly associated with tillage in the field. Greenwood *et al.* (1970) working on a red-brown earth showed that compared with tillage, the use of herbicides increased N stress and reduced growth rate and N uptake of wheat. However, Reeves and Ellington (1974) found that soil mineral N levels at seeding were lower on tilled plots than on direct-drilled plots in 1 year and not different in 2 other years. In our experiment there is little evidence that nitrate-N production with zero tillage is lower than that obtained with fallow tillage.

A nitrate-N accumulation at depth has been reported for other black earth sites on the Darling Downs by Waring and Teakle (1960). The marked accumulation of nitrate-N below 90 cm with TcSb, which was greater with applied N fertiliser than with no fertiliser, indicates that leaching of nitrate-N to this depth can occur. There is evidence of significant use of N from these deep reserves by the 1977 and 1978 crops. The lack of significant nitrate accumulation at depth under the TzSr treatment could be explained by leaching beyond the sampled depth and/or the uncontrolled growth of barnyard grass under that treatment during the fallow periods of 1971–72 to 1975–76.

Grain yield and crop growth responses to stored water

Positive correlations between pre-sowing stored water and wheat grain yields have been reported for vertisols of the Darling Downs (Waring *et al.* 1958*b*) and northern New South Wales (Fawcett *et al.* 1974). The results of other tillage-treatment experiments in Australia (summarised in Fischer 1979) show that extra stored water at sowing has generally resulted in increased evapotranspiration, increased crop biomass production and increased grain yield. The MWUEs for grain yield have been higher (with the exception of Fawcett and Carter 1973) than the average WUE. In this experiment, Tz and/or Sr have resulted in stored water advantages of TzSr over TcSb in 8 of the 11 years reported (viz., 1969, 1970, 1972, 1973, 1974, 1975, 1978 and 1979). However, only in 1970 and 1979 has the greater stored water of the TzSr treatment resulted in greater grain yield. We consider the grain yield advantage of TzSr over TcSb in 1975, when N fertiliser was applied, resulted from lodging of the crop in TcSb shortly after anthesis. The yield advantage in 1979 occurred with barley but not with wheat.

In 1969, although Tz resulted in increased DM at anthesis and both Tz and Sr resulted in increased water use, the grain yield response to Tz (117 kg/ha), its WUE of 4.1 kg/ha.mm and its MWUE of 3.8 kg/ha.mm were all low compared with Tc. This was caused by severe head damage from 2 late frosts at crop booting, which were closely followed by good rainfall that promoted a greater flush of late tillering under Tc than Tz.

In 1970 the greater stored water associated with Tz and Sr resulted in greater anthesis DM and grain yield with TzSr. The correlation between water stored and anthesis DM is 0.71 and between water stored and grain yield is 0.82. The correlation between anthesis DM and grain yield is 0.95. It is not apparent why water use did not increase under TzSr but it may have been due to the greater efficiency of this treatment, as demonstrated during fallows, in storing excess rain received during the later period of crop growth.

In the 1979 barley crop, Tz and Sr treatments were both associated with increased stored water, but DM at both tillering and anthesis was significantly lower under TzSr than under the other 3 treatments. Water use was increased under both Tz and Sr, but the yield advantage of Tz compared with Tc (MWUE of 9.6 kg/ha.mm) was much larger than Sr compared with Sb (MWUE of 0.5 kg/ha.mm). In this dry growing season, where little significant growing period rain fell until a week after anthesis, the greater moisture reserves at depth associated with Tz treatment possibly increased its WUE for grain production through improved plant water status at anthesis and hence an increased number of kernels/head. The reduced anthesis DM of the T2 treatment suggests that little, if any, increase in head number would occur. The very poor MWUE of Sr compared with Sb suggests that Sr had a detrimental effect on WUE. The large MWUE for N2 compared with N0 (17.7 *v.* 7.6 kg/ha.mm) suggests a marked improvement in harvest index with the use of N fertiliser in this crop. This may be a result of the lower incidence of crown rot observed in the N-fertilised plots.

Increased stored water associated with Tz in the 1972, 1973 and 1974 wheat crops did not result in increased crop water use or grain yield under these treatments. WUE was lowest under TzSr in each year. In 1973 and 1974, Tz and Sr operated independently in reducing WUE thus suggesting a detrimental effect or effects on crop performance associated with each treatment. The reason for the very poor yields (i.e. mean over all treatments of 1579 kg/ha) obtained in 1973, which was a year of good growing season rainfall, is not obvious.

Water use by the 1975 barley crop did not differ with treatment but was complicated by severe lodging which closely followed crop anthesis in all treatments except TzSr. The greater grain yield potential of the lodged treatments (as expressed in anthesis DM) compared with TzSr did not eventuate. Grain yield depressions in these treatments were associated with increased lodging intensity which appeared to be inversely related to individual kernel weight and grain yield. Water use under TzSr was probably less than that under other treatments before the lodging occurred but greater afterwards. We consider the more upright finish of TzSr plots promoted the WUE and grain yield superiority of TzSrN2 over TcSb treatments in that year.

Again in 1976, with the exception of the TzSr treatments, increased lodging of barley was associated with N fertiliser application, reduced individual kernel weight and, thus, reduced grain yield. Stored water preceding the 1976 crop did not differ between treatments. Reduced water use under TzSr was accompanied by low DM at tillering and anthesis and lower grain yield.

Barley grown in the 1977 season was sown with more stored water under Sr than under other treatments. However, in this very dry growing season, Sr treatments actually reduced grain yields. The poor biomass production with Sr in this season, especially when combined with Tz, would have caused the lowered water use under that treatment. However the WUE for grain yield of TzSr was greater than that of TcSr due to greater yields with Tz than with Tc in this season. Secondary root development in this very dry season was poor. Near harvest, this resulted in plants falling over, and sometimes falling down wide cracks that developed in the soil. We observed a greater loss of plants under Tc than under Tz, and this could have been the major cause of the greater yields and WUE with Tz in this year.

Greater stored water under TzSr preceding the 1978 wheat crop was followed by increased crop water use under that treatment when N2 was applied. However, this increased water use was not accompanied by increased anthesis DM or increased grain yield. WUE of the treatment for grain yield was lower than that of other treatments. In this season the growing season rainfall was 50% above average and resulted in all treatments, except TzSrN2, having slightly more water stored at harvest than was present pre-sowing. Again, a detrimental factor associated with the TzSr treatment has operated to reduce plant WUE although in this year there was no reduction in crop biomass at tillering or anthesis

Reductions in stored water over crop growing periods varied from nil in 1978, when growing season rainfall was 50% above average, to 71% in 1979 when rainfall was 15% below average. However, in 1977 when growing period rainfall was lowest (42% of the long-term average) there was a mean reduction of only 67% of the stored water. Poor crop secondary root development in this season probably led to the relatively poor exploitation of soil water below 120 cm.

The amount and distribution of water in the soil profile at harvest under the different treatments in this experiment reflect the interaction of several variables including soil water amount and profile distribution before the previous crop, and the differential effects of the treatments on crop growth including root distribution. The postharvest soil water under TzSr in 1973 reflects the pre-sowing treatment values. Stored water was apparently of little significance in that season of poor grain yields and above average rainfall on the crop. Relatively poorer crop growth associated with TzSr led to less water use and hence higher postharvest stored water in 1976 and 1977. Lower postharvest stored water was associated with N fertiliser usage in 5 seasons and followed increased yield and/or dry matter production at the N2 level by the previous crop in 1976, 1977 and 1979. In 1975 and 1978, the higher soil water at harvest under TzSrN0 than under other treatments presumably resulted from the poorer vegetative production under that treatment in those years.

The data for profile distribution of available water at harvest suggests that tillage treatment did not adversely affect root distribution (i.e. by producing soil physical barriers).

Other factors affecting crop growth and yield

Diseases and pests. Yellow spot of wheat (*Pyrenophora tritici-repentis*) was observed in the experiment at the tillering stage of the 1970 crop. The disease was most prevalent under Sr treatments and was more pronounced with Tz than with Tc. Its intensity declined during the jointing stages of growth. The disease was also observed in the 1971–74 crops, particularly in the TzSr plots in each year. One of the experimental constraints associated with this experiment has been the production of winter cereals only. The original intention of a wheat monoculture was modified in 1975 when barley was sown in response to the yellow spot disease problem that had intensified under TzSr (Rees and Platz 1979). Although lesions of the disease were observed in the 1975 barley crop in the TzSr plots, they did not have a significant effect on plant growth. The disease was not a significant problem in the 1976–79 crops.

The magnitude of the depressing effect of yellow spot on the yield of TzSr relative to that of other treatments for the period 1970–74 is unknown. However, Rees and Platz (1983) have reported wheat yield losses of up to 48% under environmental conditions which favoured it. It is therefore likely that the disease contributed significantly to the poor WUE of TzSr in the 1972–74 wheat crops.

In the 2 seasons when the effect of fallow management treatments on crown rot intensity was measured, the treatment associations with the disease varied markedly. As the disease was intensified by Sr in the 1977 barley crop it may have been at least partly responsible for the lowered biomass production and reduced WUE associated with Sr in that crop.

The root lesion nematode (*Pratylenchus thornei*), identified by Thompson (1984), was another important factor adversely affecting wheat yields in this experiment. Thompson's study, which shows large numbers of the parasites associated particularly with Tz treatments in this experiment, will be the subject of a following publication. The problem can be countered by rotation of wheat with non-susceptible crops such as barley (Mackenzie *et al.* 1982). The reduced WUE associated with Tz in the 1973 and 1974 wheat crops is probably (at least partly) attributable to the activity of the root lesion nematode. We consider the relative improvement in wheat yields of TzSr in 1978 following 3 years of barley is a response to control of yellow spot disease and reduction in root lesion nematode numbers effected by the rotation. However, the reason for the reduced WUE associated with that treatment in 1978 remains unclear. A further increase in nematode numbers under Tz in the 1978 wheat crop may have been responsible for the poorer growth measured at tillering and anthesis in the 1979 wheat crop.

Effect of nitrogen on crop growth and yield. The several examples of a stubble management x nitrogen fertiliser interaction for anthesis dry matter and grain yield data reflect the treatment trends obtained for fallow period N mineralisation. With the exception of the 1970 crop, the interaction, when it occurred, produced a decrease in anthesis dry matter and/or grain yield when stubble was retained in the absence of N fertiliser addition. Meaned over all crops, the grain yield depression with stubble retention was overcome by the addition of 23 kg/ha of N fertiliser applied before sowing. These results differ from those of Littler (1964) working with dryland wheat on Darling Downs Vertisols and White *et al.* (1985) with irrigated wheat on the same soils who noted no extra requirement by the crop for N when stubble was retained. Seasonal variation in rainfall and temperature are of major importance in determining crop growth and hence N requirements. These climatic changes can also influence N availability during the growing season by their effects on microbial activity, wetting and drying cycles and leaching. It is possible that seasonal variations in weather conditions during the crop growth period may explain the variability in the stubble management x N fertiliser interaction in this experiment.

They may also be a major cause of the disparity of our results with those of the other workers.

A tillage x N interaction in crop growth or yield occurred in only 2 years. This is consistent with the lack of significance of this interaction in the values obtained for pre-sowing soil nitrate-N.

The consistent N fertiliser main effect for 0–90 cm profile nitrate-N quantity indicates a carryover effect of available N in excess of crop requirements at the higher level of fertiliser application. The high 1977 postharvest N levels were concentrated in the surface 15 cm of the soil and were not effectively exploited by that crop because of minimal secondary root development in the dry surface soil zone in that year. High postharvest N levels in 1978 with the N2 treatment may have been caused by the abnormally high levels pre-sowing and hence low use of fertiliser N by the crop.

Poor early growth of barley under zero tillage with stubble retention. Unexplained poor early growth associated with direct drilling of cereals has been reported by a number of workers from southern Australia (Greenwood *et al.* 1970; Reeves and Ellington 1974; Holmes 1976). In this experiment, wheat growth of uneven vigour during tillering in TzSr plots in 1974 can probably be attributed to a combination of the effects of uneven germination (following poor seed coverage with soil in that treatment), yellow spot disease and root lesion nematode. Poorer early growth of TzSr plots for the 1979 wheat crop has been attributed to the effects of root lesion nematodes, because the Tz effect was dominant.

However, the reason(s) for consistently poorer early growth of barley crops under TzSr compared with the other treatments (i.e. as shown by the tillering and/or anthesis DM measurements) is not apparent. The lower average winter soil temperatures measured under the treatment in this experiment are unlikely to be causal as the poor growth was evident in the 1976 crop which was not sown until August. This crop emerged and grew when soil temperature differences between treatments were probably slight. Phytotoxins do not appear to be involved (Thompson 1984). He found, working with stubble from the experiment, that neither their macerates nor their filtrates, either before or after incubation to promote microbial growth, inhibited seedling growth. His findings agree with those of Guenzi *et al.* (1967) who found that wheat and oat residues contained no water-soluble toxic components after 8 weeks of exposure to field environmental conditions. N deficiency appears an unlikely primary cause of the problem. There were no significant T x S x N interactions for DM production or tissue N concentration at tillering or anthesis for any of the barley crops where these measurements were taken. Measurements at anthesis for the 1977 and 1979 crops showed that plants grown under the TzSr treatment responded to N fertiliser by increasing tissue N concentration rather than by increasing DM production.

We observed in 1975 and 1979 that foliage of barley seedlings in contact with, or in close proximity to, clumps of stubble was more heavily frosted than that of plants of more exposed sites in the treatment. It is possible that surface stubble may have reduced heat radiation from the soil during winter and increased the intensity of frosting, resulting in reduced growth rate of the crop. When wheat and barley were grown in split plots in 1979 we observed that leaf frosting of barley was more severe than that of wheat. It is notable that in each of the 4 barley crops the TzSr treatment 'finished' better (as measured by the ratio of grain yield to anthesis DM production) than did each of the other cultivated treatments. This suggests that the problem was a temporary one (i.e. affecting early growth) which probably did not persist to post-anthesis.

Sowing date. A late-May through to mid-July sowing is important for attaining maximum wheat yields in the Darling Downs area (Woodruff and Tonks 1983). Earlier sowings are predisposed to frost damage during flowering (Single 1961). Delaying sowing beyond the end of June results in progressively lower yields associated with low leaf area duration after flowering (Doyle and Marcellos 1974). The low and erratic winter rainfall on the Darling Downs often leads to sowings being delayed well beyond the optimum period.

For meaningful interpretation of treatment effects on crop growth, yield, fallow water and nitrate-N accumulation we decided that all treatments in this experiment should be sown on the same date. In all years of the experiment the soil moisture conditions at seeding depth of the TzSr plots have been suitable for sowing during the optimum period. Poor seed-bed moisture during the optimum period in plots of other treatments delayed sowing to August and beyond in 4 out of 11 years. Lower evaporative losses prior to rain, and deeper infiltration following light falls are the suggested reasons for the superior seed-bed moisture properties associated with TzSr. Lower grain yields from late sown crops are associated with lower leaf area duration (Doyle and Marcellos 1974). Lower leaf area duration after flowering will also reduce the potential response of crops to extra stored water. Commercially, TzSr plots could have been planted at the optimum time in all years and thereby obtained yield advantages over other treatments which could not be obtained in this experiment.

Crop seeding machinery and establishment. Problems experienced during the sowing operation in many years demonstrated the inadequacy of commercial and experimental seeding machinery for zero tillage situations on Vertisols. The main problem was in obtaining adequate coverage of the seed with friable soil to maintain moist conditions in the seed placement zone during the germination to emergence phase in the Tz plots. The problem was accentuated in the wheel tracks of the seeding tractor. After 1976 the experiment was sown with a rigid-tined machine which was superior in penetration, stubble handling and seed coverage to the triple-disc coulter seeder which had usually been used previously. However, its performance still suffered from lack of contour-following ability of the tines, and less than adequate seed coverage and lack of tilth in the base of the seed trench in Tz plots. In many years, rainfall shortly after sowing rectified the problem. However, we consider that crop density adequate for attaining maximum yields was obtained under all treatments in all years. The significance or otherwise of the poor seed coverage and seed-bed tilth with respect to rate of seedling root penetration and development was not adequately assessed due to the practical difficulties associated with sampling of root growth.

Abnormal weather conditions. The late September frosts of 1969, which largely nullified potential yield increases of the TzSr treatment in that year, were unusual in that there is no similar record for the region of 5 weeks of extremely mild winter temperatures followed by such low spring temperatures (Doyle and Marcellos 1974).

Above-average growing period rainfall occurred in 8 years out of 11. It is expected that more normal cropping period rainfall conditions would have produced greater yield responses to the extra stored water of the TzSr treatment.

Grain nitrogen

A reduction in percentage grain N with TzSr occurred with all 4 barley crops and did not appear related to grain yield. The factor or factors operating are unclear and are probably those also responsible for the poor early growth of barley in this treatment. The reduction in percentage grain N with the same treatment of the 1970 wheat crop was probably associated with the much higher yields associated with that treatment in that crop. Reasons for the reduction in percentage grain N with the same treatment in the 1969 and 1973 wheat crops are not clear.

The lack of grain N response to applied N fertiliser in the first and third crop and the small responses in the second crop are surprising. The results of Russell (1964) suggest an expected grain N response to N fertiliser when the percentage grain N of unfertilised plots is in the range encountered in these crops of 2.33 and 3.00%.

Conclusions

The results of this experiment suggest that for annual winter cereal production on non-sloping Darling Downs Vertisols, zero tillage with stubble retained is more effective than tillage during the fallow in maximising pre-sowing water storage. In fallows with low initial soil water reserves the water accumulation efficiency of the treatment is markedly superior to that of other treatments. The results also suggest a small water storage advantage for stubble mulching over stubble burning for tilled, non-sloping fallows.

The lack of grain yield response to the improved water storage under zero tillage with stubble retention was associated with reduced water use efficiency of several wheat crops and lowered water use by several barley crops. The incidence of yellow spot disease and root lesion nematode was greatest in wheat crops under the zero tillage with stubble retained treatment. These diseases were probably major contributors to the lowered WUE for grain production with that treatment. Both problems can be controlled by rotation to other crop species. Poor early growth of barley under the zero tillage with stubble retention treatment was associated with reduced water use by several crops and reduced dry matter production, and hence grain yield potential, at anthesis. The cause of this problem has not been defined.

There was a trend for stubble retention, either partly incorporated by tillage or left on the surface with zero tillage, to reduce the amount of soil nitrate accumulated during fallow periods. This was reflected by a need, in several years, for N fertiliser addition to optimise plant growth and/or grain yield when stubble was retained which did not occur when stubble was burnt. There was no indication of this need lessening as the trial progressed which may indicate a permanently slightly higher N fertiliser requirement for cropping when stubble is retained.

Zero tillage with stubble retention offers improvement in fallow water accumulation efficiency over that of tilled fallows and the opportunities for more careful timing of sowing. We expect that these advantages, combined with control of pathogens and parasites through a suitable crop rotation or development of resistant crop varieties, would result in grain yield advantages above those attained in this experiment. Other potential advantages of zero tillage with stubble retention are reductions in machinery requirements and savings in fuel and time. The major current impediments to the general adoption of the system are the lack of suitable commercially available sowing machinery for Vertisols and the cost and greater management skills associated with full substitution of herbicides for tillage for fallow weed control.

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