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Yield response and N-fertiliser recovery of rainfed wheat growing in the Mediterranean region

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Abstract

Yield response and isotopic N-fertiliser recovery of rainfed wheat were assessed as influenced by fertiliser rate and timing. A popular bread wheat cultivar, Seri 82, was planted in a 4-year experiment from 1994/1995 to 1997/1998. Urea fertiliser was applied at rates of 0–240 N ha^{-1} in two split applications. Fertiliser-N recovery and residual N remaining in the soil after wheat harvest were measured using ^{15}N-labelled fertilisers. The highest wheat grain yield ranged from 4.9 to 6.9 t ha^{-1} with 240 kg N ha^{-1} fertiliser. The 4-year results showed that wheat benefited least from the fertiliser applied near planting. N-fertiliser recovery was higher from fertiliser applied during tillering compared with application at emergence. The results suggest that applying one-third or less of the total N at planting and applying the remainder at tillering can minimise leaching risks. Another benefit of this strategy would be an overall increase in N-fertiliser recovery. Residual fertiliser-N left in soil after wheat harvest was proportional to N application rates and mainly confined to the upper 40 cm depth. ^{15}N recovery by wheat at maturity was 50–60%, indicating that 40–50% of fertiliser-N remained in the soil or was lost. Over 95% of total fertiliser application to wheat could be accounted for in the wheat crop or soil after harvest at the 240 kg N ha^{-1} rate. The results, therefore, suggest that leaching losses of fertiliser-N below 90 cm were not likely during the growing season for rainfed wheat grown on these heavy-textured soils (Palexerollic Chromoxeret) of the Mediterranean region.

Keywords: ^{15}N; Residual N-fertiliser; Fertiliser recovery; Rainfed wheat; Wheat yield response

1. Introduction

The introduction of high-yielding wheat cultivars has prompted increased use of fertiliser-N in the Mediterranean region. Increasing N rates does not necessarily, however, improve grain yield and quality unless tailored to crop requirements for a variety of conditions. Inappropriate N management may result in lodging and loss of N through leaching, denitrification, and volatilisation. Considerable research on the best timing of N applications has been conducted to match plant uptake and utilisation during various stages of growth. The effects of split-N applications (i.e. pre-plant and at anthesis) on fertiliser-use efficiency have been the subject of extensive research (Alcoz et al., 1993; Isfan et al., 1995; Mahler et al., 1994). Splitting fertiliser-N applications has also been shown to influence harvest index (Papakosta and Gaginas, 1991; Wuest and Cassman, 1992; Corbels et al., 1998) and N losses (Papakosta and Gaginas,

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1991; Alcoz et al., 1993). These studies show that split applications of N-fertiliser resulted in higher plant recovery, larger harvest index, and higher grain yields compared with single applications. However, the proportions of the split should be determined locally with due consideration of initial soil fertility status.

Objectives of this work were to (1) measure and compare recoveries of N-fertiliser applied to rainfed wheat at emergence (Fall) and at tillering (Spring); (2) establish wheat yield response to N-fertiliser application; and (3) monitor the fate of applied ^{15}N-fertiliser in terms of crop uptake (wheat and second crop maize) and residual N-fertiliser left within the soil profile after wheat.

2. Methods and materials

The experimental site was at the Faculty of Agriculture, Cukurova University, Adana, Turkey. The soil has a heavy clay texture composed of predominantly smectite-type clay minerals (Palexerollic Chromoxeret). The soil organic matter content is ~1% in the surface 30 cm and declines with depth (Table 1). Soil pH was slightly alkaline. The wheat cultivar, Seri 82, popular for bread in the region, was planted at 220 kg ha^{-1} into a new uniform site in each of 4 years. Wheat is normally planted around mid November in the region. However, due to low plant available water content, only 40–60 mm, remaining within top 90 cm of the soil profile after harvest of the preceding crops, the planting date of wheat was adjusted depending on when the rainy winter season was predicted to start. Mean monthly minimum and maximum temperatures are 8.5 and 22.6°C, respectively, during wheat growing season (November to May) in the region (Table 2).

The prior crop for the first two wheat crops was corn, whereas cotton was planted before wheat in the last 2 years. All prior crops had been uniformly fertilised at 200 kg N ha^{-1}. Soil mineral nitrogen measured before sowing of wheat varied depending on the previous crop (Table 3). The site that previously had corn had lower mineral nitrogen (22 to 37 kg N ha^{-1}), compared with the site having cotton (>50 kg N ha^{-1}). Nitrogen fertiliser treatments applied to wheat were 0 (N_0), 80 (N_1), 160 (N_2) and 240 (N_3) kg N ha^{-1} as urea broadcast in two split parts, one-third at emergence and two-thirds at tillering. A randomised complete block design with four replicates was used in the experiment. Each whole plot was 6 m × 12 m. Because the soil contained sufficient amounts of plant available P (>100 kg P ha^{-1}, 0.5 M $NaHCO_3$ extractable) and K (>450 kg ha^{-1}, 1 M HNO_3 extractable), phosphorous and potassium fertilisers were not applied.

Two isotope microplots receiving ^{15}N-labelled urea were established within each 160 and 240 kg N ha^{-1} treatment. Separate microplots were used for each split application. They contained six 1.5 m long rows of wheat, with 15 cm row spacing (1.35 m^2 of plot area). One received tagged N-fertiliser at emergence and the other at tillering following the procedure of Fried et al. (1975) for 'single treatment fertility experiments'. An enrichment of 5% atom excess ^{15}N urea was used. ^{15}N-labelled urea required for each microplot was taken from a stock solution (290 g, 5% atom excess ^{15}N urea in 2500 ml) and sprinkled on the microplots in 10 l of water to ensure uniform application. Immediately after application of labelled fertiliser, both microplots and the rest of the plots were irrigated (10 mm) with a sprinkler system to leach the fertiliser below soil surface. Plants from the central 0.45 m^2 of the isotope plots were harvested for total N

Table 1
Soil properties as a function of depth

Soil layer (cm)	Texture	Organic matter (%)	Total N (%)	Plant available water (mm/100 cm)	pH	Bulk density (g cm^{-3})
0–5	CL	1.5	0.08	120	7.8	1.19
5–15	CL	1.5	0.08	140	7.8	1.19
15–30	CL	1.1	0.06	140	7.8	1.19
30–60	CL	0.9	0.05	140	7.7	1.16
60–90	CL	0.5	0.03	130	7.7	1.16
90–120	CL	0.1	0.01	130	8.0	1.25

Table 2
Wheat planting dates, length of growing season, and climatic data in for the experimental site

Year	Planting date	Growing season days	Climatic data	Months							Off-season Rainfall (mm)
				November	December	January	February	March	April	May	
			Temperature (°C)	14.2	8.7	10.2	11.7	13.5	16.4	22.6	
1994/1995	11/11/1994	200	Rainfall (mm	73	74	153	109	123	52	16	167
			Evaporation (mm)	55.7	28.9	56.9	59.4	82.7	106.5	160.5	
			Temperature (°C)	12.6	10.2	9.6	10.9	12.2	15.5	22.8	
1995/1996	5/12/1995	182	Rainfall (mm)	195	175	76	72	71	69	65	524
			Evaporation (mm)	62.5	43.9	47.3	65.0	54.2	102.7	156.4	
			Temperature (°C)	16.2	12.7	9.7	8.0	10.2	14.2	22.6	
1996/1997	13/11/1996	200	Rainfall (mm)	114	123	38	67	19	104	20	121
			Evaporation (mm)	74.7	18.6	43.2	40.3	80.8	66.7	134.3	
			Temperature (°C)	15.4	10.7	8.5	9.9	11.3	18.2	21.7	
1997/1998	28/12/1997	156	Rainfall (mm)	107	178	44	7	114	61	37	217
			Evaporation (mm)	45.3	21.4	38.4	55.3	62.6	79.4	120.9	
Long term (60 years) average			Temperature (°C)	14.7	10.3	8.9	9.9	12.7	16.6	20.6	
			Rainfall (mm)	67	118	112	93	68	51	47	
			Evaporation (mm)	68	44	44	52	88	121	171	

Table 3
Mineral nitrogen reserves to 60 cm soil depth before sowing of wheat crop during four growing seasons[a]

Growing season	Previous crop	Mineral nitrogen (N kg ha^{-1})		
		NH_4–N	NO_3–N	Total
1994/1995	Corn	11.0	11.4	22.4
1995/1996	Corn	30.1	7.1	37.2
1996/1997	Cotton	40.8	11.9	52.7
1997/1998	Cotton	48.0	16.8	64.8

[a] Mineral nitrogen analysis was carried out in composite soil samples collected from five randomly selected field sites from three soil depths 0–20, 20–40 and 40–60 cm.

(Eastin, 1978) and ^{15}N determinations (Fiedler and Proksch, 1975). Total biomass and grain yield were measured in a 3 m × 4 m area within the plots. Concurrently, soil samples were also collected from the isotope plots of the highest N treatment (i.e. 240 kg N ha^{-1}), and analysed for ^{15}N to determine fertiliser-N remaining in soil after harvest. Ratios of $\%^{15}N$ atom excess values in fertiliser, soil, and plant samples were used to evaluate the relative crop recovery and residual fertiliser remaining in soil for early or late applications of N-fertiliser. Percent N derived from fertiliser-N ($\%N_{dff}$) and soil ($\%N_{dfs}$) were calculated using the following equations (Zapata, 1990; Kirda et al., 1996):

$$\%N_{dff} = \frac{^{15}N_{ae\,sample}}{^{15}N_{ae\,fertiliser}} \times 100$$

$$\%N_{dfs} = 100 - \%N_{dff}$$

where $\%^{15}N_{ae\,sample}$ and $\%^{15}N_{ae\,fertiliser}$ are atom $\%^{15}N$ excess in plant or soil samples and fertiliser material, respectively. Nitrogen fertiliser recovery by wheat (grain plus straw) was calculated with the following equations:

$$N_y = \frac{\text{dry matter}(\text{kg ha}^{-1}) \times \%N}{100}$$

$$N_{fy} = \frac{N_y \times \%N_{dff}}{100}$$

$$\%NFR = \frac{N_{fy}}{N_{fr}} \times 100$$

where N_y is the total N yield (kg N ha^{-1}) taken up from both soil and fertiliser sources; N_{fy} the N yield (kg N ha^{-1}) coming from fertiliser only; N_{fr} the N-fertiliser applied (kg N ha^{-1}) in both applications (emergence or tillering); and %NFR is the partial N-fertiliser recovery of any given split application. Partial %NFR shows which of the split applications of N-fertiliser was taken up with proportionally greater efficiency. Total %NFR is the sum of the partial %NFR of the two split applications. This value indicates what portion of N_{fy} comes from the applied N-fertiliser.

Maize, a widely used crop in the Mediterranean region, was planted three weeks after wheat harvest. A uniform rate of 80 kg N ha^{-1} as ammonium sulfate was applied to maize plots. New isotope microplots containing three 1.5 m long rows of maize, with 80 cm row spacing (3.6 m^2 of plot area) were established within each plot. Care was taken to avoid the isotope–microplots used for the previous wheat crop. Nitrogen fertiliser applied to isotope–microplots was labelled with 1% atom excess ^{15}N, which was sufficient for ^{15}N determination in plant samples. Maize samples from the central 0.80 m^2 of the isotope plots were collected at physiological maturity for dry weight, total N, and ^{15}N determinations, following the same procedure used for wheat crop. The maize-isotope data were used to assess what fraction of fertiliser-N applied to the preceding wheat crop could be utilised by maize. Analytical determinations followed the ^{15}N-isotope dilution technique described by Senaratne and Hardarson (1988) and Danso and Papastylianou (1992). The percentage of total N that was uptaken by maize, but that was derived from N applied to the preceding crop wheat ($\%N_{dfp}$), was calculated using the following equation:

$$\%N_{dfp} = \left(1 - \frac{^{15}N_{ae\,sc}}{^{15}N_{ae\,control}}\right) \times 100$$

where $\%^{15}N_{ae\,sc}$ is the % atom access ^{15}N in maize samples collected from the wheat microplots that received 80, 160 and 240 kg N ha^{-1} in the previous year, and $\%^{15}N_{ae\,control}$ is the % atom access ^{15}N in maize samples collected from the wheat microplots that received no N-fertiliser in the previous year. ^{15}N recovery (by maize) of the original isotope fertiliser applied to maize-microplots is expected to be reduced by dilution with the 80 kg N ha^{-1} applied to maize and the N residue remained in soil after wheat harvest. If no N-fertiliser residue was left from the previous wheat crop, ^{15}N determinations in maize samples (i.e. $\%^{15}N_{ae\,sc}$) should be comparable to ^{15}N assays of maize samples from control plots (i.e. $\%^{15}N_{ae\,control}$).

During two seasons (1995/1996 and 1997/1998), the soil solution was sampled at 60 and 90 cm depths using soil–water samplers (Litaor, 1988). Solution samples were analysed for nitrate concentration. The data were used to determine the relationship between fertiliser-N application rate and the extent of nitrate leaching. An increase of nitrate concentration is hypothesised to indicate that fertiliser-N was leached to the depth of sampling.

3. Results and discussion

3.1. Grain and biomass yield

Differences in yield response to N-fertiliser rates between years are attributed to climatic variability and disease problems (Fig. 1). Low grain yields (3.0–4.0 t ha^{-1}) attained during the initial 2 years of the experiment were due to yellow rust infestation (*Puccinia striformi* or *Pucinia glumarum*) in the region (Fig. 1). A good yield response to N-fertiliser was obtained during the last 2 years of the experiment. The largest yield responses to N fertiliser were consistently achieved within the range 0–100 kg N ha^{-1} (Fig. 1). The 160 kg N ha^{-1} treatment, the rate common in the region, was adequate to produce the highest statistical yield in this study.

The wheat cultivar (Seri 82) typically has a good yield response to N input. The potential yield ranges from 4.3 to 6.8 t ha^{-1}, depending on climatic conditions and planting time (Taskiran, 1994). Our results show that decisions about N management practices for wheat grown in the Mediterranean region should not only be based on the fertiliser rate, but also on the timing of split N-fertiliser applications. These considerations are essential as producers strive to achieve a high recovery of fertiliser-N and leave a minimum amount of N-fertiliser residue in the soil after harvest. Harvest index (HI) is a measure of how plants partition assimilates between grain and straw production. During the first growing season (1994/1995), the first two months were very dry, which limited biomass production and perhaps even reduced yield potential. Precipitation during the next 3 months was considerably

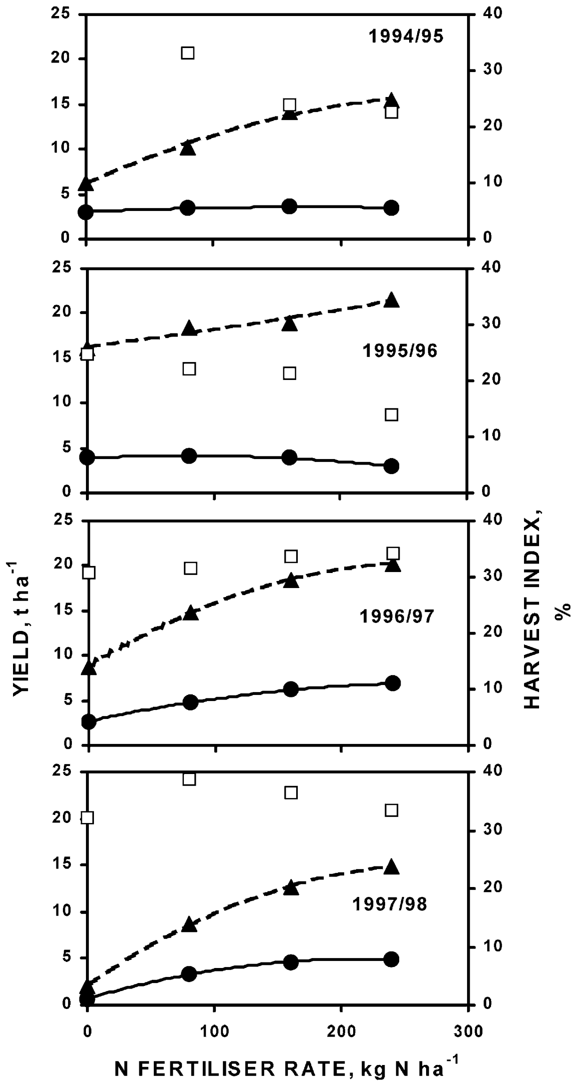

Fig. 1. Wheat grain yield (circles), biomass (triangles), and harvest index (HI) (squares) responses to varius rates of N-fertiliser during four growing seasons. Dashed and solid lines are fitted curves for biomass and grain yields, respectively.

above normal, which set the stage for a widespread infestation of yellow rust. The effect of the early season drought and late-season disease reduced the normal yields without response to N-fertiliser rate. The higher than normal HI values are attributed to the yellow rust infestation that hindered grain development (Fig. 1). Essentially, the size of the photosynthetic source was first reduced by the drought and then its output was inhibited by the rust infestation.

Harvest index values <30% for the 1995/1996 growing season are attributed to a severe frost that occurred in February. It is hypothesised that the higher N rate treatments were at a somewhat more susceptible growth stage at the time of the frost. While total biomass production for 1995/1996 exceeded the other years, there was limited opportunity to partition biomass to grain. Essentially, climatic conditions were such that photosynthesis could proceed at a rapid pace, but the size of the sink for storage was limited by the frost (Fig. 1). During the last 2 years of the experiment (1996/1997 and 1997/1998), however, both biomass and grain yield showed a good response to N-fertilisation.

Harvest index during the last 2 years exceeded 30% and were not affected by fertiliser-N rate. Results from the last 2 years are considered representative for the region, while results from the first 2 years help characterise scenarios with climatic abnormalities.

3.2. Nitrogen fertiliser utilisation

The use of ^{15}N-labelled fertiliser revealed that wheat benefited most from fertiliser-N applied at tillering (Table 4). Percent N derived from fertiliser (%N_{dff}) was consistently higher from the last two-thirds of the split application for both 160 and 240 kg N ha^{-1} rates. Partial fertiliser-N recoveries (%NFR) were significantly ($P \leq 0.05$) higher for the two-thirds split application at tillering than for the one-third applied at emergence. In an earlier study, Olson and Kurtz (1982) suggested the practice of late-season N application to obtain the highest possible fertiliser recovery. Although, there are conflicting reports in the literature (Grant et al., 1985; Vaughan et al., 1990), the general practice of split fertiliser-N applications is preferred, with the larger portion applied later, at tillering or near anthesis. Isfan et al.

Table 4
N-fertiliser utilisation by wheat during four growing seasons

N treatment[a]		TDM[b]	N yield[c]	%N_{dff}[d]	Partial %NFR[e]	Total %NFR[f]
1994/1995 Growing season						
160 kg N ha^{-1}	1/3	1420 ± 222	19.6 ± 1.9	14.5 B	53.0	66.2
	2/3			40.1 A	72.7	
240 kg N ha^{-1}	1/3	1554 ± 207	21.7 ± 3.7	20.8 B	49.4	52.6
	2/3			38.8 A	54.4	
1995/1996 Growing season						
160 kg N ha^{-1}	1/3	1894 ± 120	24.9 ± 7.3	13.2 B	59.4	49.1
	2/3			21.9 A	44.3	
240 kg N ha^{-1}	1/3	2162 ± 91	24.0 ± 4.1	17.0 B	45.6 B	55.5
	2/3			37.5 A	60.6 A	
1996/1997 Growing season						
160 kg N ha^{-1}	1/3	1844 ± 66	20.5 ± 1.7	11.5 A	46.1 B	69.3
	2/3			44.9 B	81.5 A	
240 kg N ha^{-1}	1/3	2031 ± 234	26.7 ± 2.4	12.4 A	43.1 B	67.6
	2/3			43.1 B	65.4 A	
1997/1998 Growing season						
160 kg N ha^{-1}	1/3	1263 ± 98	13.5 ± 0.7	13.4 B	33.9 B	52.1
	2/3			56.9 A	61.2 A	
240 kg N ha^{-1}	1/3	1492 ± 198	18.7 ± 1.7	16.9 B	38.0 B	55.0
2/3	2/3			55.4 A	53.9 A	

[a] 1/3 and 2/3 designate split application of N-fertiliser at sowing and tillering, respectively.
[b] Above ground total dry matter yield g m^{-2}, sampled from yield plots of 3 m × 4 m and averaged over four replicates.
[c] N yield (g N m^{-2}) calculated using the data on plant N content (%N) which was measured in two samples collected from each sub-plot and averaged over four replicates.
[d] %N derived from fertiliser-N.
[e] Partial N-fertiliser recovery (%).
[f] Total N-fertiliser recovery (%). Two means given in columns followed by different letters are significantly different ($P \leq 0.05$) as determined with Duncan's multiple range test.

(1995) showed that equal split applications of N fertiliser at sowing and when the first node was detectable nearly doubled plant fertiliser recovery, compared with a single application at sowing. Late-applied fertiliser-N, near anthesis, helps maintain relatively high mineral N levels in soil at late-growth stages when high N uptake rates can occur (Ellen and Spiertz, 1980; Alcoz et al., 1993). Garabet et al. (1998) also reported that fertiliser recovery is not uniform, but increases through the season and reach to a maximum near anthesis.

High fertiliser-N rates during early growth stages do not necessarily guarantee maintenance of high mineral N levels in soil during later periods around anthesis, when N uptake is the highest. The results of this work suggest that wheat benefits more from N applied at tillering compared to earlier (near planting) in Mediterranean coastal regions where precipitation is usually greatest between November and February or March. The proportion of the first split can perhaps be reduced below, the present practice one-third of total N at planting, depending on the pre-plant N content in soil. This would leave a greater proportion of fertiliser for later application (i.e. tillering) when crop demand and uptake efficiency are usually greater.

3.3. *Residual fertiliser-N after wheat*

Fertiliser-N remaining in soil after wheat harvest helps illustrate the dominant influence that climate has on nitrate leaching potential (Fig. 2). For both N application scenarios (one-third at emergence and two-thirds at tillering), the largest fraction of residual N from fertiliser remained in the upper 40–50 cm for 3 of the 4 years (Fig. 2). The exception was the first growing season (1994/1995) when precipitation was excessive after tillering and the yellow rust infestation became wide spread. As a result of poor plant growth, plant N uptake must have been reduced, especially from the second split N application. The N-fertiliser not taken up by the crop was subject to leaching to soil layers below 50–60 cm (Fig. 2). Results by Garabet et al. (1998) on N use by wheat were similar to our findings in that more than 50% of the fertiliser-N applied to wheat resided within the surface 20 cm. The proportion of inorganic to organic N in this layer is not known. In our work, residual N distribution for both one-third and two-thirds applications decreased

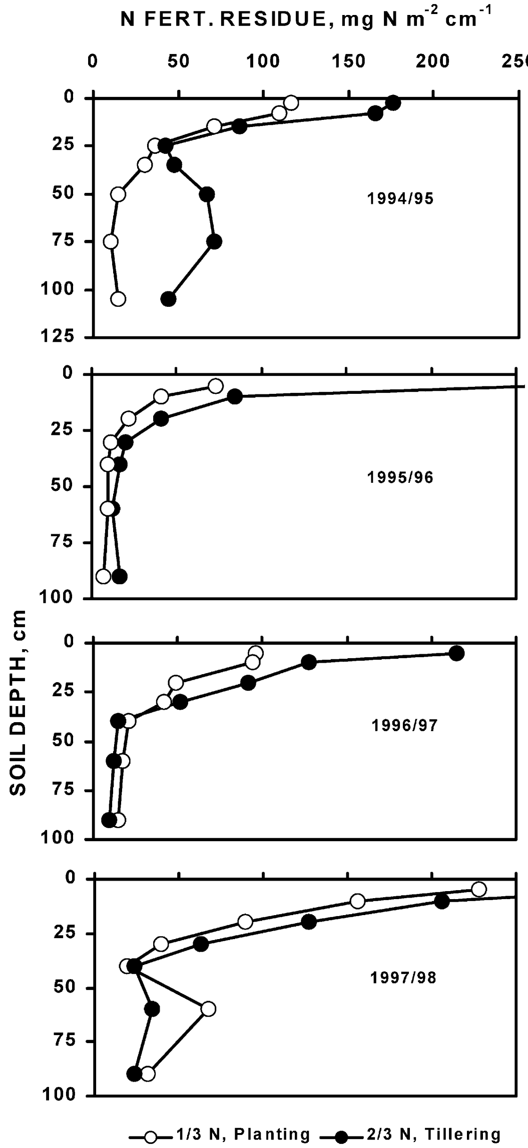

Fig. 2. Fertiliser-N residue remaining in the soil after wheat harvest under the highest rate (240 kg N ha^{-1}) of N-fertiliser application, during four growing seasons.

with soil depth and reached barely detectable levels ($\leq$25 mg N m^{-2} cm^{-1}) beyond 90–100 cm soil depth (Fig. 2). The high recovery for the isotopic N-fertiliser after wheat harvest further substantiates the apparent containment of nitrate within the surface 100 cm of soil. For the 240 kg N ha^{-1} N-fertiliser treatment, plant uptake and ^{15}N residue remaining in the soil

Table 5
Plant recovery and soil residue of N-fertiliser applied to wheat crop at a rate of 240 kg N ha^{-1}

N application		Plant uptake (kg N ha^{-1})	Residue in soil[a] (kg N ha^{-1})	Measured fertiliser recovery (%)
1994/1995 Growing season				
1/3	80 kg N ha^{-1}	33.8 ± 3.1	35.3 ± 2.5	
2/3	160 kg N ha^{-1}	86.2 ± 15.5	81.8 ± 9.0	98.8
1995/1996 Growing season				
1/3	80 kg N ha^{-1}	36.2 ± 7.7	32.2 ± 3.9	
2/3	160 kg N ha^{-1}	97.2 ± 9.3	14.1 ± 2.5	75.0
1996/1997 Growing season				
1/3	80 kg N ha^{-1}	47.0 ± 3.1	24.3 ± 3.2	
2/3	160 kg N ha^{-1}	115.2 ± 12.0	46.8 ± 4.8	97.2
1997/1998 Growing season				
1/3	80 kg N ha^{-1}	31.6 ± 5.6	50.1 ± 2.9	
2/3	160 kg N ha^{-1}	86.4 ± 7.8	61.2 ± 11.7	95.5

[a] N residue in soil is calculated based on N-fertiliser residue distribution profiles (Fig. 2), measured through soil sampling and analysed for ^{15}N, immediately after harvest of wheat.

accounted for at least 95% in 3 out of 4 years (Table 5). The exception was the second growing season (1995/1996) when record high early season rainfall likely caused some N loss (Table 5). However, nitrate concentrations in soil–water samples collected at 90 cm depth did not show any significant increase with the split N application in the 1995/1996 and 1997/1998 growing seasons at the farmer's application rate of 160 kg N ha^{-1} (Fig. 3). These years represent the wettest and driest years, respectively, and yet the results suggest that leaching of N-fertiliser below 90 cm was not likely. However, the unaccounted N losses in 1995/1996 suggest that the excessive early season rainfall caused in runoff or denitrification losses. The other possibility is that there was enhanced N volatilisation from the lush vegetation because the sink size (number of grain kernels) had been reduced by frost damage (Francis et al., 1997). It is reasonable to conclude from these observations that leaching risks of N-fertiliser applied to wheat at rates as high as

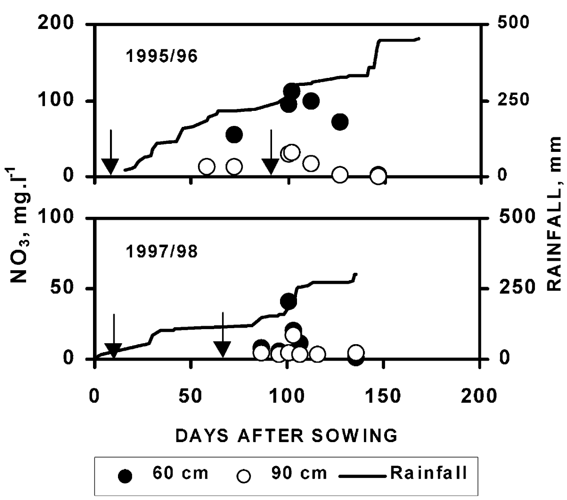

Fig. 3. Changes of NO_3 concentration of soil water samples extracted at two soil depths in 1995/1996 and 1997/1998 growing seasons under farmers' rate of N-fertiliser application, 160 kg N ha^{-1}. Rainfall data are cumulative values after planting. Arrows from left to right show first and second split N-fertiliser applications.

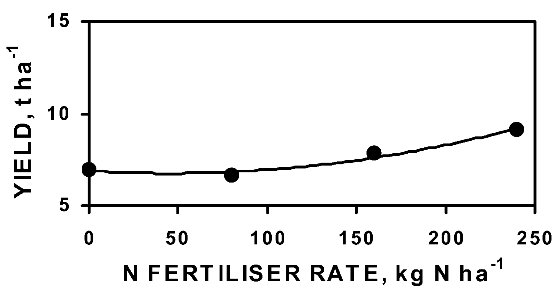

Fig. 4. Yield response of following crop maize receiving 80 kg N ha^{-1} after wheat fertilised at four N rates.

Table 6
Recovery of residual N-fertiliser applied to wheat during the 1994/1995 growing season by a following crop maize receiving 80 kg N ha^{-1}

	N treatments for the preceding crop[a]		
	N_1 (80 kg N ha^{-1})	N_2 (160 kg N ha^{-1})	N_3 (240 kg N ha^{-1})
In grain (kg N ha^{-1})	4.0 B	7.8 B	21.7 A
In stover (kg N ha^{-1})	5.2 B	12.5 A	14.5 A
Total recovered (kg N ha^{-1})	9.2	20.3	36.2
Percent of total N applied	11.5	12.7	15.0
Percent of residual N recovery[b]	–	37.5	31.8

[a] Data given in rows followed by different letters are significantly different ($P \leq 0.05$) as determined with Duncan's multiple range test.
[b] Percent of residual N recovery by corn crop is calculated utilising wheat N recovery data in Table 4.

240 kg N ha^{-1} are very low on these soils. This is because evapotranspiration accounts for most the seasonal average rainfall (500–600 mm) at this location. However, this conclusion does not mean that there would be no leaching loss from mineralised native soil nitrogen when seasonal rainfall exceeds evapotranspiration. Further work is needed, therefore to determine how N transformations (i.e. immobilisation and mineralisation) would affect crop utilisation and leaching of N-fertiliser remaining within the soil profile in future years.

3.4. Second crop maize, succeeding wheat

As shown by many earlier studies (e.g. Carranca et al., 1999), it is expected that significant proportions of fertiliser-N applied to wheat may remain in the soil (both in mineral and organic forms) after harvest. Under Mediterranean conditions, %NFR reported earlier for rainfed wheat ranged from 20 to 75% (Wood et al., 1997; Abdel-Monem and Ryan, 1997; Asfary and Charanek, 1997; Garabet et al., 1998). In our work, the range of crop recovery of applied fertiliser-N was 50–70% under N application rates of 160 and 240 kg N ha^{-1} (Table 4). The remaining fraction (30–50%) was retained within the soil profile after harvest or lost (Table 4). Yield of a 2nd-year maize that uniformly received 80 kg N ha^{-1} showed a good response to the preceding N treatments applied to wheat (Fig. 4). This clearly indicates that maize benefited from the residual N remaining in the soil profile after wheat. Residual N recovered by the 2nd-year maize varied from 10–15% of N-fertiliser applied to the preceding crop (Table 6), which amounts to over 30% of the N-fertiliser remaining in the soil after the harvest of the wheat crop.

4. Conclusions

Nitrogen fertiliser practices used for rainfed wheat in the Mediterranean coastal regions require a thorough evaluation, both in terms of rates and timing. The 160 kg N ha^{-1} rate commonly used by farmers can be increased to over 200 kg N ha^{-1} without apparent environmental consequences. However, these data suggest that it might be possible to apply less than one-third of the N-fertiliser at planting and the remainder at tillering to increase N-fertiliser recovery and minimise the residue remaining in soil after wheat harvest. Nitrogen fertiliser applied at tillering was recovered more efficiently than that applied at emergence. There was little difference in the amount of residual N remaining in the root zone after wheat harvest using either N-timing approach. Residual N-fertiliser remaining in the soil after wheat harvest was mainly confined to the surface 40–50 cm of soil. Under the conditions of this study, the risk of leaching fertiliser-N during the wheat growing season was very low. The corn crop succeeding wheat took up over 30% of residual fertiliser-N left from the preceding wheat crop.

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