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Effects of tillage, stubble, gypsum, and nitrogen fertiliser on cereal cropping on a red-brown earth in south-west Queensland

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Summary. We describe effects of a range of fallow and crop management practices on soil properties and crop growth in wheat and grain sorghum on a red-brown earth in south-west Queensland. Results from the first 4 years of the experiment, which commenced in 1983, have been published. This paper reports results from the next 6 years.

No tillage (NT) and reduced tillage (RT), combined with stubble retention, resulted in better soil-water storage during fallow but less soil nitrate-nitrogen (N) at sowing than observed with more frequent and aggressive mechanical tillage treatments such as discing, and stubble removal. In drier growing seasons, when N application often resulted in yield reductions in wheat, NT and RT with stubble retention resulted in higher grain yields than other treatments in both crops. In a wetter growing season, when N application resulted in yield increases, wheat yields under NT and RT with stubble retention were lower than those of other treatments, even at the highest rate of N application, indicating that factors such as plant disease were also affecting yields. With stubble retention, average yields of 6 wheat crops were 12% higher under NT and reduced blade tillage, and average yields of 4 sorghum crops were 20–30% higher under NT, than other tillage treatments. Gypsum application resulted in an average yield increase of 15% in both crops under conventional disc tillage with stubble retention.

In wheat, NT and RT with stubble retention were generally associated with lower grain protein concentration, and N application was necessary to maximise profitability of these practices.

Introduction

In the south-west Downs area of southern Queensland, successful production of both winter and summer crops largely depends on water stored in the soil during a 6–8-month fallow between crops. Mean annual rainfall at Goondiwindi is 620 mm, with an average of 62% falling during October–March. Cultural practices that lead to improved fallow soil-water storage may increase the reliability and profitability of cropping in this area.

Experiments have been conducted since 1983 to determine the effect of a range of fallow and crop management practices on soil properties and crop growth in wheat and grain sorghum. Results from the first 4 years of these experiments with wheat (Radford *et al.* 1992) and sorghum (Gibson *et al.* 1992) have shown that reduced soil disturbance and stubble retention generally increased soil-water storage but diminished nitrate-nitrogen (N) in the soil profile at the end of the fallow, compared with more frequent or aggressive tillage treatments and stubble removal. Consequently, no tillage and reduced tillage, coupled with stubble retention, generally gave higher grain yields than other treatments in drier growing seasons. In wetter growing seasons, however, wheat yields were lower under no tillage with stubble retention than in most other treatments. It was concluded that this effect was the result of reduced N supply and greater incidence of plant diseases under no tillage with stubble retention.

This paper reports results from 1988 to 1993, when N fertiliser treatments were imposed on the original treatments to investigate the interactions between N supply, tillage, stubble management, and gypsum application with respect to soil-water storage and use, crop growth, and grain yield and protein concentration.

Materials and methods

Site

The experiments were located on a property at Billa Billa (28°10'S, 150°15'E), about 40 km north of Goondiwindi in south-west Queensland. The site had a

Table 1. Timing of cultural operations, rainfall during fallow and crop periods, and plant establishment data for six wheat and four grain sorghum crops

	Wheat						Sorghum			
	1988	1989	1990	1991	1992	1993	1989	1990	1991	1992
Primary tillage	24.xi.87	30.xi.88	20.xii.89	10.xii.90	19.xii.91	14.xii.92	3.vi.88	17.vii.89	17.vii.90	26.vi.91
Secondary tillage	17.xii.87	22.xii.88	24.i.90	15.i.91	30.i.92	6.i.93	4.viii.88	14.viii.89	8.viii.90	18.vii.91
	13.i.88	19.i.89	23.ii.90	19.ii.91	26.ii.92	4.ii.93	30.ix.88	30.x.89	3.x.90	28.xi.91^{A}
	9.ii.88	8.iii.89	5.v.90^{A}	25.iii.91	28.iv.92^{A}	7.iv.93	15.xi.88^{A}	2.xi.89^{A}	23.x.90	
	14.iii.88^{A}	21.iv.89^{A}		12.iv.91^{A}		5.v.93^{A}	6.xii.88	1.xii.89	6.xii.90^{A}	
Sowing	19.v.88	25.v.89	13.vi.90	14.vi.91	2.vi.92	17.vi.93	15.xii.88	13.xii.89	9.i.91	10.xii.91
Harvest	21.x.88	31.x.89	2.xi.90	31.x.91	29.x.92	5.xi.93	20.iv.89	26.iii.90	16.iv.91	2.iv.92
Fallow rain (mm)	665	367	476	322	362	246	557	431	416	246
In-crop rain (mm)	196	97	102	54	72	157	104	84	165	191
Mean plant estab. (%)	53	86	90	67	71	52	67	61	69	86
Mean plant density (no./m^2)	41	80	113	79	79	51	5	5	5	5

^{A} Second tillage operation in RTB and RTD.

slope of 1%. The native vegetation, which was cleared in 1971, was belah (*Casuarina cristata*) open forest, with some brigalow (*Acacia harpophylla*), occasional poplar box (*Eucalyptus populnea*), and an understorey of wilga (*Geijera parviflora*) and false sandalwood (*Eremophila mitchelii*). Soil type was a red-brown earth (Stace *et al.* 1968), with Principal Profile Forms Db2.33, Db2.13, and Dr2.33 (Northcote 1977), or Typic Natrustalf (Soil Survey Staff 1975). Further site details are described by Gibson *et al.* (1992) and Radford *et al.* (1992).

Treatments

The 13 main treatments involved combinations of tillage frequency (no tillage, reduced, conventional); primary tillage with a disc, blade, or chisel plough; stubble retention or removal; and gypsum application (Gibson *et al.* 1992; Radford *et al.* 1992) (see Table 2). Each of the main treatments was split for 3 N fertiliser application rates.

No tillage (NT) involved the use of herbicides for weed control. Reduced tillage (RT) had a postharvest primary tillage operation and a pre-plant cultivation for seedbed preparation, with herbicides used for weed control at other times. Conventional tillage (CT) had a primary tillage operation and 3–4 secondary tillage operations.

Disc primary tillage (D) was performed with a 1-way disc plough 105 cm wide, with three 63-cm-diameter discs. Blade primary tillage (B) was carried out with a 260-cm-wide blade plough, comprising three 60° blades, each 90 cm wide and mounted on shanks 85 cm apart. Chisel primary tillage (Ch) was done with a 210-cm-wide chisel plough with narrow points 2.5 cm wide and 30 cm apart.

Secondary tillage in the CT treatments was generally carried out with a 210-cm-wide scarifier with points 40 cm wide and 30 cm apart. A 260-cm-wide cultivator with points 12.5 cm wide and 11.5 cm apart, followed by harrows, was used for the final tillage operation in RT and CT treatments.

Details of the timing of tillage operations are given in Table 1. Depths of primary and secondary tillage operations were 10–20 and 8–15 cm, respectively.

With stubble retention (St), tillage treatments were imposed on the stubble remaining on the plots after harvest of grain from the preceding crop. With stubble removal (So), crop residues after harvest were cut at ground level and raked off the plots before tillage operations began.

Gypsum was applied by hand to the soil surface at 5 t/ha on 19 November 1987 and 7 April 1993 in the wheat experiment, and 23 July 1987 and 15 April 1993 in the sorghum experiment. Gypsum (5 t/ha) had also been applied at the start of the experiments (Gibson *et al.* 1992; Radford *et al.* 1992).

Nitrogen fertiliser treatments of 0, 20, and 60 kg N/ha were applied at sowing as urea drilled into the soil in bands 12.5 cm from the seed rows.

Experimental design

The design was a randomised block with 13 main treatments and 3 replications. Each of the main treatments was split randomly for the 3 N rates. The same treatments were included in separate, adjacent wheat and grain sorghum experiments. Different randomisations of treatments were made for each experiment.

The main treatment plots measured 30 by 6 m, and the N fertiliser subplots were 10 by 6 m. Small banks were constructed between main plots to prevent water runoff between plots.

Experimental details

Treatments were imposed on the same plots each year, and plots were sown to either wheat or grain sorghum in their respective experiments, with a 6–8-month fallow between crops.

Glyphosate was the main herbicide used for weed control during fallow, at rates of 0.25–0.72 kg a.i./ha, depending on the size and species of weeds. The number of herbicide applications during a fallow was generally similar to the number of tillage operations.

Wheat (cv. Hartog) was sown in May or June (Table 1) at a rate of 35–40 kg/ha and at 25-cm row spacing. Grain sorghum (cv. Prize in 1989, 1991, 1992; cv. Pride in 1990) was sown in December or January (Table 1) at 4–5 kg/ha in rows 1 m apart. A 1993 sorghum crop was sown, but it failed to produce grain due to dry seasonal conditions. Crops were sown with rigid, spearpoint tines, followed by solid, centre-ribbed presswheels. Sowing depth was 3–8 cm. After emergence, grain sorghum seedlings were hand-thinned to a density of 50 000 plants/ha.

All treatments received an annual basal application of 20 kg/ha of phosphorus as triple superphosphate (19.4% P, 2% S, 18.5% Ca), banded with the seed at sowing for wheat, and in and between the seed rows for sorghum.

Measurements

Weather. An automatic weather station at the site measured rainfall, wet and dry bulb screen temperature, soil temperature at 5 and 10 cm, relative humidity, solar radiation, wind run, and evaporation. Rainfall recorded during fallow and crop growth is given in Table 1.

Soil-water. Total soil-water content was determined at sowing, anthesis, and maturity in the 0 and 60 kg N/ha subplots of all treatments in the 1988, 1989, and 1990 crops in the wheat experiment and the 1989, 1990, and 1991 crops in the sorghum experiment. Measurements were only made in selected treatments in the 1991, 1992, and 1993 wheat crops.

Soil-water measurements were made in 10-cm increments to a depth of 1.2 m using a neutron probe, complemented with gravimetric moisture content readings for 0–10 and 10–20 cm depths. Neutron probe measurements were made in aluminium access tubes (1 tube/subplot).

Total soil-water content to a depth of 1.2 m was determined by addition of water content in each 10-cm increment. Plant-available soil-water was calculated by subtracting the water content of the driest profile measured from the total water content.

Soil nitrogen and chloride. Soil cores for available N determination were taken just before sowing and after harvest in all treatments in the 1988, 1989, and 1990 wheat crops and the 1989, 1990, and 1991 sorghum crops, and in selected treatments in the 1991, 1992, and 1993 wheat crops. Samples were taken in 30-cm segments to a depth of 1.2 m, dried at 40°C in a forced-draught oven, and ground to <2 mm. Following extraction in 2 mol KCl/L at a soil to extractant ratio 1:10 (Bremner 1965), nitrate was determined by an automated hydrazine reduction procedure for the Griess-Ilosvay reaction for nitrite (Best 1976). Nitrate concentrations for each depth increment were multiplied by the corresponding bulk density to give a quantity per ha for each increment, and the amounts in all increments were added to give the quantity in the profile to a depth of 1.2 m.

Soil chloride was measured in samples from selected treatments from the pre-sowing sampling of the 1989 wheat crop and the postharvest sampling of the 1991 sorghum crop. Chloride concentration was determined on a 1:5 soil:water suspension by potentiometric titration with silver nitrate using a quinhydrone half cell and a silver/silver chloride electrode (Piper 1942).

Plant data. Plant density at seedling emergence was determined from plant counts in areas of 2 and 4 m^2 in each subplot in the wheat and grain sorghum experiments, respectively. Establishment percentage was then calculated from seed numbers sown and plant density data.

Dry matter yields at anthesis were determined from whole-plant samples cut at ground level in areas of 1 and 2 m^2 in each subplot in the wheat and grain sorghum experiments, respectively. All treatments were sampled in the 1988, 1989, and 1990 wheat crops and the 1989, 1990, and 1991 sorghum crops. Only selected treatments were sampled in the 1991, 1992, and 1993 wheat crops. Samples were dried to constant weight at 80°C in a forced-draught oven. Samples from the 1988, 1989, 1990, 1991, and 1993 wheat crops and the 1990 and 1991 sorghum crops were ground to <1 mm and processed through a semi-microKjeldahl digestion procedure. Nitrogen concentration was then measured by automated, continuous flow methods, which are modifications of those of Technicon (1976, 1977).

In the wheat experiment, grain yields were determined from an area of 14 m^2 in each subplot, using a small-plot autoheader with a 1.75-m width of cut. In the sorghum experiment, grain yields were obtained from an area of 4 m^2 in each subplot, which was hand-harvested and threshed. Grain moisture content was determined for all samples, and grain yields were adjusted to 12% moisture content. Grain weight was determined from counts of 2 lots of 200 seeds in each subplot.

Grain samples were ground to <1 mm, and N concentration was determined by the procedures used for plant samples at anthesis. Grain protein concentration was calculated as percent grain N x 5.7 for wheat and x 6.25 for grain sorghum (Tkachuk 1969).

Crop water use was calculated as the difference in soil-water content to a depth of 1.2 m between sowing and maturity, plus rainfall received between these

Table 2. Available soil-water at sowing (mm, 0–1.2 m) in six wheat and three grain sorghum crops

NT, no tillage; RT, reduced tillage; CT, conventional tillage; B, blade primary tillage; D, disc primary tillage; Ch, chisel primary tillage; So, stubble removal; St, stubble retention

There were no significant N treatment effects, and no fallow management x N rate interactions

	Wheat						Sorghum		
	1988	1989	1990	1991	1992	1993	1989	1990	1991
Fallow management									
NTSo	151	129	116	101	109	95	129	126	120
NTSt	154	142	144	134	135	116	129	126	117
NTSt + gypsum	159	149	150				143	138	138
RTBSo	150	132	124	114	116	100	132	124	121
RTBSt	157	136	135	119	127	107	123	123	119
CTBSo	139	115	122				126	112	117
CTBSt	147	127	132				127	115	117
RTDSo	144	124	114			95	119	113	115
RTDSt	152	134	129			91	124	122	120
CTDSo	148	122	126	113	113	100	123	117	112
CTDSt	148	121	128	114	113	97	132	116	114
CTDSt + gypsum	159	132	141				143	129	119
CTChSt	151	129	133				121	121	117
l.s.d. ($P = 0.05$)	16	n.s.	14	n.s.	n.s.	n.s.	16	n.s.	n.s.
Nitrogen									
Nil	150	132	130	114	116	100	129	120	116
60 kg/ha	151	128	130	117	121	100	128	123	121

n.s., not significant.

2 times. Runoff and through drainage were assumed to be zero. Efficiency of water use for grain production was calculated by dividing grain yield by crop water use.

Value of grain. The value of grain produced was calculated for NTSt, RTBSt, CTBSt, and CTDSt treatments using estimated on-farm payments for grain in the year of production. For wheat, the value of the grain took into account both yield and grain protein concentration, while sorghum value was based only on grain yield. The cost of N fertiliser applied was deducted from the value of the grain, and the resultant values were compared.

Statistical analyses

Analysis of variance was used to test the treatment effects on data recorded. Treatment means were compared using the protected least significant difference procedure at the 5% level of significance.

Results

Soil-water storage at sowing

In the wheat experiment, soil-water levels at sowing were consistently higher in NTSt than in other treatments (Table 2), particularly during drier fallows. On average over 6 years, soil-water storage at sowing was 18 mm higher in NTSt than in CTDSt. Improvement in soil water storage with stubble retention was greater under NT than other tillage treatments. Gypsum application resulted in consistent increases in soil water at sowing, particularly in CTDSt.

In the sorghum experiment, NT and RTB treatments had higher available soil-water at sowing than most other treatments in 1990 (Table 2). Gypsum application resulted in higher soil-water levels at sowing in NTSt, and, to a lesser extent, in CTDSt, in all 3 years.

Nitrogen application had no significant ($P>0.05$) effect on soil-water storage at sowing.

Soil nitrate-N at sowing

In both the wheat and sorghum experiments, soil nitrate-N levels at sowing were generally lower with NT and RT than with more frequent or aggressive tillage treatments, and lower with St than with So (Table 3). Soil nitrate-N was therefore generally lower in NTSt and RTBSt than in most other treatments. Gypsum application also tended to result in lower soil nitrate-N levels in NTSt and CTDSt; differences were significant ($P<0.05$) in the sorghum experiment in 1990 and 1991.

In the wheat experiment, soil nitrate-N levels at sowing increased significantly ($P<0.05$) with N applications made in previous years (Table 3). The differences in a number of years corresponded approximately to the cumulative amounts of N applied at sowing of previous crops. A similar trend was starting to occur prior to sowing of the third sorghum crop.

Where no N fertiliser was applied, mean soil nitrate-N

Table 3. Soil nitrate-N at sowing (0–1.2 m) and plant dry matter yield at anthesis in six wheat and three grain sorghum crops

NT, no tillage; RT, reduced tillage; CT, conventional tillage; B, blade primary tillage; D, disc primary tillage; Ch, chisel primary tillage; So, stubble removal; St, stubble retention

There were no significant fallow management x N rate interactions for soil nitrate-N

	Wheat						Sorghum		
	1988	1989	1990	1991	1992	1993	1989	1990	1991
	Soil nitrate-N (kg/ha)								
Fallow management									
NTSo	262	162	153	166	217	266	186	147	219
NTSt	169	110	110	137	179	176	186	173	205
NTSt + gypsum	113	84	77				73	99	95
RTBSo	224	128	140	163	199	201	179	201	224
RTBSt	214	133	141	141	162	172	157	173	229
CTBSo	310	241	257				248	251	311
CTBSt	166	120	147				222	254	279
RTDSo	220	183	168				236	297	314
RTDSt	340	250	218				228	222	261
CTDSo	330	230	240	247	286	312	236	272	307
CTDSt	279	174	203	215	252	264	212	202	252
CTDSt + gypsum	235	135	171				125	163	133
CTChSt	198	177	184				222	240	227
l.s.d. (*P* = 0.05)	118	78	87	n.s.	n.s.	130	n.s.	79	88
Nitrogen									
Nil		137	137	126	147	136		213	204
20 kg/ha		161	177	182	209			196	219
60 kg/ha		192	195	226	292	328		214	281
l.s.d. (*P* = 0.05)		23	25	31	34	47		n.s.	38
	Plant dry matter (t/ha)								
Fallow management									
NTSo	5.81	4.75	4.47	1.84	1.91	3.35	2.67	1.64	3.12
NTSt	4.09	4.64	5.32	3.91	3.65	4.92	4.62	3.30	3.79
NTSt + gypsum	4.28	5.12	5.49				4.47	3.08	4.05
RTBSo	5.55	5.01	5.14	3.42	2.98	4.04	3.50	2.70	3.66
RTBSt	5.29	4.94	5.61	3.59	3.82	4.59	4.20	3.07	3.84
CTBSo	6.21	4.91	5.24				2.78	1.92	3.30
CTBSt	5.60	5.02	5.83				3.02	1.71	3.53
RTDSo	5.39	4.74	5.30				3.51	2.75	3.25
RTDSt	4.85	5.49	5.97				3.25	2.69	4.30
CTDSo	5.77	5.10	5.30	3.15	2.61	3.13	2.63	2.17	3.52
CTDSt	5.78	4.92	5.71	3.32	3.04	3.25	3.48	2.80	3.96
CTDSt + gypsum	5.38	4.90	5.85				3.29	2.91	4.10
CTChSt	5.64	5.10	5.55				3.17	3.00	3.80
l.s.d. (*P* = 0.05)	0.64	n.s.	0.55	0.40	0.46	0.54	0.94	0.72	n.s.
Nitrogen									
Nil	5.24	4.66	5.12	3.14	2.97	3.49	3.35	2.52	3.59
20 kg/ha	5.33	5.12	5.44	3.07	3.00	4.14	3.54	2.70	3.87
60 kg/ha	5.49	5.14	5.78	3.40	3.02	4.00	3.40	2.57	3.67
l.s.d. (*P* = 0.05)	n.s.	0.26	0.21	0.20	n.s.	0.24	n.s.	n.s.	n.s.
Fallow management x N interaction									
l.s.d. (*P* = 0.05)	n.s.	n.s.	0.82	n.s.	n.s.	0.59	n.s.	n.s.	n.s.

n.s., not significant.

levels at 0–60 cm were 58 and 76 kg N/ha in NTSt and CTDSt, respectively, across 6 years in the wheat experiment, and 91 and 115 kg N/ha in NTSt and CTDSt, respectively, across 3 years in the sorghum experiment.

Soil chloride

In both the wheat and sorghum experiments, soil chloride levels down the profile were lower under NT than in CT and lower with St than with So (Fig. 1).

Chloride levels were generally lower, and differences were more marked, in the wheat than the sorghum experiment. Significant ($P<0.05$) treatment effects occurred in the lower section of the profile in wheat and in the upper section in sorghum.

Plant establishment

In the wheat experiment, mean percentage establishment varied from about 50 (1988, 1993) to 90 (1990), resulting in average plant densities ranging from 40 to 113 plants/m^2 in different years (Table 1). There were no consistent trends for treatment effects on plant establishment.

In the sorghum experiment, mean percentage establishment ranged from 61 (1990) to 86 (1992) (Table 1). The main treatment effect was significantly ($P<0.05$) lower establishment in NTSo than in other treatments.

Establishment was not influenced by N application in either experiment.

Dry matter and N yields at anthesis

In 1988, wheat dry matter yields were generally higher with So than St, except in CTD, and were significantly ($P<0.05$) lower in NTSt and NTSt + gypsum than in most other treatments (Table 3). From 1990 to 1993, the opposite trend occurred, with St resulting in higher dry matter yields than So, most markedly under NT. Treatments NTSt and RTBSt resulted in higher dry matter yields than CTDSt in 1991, 1992, and 1993. Significant ($P<0.05$) increases in dry matter yield occurred with N application in 4 of the 6 years.

In the sorghum experiment, NTSo had significantly ($P<0.05$) lower dry matter than all other treatments in 1989 and 1990 (Table 3). Dry matter yields were generally higher under NTSt, NT + gypsum, and RTBSt than in other treatments, particularly in 1989. There were no significant ($P>0.05$) sorghum dry matter responses to N application.

Average N yields of dry matter at anthesis in the 0, 20, and 60 kg N/ha treatments were 60, 72, and 82 kg/ha, respectively, across 5 wheat crops, and 50, 54, and 52 kg/ha, respectively, across 2 sorghum crops.

Grain yield

In the wheat experiment, NTSt and NTSt + gypsum gave the lowest yields at the relatively high yield levels obtained in 1988 and were significantly ($P<0.05$) outyielded by all other treatments except CTBSt and RTDSo (Table 4). There were significant ($P<0.05$)

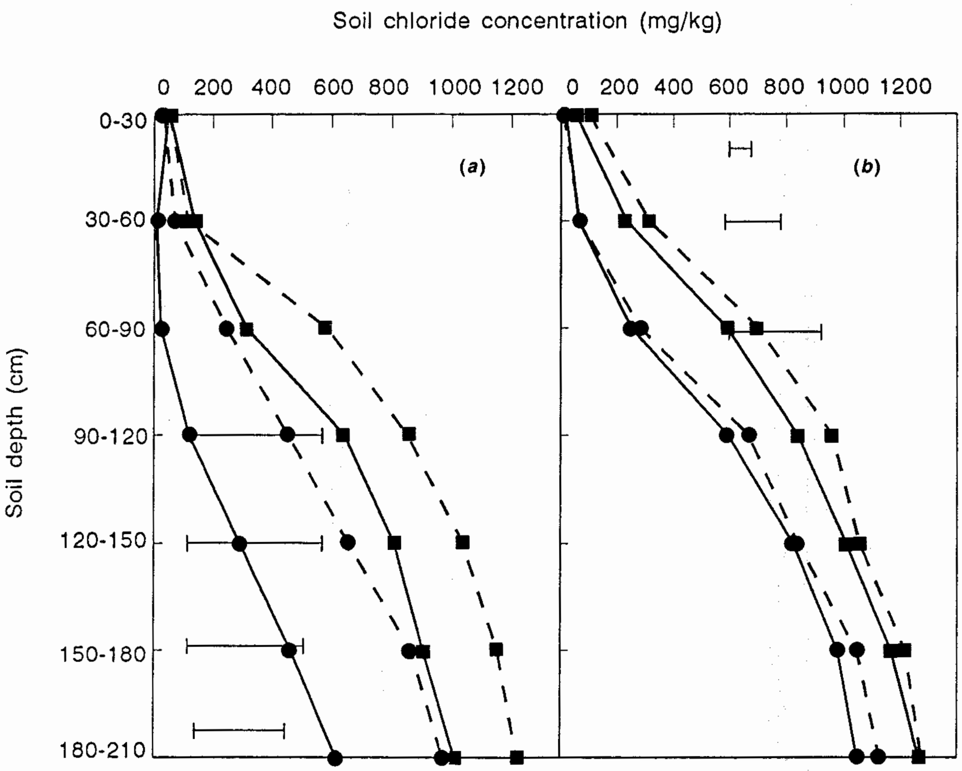

Figure 1. Effect of tillage and stubble treatment on the profile distribution of soil chloride in (*a*) wheat in May 1989 and (*b*) sorghum in May 1991. (● - - - ●, NTSo; ● — ●, NTSt; ■ - - - ■, CTDSo; ■ — ■, CTDSt). Horizontal bars indicate l.s.d. ($P = 0.05$) at each depth.

Table 4. Grain yield and weight in six wheat crops and four and three grain sorghum crops, respectively

NT, no tillage; RT, reduced tillage; CT, conventional tillage; B, blade primary tillage; D, disc primary tillage; Ch, chisel primary tillage; So, stubble removal; St, stubble retention

	Wheat						Sorghum			
	1988	1989	1990	1991	1992	1993	1989	1990	1991	1992
	Grain yield (t/ha)									
Fallow management										
NTSo	4.37	2.21	1.63	0.46	1.48	1.82	3.92	1.48	1.40	1.97
NTSt	3.30	2.40	2.10	1.43	2.46	2.45	3.62	3.16	1.57	2.08
NTSt + gypsum	3.17	2.86	2.46	1.30	2.39	2.63	3.09	2.72	2.20	2.12
RTBSo	4.21	2.43	1.76	1.09	2.05	2.21	2.76	1.91	1.76	1.26
RTBSt	4.02	2.34	2.08	1.16	2.19	2.31	2.64	2.44	2.20	1.36
CTBSo	4.18	2.04	1.57	0.91	2.05	1.97	2.47	1.84	1.60	1.17
CTBSt	3.67	2.06	1.82	0.99	2.13	1.80	2.47	1.99	1.68	1.55
RTDSo	3.57	2.31	1.98	1.17	1.93	1.91	2.59	1.98	1.56	0.95
RTDSt	4.04	2.16	1.76	0.93	2.00	1.99	2.76	1.87	2.02	1.17
CTDSo	3.97	2.07	1.71	0.86	1.88	1.91	2.38	1.90	1.63	0.79
CTDSt	4.24	2.14	1.74	0.88	1.85	1.73	2.95	2.06	1.66	1.21
CTDSt + gypsum	4.04	2.61	2.36	0.93	2.25	2.30	2.84	2.41	2.21	1.52
CTChSt	3.97	2.08	1.63	0.89	2.14	1.97	2.99	2.24	1.99	1.53
l.s.d. ($P = 0.05$)	0.53	0.37	0.47	0.24	0.31	0.26	0.63	0.58	0.47	0.60
Nitrogen										
Nil	3.75	2.38	2.15	1.04	2.01	2.01	2.74	2.15	1.71	1.35
20 kg/ha	3.99	2.29	1.82	0.92	2.06	2.11	2.98	2.08	1.84	1.38
60 kg/ha	3.97	2.19	1.70	1.04	2.12	2.11	2.93	2.24	1.87	1.58
l.s.d. ($P = 0.05$)	0.14	0.10	0.13	0.07	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Fallow management x N interaction										
l.s.d. ($P = 0.05$)	n.s.	n.s.	n.s.	0.27	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
	Grain weight (mg)									
Fallow management										
NTSo	39.1	34.9	31.1	27.0	33.3	29.6	29.7	30.4	18.9	
NTSt	36.1	31.7	27.2	22.6	29.1	30.7	27.4	30.6	17.5	
NTSt + gypsum	35.3	34.0	29.4	21.3	28.4	29.6	27.3	29.6	20.6	
RTBSo	39.4	33.3	28.0	25.8	33.6	30.8	27.7	30.4	18.6	
RTBSt	38.4	33.3	28.8	23.8	30.0	30.0	26.8	30.3	18.3	
CTBSo	40.5	33.7	27.8	27.8	34.9	29.9	27.8	31.5	18.4	
CTBSt	38.6	32.4	26.7	23.8	30.7	27.6	27.3	30.8	18.5	
RTDSo	37.9	31.7	28.0	26.6	34.4	29.3	26.9	29.8	18.5	
RTDSt	39.2	31.0	27.4	25.9	33.0	28.9	27.9	30.0	17.7	
CTDSo	40.0	33.7	28.5	28.5	34.4	30.7	26.7	30.6	18.2	
CTDSt	40.4	32.3	28.4	26.0	32.4	29.8	27.9	30.3	17.4	
CTDSt + gypsum	37.6	32.5	29.8	26.2	32.2	30.0	28.5	32.1	19.8	
CTChSt	39.6	31.1	25.6	24.6	31.1	28.3	26.9	30.6	18.3	
l.s.d. ($P = 0.05$)	1.7	1.9	2.2	1.2	1.3	1.3	1.6	n.s.	n.s.	
Nitrogen										
Nil	39.3	34.7	31.8	26.0	33.0	31.2	27.1	30.4	18.0	
20 kg/ha	38.4	32.7	27.5	25.3	31.8	29.0	27.8	30.5	18.6	
60 kg/ha	38.1	30.9	25.4	24.9	31.6	28.7	27.9	30.7	19.0	
l.s.d. ($P = 0.05$)	0.5	0.7	1.0	0.5	0.5	0.6	n.s.	n.s.	n.s.	
Fallow management x N interaction										
l.s.d. ($P = 0.05$)	n.s.	2.6	n.s.	1.9	n.s.	n.s.	n.s.	n.s.	n.s.	

n.s., not significant.

overall yield increases in response to N application in 1988, with the response being greater in NTSt and RTBSt than in CTBSt and CTDSt (data not shown). However, yield of NTSt with 60 kg N/ha was similar to, or lower than, that of most other treatments with nil N. In the drier seasons 1989–1993, NTSt and RTBSt generally gave higher grain yields than the other treatments. The St treatment resulted in significantly

($P<0.05$) higher yields than So under NT in 1990–93, but no significant ($P>0.05$) stubble effect occurred in the other tillage treatments. Gypsum application resulted in significantly ($P<0.05$) higher yields in NTSt in 1989, and in CTDSt in 1989, 1990, 1992, and 1993. From 1989 to 1993, there were either no significant ($P>0.05$) effects of N application on grain yields (1992, 1993), or significant ($P<0.05$) yield reductions (1989, 1990, 1991). The reduction in yield with N application tended to be greater in NTSt than other treatments, and was significant ($P<0.05$) in 1991 (data not shown). Mean yields of NTSt and RTBSt over 6 years were similar and averaged 246 kg/ha (12%) higher than those of CTBSt, RTDSt, CTDSt, and CTChSt, which were also similar. Gypsum application resulted in 5 and 15% higher yields in NTSt and CTDSt, respectively.

In the sorghum experiment, NTSt resulted in significantly ($P<0.05$) higher yields than most other treatments in 1989, 1990, and 1992 (Table 4). The NTSt + gypsum, RTBSt, and CTDSt + gypsum treatments gave the highest yields in 1991. Gypsum application resulted in significant ($P<0.05$) yield increases in NTSt and CTDSt in 1991. There were no significant ($P>0.05$) main effects of N application on grain yield. Across the 4 years, mean yield of NTSt was higher than RTBSt by 450 kg/ha (21%) and higher than CTBSt, RTDSt, CTDSt, and CTChSt, by an average of 600 kg/ha (30%). Gypsum application resulted in 3% lower and 14% higher yields in NTSt and CTDSt, respectively.

Grain weight

In the wheat experiment, grain weights were higher in NTSo (1989, 1990) and lower in NTSt and NTSt + gypsum (1988, 1991, 1992) than in other treatments in a number of years (Table 4). Grain weights declined significantly ($P<0.05$) with N application in all years. Where significant ($P<0.05$) interactions occurred, the reduction in grain weight with N application was greater in NTSt than in most other treatments (data not shown).

In the sorghum experiment, the only significant ($P<0.05$) treatment effects on grain weight were higher values in NTSo and CTDSt + gypsum than some other treatments in 1989 (Table 4).

Grain protein concentration and N yield

In the wheat experiment, grain protein concentration was generally higher with So than St, and higher with increasing frequency and aggressiveness of tillage

Table 5. Grain protein concentration (%) in six wheat and four grain sorghum crops

NT, no tillage; RT, reduced tillage; CT, conventional tillage; B, blade primary tillage; D, disc primary tillage; Ch, chisel primary tillage; So, stubble removal; St, stubble retention

	Wheat						Sorghum			
	1988	1989	1990	1991	1992	1993	1989	1990	1991	1992
Fallow management										
NTSo	11.4	12.8	11.5	15.7	14.4	14.0	13.6	14.3	13.1	14.1
NTSt	11.0	11.7	10.8	13.2	12.4	12.3	12.6	14.0	13.1	14.1
NTSt + gypsum	10.7	10.9	10.3	13.2	13.1	12.6	11.4	12.8	11.9	13.3
RTBSo	11.3	12.7	11.3	15.4	14.0	13.3	13.0	13.9	13.3	15.3
RTBSt	11.2	11.9	11.1	14.5	13.3	12.8	12.7	14.0	13.0	15.1
CTBSo	11.7	14.0	12.3	16.2	14.1	13.8	13.0	14.3	13.5	15.2
CTBSt	10.8	12.5	11.0	15.2	13.7	13.4	12.9	13.8	13.5	15.0
RTDSo	11.5	13.8	11.9	15.9	14.5	14.0	12.9	14.2	13.6	15.2
RTDSt	11.6	14.0	12.2	15.9	14.4	13.7	13.0	14.4	13.5	15.1
CTDSo	11.5	14.3	12.4	16.5	14.0	14.0	13.0	14.2	13.5	15.4
CTDSt	11.1	13.7	11.7	15.9	14.1	13.9	12.6	14.1	13.5	15.0
CTDSt + gypsum	11.4	13.3	11.8	15.7	13.9	13.7	12.5	14.1	13.1	14.9
CTChSt	10.8	12.7	11.5	15.4	13.9	13.5	12.9	14.3	13.3	14.7
l.s.d. ($P = 0.05$)	0.4	0.9	0.7	0.6	0.5	0.6	0.6	0.6	0.5	0.6
Nitrogen										
Nil	11.1	12.0	10.4	14.7	13.3	12.7	12.6	13.8	13.2	14.7
20 kg/ha	11.2	13.0	11.5	15.5	14.0	13.6	12.9	14.1	13.3	14.9
60 kg/ha	11.4	13.9	12.6	15.6	14.2	14.1	12.9	14.2	13.2	14.7
l.s.d. ($P = 0.05$)	0.1	0.4	0.2	0.2	0.2	0.2	n.s.	n.s.	n.s.	n.s.
Fallow management x N interaction										
l.s.d. ($P = 0.05$)	n.s.	n.s.	n.s.	0.8	0.6	0.7	n.s.	n.s.	n.s.	n.s.

n.s., not significant.

(Table 5). These trends resulted in NTSt and RTBSt having lower grain protein concentration than other treatments. Significant ($P<0.05$) increases in grain protein concentration occurred with N application. This effect was greater in NTSt and RTBSt than in other treatments, resulting in significant ($P<0.05$) interactions in 1991, 1992, and 1993 (data not shown).

Average grain N yields in the 0, 20, and 60 kg N/ha treatments were 47, 49, and 51 kg/ha, respectively, across 6 wheat crops, and 43, 45, and 47 kg/ha, respectively, across 4 sorghum crops.

Similar, though less marked, main treatment effects on grain protein concentration occurred in the sorghum experiment, but there was no significant ($P>0.05$) effect of N application on grain protein concentration (Table 5). Gypsum application resulted in significantly ($P<0.05$) lower grain protein concentration in NTSt in all years.

Crop water use

In 1988, when NTSt had lower wheat yields than most other treatments, its water use was similar to that of other treatments, but its efficiency of water use was lower (Table 6). Nitrogen application significantly ($P<0.05$) improved water use in this year. In drier years such as 1991, when NTSt and RTBSt had higher wheat yields than other treatments, they also had higher water use and efficiency of water use. NTSo had lower water use and efficiency of water use in 1991.

In the sorghum experiment, higher yields in 1990 with NTSt and, to a lesser extent, RTBSt were also associated with higher water use and efficiency of water use (Table 6). Stubble retention also resulted in higher water use, particularly under NT. In 1991, the higher yield of RTBSt was associated with higher efficiency of water use.

Value of grain less N fertiliser costs

In the wheat experiment, the average value of grain produced over 6 years, after N fertiliser costs were deducted, was lower for NTSt than for RTBSt, CTBSt, and CTDSt when no N fertiliser was applied (Table 7). Highest average values were obtained from NTSt and RTBSt when 20 kg N/ha was applied.

In the sorghum experiment, the highest average values came from NTSt, with values tending to decrease with N application.

Discussion

Treatment effects on soil-water and nitrate-N levels at sowing were similar to those reported for earlier years of the experiments (Gibson *et al.* 1992; Radford *et al.* 1992). Stubble retention, reduced soil disturbance, and gypsum application generally resulted in higher water storage (Table 2) but lower nitrate-N concentrations in the soil profile at sowing (Table 3).

Soil profile chloride analyses indicate greater and deeper water movement in the soil with NT and St than with CTD and So, and hence greater leaching of nitrate (Fig.1). Similar effects have been observed on a black

Table 6. Crop water use (mm) and efficiency of water use for grain production (kg/ha.mm) in selected treatments in two wheat and two grain sorghum crops

NT, no tillage; RT, reduced tillage; CT, conventional tillage; B, blade primary tillage; D, disc primary tillage; So, stubble removal; St, stubble retention

	Water use				Efficiency of water use			
	Wheat		Sorghum		Wheat		Sorghum	
	1988	1991	1990	1991	1988	1991	1990	1991
Fallow management								
NTSo	284	115	154	234	15.4	3.9	10.2	5.7
NTSt	284	155	177	238	11.6	9.8	18.0	6.5
RTBSo	284	140	162	230	15.0	7.8	10.8	7.3
RTBSt	283	145	165	231	14.0	8.4	15.2	9.8
CTDSo	282	138	149	230	13.5	6.7	11.8	6.3
CTDSt	279	135	162	237	14.8	6.7	13.1	7.6
l.s.d. ($P = 0.05$)	n.s.	n.s.	19	n.s.	2.1	1.9	4.4	2.2
Nitrogen								
Nil	279	136	162	231	13.5	7.3	12.7	6.4
60 kg/ha	286	140	161	235	13.9	7.2	13.7	8.8
l.s.d. ($P = 0.05$)	5	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Fallow management x N interaction								
l.s.d. ($P = 0.05$)	n.s.	n.s.	n.s.	n.s.	n.s.	1.9	n.s.	n.s.

n.s., not significant.

Table 7. Mean on-farm returns for grain, minus N fertiliser costs ($A/ha), in selected treatments from six wheat and four grain sorghum crops

NT, no tillage; RT, reduced tillage; CT, conventional tillage; B, blade primary tillage; D, disc primary tillage; St, stubble retention

	Wheat			Sorghum		
N rate (kg/ha):	0	20	60	0	20	60
NTSt	269	298	274	247	245	228
RTBSt	280	298	291	215	190	177
CTBSt	278	285	246	219	182	185
CTDSt	289	276	235	176	163	185

earth in southern Queensland (Loch and Coughlan 1984; Dalal 1989; Turpin *et al.* 1992). The leaching effects were greater in the wheat than the sorghum experiment, possibly because of differences in the timing and amount of rainfall in relation to the fallow and cropping phases of the 2 experiments. In both experiments, stubble retention reduced the proportion of soil particles (aggregates and primary particles) of size <0.125 mm in the soil surface after high intensity rain (Loch 1994). In the wheat experiment, NTSt has been shown to have a higher proportion of larger macropores (>1 mm diameter) in the soil surface than NTSo and CTDSo (Coughlan *et al.* 1991). Both these characteristics would contribute to improved water infiltration into the soil in NTSt.

Tillage and stubble treatment effects on grain yields were also similar to those reported by Gibson *et al.* (1992) and Radford *et al.* (1992). In wheat, NTSt and RTBSt gave the highest yields in drier growing seasons, but NTSt was outyielded by other treatments in wetter seasons (Table 4). In grain sorghum, NTSt and RTBSt consistently gave the best yields.

The lower dry matter (Table 3), grain yield (Table 4), and efficiency of water use (Table 6) of NTSt in 1988 in the wheat experiment, even with 60 kg N/ha, indicate that other factors were also limiting yields of NTSt in this wetter season. The greater amounts of surface crop residue resulting from practices such as no tillage and stubble retention are associated with increased severity of the disease yellow spot (*Pyrenophora tritici-repentis*) of wheat (Rees 1987). In commercial crops, yield losses due to yellow spot can be 10–15% when reasonable rain falls during the growing season and can exceed 40% in a very wet season. Yellow spot was observed to be more severe in NTSt than other treatments in 1988 and may have contributed to its lower yield.

In drier growing seasons such as 1991, higher wheat grain yields in response to NTSt and RTBSt (Table 4) were associated with both higher water use and higher efficiency of water use (Table 6). The general reduction in grain yields with N application in these years was associated with increased dry matter production and lower grain weight, indicating that the dry matter response to N application resulted in greater water stress during grain development. The greater reduction in yield in a number of years when N was applied to NTSt appeared to be related to a greater occurrence of 'dead heads' due to crown rot (*Fusarium graminearum*) with N application (Wildermuth *et al.* 1993).

In the sorghum experiment, higher yields with NTSt or RTBSt (Table 4) occurred over a range of seasonal conditions and were associated with higher water use and/or efficiency of water use (Table 6). No significant ($P>0.05$) dry matter or grain yield responses to N application occurred in sorghum.

Gibson *et al.* (1992) and Radford *et al.* (1992) reported no useful grain yield responses to gypsum application in wheat or sorghum. During the current phase of the experiment, gypsum application resulted in fairly consistent yield increases in the drier growing seasons, particularly in CTDSt in both the wheat and sorghum experiments, although the average responses were not economic. The yield increases were associated with higher soil-water storage at sowing with gypsum application. Smith *et al.* (1986) recorded consistent increases in wheat yield with gypsum application in south-west Queensland, but the responses were attributed to improved physical condition of soil or to increased availability of phosphorus rather than water availability. Phosphorus availability should not have been a factor in our experiments, because phosphorus-based fertiliser was applied annually.

The effects of fallow management treatments on grain protein concentration were also similar to those reported for earlier years of the experiment (Gibson *et al.* 1992; Radford *et al.* 1992). The general trend for grain protein concentration to increase with N application (Table 5) was partly related to lower grain yields with N application in the wheat experiment but was also due to slight additional N uptake, as indicated by higher average grain N yields with increasing N application in both experiments.

The yields of N in plant dry matter at anthesis and in grain, together with the progressive rise in soil nitrate-N levels at sowing during the 6 years of the experiment, indicate that a considerable proportion of the additional N applied was not required by the crops, and only a small proportion was removed in the grain. In the wheat experiment, mean soil nitrate-N levels at 0–60 cm were in the low to medium range, in which yield responses to fertiliser N might be expected to occur (Strong 1975). However, these levels, together with similar reserves at 60–120 cm, were adequate to support optimum growth and grain yields under the conditions in 5 of the 6 years. Mean soil nitrate-N levels in the sorghum experiment were in the high to very high range, in which, at most, only a small response to N fertiliser would be expected.

Because of the premiums paid for high grain protein concentration in wheat, the value of grain produced without N fertiliser was lower in NTSt than other treatments (Table 7) despite the higher average grain yield of NTSt. Maximum value of grain, less N fertiliser costs, was given by NTSt and RTBSt with 20 kg N/ha in wheat and NTSt with nil N in grain sorghum. In wheat, therefore, an economic advantage was gained by applying a low rate of N fertiliser in NTSt and RTBSt, because of its beneficial effect on grain protein. In commercial practice, other costs associated with no tillage and reduced tillage practices can be similar to, or less than, those for conventional tillage because of decreasing herbicide costs and rising fuel and machinery costs, improved herbicide application technology, and the use of sheep to control fallow weeds (Wylie and Clarke 1992).

Conclusions

In low rainfall environments, where water is the major factor limiting crop production, no tillage and reduced tillage, combined with stubble retention, can increase soil-water storage and subsequent grain yields in both wheat and grain sorghum. Where wheat is grown continuously, cultivars with some resistance or tolerance to plant diseases such as yellow spot and crown rot should be chosen if possible, to gain maximum benefit from additional soil-water storage. In commercial practice, rotation of wheat with crops other than winter cereals may also reduce the effects of plant diseases in wheat crops.

With the current level of soil fertility at this site, grain yield responses to N fertiliser application are only likely in favourable seasons that result in relatively high-yielding crops. However, even in dry seasons, some applied N (about 20 kg N/ha) may be necessary to ensure maximum returns under no tillage and reduced tillage with stubble retention because of the premium obtained for high protein grain.

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