**CSIRO** PUBLISHING

www.publish.csiro.au/journals/ajea *Australian Journal of Experimental Agriculture*, 2007, **47**, 965–975

# Zero tillage and nitrogen fertiliser application in wheat and barley on a Vertosol in a marginal cropping area of south-west Queensland

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**Abstract.** Winter cereal cropping is marginal in south-west Queensland because of low and variable rainfall and declining soil fertility. Increasing the soil water storage and the efficiency of water and nitrogen (N) use is essential for sustainable cereal production. The effect of zero tillage and N fertiliser application on these factors was evaluated in wheat and barley from 1996 to 2001 on a grey Vertosol. Annual rainfall was above average in 1996, 1997, 1998 and 1999 and below average in 2000 and 2001. Due to drought, no crop was grown in the 2000 winter cropping season.

Zero tillage improved fallow soil water storage by a mean value of 20 mm over 4 years, compared with conventional tillage. However, mean grain yield and gross margin of wheat were similar under conventional and zero tillage. Wheat grain yield and/or grain protein increased with N fertiliser application in all years, resulting in an increase in mean gross margin over 5 years from \$86/ha, with no N fertiliser applied, to \$250/ha, with N applied to target ≥13% grain protein. A similar increase in gross margin occurred in barley where N fertiliser was applied to target malting grade. The highest N fertiliser application rate in wheat resulted in a residual benefit to soil N supply for the following crop.

This study has shown that profitable responses to N fertiliser addition in wheat and barley can be obtained on long-term cultivated Vertosols in south-west Queensland when soil water reserves at sowing are at least 60% of plant available water capacity, or rainfall during the growing season is above average. An integrative benchmark for improved N fertiliser management appears to be the gross margin/water use of ~\$1/ha.mm. Greater fallow soil water storage or crop water use efficiency under zero tillage has the potential to improve winter cereal production in drier growing seasons than experienced during the period of this study.

## Introduction

The south-west Queensland cropping region, which includes the Roma, St George and Dirranbandi districts, is marginal for rainfed crop production. The region receives an average annual rainfall of 500–600 mm with 20–30% year-to-year variability and has annual potential evapotranspiration of ~2000 mm, resulting in a rainfall : potential evapotranspiration ratio of <0.3 (Weston *et al*. 1975). Moreover, as the period of cereal cropping has increased, grain yield and grain protein have decreased as soil fertility, particularly soil nitrogen (N) supply, has declined (Dalal and Mayer 1986*a*). On a Vertosol, which is the main cropping soil in the region, the mean rate of net N loss from the soil profile was 35.8 kg N/ha.year (Dalal and Mayer 1986*b*). Therefore, it is essential to address these issues of water and N supply to crops in developing sustainable farming systems for this area if it is to continue to support grain cropping.

Winter cereal cropping, with wheat as the main rainfed crop, is carried out over 200 000 ha in south-west Queensland (Australian Bureau of Statistics 2001). Winter cereals are usually sown between mid April and late June, depending on sowing opportunity, following a 6–8 month fallow period after harvest of the preceding crop in October–November. Reduced tillage practices during the fallow period, including zero tillage, have been shown to result in better soil water storage and grain yield of wheat and barley than conventional tillage in other parts of southern Queensland (Thomas *et al*. 1997). These practices therefore offer potential to improve the reliability of cropping in the south-west area. Nitrogen fertiliser application is an option for compensating for N fertility decline under winter cereal cropping. However, when the experiments discussed in this paper commenced in 1996, N fertiliser use in the south-west

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10.1071/EA05253 0816-1089/07/080965

**Table 1. Soil chemical and physical characteristics, Nindigully trial**

| Soil depth (cm) | pH (1:5 $H_2O$) | Electrical conductivity (1:5 $H_2O$) (dS/m) | Chloride (mg/kg) | Cation exchange capacity [cmol(+)/kg] | Exchangeable sodium (%) | Clay (%) | Plant available water capacity (mm) |
|---|---|---|---|---|---|---|---|
| 0–10 | 8.6 | 0.10 | 10 | 25 | 3.8 | 52 | 24 |
| 10–30 | 9.0 | 0.11 | 11 | 26 | 6.2 | 53 | 40 |
| 30–60 | 9.2 | 0.18 | 36 | 24 | 11.7 | 55 | 60 |
| 60–90 | 8.8 | 0.59 | 144 | 22 | 15.5 | 54 | 64 |
| 90–120 | 8.1 | 1.58 | 305 | 20 | 17.0 | 54 | 57 |

area was none or low and little was known about the economics of N fertiliser application in the area.

The aim of this study was to determine whether zero tillage fallow management and N fertiliser application improve grain yield and quality and gross margin in wheat and barley on a Vertosol in the marginal cropping region of south-west Queensland.

## Materials and methods

### *Field trial site*

We established a farming systems trial at Nindigully, on the property 'Dunkerry South' (28°30′S, 148°45′E), ~50 km south of St George in south-west Queensland, in May 1996. The site was on a grey Vertosol soil (Isbell 1996) that had been under cultivation since 1956. Native vegetation at the site was primarily coolibah (*Eucalyptus microtheca*) open woodland and Mitchell grass (*Astrebla lappacea*). The site was chosen as being representative of a land system in the region with a large area of cropping (~100 000 ha, Robinson 2005) and in which soil fertility decline had been identified (Dalal and Mayer 1986*a*, 1986*b*). At the start of the trial, soil organic carbon, total nitrogen and bicarbonate-extractable phosphorus at 0–10 cm were 0.65%, 0.07% and 9 mg/kg, respectively. Other chemical and physical characteristics of the soil profile are given in Table 1. Details of the analytical methods used for these analyses are given by Bruce and Rayment (1982).

At St George, long-term (1943–96) mean daily maximum and minimum temperatures range from 19°C and 5.4°C, respectively, in July, to 34.5°C and 21.5°C, respectively, in January (Bureau of Meteorology). Frosts (mean screen temperature ≤2.2°C) may occur between early May and mid September. Mean daily evaporation ranges from 3.1 mm in June to 11.0 mm in December. Long-term mean monthly rainfall at St George and actual monthly rainfall at the Nindigully trial site from 1996 to 2001 are shown in Table 2.

### *Field trial establishment and crop management*

The field trial commenced in May 1996 following a wheat crop in 1995 and three tillage operations with a chisel plough during the fallow period. Several experiments were conducted within the trial area. In this paper, we report on studies on tillage method (conventional and zero) (experiment 1) and N fertiliser application (experiment 2). The experiments were sown and harvested in 1996, 1997, 1998, 1999 and 2001. Due to drought, no crop was grown in the 2000 winter cropping season.

In experiment 1, following harvest of wheat in 1996, main plots, 40 m long and 36 m wide and replicated three times, were

**Table 2. Long-term mean monthly, in-crop and fallow rainfall for St George (1881–1996), and monthly, in-crop and fallow rainfall recorded at the Nindigully trial site from 1995 to 2001**

n.m., not measured

| Month | Mean rainfall for St George, 1881–1996 (mm) | Rainfall (mm) at Nindigully trial site | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 |
| Jan. | 74 | | 238 | 135 | 35 | 118 | 45 | 95 |
| Feb. | 61 | | 22 | 106 | 13 | 62 | 50 | 44 |
| Mar. | 54 | | 0 | 24 | 13 | 189 | 61 | 33 |
| Apr. | 33 | | 63 | 0 | 24 | 22 | 4 | 1 |
| May | 39 | | 87 | 64 | 72 | 11 | 18 | 35 |
| June | 33 | | 33 | 27 | 66 | 60 | 9 | 45 |
| July | 33 | | 43 | 3 | 124 | 31 | 2 | 63 |
| Aug. | 25 | | 54 | 2 | 108 | 41 | 9 | 1 |
| Sept. | 27 | | 23 | 20 | 78 | 32 | 0 | 3 |
| Oct. | 39 | | 48 | 65 | 48 | 94 | 73 | 47 |
| Nov. | 46 | 55 | 57 | 51 | 32 | 68 | 93 | 67 |
| Dec. | 52 | 32 | 62 | 203 | 3 | 58 | 8 | 18 |
| Total | 516 | n.m. | 730 | 700 | 616 | 786 | 372 | 452 |
| May–Oct. (usual in-crop) | 196 | n.m. | 288 | 181 | 496 | 269 | 111[A] | 194 |
| Nov.–Apr. (usual fallow) | 320 | | 410 | 384 | 339 | 426 | 286 | 274 |

[A] No crop sown due to lack of sowing rainfall.

each split into two treatments, conventional tillage (CT) and zero tillage (ZT). The main plots comprised 16 runs of a 2.25-m wide seeder. The tillage subplot width was 18 m (eight seeder-runs). Tillage treatments were imposed after the harvest of 1996 cereal crops and maintained until the harvest of 2001. The CT treatment had 3–4 cultivations with a chisel plough or scarifier for weed control during the fallow period. A similar number of herbicide applications were used for weed control during the fallow period under the ZT tillage system. At sowing of wheat in 1997, 1998, 1999 and 2001, the CT and ZT treatments were split further into two sub-subplots, each 9 m wide (four seeder-runs), one without and one with N fertiliser application.

In experiment 2, four N fertiliser treatments (one without and three with N fertiliser application) were applied at sowing in wheat under the ZT system in all years. The main plots were 40 m long and 36 m wide (16 runs of a 2.25-m wide seeder) with three replications and were split into four N fertiliser subplots that were each 9 m wide (four seeder-runs). From 1996 to 1999, N fertiliser treatments in wheat were applied to the same subplots each year.

Two N fertiliser treatments (one without and one with N fertiliser application) were applied at sowing in barley under ZT in all years. The main plots of barley were 40 m long and 18 m wide (eight seeder-runs) with three replications and were split into two N fertiliser subplots that were each 9 m wide (four seeder-runs). The location of the main plots of barley varied from year to year within the trial area.

In experiments 1 and 2, a basal application of 40 kg/ha of mixed fertiliser (9.4% N, 20.5% P, 2.2% S, 2.5% Zn) was banded with the seed at sowing in all years except 1998.

In both experiments, N fertiliser application rates were determined from consideration of soil water and soil nitrate-N content obtained from soil sampling before sowing. Using the equation of Dalal *et al*. (1997), relating grain protein concentration to the ratio between available soil water (mm) and N supply (soil nitrate-N + N fertiliser) (kg/ha) at 0–120 cm depth at sowing, the amount of N fertiliser required to target a given grain protein concentration was calculated. The required ratios were 2.5 for malting barley (10.2 ± 1% protein on oven-dry basis) and for wheat grain at 12% moisture, 2 for 10.5 ± 1% protein, 1.5 for 11.5 ± 1% protein and ≤1 for ≥13% protein. Wheat protein concentrations of 10.5%, 11.5% and 13% are the minimum requirements for the Australian Premium White (APW), Australian Hard (AH) and Australian Prime Hard (APH) grades, respectively. A retrospective assessment of N fertiliser requirements to achieve grain protein concentration of 10.2% in barley and 13% in wheat was also carried out using the computer program HOWWET? (Freebairn *et al*. 1997). In the N requirement section of the program, measured available soil water and soil nitrate-N at sowing from experiment 2 were entered with both a commonly used estimate for water use efficiency (WUE) (10 kg/ha.mm, 100-mm threshold soil water) and a mean measured value for WUE (9.5 kg/ha.mm) from the experiment from 1996 to 2001. The N fertiliser requirements estimated from HOWWET? were then compared with those using the available soil water/N supply method.

In experiment 1, the N fertiliser application rate varied from year to year, depending on soil water and nitrate-N content, and was chosen to target wheat grain protein of 11.5 ± 1% at 12% moisture content in 1997 and 13 ± 1% at 12% moisture content in 1998, 1999 and 2001. In experiment 2, application rates of N fertiliser also varied from year to year, depending on soil water and nitrate-N content (Tables 5 and 6). In each year, increasing N fertiliser rates were chosen to target grain protein of 10.5%, 11.5% and 13% (±1%) at 12% moisture in wheat, and a single rate was chosen to target malting barley of 10.2 ± 1% grain protein on an oven-dried basis.

In 1996, 1999 and 2001, wheat under CT and ZT and barley under ZT were sown with a small-plot seeder which had nine rigid, spear point tines followed by solid, centre-ribbed press wheels, at a row spacing of 25 cm. Sowing depth was 5–8 cm. In N fertiliser treatments, urea was applied at sowing at 5–8 cm depth in the centre of alternate seed rows. In 1997 and 1998, wheat and barley were sown with a small-plot air seeder of similar configuration, but with sowing tines modified to distribute N fertiliser in bands 3–4 cm on either side of the seed row.

Wheat (cv. Hartog) and barley (cv. Tallon) were both sown on 24 May 1996 and on 29 May 1997. In 1998, wheat (cv. Sunco) was sown on 23 May and barley (cv. Tallon) was sown on 14 May. Wheat (cv. Kennedy) and barley (cv. Tallon) were both sown on 22 June 1999 and 21 June 2001. Both crops were sown at 40 kg/ha in 1996, 1999 and 2001 and at 30 kg/ha in 1997 and 1998.

### *Soil and plant sampling and analysis*

Soil profile nitrate-N concentration and water content were measured from soil samples collected in April, 4–8 weeks before sowing and in October–November, shortly after harvest, each year. At each sampling time, four soil cores were taken in a line across two adjacent crop rows and inter-rows at a randomly selected location in each plot. Two samples were taken in the crop rows to a depth of 120 cm in 1996 and 150 cm in subsequent years, and two samples were taken in the centre of the inter-row space to a depth of 30 cm. Cores were 50 mm in diameter in 1996 and 1997 and 38 mm in following years. Cores were divided into 0–10, 10–30, 30–60, 60–90, 90–120 and 120–150 cm layers, according to depth of sampling. For each plot, the samples from corresponding layers were bulked, sealed in plastic bags and stored at 4°C until analysed for nitrate-N concentration and moisture content.

Soil was dried at 35 ± 5°C in a forced draught oven and ground <2 mm for colorimetric determination of nitrate-N (Best 1976) after extraction of 10 g of soil in 100 mL of 2 mol/L KCl. Nitrate-N in kg/ha was calculated from the nitrate-N concentration for each layer, depth of the layer and its bulk density, and then summed for the whole profile.

Gravimetric soil water content (g/g) was determined by drying soil samples at 105°C for 48 h. Volumetric soil water content (mm) for each layer was then calculated using bulk density values determined from soil cores taken when the soil profile was fully wet. Plant available soil water content was determined for each layer by subtracting the lowest soil water content recorded during the trial for that layer in a mature, stressed crop (lower limit of water extraction) (Gardner 1985) from the measured soil water content, and was then expressed as equivalent depth of water (mm) for the whole profile.

The number of ears/m$^2$ was determined from one or two 0.25-m$^2$ samples taken from each subplot at crop maturity. Crop grain yield at maturity was determined from machine harvesting

1.75 m × 36 m of each of the inner two seeder-runs of each subplot. Grain samples were taken from each subplot for grain N and grain weight determination. Grain N concentration was determined from Kjeldahl digests using automated ammonium analysis (Crooke and Simpson 1971). Grain yield, grain protein concentration and grain weight were calculated at 12% moisture content, except for barley grain protein concentration, which was expressed at 0% moisture content.

### Water use efficiency and nitrogen use efficiency

Water use efficiency for grain yield (kg/ha.mm) was determined by dividing grain yield by crop water use (mm). Crop water use was calculated as profile soil water content in April before sowing, minus soil water content in October–November after harvest, plus in-crop rainfall received between these sampling times, mostly during crop growth.

Nitrogen use efficiency (NUE) for grain N yield was calculated as follows: NUE (%) = 100 × grain N yield (kg/ha)/plant utilisable N (kg/ha). Plant utilisable N was equal to soil nitrate-N before sowing, plus N fertiliser (if applied), minus soil nitrate-N after harvest, plus soil nitrate-N mineralised during the cropping period. Soil nitrate-N mineralised during the cropping period was estimated from the change in soil nitrate-N during this period in an unplanted area adjacent to the trial.

### Gross margin

To compare the profitability of treatments, gross margins were calculated as the on-farm income from the grain produced, less the variable or operating costs involved in fallow and crop management. Gross margins do not take into account fixed or overhead expenses such as rates, taxes, insurance, interest and depreciation on machinery and buildings. The on-farm income from the grain was calculated from the Australian Wheat Board prices for grain at the nearest grain depot (Thallon), at the grain protein concentration recorded for each treatment. Variable costs were estimated from a record of operations and materials and their costs (Department of Primary Industries 2000). Gross margins were calculated using grain prices and costs pertaining to each year and also using mean grain prices between 1996 and 2004.

Profitability of water use ($/ha.mm) was determined by dividing the gross margin by the crop water use.

### Infiltration measurements

In April 1999, infiltration of water into the soil was measured in the field in CT and ZT treatments using a portable rainfall simulator based on the design of Bubenzer and Meyer (1965). One hundred mm of simulated rainfall was applied simultaneously over 1 h to two 100-cm wide and 160-cm long plots in each of the three replicates of CT and ZT treatments. Crop stubble was cut and removed from one of these plots to approximate 0% cover and was added to the other plot to give 100% cover. Runoff water was collected at the downslope edge and routed by vacuum through calibrated tipping buckets. Tip rate was logged at 1-min intervals. Water used for simulations was rainwater with electrical conductivity <3 μS/m.

After rainfall simulation, soil hydraulic conductivity was measured with disc permeameters (Perroux and White 1988) in the same area of each CT and ZT treatment that received simulated rainfall. Disc permeameters were applied using the method of Reynolds and Elrick (1991) to measure hydraulic conductivity and pore size distribution. Rainwater (electrical conductivity <3 μS/m) was also used for these measurements. Fine bedding sand (mean diameter <0.001 m) was used to ensure good contact between the disc permeameter and the soil. The disc permeameters did not measure flow in pores >3 mm, so large cracks and micropores were not characterised. Measurements were made from four disc permeameters per treatment in each replicate.

Using a linear relationship between infiltration and surface cover (Freebairn *et al.*1993), infiltration measurements for 0% and 100% cover were used to estimate values for existing cover levels under CT and ZT.

### Statistical analysis

Significant differences ($P = 0.05$) between treatments for the various measurements in each experiment were determined using standard analyses of variance (Snedecor and Cochran 1967). Experiment 1 was analysed as a factorial design (two tillage treatments, each split for two N fertiliser treatments × three replications). In experiment 2, N fertiliser treatments in wheat and barley were analysed as a randomised block design with three replications.

## Results

### Seasonal conditions

Annual rainfall was above average in 1996, 1997, 1998 and 1999 and below average in 2000 and 2001 (Table 2). Rainfall was insufficient to enable sowing of the crop in 2000. In-crop rainfall was below average in 1997. In 1998, when in-crop rainfall was well above average, there were severe infestations of yellow spot (*Pyrenophora tritici-repentis*) in wheat and net blotch (*Pyrenophora teres*) in barley.

### Effects of tillage practice on wheat grain yield, grain protein concentration, gross margin and water use efficiency

Because there were no significant interactions between tillage practice and N fertiliser application, mean effects of CT and ZT across N fertiliser treatments are presented. Grain yield of wheat was greater under ZT than under CT in 1997, but was similar under CT and ZT in all other years and for the mean values over 4 years (Table 3). There were no differences in grain protein concentration between CT and ZT.

Gross margins calculated using grain prices and costs pertaining to each year were greater under ZT than under CT in 1997, but greater under CT than under ZT in 1998 and 1999 (Table 3). Gross margins in 2001 and mean gross margins over 4 years were similar under CT and ZT.

There were no differences in crop water use between CT and ZT (data not shown), but efficiency of water use for grain production was greater under ZT than under CT in 1997 (Table 3).

### Effects of tillage practice on infiltration and soil water and nitrate-N at sowing

At the end of the fallow period in 1999, cumulative infiltration after 100 mm of simulated rainfall over 1 h was greater under ZT than under CT at existing stubble cover levels (60% and

**Table 3. Effects of conventional tillage (CT) and zero tillage (ZT) on plant available soil water at sowing (0–120 cm), wheat grain yield, grain protein, gross margin and water use efficiency**
n.s., not significant

| Tillage method | Available soil water at sowing (mm) | Grain yield (t/ha) | Grain protein (%) | Gross margin ($/ha) | Water use efficiency (kg/ha.mm) |
|---|---|---|---|---|---|
| | | *1997 crop* | | | |
| CT | 140 | 2.11 | 9.6 | 106 | 8.3 |
| ZT | 150 | 2.59 | 9.8 | 154 | 9.8 |
| l.s.d. ($P$ = 0.05) | n.s. | 0.13 | n.s. | 32 | 1.0 |
| | | *1998 crop* | | | |
| CT | 82 | 1.62 | 13.0 | 27 | 2.9 |
| ZT | 105 | 1.54 | 13.0 | –2 | 2.8 |
| l.s.d. ($P$ = 0.05) | n.s. | n.s. | n.s. | 21 | n.s. |
| | | *1999 crop* | | | |
| CT | 165 | 3.11 | 10.7 | 225 | 8.0 |
| ZT | 199 | 3.08 | 10.6 | 163 | 7.4 |
| l.s.d. ($P$ = 0.05) | 27 | n.s. | n.s. | 29 | n.s. |
| | | *2001 crop* | | | |
| CT | 145 | 2.27 | 12.7 | 145 | 6.4 |
| ZT | 160 | 2.40 | 12.4 | 55 | 6.5 |
| l.s.d. ($P$ = 0.05) | n.s. | n.s. | n.s. | n.s. | n.s. |
| | | *Mean of 1997–2001 crops* | | | |
| CT | 133 | 2.23 | 11.4 | 125 | 6.4 |
| ZT | 153 | 2.36 | 11.4 | 92 | 6.7 |
| l.s.d. ($P$ = 0.05) | 18 | n.s. | n.s. | n.s. | n.s. |

10%, respectively) and with 0% cover, but was greater under CT than under ZT with 100% cover (Table 4). Mean final infiltration rate after 1 h was greater with 100% cover (17 mm/h) than with existing cover (5 mm/h) and 0% cover (2 mm/h) [l.s.d. ($P$ = 0.05) = 11]. Saturated hydraulic conductivity of surface soil after simulated rainfall was greater under ZT than under CT at existing stubble cover levels (Table 4). Mean pore density in the 1.5–3.0 mm diameter pore range in surface soil was greater under CT (mean of 9.3 pores/$m^2$) than under ZT (mean of 6.8 pores/$m^2$) [l.s.d. ($P$ = 0.05) = 1.7]. There were no significant differences between CT and ZT in saturated hydraulic conductivity and pore density in the 1.5–3.0 mm diameter pore range in subsurface soil (13 cm depth) (data not shown).

Mean plant available water in the soil profile at sowing over 4 years was 20 mm greater under ZT than CT (Table 3). However, in individual years, plant available soil water at sowing was greater under ZT than under CT only in 1999, when this effect was not reflected in improved grain yield (Table 3). Mean fallow water storage efficiency (percentage of rainfall stored in the soil during the fallow period between crops) for the 1996–97, 1997–98, 1998–99 and 1999–2001 fallow periods was 16% under ZT and 13% under CT.

There were no differences between CT and ZT in soil nitrate-N at sowing (data not shown).

### *Effects of N fertiliser application on wheat grain yield, grain protein, yield components, gross margin and water use efficiency*

Since grain yield responses to N fertiliser were similar under CT and ZT practices in wheat, only data for ZT practice are presented. Wheat grain yield increased with increasing rates of N fertiliser addition and N supply in all years except 2001 (Table 5). However, grain protein concentration increased with increasing rates of N fertiliser addition and N supply in all years. The first increment of N application generally resulted in significantly greater grain yield and protein than when no N was applied. Although increases in grain yield with subsequent

**Table 4. Cumulative infiltration and saturated hydraulic conductivity of surface soil after simulated rainfall (100 mm rain over 1 h), for conventional tillage (CT) and zero tillage (ZT) with stubble removed (0% cover), at existing stubble cover levels (10% and 60%, respectively) and with stubble added to give 100% cover**

| Tillage method | Cumulative infiltration (mm) | | | Saturated hydraulic conductivity (mm/h) | | |
|---|---|---|---|---|---|---|
| | 0% cover | Existing cover | 100% cover | 0% cover | Existing cover | 100% cover |
| CT | 19 | 23 | 65 | 195 | 340 | 1740 |
| ZT | 35 | 42 | 47 | 440 | 1260 | 1720 |
| l.s.d. ($P$ = 0.05) (tillage × cover) | | 10 | | | 435 | |

increments of N addition were not generally significant, grain protein concentration often continued to increase significantly as N fertiliser addition and N supply increased. As a result, gross margins calculated using costs and returns pertaining to each year increased with increasing N supply in 1996, 1997 and 1999 and for the mean values over 5 years. In a wet growing season and disease-affected crop in 1998, there was no effect of N fertiliser application on gross margins. When gross margins were calculated using mean grain prices between 1996 and 2004, mean gross margin increased from $30/ha, with no N fertiliser applied, to $150/ha, with the highest rate of N addition (data not shown).

Except for 1998, grain weight decreased with increasing N supply. The decrease in grain weight was compensated by increasing tiller numbers, as shown by the increasing number of ears (Table 5).

Plant available soil water at sowing and crop water use were not significantly affected by N fertiliser application in individual years (data not shown). However, mean crop water use over 5 years was greater with mean annual N fertiliser application rate of 64 kg N/ha (399 mm) than with no N fertiliser application (374 mm) [l.s.d. ($P$ = 0.05) = 23]. Water use efficiency for grain yield of wheat increased with N fertiliser application in all years except 2001 and for mean values over 5 years (Table 5). As for grain yield, the greatest increase in WUE was generally with the first increment of N addition. In the wet growing season of 1998, WUE was below 4 kg/ha.mm, indicating the adverse effects of periodic

**Table 5. Effects of N supply (N fertiliser applied at sowing + soil nitrate-N before sowing, 0–120 cm) on grain yield, grain protein, grain weight, number of ears, gross margin and water use efficiency for continuous zero tillage (ZT) wheat**

n.s., not significant

| N fertiliser (kg N/ha) | Soil nitrate-N (kg N/ha) | Grain yield (t/ha) | Grain protein (%) | Grain weight (mg) | Number of ears/m$^2$ | Gross margin ($/ha) | Water use efficiency (kg/ha.mm) |
|---|---|---|---|---|---|---|---|
| | | | *1996 crop* | | | | |
| 0 | 75 | 3.01 | 8.5 | 40.3 | 313 | 189 | 8.1 |
| 30 | 75 | 3.50 | 9.2 | 38.5 | 306 | 239 | 8.9 |
| 60 | 75 | 3.66 | 10.7 | 35.6 | 355 | 289 | 9.8 |
| 90 | 75 | 3.82 | 12.3 | 33.2 | 372 | 353 | 10.0 |
| l.s.d. ($P$ = 0.05) | n.s. | 0.29 | 0.9 | 2.5 | 93 | 46 | 0.9 |
| | | | *1997 crop* | | | | |
| 0 | 39 | 2.20 | 7.7 | 38.5 | 178 | 79 | 7.5 |
| 40 | – | 2.70 | 9.9 | 35.8 | 281 | 161 | 9.3 |
| 70 | – | 2.81 | 11.8 | 32.9 | 344 | 190 | 9.3 |
| 100 | 54 | 2.93 | 13.1 | 32.0 | 333 | 224 | 10.3 |
| l.s.d. ($P$ = 0.05) | 15 | 0.17 | 0.7 | 1.9 | 76 | 48 | 1.4 |
| | | | *1998 crop* | | | | |
| 0 | 33 | 1.12 | 11.8 | 20.7 | 230 | –26 | 2.6 |
| 30 | 55 | 1.51 | 12.6 | 20.3 | 282 | 2 | 3.4 |
| 40 | 55 | 1.83 | 13.4 | 20.9 | 309 | 57 | 3.8 |
| 50 | 90 | 1.79 | 13.8 | 20.6 | 296 | 47 | 3.7 |
| l.s.d. ($P$ = 0.05) | 18 | 0.27 | 0.4 | n.s. | n.s. | n.s. | 0.7 |
| | | | *1999 crop* | | | | |
| 0 | 36 | 2.58 | 8.0 | 40.9 | 155 | 2 | 6.2 |
| 60 | 32 | 3.84 | 11.3 | 38.2 | 234 | 198 | 9.4 |
| 90 | 37 | 4.01 | 12.2 | 38.6 | 297 | 220 | 9.1 |
| 150 | 49 | 4.02 | 13.4 | 37.3 | 240 | 344 | 9.2 |
| l.s.d. ($P$ = 0.05) | n.s. | 0.28 | 0.9 | 1.8 | 115 | 52 | 1.3 |
| | | | *2001 crop* | | | | |
| 0 | 90 | 2.92 | 10.0 | 36.5 | 255 | 186 | 8.6 |
| 40 | 90 | 3.13 | 11.7 | 33.5 | 255 | 238 | 8.8 |
| 60 | 90 | 3.00 | 13.4 | 32.2 | 333 | 256 | 8.0 |
| 100 | 90 | 2.99 | 14.9 | 31.7 | 269 | 280 | 7.9 |
| l.s.d. ($P$ = 0.05) | n.s. | n.s. | 1.8 | 3.6 | 77 | n.s. | n.s. |
| | | | *Mean of 1996–2001 crops* | | | | |
| 0 | 54 | 2.36 | 9.2 | 35.4 | 226 | 86 | 6.7 |
| 40 | 59 | 2.94 | 10.9 | 33.3 | 274 | 168 | 8.0 |
| 64 | 60 | 3.06 | 12.3 | 32.0 | 328 | 202 | 7.9 |
| 98 | 71 | 3.11 | 13.5 | 30.9 | 302 | 250 | 8.3 |
| l.s.d. ($P$ = 0.05) | 9 | 0.13 | 0.4 | 0.9 | 47 | 20 | 0.7 |

waterlogging and plant disease on crop growth and yield in this year.

Gross margin/water use increased with N fertiliser addition and greater N supply in 3 out of 5 years (1996, 1997 and 1999) (data not shown) and for mean values over 5 years (Fig. 1). The highest value recorded for gross margin/water use in individual years was $0.93/ha.mm, for wheat with the highest N fertiliser application and the greatest N supply in 1996.

### *Effects of N fertiliser application on barley grain yield, grain protein concentration, yield components, gross margin and water use efficiency*

Significant increases in barley grain yield resulted from the addition of N fertiliser in 1996 and 1999 (Table 6). In 1996, 1997, 1998 and 1999 seasons, grain protein concentration with N fertiliser application was in the range to qualify for malting grade barley (9–12% at 0% moisture content) and, except for the 1998 crop, resulted in similar gross margins to those for wheat at 12.3% grain protein in 1996 and APH grade wheat (≥13% grain protein) in 1997 and 1999. Barley was of feed grain quality and of lower value because of weather damage in 1998 and high grain protein in 2001, due to high residual nitrate-N in soil from the unavoidable long fallow (no crop in 2000 due to lack of sowing rain). Where gross margins were calculated using costs and returns pertaining to each year, mean gross margin over 5 years, where malting grade barley was targeted, was almost double that where it was not. Using mean grain prices between 1996 and 2004, mean gross margin where malting barley was targeted was $180/ha (data not shown).

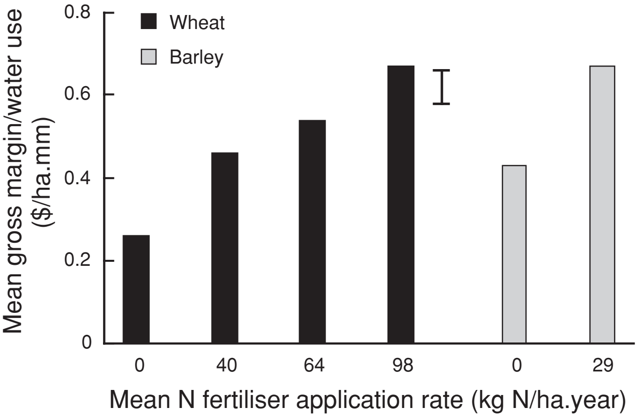

**Fig. 1.** Mean effects of N fertiliser application on gross margin/water use for wheat and barley, 1996–2001. Vertical line indicates the l.s.d. value ($P = 0.05$).

Grain weight of barley was greater with N fertiliser application than without in 1999, and lower with N fertiliser

**Table 6. Effects of N supply (N fertiliser applied at sowing + soil nitrate-N before sowing, 0–120 cm) on grain yield, grain protein (0% moisture content), grain weight, number of ears, gross margin and water use efficiency for zero tillage (ZT) barley**

n.s., not significant

| N fertiliser (kg N/ha) | Soil nitrate-N (kg N/ha) | Grain yield (t/ha) | Grain protein (%) | Grain weight (mg) | Number of ears/m$^2$ | Gross margin ($/ha) | Water use efficiency (kg/ha.mm) |
|---|---|---|---|---|---|---|---|
| | | | *1996 crop* | | | | |
| 0 | 75 | 3.15 | 9.1 | 47.5 | – | 174 | – |
| 40 | 75 | 3.68 | 11.6 | 38.9 | 1036 | 448 | 10.2 |
| l.s.d. ($P = 0.05$) | n.s. | 0.29 | 1.0 | 2.5 | – | 46 | – |
| | | | *1997 crop* | | | | |
| 0 | 67 | 2.48 | 11.1 | 39.1 | 461 | 245 | 10.9 |
| 20 | 68 | 2.48 | 12.4 | 39.2 | 511 | 226 | 9.5 |
| l.s.d. ($P = 0.05$) | n.s. | n.s. | 0.8 | n.s. | n.s. | n.s. | 1.4 |
| | | | *1998 crop* | | | | |
| 0 | 49 | 1.92 | 10.5 | 27.4 | 394 | 20 | 4.5 |
| 20 | 49 | 2.25 | 11.4 | 28.4 | 379 | 33 | 5.2 |
| l.s.d. ($P = 0.05$) | n.s. | n.s. | 0.5 | n.s. | n.s. | n.s. | 0.7 |
| | | | *1999 crop* | | | | |
| 0 | 36 | 2.96 | 7.2 | 37.0 | 476 | 62 | 7.1 |
| 45 | 36 | 4.06 | 9.8 | 39.2 | 533 | 360 | 9.2 |
| l.s.d. ($P = 0.05$) | n.s. | 0.28 | 1.0 | 1.8 | n.s. | n.s. | 1.3 |
| | | | *2001 crop* | | | | |
| 0 | 95 | 3.17 | 13.2 | 33.8 | 464 | 155 | 8.6 |
| 20 | 95 | 3.15 | 14.4 | 31.1 | 376 | 133 | 8.9 |
| l.s.d. ($P = 0.05$) | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. |
| | | | *Mean of 1996–2001 crops* | | | | |
| 0 | 65 | 2.74 | 9.3 | 37.0 | 431 | 131 | 7.9 |
| 29 | 65 | 3.12 | 10.8 | 35.3 | 567 | 240 | 8.5 |
| l.s.d. ($P = 0.05$) | n.s. | 0.13 | 0.4 | 0.9 | 47 | 20 | n.s. |

than without in 1996 and for mean values over 5 years (Table 6). Tiller numbers were not affected by N application in any individual year, but mean tiller numbers over 5 years were greater with N fertiliser application than without.

There were no significant differences in crop water use between N fertiliser treatments in barley in any year or across years (data not shown). Water use efficiency was significantly lower in N fertilised treatment than without N application in 1997, but increased with N fertiliser application in 1998 and 1999 seasons (Table 6). Mean gross margin/water use over 5 years for barley increased significantly with N fertiliser application (Fig. 1). Mean gross margin/water use values were greater in barley than in wheat where no N fertiliser was applied, while maximum values were similar in wheat and barley. The highest gross margin/water use in barley in individual years ($1.24/ha.mm) was obtained for malting grade barley in 1996 (data not shown).

### *Residual benefit of applied N fertiliser*

In all years, the N fertiliser application to wheat resulted in a residual benefit to soil N supply for the following crop, as measured by soil nitrate-N (0–120 cm depth) before sowing (Fig. 2). Thus, in this semiarid, marginal crop growing environment, a substantial amount of N fertiliser that is unused by a crop is carried over to the next season.

### *Nitrogen use efficiency for grain N yield*

Apparent N fertiliser use efficiency for wheat and barley grain [(grain N yield of N treatment – grain N yield of control)/N fertiliser applied] was 41% (Fig. 3), with no significant tillage or N fertiliser application rate effects. There were no significant differences between N fertiliser treatments in NUE for grain N yield. Accounting for residual N fertiliser and in-crop N mineralisation increased NUE for grain N yield, which ranged from a mean of 43% in 1996 to 59% in 1999 (data not shown).

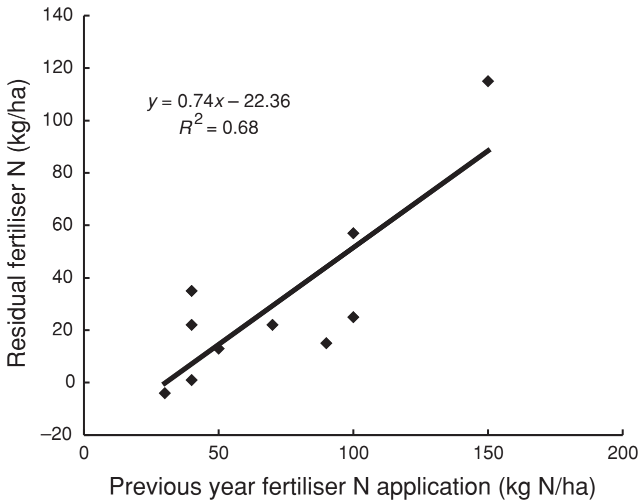

**Fig. 2.** Soil nitrate-N (0–120 cm) at sowing following N fertiliser application in the previous year, in excess of that with no N fertiliser application.

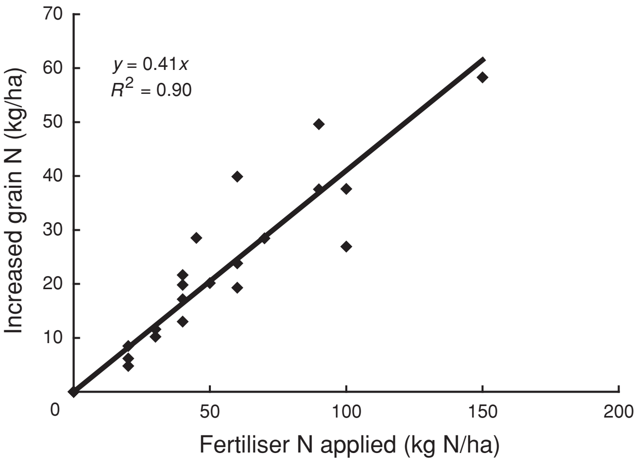

**Fig. 3.** Relationship between increased grain N (grain N yield in the N treatment – grain N yield in the control) in wheat and barley and N fertiliser applications. The slope of the regression line × 100 is the apparent N recovery in grain.

### *Prediction of grain protein concentration from the ratio of available soil water/N supply before sowing*

Measured grain protein concentrations of wheat and barley were compared with the predicted values using the equation derived by Dalal *et al.* (1997):

$$\text{Grain protein (\%)} = 6.52 + 10.0 \times \exp(-0.44 \text{ available water/available N})$$

where plant available water (mm) and available N (soil nitrate-N + N fertiliser) (kg/ha) in 0–120 cm depth of soil were measured at or near sowing.

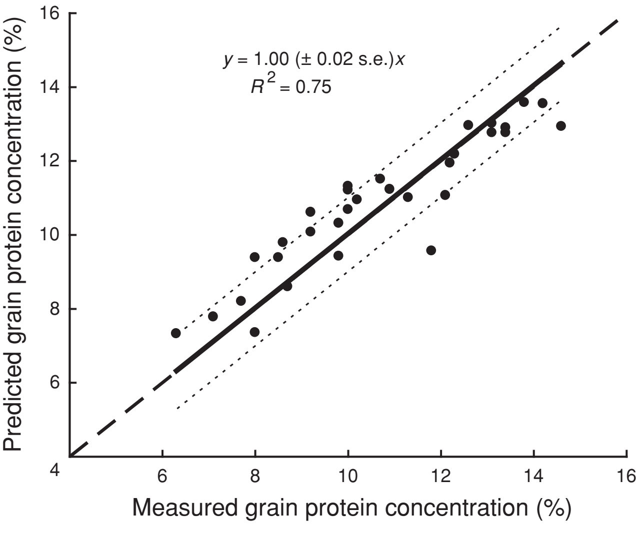

**Fig. 4.** Relationship between the predicted (Dalal *et al.* 1997) (*y*) and measured (*x*) grain protein concentrations for wheat and barley. The equation of regression line (full) through the origin is: $y = 1.00\ (\pm 0.02\ \text{s.e.})x$ ($R^2 = 0.75$). The dotted lines show ±1% range in grain protein about the regression line. The dashed line is the 1 : 1 line.

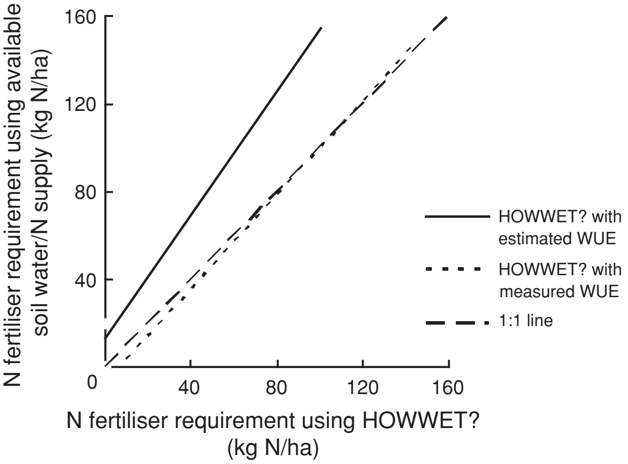

**Fig. 5.** Relationship between the N fertiliser requirement to target grain protein concentration of 10.2% in barley (0% moisture content) and 13% in wheat (12% moisture content) using the available soil water/N supply method (Dalal *et al.* 1997) to calculate $y$, and HOWWET? (Freebairn *et al.* 1997) to calculate $x$ with (i) a commonly used estimate of water use efficiency (WUE) ($y = 1.41x + 13.31$, $R^2 = 0.91$) and (ii) a measured mean value for WUE from this experiment ($y = 1.07x - 7.08$, $R^2 = 0.92$).

There was a significant and a 1 : 1 relationship between the predicted ($y$) and measured ($x$) grain protein values (Fig. 4).

Including a commonly used estimate of WUE, HOWWET? (Freebairn *et al.* 1997) under-predicted grain yield and therefore the N fertiliser requirements to achieve grain protein concentration of 10.2% in barley and 13% in wheat, compared with the available soil water/N supply method (Fig. 5). Using a measured mean value for water use efficiency from the experiment in HOWWET? resulted in better agreement between these two methods.

## Discussion

At the existing levels of soil cover during the 1998–99 fallow period, the soil under ZT had four times greater hydraulic conductivity and two times greater water infiltration than the soil under CT, resulting in 27 mm extra water in the soil profile under ZT practice at the end of the fallow period. In Vertosols, Dalal (1989) showed a much higher rate of Cl leaching under ZT than CT, indicating greater water infiltration under ZT, and Turpin *et al.* (1999) measured much faster water infiltration and bromide movement under ZT than CT, especially when stubble was retained.

Although mean plant available water in the soil profile at sowing over 4 years was 20 mm greater under ZT than under CT, the mean grain yields and gross margins were similar under CT and ZT over this period. ZT resulted in higher grain yield, gross margin and water use efficiency than CT in 1997, when plant available soil water levels at sowing were similar for the two tillage practices, indicating that ZT made more efficient use of stored soil water and in-crop rainfall in this near-average growing season. CT and ZT resulted in similar grain yields in 1998, 1999 and 2001, even though available soil water before sowing was higher under ZT than under CT in 1999. Above average in-crop rainfall may have negated differences in soil water at sowing in 1999. The lower gross margin under ZT than under CT in 1998 and 1999 was due to higher fallow weed control costs with herbicide under ZT than tillage costs under CT in these years.

Other experiments in southern Queensland have shown that there is a greater advantage in yield with ZT over CT in drier growing seasons, as a result of greater soil water storage or water use efficiency (Freebairn *et al.* 1986; Marley and Littler 1989; Radford *et al.* 1992; Thomas *et al.* 1995; Strong *et al.* 1996*a*). Retention of crop residues on the soil surface, as occurs under ZT, has also been shown to extend crop sowing time and facilitate timeliness of sowing during dry weather (Radford and Nielsen 1983), thus providing more sowing opportunities and enhancing potential yield benefits associated with optimum sowing time (Woodruff and Tonks 1983). Therefore, ZT may provide yield and economic benefits to longer-term crop production under the drier conditions more likely to be experienced in this environment than those that occurred from 1996 to 2001.

We observed significant grain yield responses to N fertiliser application in all cropping years except the 2001 season, when the crop followed a long fallow of 18 months (due to lack of sowing rains in 2000) and 80 kg N/ha was accumulated in the soil profile. Except for a wet growing season in 1998, gross margins significantly increased from fertiliser application. We suggest that profitable responses to N fertiliser addition can be obtained in the marginal cropping area of south-west Queensland on deep grey clay soil that has been cropped for several years and is of relatively low fertility. However, all trials that produced grain yields commenced with soil water storage >60% of the plant available water capacity, or received above average rainfall over the growing season. In drier growing seasons, crops were either not sown (2000, 2002) or failed to produce harvestable grain yield (2003, data not shown). Robinson *et al.* (1999) concluded from simulation modelling that positive responses to applying 60 kg N/ha at sowing occurred in 97% of years under conditions similar to those experienced in 1996, but in less than 40% of years when soil water at sowing was less than 50% plant available water capacity. However, on a Vertosol at Warra, ~300 km north-east of Nindigully, N application increased gross returns from five of the seven wheat crops grown, because of increasing grain yield and/or grain protein responses (Strong *et al.* 1996*a*). These results occurred over the 1987–94 period, which included a 4-year period of exceptionally dry seasonal conditions. At Warra, although grain yield responses were inconsistent in the first year of fertiliser application where no N fertiliser had been applied to preceding crops, grain protein usually increased with increasing N application. Holford and Doyle (1992) also showed profitable grain yield responses with wheat to varying rates of N application during a dry growing season in northern New South Wales. Similar effects to those at Warra and in northern New South Wales may also occur under drier seasonal conditions in the south-west Queensland region.

This study has also shown that unused available soil and fertiliser N generally remains in the soil profile to benefit the following crop. This benefit results in a lower N fertiliser requirement in the following crop. Similar effects were also recorded at Warra (Strong *et al.* 1996*b*). However, unused nitrate-N in the soil profile may be lost occasionally by leaching below the root zone and by denitrification, depending on seasonal conditions. Its benefit (and that of fresh N fertiliser application) may also be lost to the following crop if factors such as plant disease limit the response to the additional N supply.

Apparent N fertiliser use efficiency of 41% (Fig. 3) is comparable to that obtained by Strong *et al.* (1996*b*) in the Warra experiment (45%) over a 6-year period that had a range of seasonal conditions. Values for NUE for grain N yield (43–59%) were similar to those recorded by Huggins and Pan (1993) (51–72%) and Dalal *et al.* (1996) (43–65%).

We found that the relationship between the ratio of plant available water and available N supply at sowing and grain protein concentration developed by Dalal *et al.* (1997) for wheat and barley is applicable in this environment. As concluded by Dalal *et al.* (1997), the amount of plant available water (mm) to a depth of 120 cm at sowing should be equally matched by available N (kg N/ha), to produce approximately the 13% protein concentration required for the APH grade of wheat. Malting grade barley (10.2% protein concentration at 0% moisture content) would require ~40% of the available N needed for APH wheat. This knowledge enables the protein concentration for APH grade wheat or malting grade barley to be targeted by meeting any deficit in N supply from nitrate-N present in the soil with that from fertiliser application at sowing. In 1996, grain protein concentration did not reach the level for APH classification, even with the highest rate of N addition (90 kg N/ha), indicating that the top N fertiliser application rate should have been higher for this relatively high-yielding crop. At sowing in 1996, soil water characteristics of the site (crop lower limit) had not been clearly defined, and available soil water at sowing was apparently underestimated. Subsequent determinations showed that plant available water/nitrogen ratio was greater than 1 (1.3) and, therefore, APH grade wheat would not have been expected (estimated grain protein, 12.2% *v.* observed value of 12.3%). However, grain protein concentration was >13% with the highest rate of N addition in all other cropping years.

In this example, the ability of HOWWET? (Freebairn *et al.* 1997) to predict N fertiliser requirements was greatly improved when used with measured, rather than estimated, water use parameters. This indicates the importance of on-farm records in validating such decision support programs.

The highest WUE for grain yield recorded in wheat was ~10.0 kg grain/ha.mm of water used, which was lower than the maximum value recorded for wheat by Radford *et al.* (1992) (18 kg grain/ha.mm) and Thomas *et al.* (1995) (15 kg grain/ha.mm) in south-west Queensland. The considerably lower values recorded in 1998 (2.6–3.7 kg grain/ha.mm) were associated with above average rainfall during the growing period, which resulted in periodic waterlogging, and the severe occurrence of the leaf diseases, such as yellow spot in wheat and net blotch in barley. The lower values for WUE for grain yield obtained at Nindigully may have been associated with the timing and effectiveness of rainfall in relation to stage of growth of the crop and higher potential evaporative demand. Other factors, such as soil-borne disease, may also have limited the efficiency of water use under the continuous winter cereal system. Wildermuth (2001) found that the incidence and severity of crown rot (*Fusarium pseudograminearum*) in continuous wheat increased at a faster rate and to a higher level with the application of N fertiliser in this experiment. However, higher wheat yield with N fertiliser application was associated more consistently with greater water use efficiency than with greater water use.

Gross margin/water use could be a useful concept for comparing the relative value and economic efficiency of crops and management practices, as it integrates grain yield, grain quality and water use. Although it is influenced by the relative prices of crops within and between years, a value of ~$1/ha.mm, which was the highest value recorded in these experiments, appears to be a potential benchmark in this region.

## Conclusions

Zero tillage has potential to improve winter cereal production in south-west Queensland, particularly in drier growing seasons than experienced in this study, by resulting in greater fallow soil water storage or crop water use efficiency than conventional tillage.

Profitable responses to N fertiliser addition in wheat and barley can be obtained on long-term cultivated Vertosols in south-west Queensland when soil water reserves at sowing are at least 60% of plant available water capacity or rainfall during the growing season is above average. Presowing soil profile water and nitrate-N levels can be used to determine the N fertiliser rate required to target grain protein concentration in this environment. An integrative benchmark for improved N fertiliser management appears to be gross margin/water use of ~$1/ha.mm.

## Acknowledgements

The authors thank the Grains Research and Development Corporation (GRDC) for financial assistance and Mr and Mrs D. Hill, 'Dunkerry South' Nindigully, who provided land and other assistance for the trial. We gratefully acknowledge the involvement and advice of members of the trial management committee. We also thank Dr J. Standley, Mr J. Hagedoorn, Mr K. Spann, Mrs J. Glasby and Mrs A. Pumfrey for soil and plant chemical analyses, Mr G. McNamara, Ms J. Riddell and Ms M. Fraser for technical assistance, Messrs, J. Henderson, G. Pauli, G. Kedzlie, D. Cooper, R. Norris, D. Baills, M. Weston and P. Marsh for field operations, and Mrs A. Kelly and Ms K. Bell for advice on trial design and statistical analysis.

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Manuscript received 1 June 2005, accepted 6 February 2007