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Effect Of Nitrogen Fertiliser Applied To Tef On The Yield And N Response Of Succeeding Tef And Durum Wheat On A Highland Vertisol

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ABSTRACT

A trial was conducted on an Ethiopian Vertisol from 1990 to 1995 to determine the residual effect of fertiliser N applied to tef (*Eragrostis tef*) following chickpea (*Cicer arietinum*) on the grain and straw yield, N content, and N uptake of succeeding crops of durum wheat (*Triticum turgidum* var. *durum*) and tef. Measures of N use efficiency across the interval 0 to 60 kg ha^{-1} of applied N contrasted between the two consecutive tef crops: tef following chickpea exhibited lower mean values for agronomic efficiency (AE), namely 11.7 vs 16.8 kg grain per kg applied N, and apparent recovery (AR), 37.8 vs. 66.4%, of N compared to the second consecutive tef crop. The magnitude and consistency of the beneficial carryover effect of N applied to tef on the succeeding tef and durum wheat crops was dramatic. The mean AE of 60 kg ha^{-1} of N applied to tef and wheat in the current season (using 0 N as the base) was 16.8 and 13.0 kg grain per kg fertiliser N, respectively; the mean AE of 60 kg N applied to tef in the previous season was 6.1 for both crop species. The results demonstrated a residual fertiliser N benefit equivalent to 36.3 and 46.9% of the response to current season N application for tef and durum wheat, respectively (i.e., across the interval from 0 to 60 kg fertiliser N ha^{-1}). Across the same interval, the mean rates of apparent recovery of fertiliser N in tef and wheat were 66.4 and 65.4% for current season N application, and 25.7 and 36.1% for previous season N application. The carryover effects of applied fertiliser N on succeeding cereal crops on Vertisols in the Ethiopian highlands have several beneficial implications. Tef and wheat grain comprise the principal dietary components of the Ethiopian highland populace, while tef and wheat straw represent the major dry season feed source for Ethiopia=s livestock population. The current study demonstrates that the carryover benefit of applied fertiliser N enhanced the yields and N contents of the grain and straw of both wheat and tef, resulting in significant increases in total N uptake. Thus, both human and livestock populations in the Ethiopian highland Vertisol zones would benefit from an increase in dietary protein intake as well as an increase in the quantity of dietary staples. Any analysis of the profitability of fertiliser N response should reflect the multi-year benefit period.

Key Words: Agronomic efficiency, cropping sequence, *Eragrostis tef,* Ethiopia, N recovery, N residue

RÉSUMÉ

Un essai a été conduit sur un Vertisol Ethiopien de 1990 à 1995, pour déterminer les effets résiduels de l=application de fertilisant azoté (N) au tef (*Eragrostis tef)* cultivé après pois chiche (*Cicer arietinum*), sur le rendement en grain et en paille, la teneur en azote et la prise d=azote par les cultures suivantes de blé dur (*Triticum turgidum* var. *durum*) et de tef. Les mesures d=efficacité d=utilisation de l=azote sur une gamme de concentration d=azote appliqué de 0 à 60 kg/ha, était différente pour les deux cultures successives de tef; tef suivant pois chiche présentait une valeur pour l=efficacité agronomique (AE) plus basse, 11,7 contre 16,8 kg de grains par kilo d=azote appliqué et une récupération apparente (AR), 37,8 contre 66,4% d=azote comparé au tef en deuxième culture successive. La magnitude et l=uniformité de l=effet bénéfique de stockage d=azote appliqué au tef et au blé dur était dramatique. La moyenne AE pour 60 kg d=N appliqué au tef et au blé durant la saison en cours (en considérant 0 N comme base) était respectivement, de 16,8 et 13 kg de grains par kg d=engrais azoté; la moyenne AE pour 60 kg d=N appliqué au tef dans la saison précédente était de 6,1 pour les deux cultures. Les résultats ont démontré un effet résiduel bénéfique de la fertilisation en azote équivalent à 36,3 et 46,9% de la réponse à l=application d=azote durant la saison en cours pour le tef et le blè dur, respectivement (c. à d. sur la marge de 0 à 60 kg d=engrais azoté à l=hectare). Sur la même marge, le taux moyen de récupération apparente d=engrais azoté sur le tef et le blé était de 66,4 et 65,4% pour la saison d=application en cours et de 25,7 et 36,1% pour une application durant la saison précédente. Les effets de stockage de l=application d=engrais azoté sur les cultures de céréales suivantes dans le Vertisol des régions montagneuses éthiopiennes a plusieurs conséquences bénéfiques. Le grain de tef et de blé constituent la composante principale du régime alimentaire du peuple des régions montagneuses éthiopiennes, tandis que la paille de tef et de blé constitue la principale nourriture pour le bétail éthiopien durant la saison sèche. Cette étude montre que l=effet de stockage bénéfique de l=application d=azote augmente les rendements et les teneurs en azote des grains et de la paille de blé et de tef, ce qui résulte en une augmentation significative de la prise totale d=azote. Ainsi, aussi bien la population humaine que le bétail de la zone Vertisol des régions montagneuses éthiopiennes bénéficieraient d=un accroissement de la prise de protéine alimentaire ainsi que d=une augmentation en quantité de nourriture de base ingérée. Toute analyse de la rentabilité de la réponse de l=apport d=engrais devrait mettre en valeur la période bénéfique pluriannuelle.

Mots Clés: Efficacité agronomique de l=azote, prise d=azote, Ethiopia, récupération d=azote, résidu d=azote

INTRODUCTION

Tef (*Eragrostis tef* (Zucc.) Trotter) is an indigenous Ethiopian cereal species which ranks first in Ethiopia in terms of production and consumption (Tareke, 1981), and provides as much as two-thirds of the protein intake in the Ethiopian diet. The traditional tef-based cropping system on the highland Vertisols of Ethiopia is characterised by a three year cropping sequence: a grain legume, commonly chickpea (*Cicer arietinum* L.), is followed in succession by tef and then durum wheat (*Triticum turgidum* var. *durum* L.). However, when the market price for tef is high, farmers plant two or more crops of tef in succession. Legumes, when included in a crop rotation, improve soil fertility, particularly soil nitrogen (N) content, and thereby enhance the productivity of subsequent cereal crops (Jones, 1974; Kumar *et al*., 1983; Amanuel *et al*., 1996b; Holford and Crocker, 1997).

Optimum nutrient rate recommendations have been developed for the major cereal crops grown in Ethiopia (ADD/NFIU, 1991). For the highland Vertisols of Ethiopia, economic optimum N rates of 55 kg ha^{-1} for tef (Tekalign *et al*., 1996) and 64 kg ha^{-1} for durum wheat (Workneh and Mwangi, 1994) have been disseminated as blanket recommendations for farmers through the extension service. Vertisols cover 8 million hectares in the Ethiopian highlands, and durum wheat and tef are among the principal traditional crops. Ethiopian highland Vertisols tend to exhibit low total N and organic matter content, and application of N fertiliser is considered essential to improve cereal production (Tekalign *et al*., 1996). However, peasant farmers in Ethiopia commonly apply sub-optimal rates of fertiliser to crops due to limited access to credit and low and untimely availability of fertilisers during the planting season (Gezahegn and Tekalign, 1995).

Application of N fertiliser to field crops has been shown to increase post-harvest levels of soil N and/or organic matter on well-drained soils (Chaney, 1990; Mahli *et al*., 1991; Tanner *et al*., 1993) and on poorly-drained Vertisols (Strong *et al*., 1996b; Tilahun *et al*., 1998). Elevated levels of soil N resulting from fertiliser N application can influence the yield and N response of subsequent cereal crops (Shepherd and Sylvester-Bradley, 1996). In fact, the carryover benefits associated with residual soil N enhanced the profitability of cereal production on a fertility-depleted Vertisol in Australia (Strong *et al*., 1996a).

Although the beneficial effects of rotating leguminous and cereal crops are well known in Ethiopia, there has been no previous study of the residual effects of fertiliser N applied within a traditional cropping sequence on an Ethiopian Vertisol. The principal objective of the current study, therefore, was to determine the residual effects of fertiliser N applied to tef on the yield and N response of succeeding durum wheat and tef crops.

MATERIALS AND METHODS

The study was conducted during the 1990-1995 cropping seasons at the research farm of the Debre Zeit Agricultural Research Centre of Alemaya University of Agriculture, located in the central highlands of Ethiopia (1,800 m a.s.l., 8° 44' N and 38° 58' E). The trial was situated on a cultivated field in which grain legumes, tef, and durum wheat had been grown in rotation for several years (i.e., similar to the conventional farmers= practice).

During the 1990 cropping season, the trial area was sown to tef without fertiliser application in order to exhaust nutrients built up during previous cropping seasons. In the following year, 1991, chickpea cv. Mariye was sown at a seed rate of 140 kg ha^{-1}.

During late June 1992, tef cv. DZ-01-354 was sown at a seed rate of 30 kg ha^{-1} with three levels of nitrogen (0, 30, and 60 kg N ha^{-1}) arranged in a randomised complete block design with three replications. The highest N level approximates the N rates recommended for tef and durum wheat production on Ethiopian Vertisols (Workneh and Mwangi, 1994; Tekalign *et al*., 1996). All N was applied in the form of urea fertiliser (i.e., 46% N) as a basal application. The gross plot size was 11m x 7m with a 1 m space between plots.

In the 1993 cropping season, each main plot from 1992 was divided into two equal parts of 11m by 3m; the two halves were sown during late June to either durum wheat cv. Boohai or tef cv. DZ-01-354 on the basis of a random allocation. Each crop species set was further subdivided into three plots of 3m by 3m on which rates of N (0, 30, and 60 kg ha^{-1}) were super-imposed. Thus, the split-plot design facilitated the measurement of the residual effect of N applied to tef in the previous season as well as the effect of current season application of N to tef and durum wheat (i.e., sown as third season crops following the chickpea-tef cropping sequence).

To capture the effects of climatic variation over years, the trial was conducted in three phases; in addition to the first phase (1990-1993) described in the preceding paragraphs, the same sequence of crops and N treatments was repeated on neighbouring trial areas during the 1991-1994 and 1992-1995 cropping seasons.

Except for the first year of each phase of the trial, all cereal plots received a basal dose of phosphorous at a rate of 10 kg P ha^{-1} as triple super phosphate (TSP). All plots were hand-weeded (i.e., similar to conventional farmers= practice), and no other crop protection measures were necessary during the conduct of the trial.

At crop maturity, each plot was harvested in its entirety and the biomass yield recorded. Subsequent to threshing, grain and straw yields were calculated on a hectare basis at 12 and 20% moisture content, respectively. Grain and straw N contents, on a dry matter basis, were determined by micro-Kjeldahl analyses. Total N uptake (TNU) was calculated by multiplying grain and straw yields by the respective N contents. Apparent N recovery (AR) in cereal biomass was calculated as: (TNU of treatment - TNU of control)) (fertiliser N applied). Agronomic efficiency (AE) of fertiliser N was calculated as: (grain yield of treatment - grain yield of control)) (fertiliser N applied).

All data were analysed using the MSTATC statistical package.

RESULTS

Climatic conditions during the 1991-95 growing seasons (i.e., June to Sept.) at Debre Zeit were relatively uniform across years (Table 1): rainfall peaked during July and August each season and tapered off during September. Seasonal rainfall totals were "25% of the five year mean precipitation of 600 mm. The initial total N level in the soil (0.09%) was low, reflecting the depleted N status of soils in the Debre Zeit area due to a long history of crop cultivation with minimal fertiliser input (Tekalign *et al*., 1996).

Tef response to N following chickpea. Effect of fertiliser N on the grain (GY) and straw yield (SY) of tef sown following a previous crop of chickpea was significant in two out of three seasons (Table 2). In the 1992 season, the effect of N on both GY and SY was not significant (P>0.1); however, GY exhibited a decreasing trend with increasing N rate. The reduction in GY in 1992 with increasing rates of fertiliser N may be attributed to early lodging associated with luxuriant crop growth. In the 1993 and 1994 cropping seasons, however, the effect of N application was significant and positive. In both seasons, the highest GYs and SYs were obtained when 60 kg N ha^{-1} was applied, although, in most cases, there was no significant difference between the yields obtained with 30 or 60 kg N ha^{-1}. SY differed between the two N rates only in 1993.

During 1993 and 1994, the agronomic efficiency (AE) of N applied to tef, measured as incremental weight of grain produced per unit weight of N applied in fertiliser, averaged 18.1 for the first N rate interval (0 to 30 kg N). The AE of N fertiliser fell to a mean rate of 5.2 for the second N rate interval (30 to 60 kg N), indicating a diminishing biological response to N rates above 30 kg ha^{-1} (Fig. 1). The percent N in tef seed (mean 1.59% N) and straw (mean 0.53% N), during the 1993 and 1994 seasons, was not affected by N application rate. However, total N uptake (TNU) increased significantly, concomitant with grain and straw yields, up to the rate of 30 kg fertiliser N ha^{-1}: TNU values were 43.9, 62.2 and 66.6 kg N ha^{-1} for 0, 30 and 60 kg fertiliser N ha^{-1}, respectively. The mean apparent recovery (AR) of fertiliser N in above-ground biomass was 61.1 and 14.5% across the two seasons for the 0 to 30 and 30 to 60 (kg N ha^{-1}) intervals, respectively.

Figure 1: Grain yields of tef (at 12% moisture) in response to N fertiliser applied to the current and the previous crop of tef. Numbers indicate N agronomic efficiency (kg grain produced per incremental kg fertiliser N applied).

TABLE 1. Rainfall distribution within the growing seasons of 1991-95 and soil characteristics of the experimental site at Debre Zeit, Ethiopia

Year	Monthly rainfall distribution (mm)				Soil characteristics[a]			
	June	July	August	September	pH	OM (%)	Total N (%)	Clay (%)
1991	47.2	169.7	191.5	50.1	6.60	2.35	0.09	70.8
1992	78.7	289.5	251.0	128.9	-	-	-	-
1993	117.7	184.0	213.2	117.7	-	-	-	-
1994	95.9	257.5	158.7	107.6	-	-	-	-
1995	41.4	208.0	188.8	100.6	-	-	-	-

a Soil sampled at 0-30 cm depth in 1991

TABLE 2. The effect of N fertiliser on the grain and straw yields (kg ha^{-1}) of tef following chickpea on a central highland Vertisol in Ethiopia (1992-1994)

N rate (kg ha^{-1})	1992		1993		1994	
	Grain	Straw	Grain	Straw	Grain	Straw
0	2802 a	6223 a	2117 a	4846 a	1905 a	4153 a
30	2508 a	5854 a	2605 b	5612 b	2502 b	5645 b
60	2404 a	6489 a	2736 b	6668 c	2683 b	6086 b
Mean	2571	6189	2486	5708	2363	5295
LSD(0.05)	NS	NS	357	710	356	947

Values within a column followed by the same letter are not significantly different LSD(0.05)

TABLE 3. Results of the ANOVA on grain and straw yields and N contents of tef and durum wheat following a chickpea-tef cropping sequence on a central highland Vertisol in Ethiopia (1993-1995)

-	Tef				Wheat			

	GY[a] (kg ha-1)	SY (kg ha-1)	%N		Total N (kg ha-1)	GY (kg ha-1)	SY (kg ha-1)	%N		Total N (kg ha-1)
			Seed	Straw				Seed	Straw	
Year (Y)	***	***	***	NS	**	*P*<0.1	**	NS	**	NS
Previous N (Pr)	***	***	*P*<0.1	*	***	***	***	***	*	***
Y x Pr	NS	NS	NS	*P*<0.1	*P*<0.1	NS	*P*<0.1	NS	NS	NS
Current N (Cu)	***	***	***	***	***	***	***	***	***	***
Y x Cu	**	**	NS	NS	*	*P*<0.1	NS	*	NS	NS
Pr x Cu	NS	NS	NS	NS	NS	**	NS	*P*<0.1	NS	***
Y x Pr x Cu	**	NS	NS	NS	NS	NS	NS	NS	NS	NS
Mean	1803	3664	2.15	0.78	58.0	1593	3453	2.19	0.85	55.5
C.V.(%)	6.13	6.79	4.52	14.6	9.5	5.81	8.60	3.41	7.94	7.11

Within each crop parameter, when a factor by year interaction exhibited significance at the 5% level, the specific factor effect was tested for significance using the factor by year interaction term as the denominator for the F-test. [a] GY = grain yield at 12% moisture; SY = straw yield at 20% moisture

Nitrogen response of the second consecutive tef crop. Current season N application (Cu) significantly and positively affected GY and SY, percent N in seed and straw, and TNU (Table 3). The significance of the interaction of year (Y) by current season N application for GY, SY and TNU was due only to minor differences in N response across years and N intervals. As shown in Table 4, GY and SY of tef increased significantly across each current season N interval. Thus, in contrast to the N response of tef following chickpea, the second consecutive tef crop exhibited dramatic yield enhancement in response to each incremental dose of fertiliser N. The mean AE of N applied to the second tef crop was 16.0 and 17.6 kg grain per kg fertiliser N for the 0 to 30 and 30 to 60 N intervals (Fig. 1), exhibiting no trend of diminishing response.

Nitrogen content (%) in tef seed increased with each increment in N fertiliser (2.05, 2.17 and 2.23%, respectively) while % N in tef straw increased only up to the intermediate level of N fertiliser applied (0.65, 0.82 and 0.88%, respectively). TNU increased significantly for each successive N increment (37.8, 58.4 and 77.7 kg N ha^{-1}, respectively), representing AR values for current season N application of 68.5 and 64.2% for the 0 to 30 and 30 to 60 (kg N ha^{-1}) intervals, respectively.

The carryover effect of N application in the previous season (Pr) also consistently and positively affected the five tef crop characters measured across the three seasons (Table 3). Except for SY in 1995, tef GYs and SYs increased significantly in response to the 60 kg N application in the previous crop of tef (Table 4). Yields also tended to increase in response to the previous application of 30 kg N ha^{-1}, but these yield levels were intermediate and not significantly different from the 0 N level. The mean AE of N applied to the previous tef crop was 4.5 and 7.6 kg grain per kg fertiliser N for the two consecutive intervals (Fig. 1).

Percent N in tef seed (2.09, 2.16 and 2.20%, respectively) was increased by the residual effect of the previous application of 60 kg N, while the N in tef straw (0.74, 0.80 and 0.80%, respectively) was enhanced by the residual effect of 30 kg fertiliser N applied to the previous tef crop. TNU in the current season tef crop increased significantly in response to each successive N increment in the previous season (50.4, 57.7 and 65.8 kg N ha^{-1}, respectively), representing AR rates for previous season N application of 24.2 and 27.3% for the two incremental N intervals.

Except for tef GY, the effect of interaction between previous and current season N application rates was not significant for the measured tef characteristics (Table 3). Previous season N application appeared to enhance current season N response, in terms of GY (Table 4). Where no N was applied to the previous tef crop, the GY response to 30 kg N ha^{-1} in the current season was non-significant in 1993 and 1994. In contrast, where 60 kg N had been applied previously, GY responded significantly to each incremental N dose in the current season.

Nitrogen response of wheat following the chickpea-tef precursor sequence. Current season N application influenced all measured durum wheat crop characters significantly, while the interaction effects were relatively unimportant across seasons (Table 3). Grain and straw yields, N in seed and straw, and TNU were quite similar for the two cereal species.

In each year, the mean GYs and SYs of durum wheat increased significantly with each incremental dose of current season N (Table 5). The mean AE of N applied to wheat in the current season (Fig. 2) was slightly lower than that of the second consecutive tef crop (Fig. 1): mean AE for wheat was 13.2 and 12.7 kg grain per kg fertiliser N for the two consecutive N intervals (Fig. 2). The trend in the second consecutive tef crop exhibited no diminution of N response up to the 60 kg N ha^{-1} rate.

Nitrogen content in wheat seed increased with each increment in N applied in the current season (2.04, 2.19 and 2.34%, respectively) as did straw N (0.75, 0.86 and 0.95%, respectively). TNU increased significantly for each successive N increment (36.1, 54.9 and 75.4 kg N ha^{-1}, respectively), representing AR values for current season N application of 62.5 and 68.3% for the incremental N intervals.

The carryover effect of N application in the previous season consistently exerted a positive effect on wheat GY and SY, N in seed and straw, and on TNU (Table 3). Except for SY in 1995, wheat yields increased significantly in response to the 60 kg N rate applied to the previous tef crop; the 30 kg N rate enhanced wheat GY in 1994 and wheat SY in 1993 (Table 5). The mean AE of N applied to the precursor tef crop was 7.0 and 5.3 kg grain per kg fertiliser N for the two incremental N intervals (Fig. 2).

Nitrogen content in wheat seed (2.08, 2.19 and 2.30%, respectively) increased with each increment in the N rate applied in the previous season, while N in wheat straw (0.80, 0.84 and 0.92%) was only significantly increased at the highest rate of previous N application. TNU increased in response to each successive N increment applied in the previous season (44.9, 55.0 and 66.5 kg N ha^{-1}, respectively); AR of N applied in the previous season was 33.9 and 38.3% for the two incremental N rates.

The interaction between previous and current season N application rates had a significant effect on wheat GY, % N in seed and TNU (Table 3). Focussing on GY, the interaction effect in durum wheat (Table 5) appeared to differ from that presented previously for the second consecutive tef crop (Table 4). Where no N was applied to the previous tef crop, wheat GY responded significantly to each incremental N dose in the current season. However, where 30 N had been applied previously, there was no significant difference between GYs obtained with 30 and 60 kg N in each current season; where 60 N had been applied previously, there was no difference between GYs obtained with 0 and 30 kg N applied in the 1993 season.

Figure 2: Grain yields of durum wheat (at 12% moisture) in response to N fertiliser applied to the previous crop of tef and the current crop of wheat. Numbers indicate N agronomic efficiency (kg grain produced per incremental kg fertiliser N applied).

TABLE 4. The effect of N fertiliser on the grain and straw yields (kg ha^{-1}) of tef grown as the third season crop following a chickpea-tef cropping sequence on a central highland Vertisol in Ethiopia (1993-1995)

Year	N applied to previous season tef (kg ha^{-1})	N applied to current season tef (kg ha^{-1})							
		0	30	60	Mean	0	30	60	Mean
		Grain yield (12% moisture)				Straw yield (20% moisture)			
1993	0	1353	1708	2074	1712 a	2525	3443	4419	3462 a
	30	1376	1826	2398	1867 ab	2844	3964	4695	3834 ab
	60	1505	2050	2679	2078 b	3324	4324	5551	4400 b
	Mean	1411 a	1861 b	2384 c	-	2898 a	3910 b	4888 c	-
1994	0	1100	1482	2234	1605 a	2299	2957	4252	3169 a
	30	1214	1844	2412	1823 ab	2353	3755	4626	3578 ab
	60	1420	2065	2615	2034 b	2965	4108	5214	4096 b
	Mean	1245 a	1797 b	2420 c	-	2539 a	3607 b	4697 c	-
1995	0	1054	1614	2115	1594 a	2211	3292	3885	3129 a
	30	1353	1565	1949	1622 a	2877	3341	4065	3427 a
	60	1388	1927	2352	1889 b	3072	3970	4584	3875 a

	Mean	1265 a	1702 b	2139 c	-	2720 a	3534 b	4178 c	-

For a particular year, mean values within a factor followed by the same letter are not significantly different at the 5% level of the LSD test
LSD (0.05) values for previous season N rates (comparisons within years) are 260 and 842 kg ha^{-1} for grain and straw yield, respectively
LSD (0.05) values for current season N rates (comparisons within years) are 224 and 505 kg ha^{-1} for grain and straw yield, respectively
LSD (0.05) values for current season N rates within a previous season N rate (comparisons within years) are 388 and 874 kg ha^{-1} for grain and straw yield, respectively

TABLE 5. The effect of N fertiliser on the grain and straw yields (kg ha^{-1}) of wheat grown as the third season crop following a chickpea-tef cropping sequence on a central highland Vertisol in Ethiopia (1993-1995)

Year	N applied to previous season tef (kg ha^{-1})	N applied to current season wheat (kg ha^{-1})							
		0	30	60	Mean	0	30	60Mean	
		Grain yield (12% moisture)				Straw yield (20% moisture)			
1993	0	1089	1422	1950	1487 a	1716	2741	4157	2872 a
	30	1390	1742	1912	1682 ab	2881	3432	4781	3698 b
	60	1428	1725	2089	1747 b	4128	4182	5433	4206 b
	Mean	1302 a	1630 b	1984 c	-	2533 a	3452 b	4791 c	-
1994	0	956	1349	1718	1341 a	1900	2829	3829	2853 a
	30	1196	1647	1915	1586 b	2477	3644	4511	3544 a
	60	1401	1814	2250	1821 b	3081	4431	5313	4276 b
	Mean	1184 a	1603 b	1961 c	2486 a	3635 b	-	4552 c	-
1995	0	958	1359	1800	1373 a	1960	2813	3884	2864 a
	30	1187	1600	1900	1563 ab	2338	3096	4064	3187 a
	60	1205	1728	2269	1734 b	2386	3901	4584	3583 a
	Mean	1117 a	1562 b	1990 c	-	2228 a	3270 b	4135 c	-

For a particular year, mean values within a factor followed by the same letter are not significantly different at the 5% level of the LSD test

LSD (0.05) values for previous season N rates (comparisons within years) are 236 and 728 kg ha^{-1} for grain and straw yield, respectively

LSD (0.05) values for current season N rates (comparisons within years) are 188 and 602 kg ha^{-1} for grain and straw yield, respectively

LSD (0.05) values for current season N rates within a previous season N rate (comparisons within years) are 325 and 1043 kg ha^{-1} for grain and straw yield, respectively

DISCUSSION

The current results demonstrate that the standard fertiliser recommendation of 60 kg N ha^{-1} for tef (Tekalign *et al*., 1996), determined under conditions of continuous cereal production, could be reduced by half without adversely affecting the grain yield of tef in the crop rotation system traditionally followed by farmers in the central highlands of Ethiopia. The major source of benefit in a crop rotation system incorporating leguminous species is the amount of fertiliser N that can be substituted by fixed atmospheric N. In this regard, chickpea clearly has a role to play in the maintenance of the soil N fertility in the cereal-based cropping systems of the Ethiopian highlands, either directly through the net effect of fixed N or more likely through the sparing of soil nitrate (Holford and Crocker, 1997). While N^2 fixed may be released into the soil or removed in the seeds of a grain legume crop, the reduced soil N uptake by the legume translates into increased N availability for a subsequent cereal crop. Kumar *et al*. (1983) reported that, despite very high N^2 fixation in pigeonpea (*Cajanus cajan*), the uptake of biologically fixed N by a succeeding sorghum crop was not significant.

Comparing the 0 N treatments in the first tef crop (Table 3) and the second consecutive tef crop (Table 4), a mean grain yield advantage of 95% (1,106 kg ha^{-1}) was obtained in the first tef crop following chickpea. This enhancement of tef GY following the legume could be partially attributed to a positive N balance. The differential response of the two consecutive tef crops to N fertiliser applied in the current season substantiates the N benefit derived from the chickpea precursor. Tef yields following chickpea did not respond to applied N in 1992 and only responded significantly to the first 30 kg of applied N in 1993 and 1994 (Table 2). In contrast, the second consecutive tef crop responded significantly to each current season incremental dose of applied N across all three years. Similarly, measures of N use efficiency across the interval 0 to 60 kg applied N contrasted between the two tef crops: tef following chickpea (excluding the 1992 season) exhibited lower mean values for AE (11.7 vs. 16.8 kg grain per kg applied N) and AR (37.8 vs. 66.4%) compared to the second consecutive tef crop. However, such a comparison may inflate the apparent legume effect as the magnitude of this effect is rarely measured unambiguously. The incorporation of legumes in a rotational cropping system can improve the productivity of cereals for reasons in addition to effects on soil nitrogen. In Ethiopia, the inclusion of a grain legume in cereal-based cropping systems exerts beneficial effects on soil nitrate and compaction levels (Amanuel *et al*., 1996b), weed density and species composition (Amanuel *et al*., 1996a), and reduces the incidence of soil-borne cereal pathogens (Tezera *et al*., 1996).

The magnitude and consistency of the beneficial carryover effect of N applied to tef on the succeeding tef and durum wheat crops was quite dramatic. The mean AE of 60 kg N applied to tef and wheat in the current season (using 0 N as the base) was 16.8 and 13.0 kg grain per kg fertiliser N, respectively; the mean AE of 60 kg N applied to tef in the previous season was 6.1 for both crop species. Shepherd and Sylvester-Bradley (1996) reported a residual fertiliser N benefit equivalent to 30% of current season benefit for bread wheat (*Triticum aestivum*) following oilseed rape (*Brassica napus*). Results obtained in this study demonstrated a residual fertiliser N benefit equivalent to 36.3 and 46.9% for tef and durum wheat, respectively (i.e., across the interval from 0 to 60 kg fertiliser N ha^{-1}).

Furthermore, previous studies indicated that carryover effects on either soil N levels or succeeding crop performance were only apparent when high, super-optimal fertiliser levels had been applied to preceding crops (Chaney, 1990; Malhi *et al*., 1991; Shepherd and Sylvester-Bradley, 1996). However, in the current study on an Ethiopian highland Vertisol, succeeding crop performance was influenced by the application to preceding crops of N rates of only 30 or 60 kg ha^{-1}.

Across the 0 to 60 kg N ha^{-1} interval, the mean rates of apparent recovery of fertiliser N in tef and wheat were 66.4 and 65.4% for current season N application, and 25.7 and 36.1% for previous season N application. On the basis of 15N labelling, Strong *et al*. (1996b) determined that actual recovery of N on an Australian Vertisol was 60.3, 4.4, 1.3 and 0.8% in four successive wheat crops. In spite of the low recoveries of applied labelled N by succeeding wheat crops (approximately 6.5% of that applied), the same authors concluded that there was considerable carryover benefit from the fertiliser applied to the initial wheat crop: additional N carried over in fertilised soil appeared to be soil-derived N, spared by the application of the labelled N.

The carryover effects of applied fertiliser N on succeeding cereal crops on Vertisols in the Ethiopian highlands have several beneficial implications for the cereal-based cropping systems. Primary among these considerations, any analysis of the profitability of fertiliser N response should reflect the multi-year benefit period. Related to this, it may be possible to partially recover financial losses associated with fertiliser application incurred in years of climate-related crop failure due to the residual effects of fertiliser N in succeeding cereal crops.

Secondly, tef and wheat grain comprise the principal dietary components of the Ethiopian highland populace (Tareke, 1981), while tef and wheat straw represent the major dry season feed source for Ethiopia=s significant livestock population (Said and Adugna, 1991). The current study demonstrates that the carryover benefit of applied fertiliser N enhanced the yields and N contents of the grain and straw of both wheat and tef, resulting in significant increases in total N uptake with each incremental dose of fertiliser N applied to the preceding tef crop. Thus, both the human and livestock populations in the Ethiopian highland Vertisol zones would benefit from an increase in dietary protein intake as well as an increase in the quantity of dietary staples.

Currently, on farm trials are being conducted in several highland Vertisol zones in Ethiopia to further examine the nature of residual response to fertiliser N applied in a cereal-based cropping system.

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