Journal of Agricultural Science (2002), **138**, 395–402. © 2002 *Cambridge University Press*
DOI: 10.1017/S0021859602002204 *Printed in the United Kingdom*

Response of safflower (*Carthamus tinctorius* L.) to residual soil N following cotton (*Gossypium* spp.) in rotation in the San Joaquin Valley of California

E. S. BASSIL[1], S. R. KAFFKA[2]* AND R. A. HUTMACHER[2]

[1] *Pomology Department, One Shields Ave., University of California, Davis, CA 95616, USA*
[2] *Department of Agronomy and Range Science, One Shields Ave., University of California, Davis, CA 95616, USA*

(*Revised MS received 11 March 2002*)

SUMMARY

Deep-rooted crops used in rotation can improve the overall water and N use efficiencies of cropping systems and help minimize nitrate leaching to groundwater. Safflower (*Carthamus tinctorius* L.) is a deep-rooted annual crop grown in Mediterranean regions that might be useful for this purpose. Safflower's response to residual soil N measured to 2·7 m in the soil profile was evaluated in 1998 in field plots in the San Joaquin Valley, California, USA that were used previously for cotton over a 9-year period and had been fertilized with nine N rates from 0 to 230 kg N/ha. Residual soil NO_3-N measured prior to safflower planting increased with prior cotton fertilization rates. Amounts present to a soil profile depth of 2·7 m varied from 760 to 2600 kg/ha. Safflower seed yield increased with increasing pre-plant residual NO_3-N levels, from 1700 kg/ha in the control to 2200 kg/ha, and then declined to 1800 kg/ha at the largest residual N level. Oil per cent, and oil yield were affected by soil N only at the largest residual N level, while oil composition was not affected. Root growth and N uptake at depth increased in plots with larger amounts of residual N compared to those with less. Results suggest that N fertilization applied to safflower could be reduced or even eliminated following crops previously fertilized at economic levels. Residual N should be accounted in growers' management programmes.

INTRODUCTION

At economic levels of fertilizer N application, not all the fertilizer applied is taken up by the crop, especially if farmers over-fertilize to ensure that crop yields are not limited by N (Bock 1984). Surplus N can accumulate in soil profiles, or be lost to the atmosphere or ground water (Machet & Mary 1989). In California the use of irrigation and N fertilizer in intensive cropping systems has been correlated with high levels of residual N in the subsoil (Hills *et al*. 1983; Franco & Cady 1997). Some locations in the San Joaquin Valley of California (SJV) contain large amounts of residual N deep in the profile, which have accumulated below the root zones of common crop species (Nitrate Working Group 1989).

Specific measures aimed at minimizing residual N include extending the period of effective N uptake (Karlsson-Stresse *et al*. 1996), planting under-sown species (Jensen 1991; Wallgren & Linden 1994), using winter catch crops (Jackson *et al*. 1993; Jensen 1991; Thorup-Kristensen 1994), coordination of N application with periods of plant demand (Bock 1984; Kurtz *et al*. 1984), and use of deep-rooted crops in rotation with shallow-rooted crops to improve both the overall water and N use efficiency of cropping systems (Kurtz *et al*. 1984; Hook & Gascho 1988; Pierce & Rice 1988). Few studies have quantified the response of deep-rooted crops to subsoil N, or demonstrated their use to recover N from deep in the soil profile.

Safflower (*Carthamus tinctorius* L.) is considered to be the deepest-rooted annual crop grown in California (Kaffka & Kearney 1998), and is able to meet its water requirements by exploring a larger volume of soil than most crops (Weiss 1971). Knowles (1989) reported that safflower roots were found at 4 m, while

* To whom all correspondence should be addressed.

studies on a Yolo loam soil at Davis California, indicated that by maturity significant water recovery occurred from 3 to 3·6 m (Henderson 1981).

As safflower uses water at depth in the soil profile, some N uptake will also occur. Typically, irrigated safflower in the Sacramento Valley is fertilized with 110 to 170 kg N/ha. This recommendation was derived from a range of trials carried out throughout the region (Werkhoven *et al.* 1968; Kaffka & Kearney 1998). In some trials in the Sacramento Valley, however, safflower produced high yields without the addition of N fertilizer or with amounts smaller than is generally recommended (Kaffka & Kearney 1998). In other locations outside of California, N fertilization also has produced varied results. Nasr *et al.* (1978) reported that 75 kg N/ha was adequate for optimum seed, oil, and protein yield for irrigated safflower grown in Lebanon. Neither yield nor any yield component were significantly improved when higher rates of N (up to 600 kg N/ha) were applied. For irrigated safflower grown in the northern Great Plains, the available N requirement was reported near 275 kg/ha, including all fertilizer and N mineralized from the soil (Haby *et al.* 1982). At Mesa Arizona, Gilbert & Tucker (1967) reported that, up to 168 kg N/ha, each additional increment of 56 kg N/ha increased yields primarily by increasing the number of heads per plant. Jones & Tucker (1968) reported that with larger rates of N, seed yield was enhanced only when irrigation was also increased, even though larger amounts of total N were found in above-ground tissue samples.

Most studies have not considered residual N, especially deeper in the soil profile, which may cause otherwise unexplained variation (Haby *et al.* 1982; Jones & Tucker 1968). If safflower is to be used to recover residual N leached beyond the root zone of less aggressive crop species, its response to such sources should be evaluated.

MATERIALS AND METHODS

The response of safflower to residual soil N was evaluated in a field experiment conducted at the University of California West Side Research and Extension Center, in the western SJV of California. This location has a semi-arid Mediterranean climate with average temperatures between 8·9 and 23·9 °C. Precipitation occurs in the November to March period and averages approximately 180 mm/year. Irrigation is necessary for commercial crop production. Greater detail about the weather occurring during this experiment is reported in Bassil & Kaffka (2002).

Over the previous 19 years, Hutmacher and others (pers. comm.) used this field to grow cotton continuously with subsurface drip or sprinkler irrigation systems. More recently, during the last 9 years, a N trial has been carried out that included 9 N-fertility treatments, with application rates ranging from 0 to 230 kg N/ha, applied with irrigation water through a subsurface pressurized (drip) system. The total N rate applied for each treatment was 0, 60, 110, 120, 170, 180 or 230 kg N/ha. There were three 230 kg N/ha treatments applied differentially at pre-plant and/or mid-season (Bassil 2000). Consequently, plots in this field had different amounts of residual soil N. The experimental site represented a unique opportunity to evaluate safflower response to a range of differing residual N levels at one location.

The soil at the experimental site is a Panoche clay loam (fine-loamy, mixed, calcareous, thermic Typic Torrienthent, USDA system). It is deep, well drained, and moderately permeable, with a high water-holding capacity. Safflower (518S-Seedtec International) was planted on 12 March 1998 in plots measuring 7·6 by 28 m on raised beds 0·75 m apart. There were a total of 54 plots representing the nine N treatments and six replications previously assigned to cotton. At planting, plots were irrigated uniformly with sprinklers until more than 520 mm of water was measured in the profile to 2·7 m in depth. This amount of water is thought to be sufficient for economic yields in California (Kaffka & Kearney 1998). Plots were uniformly moist to 2·7 m at planting. Thirteen cm of rain fell during the experiment. Plants were thinned to 7·5 to 9 cm between plants on 3 May 1998.

Cotton yields in previous trials were largely unresponsive to higher rates of N and to differing fertilizer application patterns (Table 1). For this reason, in selecting plots for soil measurements, treatments involving prior N application rates of 110 and 120 kg/ha and 170 and 180 kg/ha and all three treatments with 230 kg N/ha were considered similar. Soil core samples were taken from 20 plots representing the range of treatments as described. Two core samples were collected just prior to planting, in 30-cm increments to 2·7 m, from the top of the bed in each plot using a tractor-mounted hydraulic coring device. A similar number and method of sample collection were used for the same plots following harvest. The soil samples were analysed for NO_3-N by 2 M KCl extraction using established procedures (Keeney & Nelson 1982). Nitrate was emphasized because soils in semi-arid areas of California are low in organic matter, and the amounts of NH_4-N detected are small relative to NO_3-N (Dahnke & Johnson 1990), especially at depth (Hasegawa *et al.* 2000), and usually are not included when estimating residual N supplies for crops (e.g. Hills & Ulrich 1976). Seeds were allowed to dry to approximately 8% moisture before harvesting 14 m of the centre 4 rows, on 15 August 1998, using a modified plot combine harvester. Oil per cent and composition were analysed using NMR methods (Gambhir 1994). Timing of 90% bloom was estimated visually by counting.

Table 1. *Yield of cotton (1997*) and residual soil N at experimental site*

				Total NO_3-N estimates (kg NO_3-N/ha)		
					Pre safflower (1998)	
Treatment	Description†	Seed cotton (kg/ha)	Lint yield (kg/ha)	Post cotton (1997) 0–1·2 m†	0–1·2 m	0–2·7 m
0	No N applied	3426	1387	275	240	760
60	0; 60	4046	1568	335	350	1020
120	0; 120	4373	1617	470	570	1900
180	0; 180	4460	1635	570	570	1650
110	50; 60	4653	1738	435	440	1250
170	50; 120	4359	1610	520	520	1370
230	50; 180	4139	1510	690		
230	50; 180 early	4680	1775	730		
230	50; 180 mid	4550	1677	840		
Mean 230		4456	1654	753	710	2640
Mean		4298	1613			
LSD 0·05		573				
LSD 0·1			190			

* Data obtained from Hutmacher *et al.* (unpublished report) from the same location.
† Treatment description as follows: N applied at pre-plant; N supplied during season. All rates are in kg N/ha.

RESULTS

Noticeable differences in canopy colour were observed early in crop development among all plots. By the end of May, safflower growing in plots with larger amounts of residual soil N was dark green while plants in control plots were pale green in colour. Plots containing the largest amounts of residual N reached full bloom at approximately 112 days from planting (2 July) while plants in plots with the lowest levels reached full bloom at approximately 105 days, one week sooner. Leaf N content sampled on 6 July averaged 1·4% at the lowest residual N levels compared with 2·2% at the highest residual N levels. For all the subsamples tested, leaf N% = 1 + 0·04 mg NO_3-N/kg (0 to 2·7 m); $r^2 = 0{\cdot}68$ (Bassil 2000).

Residual soil N

Profile NO_3-N amounts following cotton harvest (1997) and prior to safflower establishment (1998) are reported in Table 1. Total NO_3-N amounts obtained from soil samples collected in 1997 following the last cotton trial were similar on average to concentrations determined from soil samples collected at safflower planting for the same depth (1·2 m) and analysed by the same method (Table 1). Analyses show that soil NO_3-N following cotton increased with increasing fertilizer applied to cotton resulting in high amounts of residual N at safflower planting (Table 1; Fig. 1). Cumulative profile NO_3-N concentrations varied from 13 to 40 mg/kg at 1·2 m and from 19 to 65 mg/kg at 2·7 m over the range of cotton fertility treatments

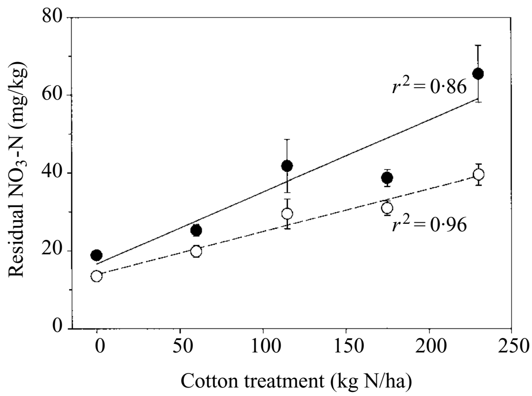

Fig. 1. Average sums of pre-plant residual NO_3-N (- - -, ○ to 1·2 m; —, ● to 2·7 m) at safflower planting (1998) as a function of N application to cotton in previous trials. Data points are the average of two soil cores collected from the top of bed in the centre of the row from each of 3 to 6 plots. Bars are S.E.; $n = 6$.

(Fig. 1). Average NO_3-N concentrations for these depths were 27 and 38 mg/kg respectively. Residual NO_3-N to 1·2 m was better correlated with prior fertilizer treatments than to 2·7 m (Fig. 1), indicating that variation in residual NO_3-N amounts increased with depth.

Changes in soil N during safflower growth

Change in soil NO_3-N concentration, calculated here as the difference between pre-plant and post-harvest

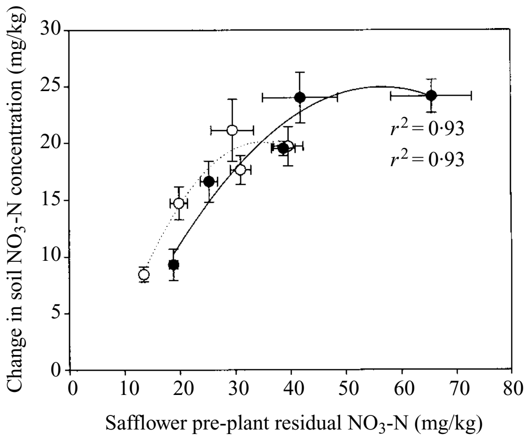

Fig. 2. Change in soil NO_3-N concentration (- - -, ○ to 1·2 m; —, ● to 2·7 m), calculated from the difference between pre-plant and post-harvest soil samples, during safflower growth in previously fertilized cotton plots. Data points are the average of two soil cores collected from the top of bed in the centre of the row from each of 3 to 6 plots. Bars are S.E.; $n = 6$.

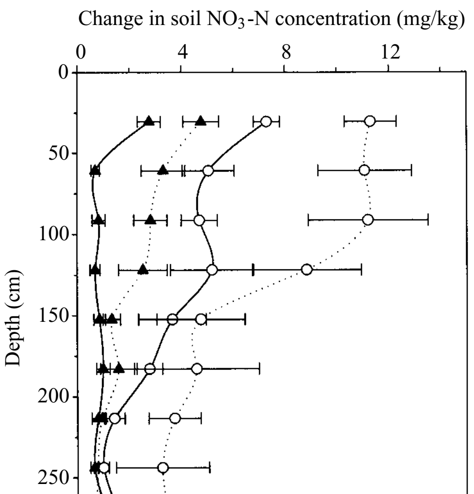

Fig. 3. Change in soil NO_3-N concentration by depth in plots having small (▲) and large (○) amounts of residual NO_3-N caused by cotton N fertilization in previous years. Dotted lines are for NO_3-N sampled at pre-plant and solid lines are for NO_3-N sampled immediately following harvest. Bars are S.E.; $n = 6$.

soil samples, is reported for lowest and highest residual N plots in Fig. 2. The difference in total NO_3-N concentration averaged for the upper 1·2 m of soil was 8·4 mg/kg for the control plot (0 kg N/ha applied to cotton) and 19·7 mg/kg for the largest residual N

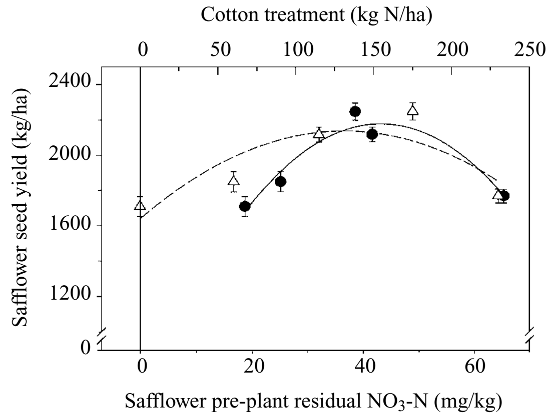

Fig. 4. Effect of pre-plant residual soil NO_3-N (●) and N applied to cotton in previous years (△) on safflower seed yield. Regression equations are yield $= 620 + 70x - 0{\cdot}8x^2$ ($r^2 = 0{\cdot}93$) for residual NO_3-N; and yield $= 1680 + 7{\cdot}6x - 0{\cdot}03x^2$ ($r^2 = 0{\cdot}73$) for cotton N fertilization. Bars are S.E.; $n = 6$.

plots (230 kg N/ha applied to cotton). Averaged over the 2·7 m depth, these differences increased to 9·3 mg/kg and 24·1 mg/kg respectively (Fig. 2). Above approximately 40 mg/kg of pre-plant residual NO_3-N, the rate of change in soil NO_3-N concentration fell to close to zero (Fig. 2), suggesting that no additional N was taken up by the crop. For the upper 1·2 m of soil, these changes in concentration correspond to a change in total soil NO_3-N of 150 kg NO_3-N/ha in the lowest residual N plots and 370 NO_3-N/ha in the highest plots.

Soil NO_3-N concentration at depth in the lowest and highest residual N plots is represented in Fig. 3. There were large and significant differences observed between plots based on prior levels of N fertilization. Significant differences occurred between pre-plant and post-harvest samples as well in the surface 1·5 m of soil for both sets of plots, and to 2·7 m in the high residual N plots. By inference from these changes, N uptake also differed between plots with larger and smaller amounts of residual N, especially in the upper part of the soil profile (Fig. 3). Under both treatments the majority of N uptake occurred in the upper 1·5 m and was (on a relative basis) 79% and 95% of total N taken up in the plots compared, respectively. Below 1·5 m, N uptake also occurred but was significant only in plots containing large amounts of residual NO_3-N (Fig. 3), suggesting that plants in these plots developed more extensive root systems than those growing in plots with less residual N.

Seed and oil yield

Safflower seed yield increased and then decreased with measured pre-plant residual NO_3-N (Fig. 4). Maximum seed yield (2100 kg seed/ha) occurred at a

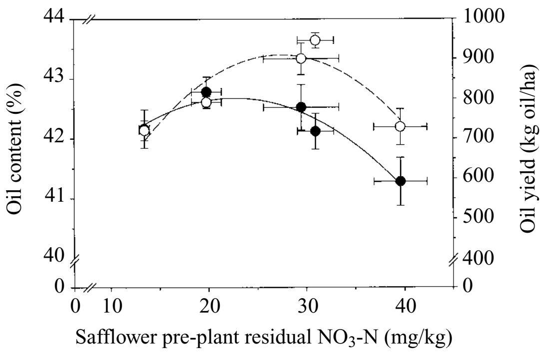

Fig. 5. Safflower oil content (—, ●), and oil yield (- - -, ○) as affected by residual soil N. Regression equations are oil yield = $82+0{\cdot}2x-1{\cdot}1x^2$ ($r^2 = 0{\cdot}84$); and oil per cent = $40+0{\cdot}01x-5E\text{-}3x^2$ ($r^2 = 0{\cdot}94$). Error bars are S.E.; $n = 6$. Bars are smaller than symbols in some data points.

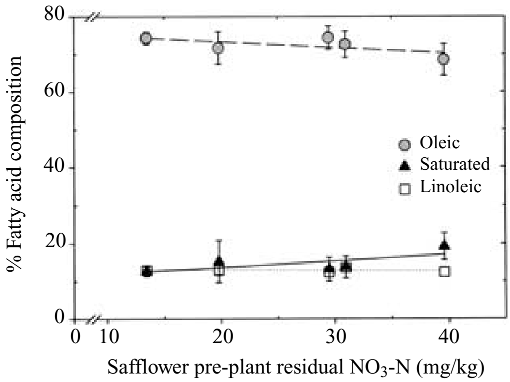

Fig. 6. Effect of pre-plant residual soil NO_3-N on fatty acid composition in safflower. Bars are S.E.; $n = 4$.

residual NO_3-N concentration of approximately 40 mg/kg (Fig. 4). Oil yield also increased then decreased with increasing pre-plant residual soil NO_3-N (Fig. 5). Oil per cent declined at larger residual NO_3-N levels (Fig. 5). Because seed yield changed more than oil content, the decrease in oil yield was more pronounced than the change in oil content at the highest residual N levels. Oil composition was not significantly affected by residual NO_3-N in this experiment (Fig. 6), although there was a small decrease in oleic acid and a small increase in saturated fatty acids.

DISCUSSION

Residual soil N

Large amounts of residual soil N had accumulated in the soil profile following intensive cotton fertilization over many years. Residual soil N measured at safflower planting was positively correlated with previous cotton treatments. Thus cotton was not taking up all the fertilizer N applied, even though N was applied with a subsurface pressurized irrigation system. The amount of N removed in cotton seed prior to safflower can be estimated. In 1997, cotton fertilized at 230 kg N/ha yielded an average of 4460 kg cotton lint plus seed/ha (Table 1). The N removed in seed is estimated at 160 kg N/ha assuming seeds contain 23% crude protein (National Research Council 1989; Loomis & Connor 1996). Even with this amount removed by each cotton crop, for the highest N rate treatments, at least 630 kg N/ha surplus N was applied over the previous 9 years (70 kg N/ha per year excess). Much of this N likely accumulated in the soil profile. Some NO_3-N measured at the time of safflower planting also could have accumulated prior to the establishment of the most recent cotton fertility trial 9 years before.

Reports of large amounts of residual N are not limited to this trial. The widespread presence of NO_3-N in wells and tile drainage water in fields in the San Joaquin Valley is evidence that fertilizer N has accumulated in soils throughout the Valley (Nitrate Working Group 1989; Franco & Cady 1997). This accumulation may be the result of the unavoidable inefficiencies associated with crop fertilization, even with best management practices, applied to crops with shallow root systems.

Uptake of residual soil N by safflower

The relative change in soil NO_3-N concentration determined from soil samples between planting and harvest of safflower correlated well with prior cotton treatments and with measured pre-plant residual NO_3-N concentrations, especially to 1·2 m. The rate of change in soil NO_3-N was greater at the smallest levels of pre-plant residual N and diminished or was not large enough to be detected above 40 mg/kg of pre-plant NO_3-N (0 to 2·7 m). In plots with the largest amounts of residual N, the change in absolute amounts of soil NO_3-N during safflower growth (370 kg NO_3-N/ha) was large relative to the capacity of the crop to take up N (Kaffka & Kearney 1998), especially if the larger amounts of total NO_3-N present to 2·7 m deep are also considered. For a seed yield of 2100 kg/ha, approximately 60 kg N/ha was removed in seed. Using leaf N concentration and estimates of biomass, Bassil (2000) estimated total above-ground plant N uptake, including seed, as approximately 200 kg N/ha. This estimate is similar to one obtained by Jones & Tucker (150 kg N/ha) in 1968 for safflower fertilized with 269 kg N/ha. It is unclear why such large differences were observed between April and August. One possibility is that N uptake could have been over-estimated because calculations were based on soil samples collected directly in the planting row where N depletion may have been greater than in areas between the plant row. This may have inflated the estimates of the absolute amount of N taken up but not the relative differences in uptake observed between higher and lower residual N plots. Some de-nitrification or ammonification could have occurred as well, though no measurements were made of these processes.

The amount of residual soil N at planting affected the depth of N uptake by safflower. Safflower growing in soil with larger amounts of residual N used a larger proportion of total NO_3-N from deeper in the profile (below 1·5 m) than in less fertile plots (approximately 16% compared with less than 1%), indicating that residual N may have stimulated root growth.

Seed yield

The seed yield response to residual N obtained in this trial is similar to other previously reported results of yield response to applied N (Gilbert & Tucker 1967; Kaffka & Kearney 1998). Safflower responded to pre-plant residual soil N at soil concentrations ranging from 15 to 45 mg NO_3-N/kg. The rate of seed yield increase was greater at smaller residual N supplies. Maximum seed yield (approximately 2200 kg/ha) occurred near a pre-plant residual N concentration of 35 to 40 mg NO_3-N/kg. At higher levels, safflower seed yield decreased. Jones & Tucker (1968) also reported a decline in fertilizer N recovery from 83% at 67 kg N/ha to 30% at 269 kg N/ha. More efficient N use at lower yield levels may be due to greater remobilization of stem and leaf N from N-deficient plants (Steer & Harrigan 1986). The increase in leaf N content observed provides additional evidence that safflower was responding to increasing residual soil N. These tissue concentrations are within the range of most crops (Marschner 1995) including safflower (Jones & Tucker 1968).

Differing amounts of available water in the soil profile or irrigation can confound N responses. N supply and plant-available water interact. N supply must be balanced with available soil moisture and estimated crop water use. When too much N is available to the crop, excessive vegetative growth can occur (Gilbert & Tucker 1967). Under such conditions the crop fails to produce much seed because it exhausts the available soil water before completion of grain fill (Kaffka & Kearney 1998). Seed yield declined at the largest levels of residual N observed in this trial, likely due to excessive vegetative growth.

It may be possible with safflower to improve water use efficiency by reducing N fertilization in order to better balance soil and fertilizer N supply with expected yields. Haby *et al.* (1982) hypothesized that increased vegetative growth, due to large amounts of available water, depleted N reserves before grain fill was completed, adversely affecting yield. At low irrigation frequency and with 336 kg N/ha, Abel (1976) found no significant yield increase when compared with the same irrigation level fertilized with 56 kg N/ha. When irrigation was increased, yields also increased progressively if N rates were increased simultaneously, otherwise yields declined. Ample water supply therefore requires higher levels of available N in order to sustain moisture-induced growth.

Balancing available N with available water is difficult to do, however, if residual N is large or unknown. Planting date also influences vegetative growth (Kaffka & Kearney 1998). Under the conditions of this experiment, a moderate seed yield was achieved by safflower following cotton in rotation when the average soil nitrate concentration was near 25 mg/kg (0 to 1·2 m) or 40 mg/kg (0 to 2·7 m) measured at planting. Pre-plant residual N can be used to predict safflower yields in the absence of additional fertilizer application. Also, it can be used, together with planting date, to estimate water requirements. If large amounts of residual N are present, more water may be required for a crop planted on a given date than otherwise.

Oil yield

Per cent oil and oil yield both decreased when residual N amounts were largest. This response to residual soil N is similar to published reports of crop response to fertilizer N. Werkhoven *et al.* (1968) found that an application of 180 kg N/ha applied to safflower reduced oil content by 1 to 2%, but oil yield did not decrease because seed yield increased. The reduction in oil content observed in the current experiment was not as great. Small, sometimes inconsistent reductions in oil content were reported by Nasr *et al.* (1978) or depending on experimental site, and by Haby *et al.* (1982). Yermanos *et al.* (1964) also reported a reduction in oil content but not in oil yield because at higher N fertilization rates greater seed yields were achieved, offsetting a decrease in oil content. In our experiment the decrease in oil yield was due to both the reduction in oil content and in seed yield at the highest levels of residual soil N. Residual N did not affect oil composition of the high oleic acid variety used in this experiment.

In conclusion, using deep-rooted crops in rotation with shallow-rooted ones can minimize the risk of leaching losses and improve the overall nitrogen use efficiency of cropping (Hills *et al.* 1983). Safflower is well suited for this purpose in a Mediterranean climate. Evidence from this experiment supports reducing N fertilization when residual N levels are high at the time of planting or following harvest of the previous crop. Residual N supplies will not always be sufficient, but if safflower is grown in fertile soils or fields with a long-term history of ample fertilization, then additional N beyond what is useful as starter fertilizer may not be needed for the safflower portion of the rotation. Since the majority of N uptake occurred from the upper 1·2 to 1·5 m of the profile in both high and low residual N plots, estimates of residual N to that depth can be used to predict the needs of a safflower crop. Relying on residual N alone under circumstances similar to those reported here can result in economic yields, while failure to account for it may result in yield losses as well as potential environmental harm. There are many examples from Europe, North America and elsewhere of the use of pre-plant soil testing for N fertilizer management of diverse crops. Similar techniques can be used for safflower, though some soil analyses should be collected deeper than 1 m.

We would like to thank Dr Dong Daxue and Mr Gary Peterson for assistance with the experiment and also Drs D. W. Rains, S. R. Grattan and M. A. Wimmer for many helpful discussions. This research was supported in part by the U. C. Salinity/Drainage Program, grant 98-9.

REFERENCES

ABEL, G. H. (1976). Effects of irrigation regimes, planting dates, nitrogen levels, and row spacing on safflower cultivars. *Agronomy Journal* **68**, 448–451.

BASSIL, E. S. (2000). *Response of safflower* (Carthamus tinctorius *L.*) *to saline soils and irrigation and uptake of residual soil nitrogen following cotton in rotation*. M.S. Thesis. University of California, Davis.

BASSIL, E. S. & KAFFKA, S. R. (2002). Response of safflower (*Carthamus tinctorius* L.) to saline soils and irrigation I. Consumptive water use. *Agricultural Water Management* **54**, 67–80.

BOCK, B. R. (1984). Efficient use of nitrogen in cropping systems. In *Nitrogen in Crop Production* (Ed. R. D. Hauck), pp. 273–293. Madison, WI: American Society of Agronomy.

DAHNKE, W. C. & JOHNSON, G. V. (1990). Testing soils for available nitrogen. In *Soil Testing and Plant Analysis*, Third Edition (Ed. R. L. Westerman), pp. 127–139. Madison, WI: Soil Science Society of America.

ERIE, L. J. & FRENCH, O. F. (1969). Growth, yields, and yield components of safflower as affected by irrigation regimes. *Agronomy Journal* **61**, 111–113.

FRANCO, J. & CADY, C. W. (1997). Preventing nitrate groundwater contamination in California: a non-regulatory approach. *Journal of Production Agriculture* **10**, 52–57.

GAMBHIR, P. N. (1994). C-13 NMR spectroscopy of intact oilseeds – a rapid method for measurement of fatty acid composition. *Proceedings of the Indian Academy of Science* **106**, 1583–1594.

GILBERT, N. W. & TUCKER, T. C. (1967). Growth, yields, and yield components of safflower as affected by source, rate and time of application of nitrogen. *Agronomy Journal* **59**, 54–56.

HABY, V. A., BLACK, A. L., BERGMAN, J. W. & LARSON, R. A. (1982). Nitrogen fertilizer requirements of irrigated safflower in the northern Great Plains. *Agronomy Journal* **74**, 331–335.

HASEGAWA, H., BRYANT, D. C. & DENISON, R. F. (2000). Testing CERES model predictions of crop growth and N dynamics in cropping systems with leguminous green manures in a Mediterranean climate. *Field Crops Research* **67**, 239–255.

HENDERSON, D. W. (1981). Developing water management recommendations for irrigated safflower on its introduction into California. In *Proceedings of the First International Safflower Conference, Davis, California, July 12–16* (Ed. P. F. Knowles), pp. 7–8.

HILLS, F. J. & ULRICH, A. (1976). Soil nitrate and the response of sugarbeets to fertilizer nitrogen. *Journal of the American Society of Sugar Beet Technologists* **19**, 118–124.

HILLS, F. J., BROADBENT, F. E. & FRIED, M. (1983). Timing and rate of fertilizer nitrogen for sugarbeets related to nitrogen uptake and pollution potential. *Journal of Environmental Quality* **7**, 368–372.

HOOK, J. E. & GASCHO, G. J. (1988). Multiple cropping for efficient use of water and nitrogen. In *Cropping Strategies for Efficient Use of Water and Nitrogen* (Ed. W. L. Hargrove), pp. 7–20. Madison, WI: American Society of Agronomy Special Publication 51.

JACKSON, L. E., WYLAND, L. J. & STIVERS, L. J. (1993). Winter cover crops to minimize nitrate loss in intensive lettuce production. *Journal of Agricultural Science, Cambridge* **121**, 55–62.

JENSEN, E. S. (1991). Nitrogen accumulation and residual effects of nitrogen catch crops. *Acta Agricultura Scandinavica Section B, Soil Plant* **41**, 333–344.

JONES, J. P. & TUCKER, T. C. (1968). Effect of nitrogen fertilizer on yield, nitrogen content and yield components of safflower. *Agronomy Journal* **60**, 363–364.

KAFFKA, S. R. & KEARNEY, T. E. (1998). Safflower production in California. *University of Califiornia Agriculture and Natural Resources Publication no. 21565*. Oakland, California.

KARLSSON-STRESSE, E. M., UMAERUS, M. & RYDBERG, I. (1996). Strategy for catch crop development. I. Hypothetical ideotype and screening of species. *Acta Agricultura Scandinavica, Section B, Soil Plant* **46**, 102–111.

KEENEY, D. R. & NELSON, D. W. (1982). Nitrogen-inorganic forms. In *Methods of Soil Analysis: Part 2. Chemical and Microbiological Properties. SSSA Monograph 9* (*2nd edn.*) (Ed. A. L. Page), pp. 643–698. Madison, WI: American Society of Agronomy.

KNOWLES, P. F. (1989). Safflower. In *Oil Crops of the World* (Eds G. Robbelen, R. K. Downey & A. Ashri), pp. 363–374. New York: McGraw Hill.

KURTZ, L. T., BOONE, L. V., PECK, T. R. & HOEFT, R. G. (1984). Crop rotations for efficient nitrogen use. In *Nitrogen in Crop Production* (Ed. R. D. Hauck), pp. 295–305. Madison, WI: ASA, CSSA and SSSA.

LOOMIS, R. S. & CONNOR, D. J. (1996). *Crop Ecology. 2nd edn*. Cambridge: Cambridge University Press.

MACHET, J. M. & MARY, B. (1989). Impact of agricultural practices on the residual nitrogen in soil and nitrate losses. In *Management Systems to Reduce Impact of Nitrates* (Ed. J. C. Germon), pp. 126–146. New York: Elsevier.

MARSCHNER, H. (1995). *Mineral Nutrition of Higher Plants. 2nd edn*. San Diego: Academic Press.

NASR, H. G., KATKHUDA, N. & TANNIR, L. (1978). Effects of nitrogen fertilization and population rate-spacing on safflower yield and other characteristics. *Agronomy Journal* **70**, 683–685.

NATIONAL RESEARCH COUNCIL (1989). *Nutrient Requirements of Dairy Cattle*. *6th edn*. Washington, DC: National Academy Press.

NITRATE WORKING GROUP (1989). Nitrate and California agriculture. *Report to California Department of Food and Agriculture*.

PIERCE, F. J. & RICE, C. W. (1988). Crop rotation and its impact on efficiency of water and nitrogen use. In *Cropping Strategies for Efficient Use of Water and Nitrogen* (Ed. W. L. Hargrove), pp. 21–42. Madison, WI: American Society of Agronomy Special Publication 51.

SMITH, J. R. (1996). *Safflower*. Champaign Ill: AOCS Press.

STEER, B. T. & HARRIGAN, E. K. S. (1986). Rates of nitrogen supply during different developmental stages affect yield components of safflower (*Carthamus tinctorius* L.). *Field Crops Research* **14**, 221–231.

THORUP-KRISTENSEN, K. (1994). The effect of nitrogen catch crop species on the nitrogen nutrition of succeeding crops. *Fertilizer Research* **37**, 227–234.

WALLGREN, B. & LINDEN, B. (1994). Effect of catch crops and plowing times on soil mineral nitrogen. *Swedish Journal of Agricultural Research* **24**, 67–75.

WERKHOVEN, C. H. E., INGEBRESEN, K. H., KEARNEY, T. E., BUSCHMANN, L. L., SAILSBERRY, R. L., MILLER, M. D. & KRANTZ, B. A. (1968). Fertilizer trials with safflower in the Sacramento Valley. *California Agriculture* **22**, 6–7.

WEISS, E. A. (1971). *Castor*, *Sesame and Safflower*. New York: Barnes and Noble.

YERMANOS, D. M., HALL, B. J. & BURGE, W. (1964). Effects of iron chelates and nitrogen of safflower and flax seed production and oil content and quality. *Agronomy Journal* **56**, 582–585.