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Combining fertilizer and organic inputs to synchronize N supply in alternative cropping systems in California

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Abstract

One of the principal aims of alternative cropping systems is to minimize excessive loss of N while maximizing N use efficiency and meeting crop N requirements. Many such cropping systems substitute intensive application of synthetic fertilizer with organic inputs, such as N_2-fixing legumes. The effectiveness of legume residues as a N source for subsequent crops depends heavily on temporal N release from the residue during the growing season. A field experiment with ^{15}N-labeled fertilizer and ^{15}N-labeled vetch residue was conducted to determine the temporal pattern of N release from both sources in conventional and alternative cropping systems in California. The experiment was conducted within conventional (fertilizer), low-input (fertilizer and organic N), and organic (organic N only) cropping systems established 9 year previously. Availability of N from the labeled inputs was determined based on uptake by maize (*Zea mays* L.). Uptake of total N and ^{15}N by maize in each cropping system was monitored at 10 day intervals from 50 to 90 days after seeding for determination of uptake rates. Uptake of N from fertilizer in the conventional system was greater than uptake of N from vetch in the low-input and organic systems. Uptake of N from vetch was delayed, but with a sustained availability later in the season. Uptake rates of N from fertilizer peaked at 4.3 kg N ha^{-1} per day between 70 and 80 days while those from vetch residue reached a maximum of 0.6 kg N ha^{-1} per day during the same time period. Grain and N yield at harvest did not differ between cropping systems despite different temporal and quantitative availability of N from organic and inorganic N inputs. This demonstrates that optimum yields can be achieved under management which uses alternative sources of N and can successfully match N availability with crop uptake.

Keywords: Nitrogen synchronization; Temporal N uptake; Long-term cropping systems; Legume residues; Nitrogen use efficiency; Alternative cropping systems; California

1. Introduction

The role of nitrogen in agroecosystems has become considerably scrutinized through research driven by the well-documented environmental and economic concerns associated with high N losses (Pimentel, 1996). The negative environmental effects of large N losses from agricultural systems and the high amount of fossil fuels involved in the industrial fixation of N for fertilization have led many to seek greater understanding of the connections between management practices and the N cycle. This impetus has led to comparison research examining the N cycle of varying cropping systems with an aim to isolate management practices favorable to decreased leakage of N from the system and to evaluate

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inputs on their ability to be retained in the crop or soil.

The long-term experiments conducted at Rothamsted have provided insight into the long-term ramifications of different N inputs on N cycling (Jenkinson, 1982; Johnston, 1994; Powlson, 1994). Other studies have been established to examine how an agroecosystem changes when transitioning from conventional to alternative management practices (Temple et al., 1994; Peters et al., 1997).

Short-term ^{15}N experiments show differences in the recovery of organic and inorganic N sources in crop and soil. A greater proportion of N from inorganic fertilizer is taken up by the crop than is N from legume residue (Ladd and Amato, 1986; Bremer and van Kessel, 1992; Harris et al., 1994). Inorganic fertilizers contribute a large flush of available N upon application, while legume residues show a delayed, sustained release of N (Azam et al., 1985; Groffman et al., 1987). This slow N release pattern of organic N sources is attributed to the dependence of organic residues on microbial decomposition and subsequent mineralization of N, a process largely affected by climate and residue quality, such as C:N ratio and polyphenolic content (Ladd and Amato, 1986; Palm and Sanchez, 1990; Sisworo et al., 1990). The disparity between crop N use efficiency of organic and inorganic sources resulting from distinct temporal N availability is reason for the legitimate concern of whether yields comparable to those of conventionally grown crops can be achieved by crops solely dependent on organic inputs.

There is considerable interest in reducing the dependency on synthetic fertilizers while maintaining crop yield. Nutrient supply by organic sources is a particular concern during the “transition period” when a system previously managed conventionally is converted to alternative management practices (Liebhart et al., 1989; Temple et al., 1994; Scow et al., 1994). Synchronizing temporal patterns of N release from organic sources with crop uptake is a key to increasing N availability for crops in systems reliant on organic N sources (Huntington et al., 1985; Stute and Posner, 1995; Ranells and Wagger, 1996). Recent modeling work has further highlighted the importance of the temporal N availability from organic sources in addressing environmental concerns and crop productivity (Pang and Letey, 2000).

Combining decreased levels of inorganic N inputs with organic N inputs may be an avenue for sustaining N availability to a crop in the transition to alternative management as well (Liebhart et al., 1989; Hussain et al., 1995; Cavero et al., 1997). The combination of organic and inorganic N inputs may be able to sustain a crop with comparable yields to one receiving only inorganic fertilizer, in part due to the two sources contributing N in temporally distinct patterns. The manipulation of the temporally distinct N release patterns may aid synchronization of N availability and crop demand throughout the duration of the season, such as a split application or slow-release inorganic fertilizer.

To explore this issue, an experiment was conducted using ^{15}N-labeled inorganic fertilizer and ^{15}N-labeled vetch residue in conventional, low-input and organic cropping systems. The objectives of the study were to (i) quantify the temporal release and uptake of N from these inputs by maize in soils under different management practices for 10 years; and (ii) juxtapose temporally quantified N uptake rates from vetch and inorganic fertilizer with crop N and grain yields to evaluate patterns of N release and uptake for effective N synchronization unique to each system.

2. Materials and methods

2.1. Experimental site

The experiment was conducted at the sustainable agriculture farming systems (SAFS) Research Center at the University of California, Davis, USA (38°32′N, 12°47′W; 18 m elevation). The SAFS project was established in 1988 and is comprised of four cropping systems, a conventional 2-year, conventional 4-year, low-input, and organic. The cropping systems are randomized and replicated four times, with all possible crop entry points represented in each block. Individual plots measure 68 m × 18 m (0.12 ha). Characteristics of each cropping system used in this study are given in Table 1. Further details and description of the project design, site characteristics, and a description of differences in chemical and physical properties and crop performance in the SAFS systems are provided in detail by Clark et al. (1998). Additional fertility-related information of the SAFS

Table 1
Description of farming systems at sustainable agriculture farming systems (SAFS) research center, Davis, California

Farming system	Crop rotation	Characteristics
Conventional	Tomato (*Lycopersicon esculentum* Mill.)	Synthetic N fertilizer and pesticides used at conventional rates
	Safflower (*Carthamus tinctorius* L.)	
	Maize (*Zea mays* L.)	
	Wheat (*Triticum aestivum* L.); bean (*Phaseolus vulgaris* L.)	
Low-input	Tomato	Reduced amount of inorganic N fertilizer; winter cover crop; reduced amount of pesticides
	Safflower	
	Maize	
	Oats (*Avena sativa* L.) + purple vetch (*Vicia benghalensis* L.); bean	
Organic	Tomato	Composted animal manure; winter cover crop; no pesticides used
	Safflower	
	Maize	
	Oats + purple vetch; bean	

site is presented elsewhere (Scow et al., 1994; Clark et al., 1999). The soil is classified as a Reiff loam (coarse-loamy, mixed nonacid, thermic Mollic Xerofluvents) and Yolo silt loam (fine-silty, mixed, nonacid, thermic Typic Xerorthents). Both the Reiff and Yolo series are classified as Mollic Fluvisols in the FAO World Reference Base. Soil C and N content for the plots used in this study are reported in Table 2.

Table 2
Average soil C and N content of the SAFS plots in which this study was conducted, measured in April 1998 after 10 years of management

Cropping system	Depth (cm)	C (kg ha^{-1})	N (kg ha^{-1})
Conventional	0–15	18560 b[a]	2050 c
Low-input		22130 a	2370 b
Organic		23210 a	2520 a
Conventional	15–30	15960 a	1720 a
Low-input		17030 a	1840 a
Organic		16980 a	1830 a
Conventional	30–60	24980 a	2650 a
Low-input		25840 a	2760 a
Organic		25070 a	2690 a

[a] Means followed by same letter within column for specified soil depth are not significantly different (ANOVA, Student–Newman–Keuls test $P \leq 0.05$).

2.2. Sampling methods

During the winter of 1997–1998, a 9 m^2 area of Lana vetch (*Vicia dasycarpa*) cover crop was labeled with $(NH_4)_2SO_4$ (49 at.% ^{15}N) in the low-input and organic system to be planted with maize in the spring of 1998. In order to ensure uniform labeling of plant components, vetch received $(^{15}NH_4)_2SO_4$ on 23 October 1997, 22 November 1997, and 27 February 1998, totaling a rate of 9 kg N ha^{-1}. In April 1998, the ^{15}N-labeled vetch shoots were harvested and shredded to simulate mowing. Similar-sized areas of unlabeled vetch were also harvested and shredded at this time.

Subplots measuring 4 m^2 were established in the maize entry point of the conventional, low-input and organic cropping systems in April 1998. To ensure integrity, subplots were established a safe distance from the areas of enriched vetch in the low-input and organic systems. The vetch cover crop was cleared from these subplots in the low-input and organic systems before application of ^{15}N-labeled and unlabeled additions. Characteristics and quantities of inorganic and organic N additions to each subplot are recorded in Table 3. Incorporation of the vetch and partially composted turkey manure was performed 6 days prior to seeding of the maize. Side dressing of ^{15}N urea was applied 36 days after seeding.

Table 3
Characteristics of N amendments to subplots in three cropping systems at SAFS

Cropping system	Subplot	Amendment	Quantity (kg N ha^{-1})	C:N ratio	^{15}N (atom%)
Conventional	1	^{15}N urea	220[a]	–	0.786
	2	–	–	–	–
Low-input	1	^{14}N vetch	100	11.2	–
		^{15}N urea	90[a]	–	0.725
	2	^{15}N vetch	120	11.8	0.653
		^{14}N urea	90	–	–
	3	–	–	–	–
Organic	1	^{15}N vetch	105	11.8	0.625
		^{14}N manure	330	9.4	–
	2	–	–	–	–

[a] An additional 7 kg unlabeled N ha^{-1} as starter was applied at seeding.

Maize (Pioneer 3162) was seeded in late April 1998 and irrigated throughout the growing season. Maize was sampled beginning at 40 days after seeding for each cropping system and continued every 10 days until 90 days after seeding. Studies of maize have shown that most of the N is accumulated by 90 days after seeding (Jordan et al., 1950; Hanway, 1962). Harvest data were taken in mid October, approximately 160 days after seeding.

Due to the size of the subplots and the number of sample dates, maize plants could not be destructively sampled within each plot until final harvest. Therefore, plants inside the subplots were sampled for atom% ^{15}N by taking punches of the second leaf from each of five random plants on each sampling date. Samples were dried at 60 °C and analyzed for atom% ^{15}N using continuous flow combustion-isotope ratio mass spectrometry at the Stable Isotope Facility, University of California, Davis. Since isotopic composition was not found to vary between different parts of the maize plants (data not shown), the atom% ^{15}N of the second leaf punches accurately reflected the atom% ^{15}N of the whole plants. Percent N in the plants derived from labeled fertilizer (%NDFF) or vetch (%NDFV) was determined using this data

$$\%\text{NDFF(V)} = \frac{\text{atom\%}^{15}\text{N excess plant}}{\text{atom\%}^{15}\text{N excess fertilizer (or vetch)}} \times 100 \quad (1)$$

To determine total plant N for each treatment, a random destructive sample of whole plants outside the subplots in each main plot area was taken on each sample date starting at 50 days after seeding. Height and weight were recorded for each plant sample. Whole plants were ground in a Wiley mill, further ground by ball milling, and analyzed for %N by a continuous flow carbon and nitrogen analyzer (Carlo Erba, Milan, Italy). Regressions using the measured height, weight and %N data were constructed for each cropping system. The R^2 values for the regression equations were between 0.86 and 0.95. Heights of the plants in the subplots were recorded on each sampling date and used with these regressions to determine the total N in each subplot. Together with Eq. (1), this provided the amount of N in each subplot derived from ^{15}N-labeled sources.

Nitrogen use efficiency (NUE) of the N additions was determined as

$$\text{NUE} = \frac{\text{kg N ha}^{-1}\text{ recovered in crop}}{\text{kg N ha}^{-1}\text{ applied}} \times 100 \quad (2)$$

Statistical analysis of total N and grain yield was conducted using ANOVA and the Student–Newman–Keuls test for significant differences between cropping systems.

Nitrogen supply power of the soils of each system was determined as the total N yield of the crop in the subplots of each system receiving no N additions.

Table 4
Grain and N yield for conventional, low-input, and organic corn subplots

Cropping system	Grain yield ($kg\,ha^{-1}$)	Above ground N yield ($kg\,ha^{-1}$)	Above ground N yield (no N added) ($kg\,ha^{-1}$)
Conventional	11930 a[a]	209 a	108 a
Low-input 1	9500 a	130 b	91 a
Low-input 2	9730 a	161 ab	91 a
Organic	11500 a	187 ab	97 a

[a] Means in columns followed by the same letter are not statistically different (ANOVA, Student–Newman–Keuls test $P \leq 0.05$).

3. Results and discussion

3.1. Yields

Grain yield and total aboveground N yields were similar for each system except the low-input treatment receiving ^{15}N-labeled fertilizer and unlabeled vetch, which had a lower aboveground N yield (Table 4). Aboveground N yields for zero N subplots were also similar, reflecting a comparable N supply capacity of the soils in each system. The similarity of grain and N yields occurred despite different management practices in each of the systems (Table 1). The similarity in yields and N supply suggest the low-input and organic systems have progressed beyond any transition period characterized by lower yields due to N constraints. Temple et al. (1994) did not find maize yields in the low-input and organic systems affected by N limitations characteristic of a transition period. The significantly lower N yield of the low-input treatment that received ^{15}N-labeled fertilizer and unlabeled vetch was likely due to less N input, 20 $kg\,N\,ha^{-1}$ less vetch-N than the treatment that received ^{15}N-labeled vetch and 30 $kg\,N\,ha^{-1}$ less than the conventional system (Table 3).

Organic N inputs often show lower crop N use efficiencies than mineral N fertilizers (Ladd and Amato, 1986; Harris et al., 1994). It was expected that the organic and low-input cropping systems would have a greater soil N supply capacity than the conventional system due to their greater total N content in the top 15 cm of soil (Table 2). It was anticipated that a greater soil N supply power in the organic and low-input systems would be the cause of comparable total N yields among all systems. However, the N yields of the zero N subplots designed to determine the intrinsic soil N supply power of each of the three systems did not support this assumption (Table 4). Aboveground N yields for zero N subplots were similar, reflecting a comparable N supply capacity of the soils in each system, despite the differences in soil C and N contents between systems in the 0–15 cm depth that have developed since the inception of SAFS.

Some caution is needed, however, as a direct comparison of N supply power between the conventional and alternative systems based on the zero N plots may be questionable. The removal of the vetch cover crop from the alternative systems before establishment of the zero N plots may have exported N since the cover crop was a sink for soil N during the winter. In contrast, the conventional soil had no crop as an N sink during the same period and thus no N was exported from the system besides naturally occurring losses before the establishment of the zero N plots.

3.2. Percent nitrogen derived from ^{15}N sources

Conventionally grown maize consistently showed the highest proportion of N from an applied, labeled source (Fig. 1). This is attributable to the conventionally grown maize receiving a substantially greater amount of labeled N in only one form, in contrast to the alternative systems receiving a combination of N sources. Combining the %NDFF and %NDFV in the low-input system still falls short of the %NDFF in the conventionally grown maize. In the low-input system, more N was derived from the inorganic fertilizer than was derived from vetch (Fig. 1). Together, these results suggest that throughout the season, N from the ^{15}N-labeled vetch was not as available as the ^{15}N fertilizer. This was particularly true early in the season and is consistent with the findings of Azam et al. (1985) who observed close to 20% of N in maize shoots derived from legume residue and close to 40%

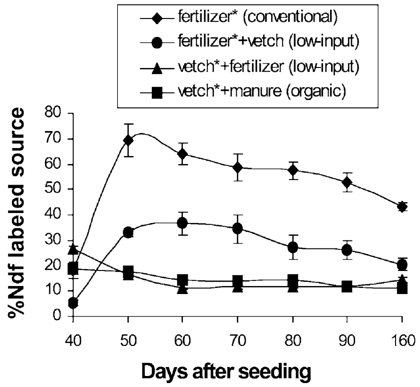

Fig. 1. Percent of total nitrogen derived from ^{15}N-labeled inputs in conventional, low-input and organic cropping systems. (*) Denotes labeled N source. Bars represent standard error.

derived from inorganic fertilizer 35 days after seeding. Hesterman et al. (1987) found N derived from alfalfa residue in maize to be somewhat more comparable to that of %NDFF, with 40% of maize N derived from each source at one location and 30% from each another. However, these results were averages for two fertilizer N levels applied, and with the higher fertilizer N level applied (168 kg N ha^{-1}), the N derived from alfalfa residue was decreased to 19%, a value closer to the results of the current study.

The %NDFF in the conventional and low-input grown maize decreased significantly from the penultimate sampling date to harvest, while %NDFV in the low-input and organic systems remained consistent over the same time period late in the season. The maintenance of a consistent %NDFV in the low-input and organic systems over the course of the season occurred while the total N uptake by the crop peaked (Fig. 2A–D). This reflects a delayed release of N from vetch residue since an increased availability of vetch N would have had to occur later in the season in order to maintain the consistent %NDFV in the crop in the face of the N uptake climax. This is in contrast to a pattern of decreasing availability of the inorganic fertilizer seen in the decreasing %NDFF in the low-input and conventional systems during the time of peak N uptake, a pattern seen in other studies as well (Bigeriego et al., 1979).

The %NDFF in the low-input system remained higher than %NDFV throughout the entire growing season. However, it is instructive to note the differing

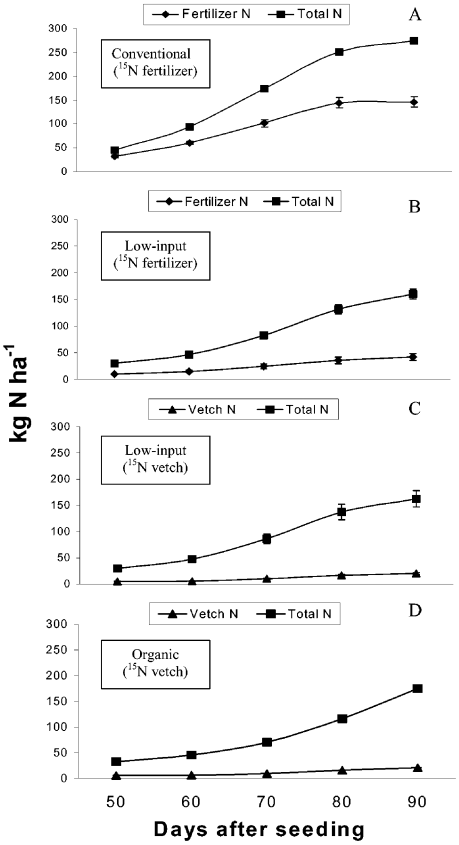

Fig. 2. Cumulative temporal uptake of N in conventional (A), low-input (B, C), and organic (D) cropping systems.

%NDFF/%NDFV patterns for the inorganic and organic N sources in the interest of optimizing N synchronization between N release and subsequent crop uptake when both inputs are applied.

3.3. *Total ^{15}N uptake*

The conventionally grown maize showed the greatest average total N uptake at all observations, although the final N yield was not significantly different from the low-input and organically grown maize receiving N additions (Fig. 2A, Table 4). Total recovery of fertilizer in conventionally grown maize was 90 kg N ha^{-1}, leading to a fertilizer NUE of 41%, an efficiency in the range of that commonly reported in ^{15}N recovery studies applying greater than 150 kg N ha^{-1} (Bigeriego et al., 1979; Russelle et al., 1981).

A somewhat similar pattern of ^{15}N uptake from fertilizer was observed in the low-input system (Fig. 2B), although on a smaller quantitative scale due to less fertilizer applied. Fertilizer NUE was significantly different between the conventional and low-input systems at 60, 70, and 80 days. At final harvest, however, there was no significant difference in net fertilizer NUE of the low-input system (29%) compared to the conventional system (41%). Unlike the conventional system, the low-input NUE at harvest was significantly lower than at 90 days (47%), suggesting that disproportionately more vetch and/or soil-N was still being released and taken up by maize after 90 days in the low-input system as compared to the conventional system. A decrease in fertilizer NUE has occurred in other studies combining organic with inorganic sources of N due to increased immobilization (Azam et al., 1985), but not to a significant degree in others (Ta and Faris, 1990).

According to the regression-based estimates for 90 days, the conventional and low-input grown maize receiving ^{15}N-labeled fertilizer showed a significant loss of N between 90 days and final harvest. It is possible that the regression caused an overestimation of crop N towards the later dates, since at this time during the growing season, the height of the plants was maximum while the crop biomass or their total N content could still increase. Under such circumstances, the same measurement for height could correspond to a range of total N in the crop. However, losses of N due to ammonia volatilization from aerial plant structures or detachment of senescent leaves may also have occurred. Based on isotopic studies, ammonia volatilization from maize has been estimated as high as 80 kg N ha^{-1}, although reports at that level remain debatable (Francis et al., 1993; Harper and Sharpe, 1995).

The pattern of temporal uptake of N from vetch in the low-input and organically grown maize was extremely similar. Temporal accumulation of N from vetch occurred similarly in these two systems despite the addition of different qualitative N sources with or following the vetch, and despite the distinct histories of management in these two systems. Compared to the low-input system, the percent recovery of vetch-N was significantly higher in the organic system at 50 and 60 days. Thereafter no differences in ^{15}N recovery between the two systems were observed. Both the low-input treatment receiving ^{15}N-labeled vetch and unlabeled inorganic fertilizer and the organic treatment receiving ^{15}N-labeled vetch and unlabeled manure showed little uptake of ^{15}N from the vetch until between 60 and 70 days after seeding. This indicates a slower temporal pattern of N release compared to estimates of some studies examining N release rates from leguminous cover crops (Bremer and van Kessel, 1992; Stute and Posner, 1995; Ranells and Wagger, 1996). Stute and Posner (1995), using buried mesh bags containing vetch and clover found half of the N released from the residue by 4 weeks after burial, while N release appeared to terminate by 10 weeks. A more rapid mineralization of vetch was reported in an incubation experiment at the SAFS site (Hu et al., 1997). In the incubation experiment, 25–30% of the N in the vetch residue was mineralized by 35 days after incorporation. However, other field studies have shown a slower availability of N from leguminous sources, similar to that determined by the current isotopic study (Huntington et al., 1985; Groffman et al., 1987). Both the low-input and organically grown maize accumulated near 20 kg N ha^{-1} from the labeled vetch by harvest, corresponding to 19% use efficiency, comparable to other field studies applying leguminous residues (Ladd and Amato, 1986; Harris et al., 1994).

Tracing ^{15}N uptake by a crop does not reflect the exact pattern of N release from an N source since the uptake is dependent on crop N demand and other sinks compete with the crop for the mineralized N. It is possible that N from labeled sources in this experiment was available to a greater extent earlier in the season than is truly reflected by N uptake in the crop due to low N demand at that time. However, the levels of ^{15}N uptake from organic and inorganic sources in the experiment at the first sampling date do not support this viewpoint. The crop in the low-input treatment receiving ^{15}N-labeled inorganic fertilizer had accumulated 10 kg N ha^{-1} of the labeled N (Fig. 2B) while at the same time less than half of that was accumulated in the other low-input treatment receiving ^{15}N-labeled vetch (Fig. 2C). Likewise, as the total accumulation of N in the crop greatly increased during the next sample dates, there was a disproportionate increase in uptake of N from the inorganic and organic sources. Much more N from fertilizer was taken up during the increase in total N uptake in the early part of the season. It can be deduced that N from the vetch was not equally available at the time of increasing total N uptake by maize. It was not until 70 days after seeding that the vetch N became available to a greater extent.

3.4. ^{15}N uptake rates

Nitrogen uptake rates further elucidate the temporal patterns of N release from inorganic and organic sources. The conventional cropping system had the highest total and ^{15}N uptake rate of any system, climaxing between 60 and 70 days close to 8 kg N ha^{-1} day of total N, and over 4 kg fertilizer-derived N ha^{-1} per day (Fig. 3A). Uptake rates at this level are similar to those reported for conventionally grown maize receiving 180 kg N ha^{-1} (Russelle et al., 1983). The uptake rate of inorganic fertilizer in the conventionally grown maize markedly declined by the last sample date. Granted, this decline occurred late in the season, when N uptake would be expected

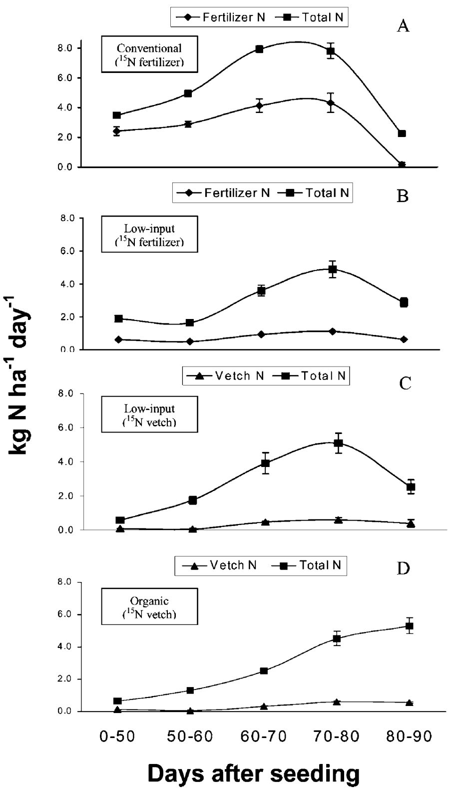

Fig. 3. Temporal N uptake rates in conventional (A), low-input (B, C), and organic (D) cropping systems. Bars represent standard error.

to decline due to decreasing crop demand. However, it is surprising that the uptake of fertilizer N declined to almost zero from 80 to 90 days, while uptake from the soil remained at a substantial level of 2 kg N ha^{-1} per day. This decline in fertilizer N uptake to zero by 90 days with a continued availability and uptake of soil N was not observed by Russelle et al. (1983), who showed an uptake rate of 2 kg N ha^{-1} d^{-1} from fertilizer from the final observation point until physiological maturity. Instead, the only report of fertilizer N uptake declining to close to zero was in a year when soil N uptake also declined to zero during the final observation before physiological maturity (Russelle et al., 1983). The decline in availability of N from fertilizer that occurred simultaneously with a continued significant level of uptake of native soil N in the present study points to microbial immobilization of the fertilizer N as a possible contributor to the stark decline in availability. Final recoveries of applied sources in crop and soil of each system at harvest (data not shown) showed no difference in losses between cropping systems, ruling out abnormally large losses as an explanation for the pronounced decline in availability.

Fertilizer was an important source of N for the crop throughout the season in the low-input system, particularly early in the season when its concentration in soil was much larger than available vetch-N (Fig. 3B and C). Proportionally, the uptake rate of N from fertilizer in the low-input system was similar to that of the conventional system, yet without the extremely pronounced decline in uptake between 80 and 90 days. The fact that the uptake rate of N from fertilizer did not decline to zero by 90 days in the low-input system attests to its continued availability throughout the growing season in contrast to the conventional system, albeit at a decreased level. The continued availability of the ^{15}N from fertilizer may be due to re-mineralization of ^{15}N from fertilizer immobilized earlier in the season due to the presence of the vetch residue.

Total N uptake rates in the low-input and organic cropping systems were lower than in the conventional system, yet maximum uptake rates (Fig. 3C and D) were comparable to those reported previously for maize supplied with both inorganic and organic sources of N (Huntington et al., 1985). Uptake rates of ^{15}N from the labeled vetch in the low-input and organic cropping systems were almost nil over the first sampling period, then gradually increased to their maximum level between 70 and 80 days (Fig. 3C and D). The uptake rates from ^{15}N-labeled vetch showed much less of a decline during the last sampling period in comparison with uptake rates from ^{15}N fertilizer. These uptake rates support the recurring trend that vetch N was not significantly available during the early part of the growing season, and therefore was not significantly exploited as an N source until later in the season when compared with the inorganic N additions. This trend of delayed N release from legume residues in comparison with that from inorganic fertilizers is consistently supported by previous studies (Huntington et al., 1985; Azam et al., 1985; Groffman et al., 1987). The study by Groffman et al. (1987) particularly depicts this difference between temporal availability of inorganic and organic N additions owing to the dependency of organic additions on microbial decomposition and C dynamics. In that study and the current one there appeared to be a large peak of available N early in the season from the applied fertilizer, followed by a decline that fell below the availability of the organic N source later in the season. In contrast, the supply of N from the organic source was retarded to some degree, in part due to the influx of applied fertilizer N, but remained more consistent throughout the whole season at a level significantly below the maximum availability of the fertilizer.

The application of fertilizer-N in the conventional system is timed to correspond with the period of maximum crop N demand. Part of the challenge of alternative agriculture lies in adequately satisfying this demand with organic sources. It appears that N from vetch residue in the organic and low-input systems became more available near the time of peak N uptake rate by the crop, suggesting good N synchronization. A. Hadas (unpublished results) modeled C and N release and turnover associated with the patterns of uptake observed in the present study, and included an estimate of the decomposition rate of the manure. Using simulation modeling, available N in the organic system showed a maximum value at approximately the same time fertilizer-N was applied in the conventional and low-input systems. The total N uptake rate in the organic system was distinct in that it did not decline over the last sampling period (Fig. 3D). This may be due in part to the delayed maturity of maize in the organic system, in which case the decline would have occurred after the last sample date. It may also have been due to the presence of two organic sources of N. The manure applied was not labeled with ^{15}N, and thus did not allow for tracing of the release and uptake of the N it contained. Although the manure likely supplied substantial N quickly upon application, as an organic N source it probably released a sustained level of N throughout the season as well. In this case, the increase in N uptake rate over the last sampling period likely stems from both organic N sources supplying substantial N later in the season that coincided with a high level of N demand in the late maturing crop. It has been shown that peak N uptake by maize is dependent to some degree on N availability after the crop has reached the rapid growth phase (Russelle et al., 1983). Delaying the availability of N until later in the season was shown to delay the period of maximum N accumulation by the crop (Russelle et al., 1983). The N uptake patterns of the maize under varying N sources with distinct temporal availability in this study may be attributed to and further attest to this plasticity of resource acquisition. In California, substituting part of a conventional application of fertilizer-N with an organic N input seems to best meet the challenge of synchronizing N supply with N uptake by maize. During the first 8 years of the SAFS project, the average maize yield in the low-input system was higher than the yield in the conventional system, while maize produced under organic management showed lower average yields (Clark et al., 1999).

4. Conclusions

Integral to the comparable yields among the three cropping systems in this study was the temporal manipulation of inorganic and organic amendments to provide sufficient N throughout the season. Fertilizer was immediately available, proving to be a significant source of N for the maize early in the growing season. Uptake of N from the vetch residue in the low-input and organic cropping systems was not substantial until between 60 and 70 days after seeding (75–85 days after incorporation). This trend was independent of whether the vetch was applied in the presence of inorganic fertilizer or animal manure. The vetch supplied a sustained level of N later in the growing season. Decreased rates of applied inorganic fertilizer can provide sufficient N early in the season, and when accompanied later in the season by a sustained release of N from mineralized legume residue incorporated prior to seeding, the two sources can meet the climax of N demand of the crop. Combination of organic and inorganic N inputs holds promise for reducing the use of inorganic fertilizers and possible N losses from agroecosystems.

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