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# Response of rainfed bread and durum wheat to source, level and timing of nitrogen fertilizer on two Ethiopian Vertisols: II. N uptake, recovery and efficiency

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## Abstract

In trials conducted at 2 highland Vertisol sites in Ethiopia in 1990 and 1991, 2 locally popular wheat cultivars, 1 spring bread wheat (*Triticum aestivum* L.) and 1 durum wheat (*T. durum* Desf.), were supplied with nitrogen (N) fertilizer at 0, 60 and 120 kg N ha$^{-1}$ in the form of large granular urea (LGU), standard urea prills or ammonium sulfate. N was applied all at sowing, all at mid-tillering or split-applied between these two stages (1/3:2/3). While durum wheat exhibited the highest N concentration in grain and straw, bread wheat, because of its higher productivity, resulted in a greater grain and total N uptake. In general, split application of N and use of LGU as N source enhanced grain and total N uptake, apparent N recovery and agronomic efficiency of N, particularly under severe water-logging stress. Where significant, the interactions among the experimental factors substantiated the superior responsiveness of the bread wheat cultivar to fertilizer N, and the beneficial effects of split N application and LGU as an N source. Split application of N tended to nullify the positive effects of LGU, presumably by approximating the delayed release of N achieved with LGU. Considering the potential benefits to Ethiopian peasant farmers and consumers, split application of N should be advocated, particularly on water-logged Vertisols; LGU could be an advantageous N source assuming a cost comparable to the conventional N source urea.

## Introduction

Ethiopia is the major producer of wheat in Eastern Africa (ca. 700,000 ha), accounting for over 70% of total wheat area in the region (Hailu, 1991). The two dominant species of wheat grown in Ethiopia are tetraploid durum (*Triticum durum* Desf.) and hexaploid bread wheat (*T. aestivum* L.) (Tesfaye and Jamal, 1982). Important wheat growing areas in Ethiopia are located in the highlands (i.e., >2000 m a.s.l.), and generally receive annual rainfall >1000 mm with mean annual temperatures between 16 and 20 °C (Hailu, 1991). Wheat is produced across a wide range of soil conditions in Ethiopia (Asnakew *et al.*, 1991).

The low mean national yield for wheat (ca. 1.3 t ha$^{-1}$) is the result of depleted soil fertility due to continuous cereal cropping, and a low frequency of usage of nitrogen (N) fertilizer or rotational legume crops (Asnakew *et al.*, 1991). In addition, N deficiency is often encountered in wheat crops growing in cool, wet areas or on soils that are frequently water-logged such as the highland Vertisols (Kamara and Haque, 1987; Asnakew *et al.*, 1991). Increased usage of N fertilizer is considered to be a primary means of improving wheat grain yields in Ethiopia (Asnakew *et al.*, 1991; Tanner *et al.*, 1993).

Compared with other nutrients, N is highly soluble and may be lost by leaching, denitrification, volatilization and in erosion runoff (Legg and Meisinger, 1982; Murthy, 1988). Researchers in other countries have frequently shown split application to be superior to applying all N at sowing in areas of high seasonal precipitation; split application increases N management flexibility and potentially reduces N losses (Vaughan *et al.*, 1990).

Differential response to alternate N sources has been observed under certain soil conditions: on water-logged soils, the rate of denitrification is greater for nitrate than for ammonium fertilizers (Braun and Roy, 1983). In some studies, large granules have been the most consistently successful N source under water-logged conditions: use of large granules delays dissolution throughout the growing season, and, in effect, programs N supply to match the physiological needs of the crop (Braun and Roy, 1983; Pearson and Muirhead, 1984; Prasad and Singh, 1985).

Several expressions of N use efficiency have been utilized in cereals, depending on whether efficiency is measured relative to the amount of N fertilizer applied (agronomic efficiency, AE) or the amount taken up in the grain (physiological efficiency, PE). Efficiency may be measured relative to the total N available (i.e., soil and fertilizer) (Bock, 1984; Campbell *et al.*, 1993) or to fertilizer N (Doyle and Holford, 1993). Given the difficulty of precise measurement of available soil N and the economic importance of fertilizer N, most efficiency studies relate to fertilizer N. The efficiency of recovery, or apparent recovery (AR), of fertilizer N (Fischer *et al.*, 1993), can be measured as a fraction of fertilizer N applied; its product with PE gives AE (i.e., AE = AR × PE).

Vertisols cover 8 million ha in the Ethiopian highlands, and wheat is one of the principal traditional crops in the highlands (Schulthess, 1992). Ethiopian highland Vertisols tend to exhibit low total N and organic matter content, and N fertilization is considered essential to improve wheat production (Miressa *et al.*, 1992). However, no studies have previously been conducted to assess the effects of alternate N fertilizer sources, rates and timing of application on the N uptake and efficiency of wheat crops grown on Ethiopian Vertisols. Thus, the objective of this study was to investigate the effects of 3 N sources applied at different rates and timings on the uptake and utilization of N by durum and bread wheat grown on 2 highland Vertisols.

## Materials and methods

### *Locations, soils and climatic conditions*

The experiment was conducted during the 1990 and 1991 main cropping seasons on 2 highland Vertisols at the Akaki and Robe research sites (Tilahun, 1994). The Akaki site is located 25 km southeast of Addis Ababa (8 °52′N lat. and 38 °47′E long.). Akaki has an altitude of 2200 m a.s.l., and mean annual rainfall of 1055 mm; mean annual minimum and maximum temperatures are 9 and 23 °C, respectively. In the surface 0 to 30 cm, the Akaki soil contains 73% clay, 1.3% sand and 25.7% silt, 1.3% organic matter, 0.05% total N, and has a pH (1:1 soil:water) of 7.5. The Robe site is located 225 km southeast of Addis Ababa (7 °53′N lat. and 39 °56′E long.) at an altitude of 2420 m a.s.l. Robe receives mean annual precipitation of 862 mm, and the mean annual minimum and maximum temperatures are 6.5 and 22.2 °C, respectively. In the surface 0 to 30 cm, the Robe soil consists of 63.9% clay, 12.6% sand and 23.5% silt, with 2.6% organic matter and 0.16% total N. Soil pH (1:1 soil:water) is 6.5.

### *Treatments and experimental design*

This experiment examined the effects of 3 N sources, 3 rates, and 3 different application timings. The N sources included ammonium sulfate (21% N), and urea and large granular urea (both 46% N). The LGU granules were roughly spherical and 5 mm in diameter. The N rates were 0, 60 and 120 kg $ha^{-1}$. The N source by rate combinations were applied: a) all at sowing; b) all at mid-tillering (i.e., Zadoks crop development stage 2.2); or c) split-applied with one-third of the N at sowing and two-thirds at mid-tillering. N fertilizer applied at sowing was broadcast and incorporated into the soil before seeding. N applied at mid-tillering was top-dressed when the soil was moist.

Two locally popular cultivars were selected to represent each wheat species: ET13 for bread wheat and Boohai for durum.

The experiment was laid out in a split-plot arrangement of a randomized complete block design with three replications in each site-season. The factorial combinations of N sources, rates and application timings plus the control treatment (i.e., nil N) were assigned as subplots within the main plot of each wheat species.

Basal P fertilizer was soil-incorporated at a rate of 10 kg P $ha^{-1}$ as triple superphosphate before sowing all plots. Plots consisted of 12 rows 4 m in length at a row spacing of 0.2 m. Seed rate was 150 kg $ha^{-1}$, and seeds were sown by hand into rows drawn using a manual row marker. Sowing dates were 15 July, 1990 and 19 July, 1991 for Akaki, while for Robe the sowing date was July 14 in both seasons. The previous crop was tef (*Eragrostis tef* L.) at Akaki and noug (*Guizotia* *abyssinica* L.) at Robe in both seasons. Fertilizer had been applied for the preceding tef crops at Akaki, but not for noug at Robe. Post-emergence weed control for the experiment was by hand weeding. Harvest extended from the middle to the end of December for each trial. The middle 6 rows 3 m in length were used for data collection.

### *Measurements*

At physiological maturity, plants were hand-harvested close to the ground surface using sickles, and the dry matter yield of above-ground biomass was determined. Grain moisture content was determined, and grain yield was converted to a 12.5% moisture basis.

### *Analytical procedures*

Grain and straw N contents were determined by micro-Kjeldahl analysis of grain and straw sub-samples taken from the oven-dried bulk samples.

Grain (GNU) and straw (SNU) N uptake values were calculated by multiplying grain and straw yields by the respective N contents. Total N uptake (TNU) was calculated as the sum of GNU and SNU. Nitrogen harvest index (NHI), the ratio of GNU to TNU, was expressed as a percentage. Apparent N recovery (AR) in wheat grain for each treatment was calculated as: (GNU of treatment - GNU of control) ÷ fertilizer N applied. Agronomic efficiency (AE) of fertilizer N was calculated as: (grain yield of treatment - grain yield of control) ÷ fertilizer N applied. Physiological efficiency (PE) was calculated as the ratio AE ÷ AR.

All data were subjected to analysis of variance, using cultivars as the main factor, and the factorial combinations of N source, rate and timing as sub-factors. Data were analyzed for individual trials and combined across sites and/or seasons. The lsd test ($p=0.05$) was used to assess differences among treatment means.

## Results and discussion

Grain yields varied markedly between the two trial sites used in this study, Akaki and Robe, reflecting differences in altitude, temperature, severity of water-logging and soil fertility. The mean grain yields of the control plots were 781 and 1616 kg ha$^{-1}$ for Akaki and Robe, respectively, while for the treatments receiving N fertilizer the corresponding mean yields were 1626 and 3165 kg ha$^{-1}$ (Tilahun *et al.*, 1995).

Examination of the climatic data revealed that growing season rainfall at Robe was similar to the long-term mean with 462 mm (+11%) and 438 mm (+5%) in 1990 and 1991, respectively. Precipitation at Akaki exceeded the long-term mean by a relatively greater margin: seasonal totals were 809 mm (+35%) and 697 mm (+16%) in the two years. Temperatures were similar to long-term means. The greater seasonal precipitation and higher soil clay content at Akaki relative to Robe generally result in more severe water-logging stress; based on visual observation, the degree of water-logging stress was greater at Akaki than Robe in both 1990 and 1991.

Combined analyses over years and locations revealed highly significant interactions among years, locations and experimental factors, often obscuring the effects of the latter. Hence, the individual site-season analyses are reported here. Alcoz *et al.* (1993) reported that year effects on grain yield and apparent N recovery exceeded the effects of N rates and application timing in their study.

Considering the 9 crop N characteristics measured (i.e., grain and straw N content and uptake, NHI, TNU, AE, AR and PE) for each of the 4 site-seasons, significant differential effects were observed due to N rate (24 of 36 comparisons), N timing (17 of 36), N source (8 of 36), wheat species (8 of 36), and the interactions of species by N timing (9 of 36) and N rate by timing (7 of 36). Significance was exhibited less frequently for all other two-way and three-way interactions.

### *Differences between wheat species*

Few differences were detected between the wheat species since, as the main factor in the split-plot layout, there were only 2 degrees of freedom for the associated error term.

Grain (GNC) and straw (SNC) N contents were greater for durum than for bread wheat in each site-season combination (data not shown), but only the differences for GNC in both seasons at Akaki were significant. Contrary to the reports of Fischer *et al.* (1993) and Alcoz *et al.* (1993), GNC was not significantly and negatively correlated with grain yield in the current study; in the Robe 1990 trial, GNC was positively correlated with grain yield for both wheat species ($r=0.60$, $p<.01$ and 0.49, $p<.05$ for bread and durum wheat, respectively).

The 2 wheat species did not differ for GNU in any of the trials, while SNU and TNU differed significantly only at Akaki in 1991. This particular site-season was characterized by prolonged duration of the main rains accompanied by severe water-logging (Tilahun *et al.*, 1995). Boohai durum exhibited a marked decline in grain and straw yield under water-logging relative to ET13, resulting in a reduction in TNU (i.e., 36.7 vs. 46.9 kg $ha^{-1}$).

Differences between the species for NHI in 1990 were inconsistent across the 2 sites, perhaps reflecting genotype by environment interaction. NHI values ranged from 54.7 to 74.7% across the 4 trials; Schulthess (1992) reported similar NHI values using ET13 and Boohai.

Wheat species differed significantly for AR in the 1990 trials at both sites; however, as for NHI, the differences were not consistent across the 2 sites. AR values for each species ranged from 12.3 to 54.9% across the trials, with site means of 15.6% for Akaki and 35.8% for Robe; thus, mean recovery of N fertilizer in wheat grain was quite low at Akaki, particularly under the severe water-logging stress of 1991 (i.e., mean AR of 13.6%).

AE values for each species ranged from 7.2 to 30.2 kg grain per kg fertilizer N across the trials, but the differences were not significant in any site-season; given that the current ratio of grain:N prices in Ethiopia is approximately 3.0, the mean response to fertilizer N was profitable in each trial.

*N rate effects*

GNC was positively affected by N rate in 2 trials, including the severely water-logged Akaki trial in 1991 (data not shown), whereas grain yield responded positively to N rate in all 4 trials (Tilahun *et al.*, 1995). Mooleki and Foster (1993) reported variation in the response of wheat GNC to N rate across locations; GNC is known to be strongly influenced by environmental factors in addition to N availability (Campbell *et al.*, 1993).

Reflecting the dramatic grain and biomass responses to applied N, GNU and TNU were significantly increased by N rate in all 4 trials (Tables 1 and 2).

NHI was significantly affected by N rate at both sites, but only in 1990. At Akaki (Table 1), NHI increased in the order: control (61%) < 60 kg N (68%) < 120 kg N (72%). At Robe, a site characterized by higher native soil fertility, NHI declined at the highest N rate in agreement with the reports of Campbell *et al.* (1993), Fischer *et al.* (1993), and Tanner *et al.* (1993). The contrasting result at Akaki probably reflects the low soil fertility status and more frequent incidence of water-logging at that site.

Increased N rate significantly reduced AE in 2 trials and AR in 1 trial (Tables 3 and 4), in agreement with the reports of Alcoz *et al.* (1993), Campbell *et al.* (1993), Doyle and Holford (1993), and Fischer *et al.* (1993). The effect of N rate on PE was inconsistent: PE was negatively related to N rate in 2 trials as in Campbell *et al.* (1993) and Doyle and Holford (1993); however, the relationship was inexplicably positive in the Akaki 1990 trial (Table 3).

*N application timing effects*

GNC and SNC were only affected by N timing at Robe in 1990 (data not shown). For both characters, N application at mid-tillering (T2) > split application (T3) > all N at sowing. Fischer *et al.* (1993) reported increased GNC with late application of N.

GNU and TNU reflected grain and biomass yield response to N application timing, varying in response to application timing in all trials except Robe in 1991 (Tables 1 and 2). Split application exhibited a marked advantage for grain and total N uptake, probably as a result of its yield enhancing effect. Alcoz *et al.* (1993) reported a similar beneficial effect of split application on TNU.

NHI was affected by N timing in 2 trials, but not in a consistent manner. At Akaki in 1991 (Table 1), the NHI for all N at mid-tillering (T2) > all N at sowing (T1), while split application (T3) was not different from either; at Robe in 1990, the NHI for all N at sowing (T1) > all N at mid-tillering (T2), and again split application (T3) was not different from either.

N timing affected AE in 2 trials, AR in 3 trials, and PE in 1 trial (Tables 3 and 4). For AE, in both cases, T1 (all N at sowing) was significantly lower than the other 2 timings, which did not differ from each other. Thus, delayed and split application of N increased the agronomic response to fertilizer N dramatically, thereby increasing the profitability of N application.

Recovery of N was similarly affected by N timing. In 2 trials, split and delayed application resulted in a higher AR than all N at sowing; in 1 trial, split application exhibited a higher AR value than the other 2 timings which did not differ from each other. Across all trials, mean recovery of fertilizer N in grain was 22% for application at sowing, and 28% for split and delayed application. The recovery of fertilizer N

*Table 1.* Effects of N fertilizer source, rate and time of application on N uptake and N harvest index of wheat at Akaki

| Treatment | Grain N uptake (kg ha$^{-1}$) | | Total N uptake (kg ha$^{-1}$) | | N harvest index (%) | |
|---|---|---|---|---|---|---|
| | 1990 | 1991 | 1990 | 1991 | 1990 | 1991 |
| N source[a] | | | | | | |
| Urea | 26.8 | 24.0 | 37.7 | 41.7 | 70.7 | 57.7 |
| LGU | 27.3 | 27.3 | 39.3 | 45.1 | 68.9 | 59.5 |
| AS | 25.9 | 22.7 | 36.6 | 38.5 | 70.4 | 58.1 |
| lsd (p=0.05) | ns | 2.1 | ns | 3.3 | ns | ns |
| N rate (kg ha$^{-1}$) | | | | | | |
| 60 | 21.3 | 21.4 | 31.4 | 35.9 | 67.8 | 59.0 |
| 120 | 32.0 | 28.0 | 44.3 | 47.7 | 72.2 | 57.8 |
| lsd ($p$=0.05) | 2.1 | 1.8 | 2.4 | 2.7 | 2.5 | ns |
| Time of N application | | | | | | |
| All at planting | 25.7 | 22.7 | 36.4 | 39.5 | 69.7 | 56.0 |
| All at mid-tillering | 25.6 | 25.6 | 36.9 | 42.2 | 69.8 | 60.9 |
| Split 1/3:2/3 | 28.7 | 25.7 | 40.3 | 43.7 | 70.6 | 58.4 |
| lsd (p=0.05) | 2.6 | 2.1 | 3.0 | 3.3 | ns | 3.3 |
| Control | 10.8 | 12.7 | 18.0 | 19.9 | 60.9 | 63.3 |

[a] LGU = large granular urea, AS = ammonium sulfate; ns = not significant ($p > 0.05$).

was particularly low (i.e., 11.4%) for N application at sowing in the severely water-logged Akaki 1991 trial (Table 3). Alcoz *et al.* (1993) reported a beneficial effect of split N application on AR, while Fischer *et al.* (1993) reported a decline in AR with late N dressings.

### *N source effects*

N source affected GNC in only 1 trial: at Akaki in 1991, urea and LGU resulted in a higher GNC than AS. This agrees with previous reports of minimal effects of N source on GNC (Campbell *et al.*, 1991; Meelu *et al.*, 1987). Alternate N sources did not affect SNC in any trial.

GNU and TNU were affected by N source in 1 and 2 trials, respectively. At Akaki in 1991, LGU resulted in the largest GNU and TNU, exceeding those of urea and AS which did not differ from each other (Table 1). At Robe in 1990, TNU from LGU and AS exceeded that from urea (Table 2). Although GNU in this site-season exhibited the same trend, the differences were not significant. Most previous reports have indicated the absence of an effect of N source on TNU (Campbell *et al.*, 1991; Meelu *et al.*, 1987; Recous *et al.*, 1992).

NHI in the current study was not affected by N source in any trial.

N source significantly affected AE, AR and PE in the Akaki 1991 trial under severe water-logging stress (Table 3). No differences among N sources were apparent at Robe (Table 4) where mean values for AE and AR were higher than at Akaki. In the Akaki 1991 trial, the AE of LGU was superior to AS and urea, and AR values followed the same ranking. For PE, AS was superior to urea while LGU did not differ from either. Thus, under severe water-logging stress, the slow release nature of LGU may have increased N recovery and efficiency. Under different soil and climatic conditions, Malhi and Nyborg (1992) reported

*Table 2.* Effects of N fertilizer source, rate and time of application on N uptake and N harvest index of wheat at Robe

| Treatment | Grain N uptake (kg ha$^{-1}$) 1990 | Grain N uptake (kg ha$^{-1}$) 1991 | Total N uptake (kg ha$^{-1}$) 1990 | Total N uptake (kg ha$^{-1}$) 1991 | N harvest index (%) 1990 | N harvest index (%) 1991 |
|---|---|---|---|---|---|---|
| N source[a] | | | | | | |
| Urea | 58.2 | 58.9 | 82.5 | 81.8 | 71.1 | 71.5 |
| LGU | 63.4 | 54.2 | 92.6 | 75.2 | 69.2 | 71.4 |
| AS | 63.1 | 55.2 | 90.4 | 77.9 | 70.0 | 71.3 |
| lsd (p=0.05) | ns | ns | 7.8 | ns | ns | ns |
| N rate (kg ha$^{-1}$) | | | | | | |
| 60 | 53.4 | 49.5 | 74.9 | 68.5 | 71.3 | 71.5 |
| 120 | 69.7 | 62.7 | 102.1 | 88.1 | 68.9 | 71.3 |
| lsd (p=0.05) | 4.5 | 7.9 | 6.4 | 10.7 | 1.7 | ns |
| Time of N application | | | | | | |
| All at planting | 51.0 | 56.2 | 70.9 | 77.7 | 72.2 | 71.8 |
| All at mid-tillering | 65.9 | 57.5 | 97.7 | 81.2 | 67.7 | 70.3 |
| Split 1/3:2/3 | 67.8 | 54.6 | 96.9 | 76.0 | 70.4 | 72.1 |
| lsd (p=0.05) | 5.5 | ns | 7.8 | ns | 2.1 | ns |
| Control | 25.4 | 30.5 | 38.7 | 45.0 | 66.0 | 67.0 |

[a] LGU = large granular urea, AS = ammonium sulfate; ns = not significant ($p > 0.05$).

distinctly inferior AR for slow release sulphur-coated urea compared to other N sources.

*Interactions among factors*

Species by N application timing had a significant effect on GNU, TNU, NHI, AE and AR at Akaki in 1991, and GNU, AE and AR at Robe in 1990. For GNU at Akaki in 1991 (data not shown), split application of N (T3) maximized GNU in bread wheat, whereas in durum, GNU was highest with late N application (T2). At Robe in 1990, bread wheat GNU was greatest for T2 and T3, while that of durum was maximized by T3. Examination of the interaction means revealed that bread wheat had a significantly higher GNU than durum for each timing in both trials with the exception of split application (T3) in the Robe 1990 trial.

Similarly, for AE, ET13 bread wheat exhibited a superior response relative to Boohai durum (Table 5). For the Akaki 1991 site-season (i.e., under severe water-logging stress), ET13 with split application of N exhibited an AE of 12.4 kg grain per kg fertilizer N which was superior to the AEs for T1 and T2; for Boohai, delayed application (T2) resulted in the highest AE of 9.7 which was superior to the AEs for T1 and T3. At Robe in 1990, for ET13, split or delayed application were equal and superior to all N at sowing; for durum, split application was superior to the other timings.

ET13 bread wheat exhibited a greater AR of fertilizer N than Boohai durum for most application timings. At Robe in 1990, bread wheat exhibited a higher AR value than durum for all 3 timings: for ET13, delayed and split application were superior to all N at sowing; for Boohai, split was superior to sowing and delayed. At Akaki in 1991, bread wheat exhibited a higher N recovery than durum with split N application: for ET13, split was superior to sowing, and delayed was intermediate; for Boohai, delayed was superior to sowing and split application.

Species by N source interaction (Table 6) was significant for AE and AR at Akaki in 1991 and for AE at Robe in 1990. For the Akaki 1991 site-season, ET13 exhibited a superior AE to Boohai for LGU, but not for AS or urea; within ET13, LGU was superior to urea and AS. In the Robe 1990 trial, the AE of ET13 was

*Table 3.* Effects of N fertilizer source, rate and time of application on agronomic efficiency (AE), apparent recovery (AR) and physiological efficiency (PE) of N for wheat at Akaki

| | AE (kg grain: kg fert. N) | | AR (kg grain N: kg fert. N) | | PE (kg grain: kg grain N) | |
|---|---|---|---|---|---|---|
| Treatment | 1990 | 1991 | 1990 | 1991 | 1990 | 1991 |
| Source[a] | | | | | | |
| Urea | 10.8 | 7.9 | 0.177 | 0.133 | 61.0 | 58.7 |
| LGU | 10.6 | 10.1 | 0.184 | 0.156 | 58.8 | 65.6 |
| AS | 9.7 | 8.0 | 0.168 | 0.117 | 56.1 | 69.3 |
| lsd (p=0.05) | ns | 1.6 | ns | 0.026 | ns | 7.4 |
| N rate (kg ha$^{-1}$) | | | | | | |
| 60 | 10.2 | 9.6 | 0.176 | 0.144 | 55.3 | 69.0 |
| 120 | 10.5 | 7.7 | 0.177 | 0.127 | 61.9 | 60.1 |
| lsd (p=0.05) | ns | 1.3 | ns | ns | 6.2 | 6.1 |
| Time of N application | | | | | | |
| All at planting | 9.5 | 6.9 | 0.161 | 0.114 | 55.9 | 61.7 |
| All at mid-tillering | 10.0 | 9.4 | 0.168 | 0.147 | 61.1 | 65.4 |
| Split 1/3:2/3 | 11.7 | 9.6 | 0.200 | 0.145 | 58.8 | 66.4 |
| lsd (p=0.05) | ns | 1.6 | 0.034 | 0.026 | ns | ns |

[a] LGU = large granular urea, AS = ammonium sulfate; ns = not significant ($p$>0.05).

*Table 4.* Effects of N fertilizer source, rate and time of application on agronomic efficiency (AE), apparent recovery (AR) and physiological efficiency (PE) of N for wheat at Robe

| | AE (kg grain: kg fert. N) | | AR (kg grain N: kg fert. N) | | PE (kg grain: kg grain N) | |
|---|---|---|---|---|---|---|
| Treatment | 1990 | 1991 | 1990 | 1991 | 1990 | 1991 |
| N source[a] | | | | | | |
| Urea | 20.4 | 16.0 | 0.385 | 0.327 | 52.3 | 49.1 |
| LGU | 21.8 | 13.9 | 0.434 | 0.276 | 49.0 | 52.6 |
| AS | 22.9 | 14.7 | 0.436 | 0.287 | 52.1 | 58.2 |
| lsd ($p$=0.05) | ns | ns | ns | ns | ns | ns |
| N rate (kg ha$^{-1}$) | | | | | | |
| 60 | 25.7 | 16.7 | 0.467 | 0.325 | 55.6 | 51.2 |
| 120 | 17.7 | 13.0 | 0.370 | 0.268 | 46.7 | 55.4 |
| lsd (p=0.05) | 2.4 | ns | 0.058 | ns | 3.5 | ns |
| Time of N application | | | | | | |
| All at planting | 17.1 | 14.8 | 0.287 | 0.295 | 55.9 | 60.4 |
| All at mid-tillering | 23.1 | 16.1 | 0.476 | 0.321 | 46.3 | 46.3 |
| Split 1/3:2/3 | 24.9 | 13.6 | 0.492 | 0.275 | 51.2 | 53.1 |
| lsd ($p$=0.05) | 3.0 | ns | 0.071 | ns | 4.3 | ns |

[a] LGU = large granular urea, AS = ammonium sulfate; ns = not significant ($p$>0.05).

*Table 5.* Effects of interaction of wheat species by N application timing on agronomic efficiency (AE) and apparent recovery (AR)

| | Akaki 1991 | | | | Robe 1990 | | | |
|---|---|---|---|---|---|---|---|---|
| | AE | | AR | | AE | | AR | |
| | BW[a] | Du | BW | Du | BW | Du | BW | Du |
| Time of N application | | | | | | | | |
| All at planting | 8.7 | 5.1 | 0.130 | 0.098 | 24.0 | 10.2 | 0.380 | 0.194 |
| All at mid-tillering | 9.2 | 9.7 | 0.137 | 0.157 | 34.8 | 11.4 | 0.681 | 0.271 |
| Split 1/3:2/3 | 12.4 | 6.8 | 0.176 | 0.115 | 31.9 | 17.9 | 0.587 | 0.398 |
| lsd1 ($p$=0.05)[b] | 2.4 | | 0.040 | | 4.45 | | 0.107 | |
| lsd2 ($p$=0.05) | 2.8 | | 0.041 | | 9.04 | | 0.152 | |

[a] BW = ET13 bread wheat, Du = Boohai durum;
[b] lsd1 = lsd for N timings within one wheat species, lsd2 = lsd for comparisons across species.

superior to Boohai for each N source, but, within ET13, the AEs for LGU and AS were superior to that of urea. For AR at Akaki in 1991, ET13 with LGU was superior to all other species by N source combinations.

Species by N rate interaction affected SNC and PE at Akaki in 1991, SNU and NHI at Robe in 1991, and AE and AR at Robe in 1990. For ET13 in the Robe 1990 trial (Table 7), AE was significantly reduced at 120 kg N ha$^{-1}$ relative to 60 N, while the significantly lower AE values for durum were not reduced by increased N rate. In the same trial, N recovery by ET13 was reduced by increasing N rate, but the ARs for durum were unchanged and significantly lower at both N rates relative to those of bread wheat. PE at Akaki in 1991 was highest for bread wheat at 60 N, while the other 3 species by rate combinations did not differ from each other.

In general, it can be concluded that the bread wheat ET13 was more responsive to N and exhibited superior N uptake, efficiency and recovery relative to the durum Boohai.

N source by rate interaction affected GNU, TNU, AE and AR at Akaki in 1991, and PE at Robe in 1990. In the Akaki trial, GNC was increased significantly by urea and LGU at the higher N rate; AS at the high rate did not increase GNC (data not shown). At the high N rate, GNU was increased by 59% with LGU (to 33.5 kg N/ha), but only by 16% for AS (24.4) and 18% for urea (26.0); the GNU for LGU at 120 kg N was significantly higher than all other source by rate combinations. For AE (Table 8), at the low N rate, there was no difference among the 3 N sources, but at 120 N, the AE of LGU was superior to those of urea and AS which did not differ from each other. AR followed the same trend: at 60 kg N, N sources exhibited the same level of recovery in grain, but, at 120 N, the AR of LGU was superior to those of urea and AS. At Robe in 1990, there was no difference in PE among the 3 N sources at 120 kg N, but, at 60 kg N, urea was superior to LGU.

N source by timing interaction had a significant effect on GNC, GNU, AR and PE at Akaki in 1991, and on GNC and SNC at Robe in 1990 (data not shown). For GNC, with application at sowing, urea (1.74) > LGU (1.63) > AS (1.45) at Akaki in 1991, while LGU (1.71) > urea (1.57) at Robe in 1990; for delayed and split applications, there were no differences among N sources. For GNU at Akaki in 1991, LGU (26.4) > AS (18.0) at sowing, LGU (29.5) > urea (24.3) and AS (23.1) at tillering, and there were no differences among the 3 N sources with split N application. N recovery was lowest for AS at sowing (0.07), and highest for LGU at tillering (0.18) at Akaki in 1991; with split application, N sources did not differ. In the same site-season, PE was highest for AS at sowing (75.8) and lowest for urea at sowing (49.1); for delayed or split N application, there were no differences among N sources.

N rate by timing interaction affected GNC, SNC, NHI, SNU and AE at Robe in 1990, and PE at Akaki in 1991 (data not shown). For the Robe 1990 trial, split or delayed application of 60 kg N ha$^{-1}$ increased AE significantly relative to all N at sowing; with 120 kg N ha$^{-1}$, there was no effect of application timing on AE. As noted previously in the discussion of main effects, AE was decreased by N rate and increased by delayed

*Table 6.* Effects of interaction of wheat species by N source on agronomic efficiency (AE) and apparent recovery (AR)

| | Akaki 1991 | | | | Robe 1990 | |
|---|---|---|---|---|---|---|
| | AE | | AR | | AE | |
| | BW[a] | Du | BW | Du | BW | Du |
| N source[b] | | | | | | |
| Urea | 7.6 | 8.2 | 0.122 | 0.144 | 26.8 | 14.0 |
| LGU | 13.7 | 6.5 | 0.198 | 0.114 | 31.9 | 11.7 |
| AS | 9.2 | 6.9 | 0.123 | 0.111 | 32.0 | 13.7 |
| lsd1 ($p$=0.05)[c] | 2.4 | | 0.040 | | 4.45 | |
| lsd2 ($p$=0.05) | 2.8 | | 0.041 | | 9.04 | |

[a] BW = ET13 bread wheat, Du = Boohai durum;
[b] LGU = large granular urea, AS = ammonium sulfate;
[c] lsd1 = lsd for N sources within one wheat species, lsd2 = lsd for comparisons across species.

*Table 7.* Effects of interaction of wheat species by N rate on agronomic efficiency (AE), apparent recovery (AR) and physiological efficiency (PE)

| | Robe 1990 | | | | Akaki 1991 | |
|---|---|---|---|---|---|---|
| | AE | | AR | | PE | |
| | BW[a] | Du | BW | Du | BW | Du |
| N rate (kg $ha^{-1}$) | | | | | | |
| 60 | 37.1 | 14.3 | 0.645 | 0.290 | 78.0 | 59.9 |
| 120 | 23.4 | 12.1 | 0.454 | 0.285 | 62.7 | 57.5 |
| lsd1 ($p$=0.05)[b] | 3.4 | | 0.082 | | 4.99 | |
| lsd2 ($p$=0.05) | 7.0 | | 0.117 | | 6.60 | |

[a] BW = ET13 bread wheat, Du = Boohai durum;
[b] lsd1 = lsd for N rates within one wheat species, lsd2 = lsd for comparisons across species.

*Table 8.* Effects of interaction of N source by N rate on agronomic efficiency (AE), apparent recovery (AR) and physiological efficiency (PE)

| | Akaki 1991 | | | | Robe 1990 | |
|---|---|---|---|---|---|---|
| | AE | | AR | | PE | |
| N rate (kg/ha) | 60 | 120 | 60 | 120 | 60 | 120 |
| N source[a] | | | | | | |
| Urea | 9.9 | 5.9 | 0.155 | 0.110 | 60.5 | 44.1 |
| LGU | 9.7 | 10.5 | 0.139 | 0.173 | 50.3 | 47.8 |
| AS | 9.4 | 6.7 | 0.138 | 0.097 | 55.9 | 48.3 |
| lsd ($p$=0.05) | 2.3 | | 0.037 | | 6.1 | |

[a] LGU = large granular urea, AS = ammonium sulfate.

or split application of N (Table 4) at this relatively productive and fertile site.

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## References

Alcoz MM, Hons FM and Haby VA (1993) Nitrogen fertilization timing effect on wheat production, nitrogen uptake efficiency, and residual soil nitrogen. Agron J 85: 1198–1203

Asnakew Woldeab, Tekalign Mamo, Mengesha Bekele and Teferra Ajema (1991) Soil fertility management studies on wheat in Ethiopia. In: Hailu Gebre-Mariam, Tanner DG and Mengistu Hulluka (eds) Wheat Research in Ethiopia: A Historical Perspective, pp 137–172. IAR/CIMMYT, Addis Ababa, Ethiopia

Bock BR (1984) Efficient use of nitrogen in cropping systems. In: Hauck RD (ed) Nitrogen in Crop Production, pp 273–294. American Society of Agronomy, Madison, Wisconsin

Braun H and Roy RN (1983) Maximizing the efficiency of mineral fertilizers. In: Efficient Use of Fertilizers in Agriculture, Developments in Plant and Soil Sciences, Vol. 10, pp 251–271. The United Nations, New York

Campbell CA, Nuttall W, Ukrainetz H, Selles F and Wright T (1991) Effect of N source, placement and time of application on winter wheat production in Saskatchewan. Can J Soil Sci 71: 177–187

Campbell CA, Selles F, Zentner RP and McConkey BG (1993) Nitrogen management for zero-till spring wheat: disposition in plant and utilization efficiency. Commun Soil Sci Plant Anal 24: 2223–2239

Doyle AD and Holford ICR (1993) The uptake of nitrogen by wheat, its agronomic efficiency and their relationship to soil and fertilizer nitrogen. Aust J Agric Res 44: 1245–1258

Fischer RA, Howe GN and Ibrahim Z (1993) Irrigated spring wheat and timing and amount of nitrogen fertilizer. I. Grain yield and protein content. Field Crops Res 33: 37–56

Hailu Gebre-Mariam (1991) Wheat production and research in Ethiopia. In: Hailu Gebre-Mariam, Tanner DG and Mengistu Hulluka (eds) Wheat Research in Ethiopia: A Historical Perspective, pp 1–15. IAR/CIMMYT, Addis Ababa, Ethiopia

Kamara CS and Haque I (1987) Characteristics of Vertisols at ILCA research sites in Ethiopia, ILCA Working Document No. B5. ILCA, Addis Ababa, Ethiopia

Legg JO and Meisinger JJ (1982) Soil nitrogen budgets. Agron J 22: 503–566

Malhi SS and Nyborg M (1992) Recovery of nitrogen by spring barley from ammonium nitrate, urea and sulphur-coated urea as affected by time and method of application. Fert Res 32: 19–25

Meelu OP, Saggar S, Maskina MS and Rekhi RS (1987) Time and source of N application in rice and wheat. J Agric Sci 109: 387–391

Miressa Duffera, Tekalign Mamo, Mesfin Abebe and Samuel Geleta (1992) Response of four wheat varieties to N on highland pellic Vertisols in Ethiopia. In: Tanner DG and Mwangi W (eds) Seventh Regional Wheat Workshop for Eastern, Central and Southern Africa, pp 480–488. CIMMYT, Nakuru, Kenya

Mooleki SP and Foster RK (1993) Effects of N and P rates and proportional timing of N application on rainfed wheat in Zambia. Plant and Soil 149: 73–86

Murthy AS (1988) Distribution, properties and management of Vertisols in India. Adv Soil Sci 8: 151–214

Pearson CJ and Muirhead WA (1984) Nitrogen uptake. In: Pearson CJ (ed) Control of Crop Productivity, pp 73–88. Academic Press, Sydney

Prasad R and Singh S (1985) Relative efficiency of urea and urea supergranules for irrigated wheat. J Agric Sci 105: 693–695

Recous S, Machet JM and Mary B (1992) The partitioning of fertilizer N between soil and crop: comparison of ammonium and nitrate applications. Plant and Soil 144: 101–111

Schulthess U (1992) The impact of Vertisol management systems on wheat production in the Ethiopian highlands, PhD thesis. Swiss Federal Institute of Technology, Zurich

Tanner DG, Amanuel Gorfu and Asefa Taa (1993) Fertilizer effects on sustainability in the wheat-based small-holder farming systems of southeastern Ethiopia. Field Crops Res 33: 235–248

Tesfaye Tesemma and Jamal Mohammed (1982) Review of wheat breeding in Ethiopia. Eth J Agric Sci 4: 11–24

Tilahun Geleto (1994) The effects of nitrogen fertilizer sources, rates and time of application on the nitrogen uptake, grain yield and yield components of wheat, MSc thesis. Alemaya University of Agriculture, Ethiopia

Tilahun Geleto, Tanner DG, Tekalign Mamo and Getinet Gebeyehu (1995) Response of rainfed bread and durum wheat to source, level and timing of nitrogen fertilizer on two Ethiopian Vertisols: I. Yield and yield components. Comm Soil Sc Plant Anal 26(11–12): 1773–1794

Vaughan B, Westfall DG and Barbarick KA (1990) Nitrogen rate and timing effects on winter wheat grain yield, grain protein, and economics. J Prod Agric 3: 324–328