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ORIGINAL PAPER

Soil aggregates control N cycling efficiency in long-term conventional and alternative cropping systems

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Abstract This paper presents novel data illustrating how soil aggregates control nitrogen (N) dynamics within conventional and alternative Mediterranean cropping systems. An experiment with ^{15}N-labeled cover crop residue and synthetic fertilizer was conducted in long-term (11 years) maize–tomato rotations: conventional (synthetic N only), low-input (reduced synthetic and cover crop-N), and organic (composted manure- and cover crop-N). Soil and nitrous oxide (N_2O) samples were collected throughout the maize growing season. Soil samples were separated into three aggregate size classes. We observed a trend of shorter mean residence times in the silt-and-clay fraction than macro- (>250 μm) and microaggregate fractions (53–250 μm). The majority of synthetic fertilizer-derived ^{15}N in the conventional system was associated with the silt-and-clay fraction (<53 μm), which showed shorter mean residence times (2.6 months) than cover crop-derived ^{15}N in the silt-and-clay fractions in the low-input (14.5 months) and organic systems (18.3 months). This, combined with greater N_2O fluxes and low fertilizer-N recoveries in both the soil and the crop, suggest that rapid aggregate-N turnover induced greater N losses and reduced the retention of synthetic fertilizer-N in the conventional system. The organic system, which received 11 years of organic amendments, sequestered soil organic carbon (SOC) and soil N, whereas the conventional and low-input systems merely maintained SOC and soil N levels. Nevertheless, the low-input system showed the highest yield per unit of N applied. Our data suggests that the alternating application of cover crop-N and synthetic fertilizer-N in the low-input system accelerates aggregate-N turnover in comparison to the organic system, thereby, leading to tradeoffs among N loss, benefits of organic amendments to SOC and soil N sequestration, and N availability for plant uptake.

Keywords Aggregate dynamics · Long-term cropping system · Mean residence time · Plant nutrient uptake · Soil organic matter sequestration · Soil nitrogen cycling

Introduction

Mounting concerns about rising greenhouse gas emissions, environmental degradation, and rural economic decline associated with modern conventional farming practices have warranted a critical need for management practices that enhance land value for producers, while promoting long-term agricultural sustainability and

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productivity (Pimentel et al. 1999; Tilman et al. 2002; Robertson and Swinton 2005). Alternative crop management practices, such as cover cropping, compost application, and reducing or eliminating synthetic fertilizer use, have emerged as integrated and ecologically sound approaches to improving soil organic matter (SOM) levels and supplying crops with sufficient N (Drinkwater et al. 1998). Results from several long-term cropping system studies suggest that, after a transition period from conventional management, alternative cropping practices can produce yields that are comparable to those of conventional systems (Temple et al. 1994; Drinkwater et al. 1995, 1998) and also impart various benefits to soil productivity (Bulluck et al. 2002; Drinkwater et al. 1995). For example, Clark et al. (1998) found cropping systems that combined decreased levels of synthetic N fertilizer with organic N inputs were more efficient at storing excess N than conventional systems. In addition, cropping systems that rely on the growth of winter-hardy cover crops to supply N to summer cash crops have been shown to reduce soil erosion and nitrate leaching, increase SOM, and improve aggregate stability as well as other soil structural properties (Roberson et al. 1991; Wyland et al. 1996; Drinkwater et al. 1998).

Despite considerable research comparing the effects of conventional and alternative farming practices on yields, N utilization, and nutrient cycling, the mechanisms governing soil C and N dynamics must be better understood and quantified in order to elucidate the effects of different cropping practices on soil fertility. Soil aggregate dynamics are integral to ecosystem functioning, in governing many processes such as, water transport (e.g., Prove et al. 1990), oxygen exchange (e.g., Sexstone et al. 1985), microbial community structure (e.g., Schutter and Dick 2002), and SOM protection (e.g., Tisdall and Oades 1982). Moreover, Elliott (1986) showed that soil aggregates form temporary C and N pools by stabilizing C and N within their structure and release C and N upon breakdown; therefore, aggregate turnover is pivotal in SOM turnover and, consequently, nutrient availability for plant uptake (Tiessen et al. 1984; Six et al. 1998).

In turn, aggregate dynamics are sensitive to changes in agricultural management (Tisdall and Oades 1982; Elliott 1986). In conventionally managed systems, where synthetic N is often applied without a C source, microorganisms will decompose C-rich binding agents (Harris et al. 1963), potentially reducing soil aggregation and, hence, diminishing SOM protection. However, N availability for plant uptake is high upon addition of only synthetic N. In contrast, the sole application of organic amendments in organically managed systems most often leads to N immobilization (i.e., reduced N availability for plant uptake) due to excess C (Palm et al. 2001), paired with the formation of aggregates and the consequent maintenance or even build up of SOM in these aggregates (Tisdall and Oades 1982). It is pertinent that cropping system management optimize the timing of net nutrient availability relative to crop uptake while assuring long-term soil fertility as well as minimizing environmental impacts (Palm et al. 2001; Cassman et al. 2002).

The objectives of this study were to: (i) determine the short-term effects of fertilizer type on soil N cycling and stabilization, (ii) elucidate the mechanisms governing N dynamics and interactions in conventional and alternative crop management practices, and (iii) quantify SOC and soil N sequestration across a gradient of long-term cropping systems. For this study, we hypothesized that (i) low-input cropping systems would exhibit intermediate aggregate-N turnover relative to conventional and organic cropping systems and (ii) the low-input system would show greater efficiency in the use of the applied N source than the conventionally and organically managed systems. We tested these hypotheses in a field study conducted in long-term (11 years) conventional, low-input, and organic maize–tomato (*Zea mays* L.–*Lycopersicon esculentum* L.) cropping systems, using ^{15}N-labeled cover crop residue and ^{15}N-labeled synthetic fertilizer.

Materials and methods

Study site

The field study took place at the Center for Integrated Farming Systems site (CIFS; Davis, CA, USA; 38°32′24″ N 121°52′12″ W), formerly known as the Long-Term Research on Agricultural Systems experiment. Since 1993, the CIFS has been a site for testing the sustainability of conventional and alternative cropping systems, which were designed to reflect cohesive cropping systems and, therefore, varied by more than one management factor (Denison et al. 2004). The soil at the CIFS site is a mixture of two soil types: (i) Yolo silt loam (fine-silty, mixed, nonacid, thermic Typic Xerothent) and (ii) Rincon silty clay loam (fine, montmorillonitic, thermic Mollic Haploxeralf). Also, the CIFS is located in a region with a Mediterranean climate regime (i.e., cool, wet winters and hot, dry summers).

Our field study was conducted during the 2004 maize growing season, within three 2-year, maize–tomato rotations, which differed in nutrient input level and source (Table 1). These maize–tomato cropping systems are arranged in a complete randomized design, consisting of the following nutrient treatments: (1) conventional (synthetic N fertilizer only), (2) low-input (alternating synthetic N fertilizer and winter legume cover crop-N) and (3) organic (composted manure- and cover crop-N). Each management system is randomly distributed in the 30-ha CIFS site as three, 0.2-ha replicates, receiving furrow irrigation, and under conventional tillage.

Experimental design and stable isotope labeling

Experimental plots (1.2 m × 1.0 m) were established within each of the cropping treatment replicates in March and simulations of field cultivation were done by hand within these plots. In mid-March, maize was direct-seeded into the conventional plots following an herbicide application. Shortly after, the conventional plots received two separate, bed-top applications of urea mixed with $(^{15}NH_4)_2SO_4$ (99 atom%) in solution for a combined enrichment of 6.5 atom% ^{15}N. The first fertilization was applied as ^{15}N-labeled N–P–K starter fertilizer, at a rate of 60 kg N ha^{-1} on April 22nd (32 days after planting). The second fertilization was an application of 220 kg urea-N ha^{-1} (also ^{15}N-enriched) on May 12th (51 days after planting). Meanwhile, the aboveground biomass of the standing cover crop, a vetch (*Vicia dasycarpa*) and pea (*Pisum sativum*) mixture, was removed from the experimental plots of the low-input and organic systems in early April. From January through March, *V. dasycarpa* and *P. sativum* plants were grown under greenhouse conditions at a density of 45:90 kg seed ha^{-1} and labeled (~7.4 atom%) with 99 atom% $(^{15}NH_4)_2SO_4$, according to Bird et al. (2003). On April 16th, after composted manure was added at a rate of 373 kg N ha^{-1} into the organic treatment, the above- and belowground biomass of the ^{15}N-labeled cover crop was incorporated, at a rate of 3 Mg dry weight ha^{-1} (100 kg N ha^{-1}), to a 15-cm depth in the low-input and organic plots. Maize was direct-seeded into the low-input and organic systems in early May. After harvest, the maize stover was returned to each system. With the exception of using a solution form of the fertilizer in the conventional system, all field operations on the experimental plots mirrored those taking place at the field-scale for the 2004 maize season.

Field sample collection

Soil core samples (4.6-cm diameter; 0–15 cm) were collected from the experimental plots within the conventional, low-input, and organic cropping systems over the course of the 2004 growing season. The first soil sampling took place on March 13th, before the addition of isotopically

Table 1 Maize–tomato cropping systems at the Center for Integrated Farming Systems site (Davis, CA, USA)

Maize–tomato cropping system	Even years of cropping	Odd years of cropping
Conventional	Fertilized maize	Fertilized tomato
Low-input	Winter legume cover crop then maize	Fertilized tomato
Organic	Winter legume cover crop then maize with composted manure (no pesticides)	Winter legume cover crop then tomato with composted manure (no pesticides)

enriched material, to establish all necessary baseline data (i.e., C and N concentrations in whole soil and ^{15}N levels of whole soil and aggregate fractions). Soil samples were collected mid-season (June 17th), after the cessation of irrigation (August 4th), and at harvest (September 21st). Two soil cores, one from the center and one immediately adjacent to the maize row, were obtained from each of the experimental plots, at each sampling event. Upon return to the laboratory, field-moist soil samples were gently broken apart, passed through an 8-mm sieve, air-dried, and the two cores sampled from each plot were composited and stored at room temperature before physical fractionation and for further analysis. Bulk density was determined on an individual soil core basis and subsequently averaged per plot.

On September 21st, the aboveground biomass of mature maize plants was collected from each experimental plot. These samples were weighed, oven-dried at 50°C, and used to extrapolate both grain-N content and ^{15}N-uptake into the maize grain and vegetative biomass.

At three-week intervals for a total of seven sampling events throughout the growing season, N_2O fluxes were measured using closed chambers that were based on the design by Hutchinson and Mosier (1981). After maize seeds were sown, 20.3-cm diameter polyvinylchloride (PVC) rings (15-cm tall) were driven in between the maize rows, to a depth of 10 cm, at the northern end of each experimental plot. The closed chamber tops were constructed from PVC irrigation caps (20.3-cm diameter) and enclosed a headspace volume of approximately 5.6 l. Gas (15 ml) was sampled from the headspace with polypropylene syringes at 0, 15, and 30-min intervals. Nitrous oxide flux measurements and the corresponding soil moisture, air temperature, and soil temperature readings were made in the early morning through mid-afternoon, on each sampling event.

Soil aggregate separation

Air-dried soil samples from the four collection points were separated into three aggregate size classes by wet sieving according to Elliott (1986). Briefly, 80-g air-dried soil samples were submerged in deionized water, at room temperature, on top of a 250-μm sieve for five minutes, effectively slaking the soil (Kemper et al. 1985). Water-stable aggregates were separated by moving the sieve in an up-and-down motion with 50 repetitions, over a period of two minutes. The material remaining on the 250-μm sieve (>250-μm macroaggregates) was backwashed into aluminum pans. The soil–water solution that passed through the 250-μm sieve was transferred onto the 53-μm sieve and sieved according to the procedure outlined above. Consequently, three aggregate fractions were produced: (i) macroaggregates (>250 μm), (ii) microaggregates (53–250 μm), and (iii) silt-and-clay (<53 μm). The aggregate fractions were oven-dried at 50°C in aluminum pans and then stored for analysis.

Elemental C and N plus isotopic N analyses

Subsamples of whole soil samples were ground and analyzed for elemental and isotopic C and N concentrations, while aggregate fractions, grain, and vegetative maize biomass samples were analyzed for elemental and isotopic N concentrations using a PDZ Europa Integra C-N isotope ratio mass spectrometer (Cheshire, United Kingdom). Because the soil samples did not react (i.e., evolve CO_2) upon addition of 12M hydrochloric acid, we concluded that the whole soil samples were free of inorganic C; therefore, the total C concentrations that were measured were considered equivalent to organic C concentrations. For whole soil and aggregates, the proportion (f) of soil N derived from ^{15}N-labeled cover crop or ^{15}N-labeled synthetic fertilizer was calculated using the ^{15}N atom% values of the ^{15}N-enriched samples against the ^{15}N natural abundance samples in the isotope dilution method:

$$f = \frac{{}^{15}\mathrm{N}_{\mathrm{sample}} - {}^{15}\mathrm{N}_{\mathrm{natural\ abundance}}}{{}^{15}\mathrm{N}_{\mathrm{labeled\ material}} - {}^{15}\mathrm{N}_{\mathrm{natural\ abundance}}}, \tag{1}$$

where $^{15}\mathrm{N}_{\mathrm{sample}}$ = ^{15}N atom% for the sample of interest, $^{15}\mathrm{N}_{\mathrm{labeled\ material}}$ = ^{15}N atom% of cover crop or synthetic fertilizer, $^{15}\mathrm{N}_{\mathrm{natural\ abundance}}$ = ^{15}N atom% of the equivalent sample taken at the first soil sampling event, before the addition of ^{15}N-labeled material (0.367 atom%). Total N concentrations for the measured variables were multiplied by f to obtain N_{new}, the concentration of N derived from the ^{15}N-labeled fertilizer or cover crop-^{15}N. All elemental and isotopic C and N measurements for the soil samples were converted to an area (m^2) basis using bulk density measurements. Partial productivity factor of N (PFP_N) values were calculated as the ratio of the maize yield to the total amount of N applied to the system (i.e., synthetic-, composted manure- and/or cover crop-N). Nitrogen use efficiency (NUE) of the crop was calculated as the ratio of the total aboveground biomass-N_{new} to the total amount of ^{15}N-labeled fertilizer- or cover crop-N applied to the system. Likewise, fertilizer- or cover crop-N recovery in the soil fractions was calculated as the ratio of the soil fraction-N_{new} to the total amount of ^{15}N-labeled applied.

Gas samples were analyzed for N_2O concentrations on a Hewlett Packard 6890 Series Gas Chromatograph, micro-electron capture detector (Palo Alto, CA). Nitrous oxide fluxes were calculated using equations from the GRACEnet Chamber-based Trace Gas Flux Measurement Protocol (Baker et al. 2003) and reported on an elemental N per area and rate basis. For each system, N_2O fluxes for the interval between two consecutive sampling events were calculated by interpolating fluxes from the averages of the two measured sampling events. Then, N_2O–N flux estimates for the six periods between the seven-gas sampling events were summed to obtain cumulative N_2O–N flux per cropping system.

Data analysis

The proportion of aggregate-N not derived from a ^{15}N source [i.e., $N_{old} = (1 - N_{new})$] was used to calculate the mean residence times of the aggregate-N pools. Mean residence times of aggregates were calculated by taking the reciprocals of the estimates of rate constants (k), obtained from the following first-order decay equation:

$$A_t = A_0(e^{-kt}) \tag{2}$$

where A_t = proportion of N_{old} at the final sampling event, A_0 = proportion of N_{old} in the fraction at the first sampling event, k = decay rate constant, and t = time between the final soil sampling event and (i) the addition of ^{15}N-fertilizer into the conventional system [t = 4.8 months] or (ii) the incorporation of the ^{15}N-cover crop into the low-input and organic systems [t = 5.8 months]. The differences in aggregate-N_{old} concentration between the first soil sampling time and the time the ^{15}N-labeled synthetic fertilizer was applied or the ^{15}N-labeled cover crop was incorporated into the soil were assumed to be negligible.

An analysis of variance (ANOVA) approach for a complete randomized design was used to compare differences in grain and soil C, N, N_{new} measurements among the three cropping systems and between the first and last soil sampling events for each cropping system, respectively. In the model, either cropping system or sampling event was the main variable. All differences discussed were significant at the $p < 0.05$ probability level, unless otherwise stated. Data were power-transformed where transformations were needed to meet assumptions of ANOVA. Pairwise comparisons were made with Tukey's Honestly Significant Difference when the ANOVA *F*-test was statistically significant. All statistical analyses were performed using JMP IN student version 4.0 (SAS Institute 2001).

Results

Maize ^{15}N uptake and productivity

The amount of grain-N derived from the synthetic ^{15}N-labeled fertilizer (10.4 kg N_{new} ha^{-1}) in the conventional system was greater than the amount of grain-N_{new} in the low-input and organic systems ($p < 0.05$; Fig. 1a). Concentrations of N derived from ^{15}N-labeled cover crop were similar between the low-input and organic systems (3.57 and 3.37 kg N_{new} ha^{-1}, respectively; Fig. 1a). In contrast, N use efficiency of the aboveground biomass (i.e., vegetative maize biomass plus grain) did not differ among the conventional, low-input, and organic cropping systems (Table 2). Grain N content of the conventional rotation (104 kg N ha^{-1}) also was not significantly

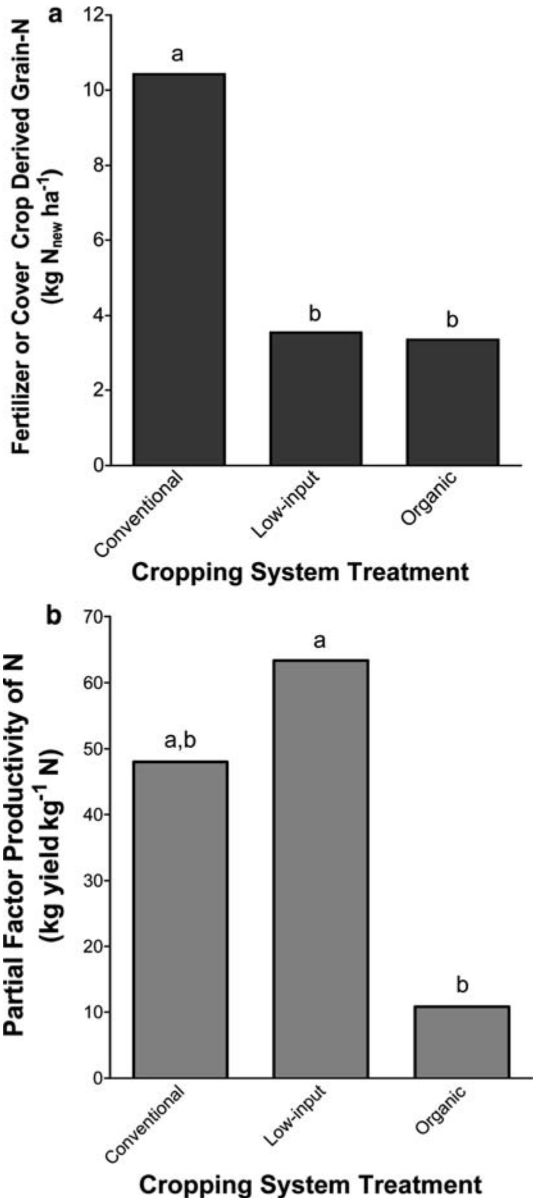

Fig. 1 (**a** and **b**) Concentration of N derived from ^{15}N-labeled cover crop (in the low-input and organic cropping systems) or ^{15}N-labeled synthetic fertilizer (in the conventional cropping system) (**a**) and partial factor of productivity of nitrogen (PFP$_N$) (**b**) during the 2004 season for the maize–tomato cropping systems, at the Center for Integrated Farming Systems site (Davis, CA, USA). Data bars with different letters are significantly different ($p < 0.05$)

different from the grain-N levels in the alternative cropping systems (data not shown). However, a greater PFP$_N$ value was observed in the low-input system (63.4 kg yield kg N applied^{-1}) than in the organic system, which had the lowest PFP$_N$ value among the three cropping systems ($p < 0.05$; Fig. 1b).

Aggregate-associated N and ^{15}N

In the conventional cropping system, total N associated with the microaggregates and macroaggregates was greater than silt-and-clay fraction-associated N concentrations at both the first and last soil sampling events ($p < 0.05$; significance not indicated in Fig. 2). In contrast, total N concentrations were evenly distributed among aggregate fractions of the low-input system. However, the macroaggregate-N levels were greater than microaggregate- and silt-and-clay fraction-N concentrations in the organic system ($p < 0.05$; significance not indicated in Fig. 2). Significant accumulations of macroaggregate- and microaggregate-N were observed in the organic and conventional systems, respectively, while the silt-and-clay fractions of both the low-input and conventional rotations accumulated N over the course of the season (Fig. 2). At the start of the experiment, the organic and low-input systems showed similar concentrations of macroaggregate-N, while a greater concentration of macroaggregate-N was found in the macroaggregates of the organic than the conventional system (Fig. 2). By the end of the season, macroaggregate-N of the organic system was the greatest ($p < 0.05$; Fig. 2).

The amount of N$_{new}$-associated with the silt-and-clay fraction of the conventional rotation was greater than the concentration of silt-and-clay-N$_{new}$ in the low-input and organic systems, as well as N$_{new}$ associated with all other aggregate fractions, at all sampling events after fertilizer applications ($p < 0.05$; Fig. 3). Macroaggregate-, microaggregate- and silt-and-clay-N$_{new}$ concentrations did not differ between the low-input and organic systems, except at the second soil sampling event; there, the macroaggregate-associated N$_{new}$ was higher in the organic system ($p < 0.05$; Fig. 3).

Mean residence times of N in the three aggregate fractions in the low-input and organic systems and the mean residence times of the macroaggregate-associated N of all three crop-

Table 2 Nitrogen use efficiency (NUE) in aboveground maize biomass and N recovery in the whole soil (0–15 cm) collected on September 21st, 2004 from the conventional, low-input, and organic maize–tomato cropping systems at the Center for Integrated Farming Systems site (Davis, CA, USA)

Variable	Cropping system		
	Conventional (%)	Low-input (%)	Organic (%)
Aboveground vegetative biomass	3.24^{a}	4.26^{a}	4.44^{a}
Grain	4.42^{a}	4.63^{a}	4.22^{a}
Whole soil	36.5^{b}	90.0^{a}	83.8^{a}

Values with letters ‘a and b’ are significantly different among the cropping systems ($p < 0.05$)

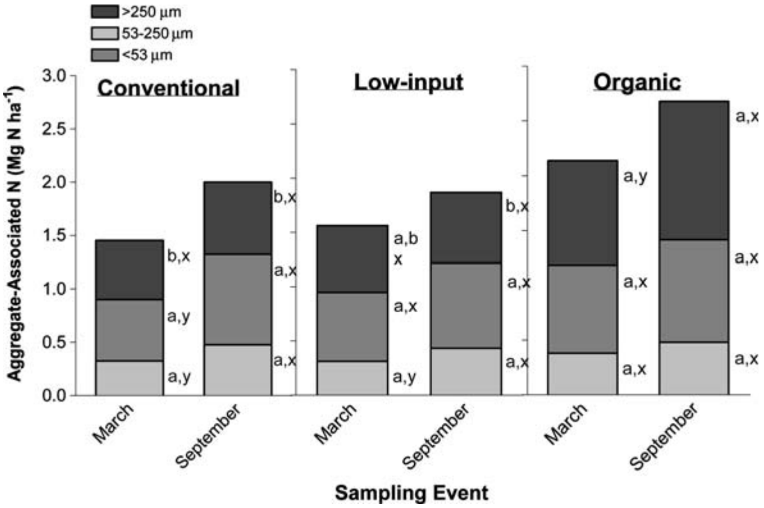

Fig. 2 Aggregate associated-N for the conventional, low-input, and organic maize–tomato cropping systems at the March (first) and September (last) soil sampling events, during the 2004 maize season at the Center for Integrated Farming Systems site (Davis, CA, USA). Values with letters ‘*a* and *b*’ indicate significant differences ($p < 0.05$) among cropping systems, for one sampling event. Within a cropping system, values shown with letters ‘*x* and *y*’ are significantly different between the first and last sampling events ($p < 0.05$)

ping systems were not different (Table 3). However, mean residence times of the N associated with the microaggregate and silt-and-clay fraction were greater in the organic and low-input systems than in the conventional system ($p < 0.05$; Table 3). The mean residence times of the aggregate-associated N within each cropping system generally decreased in the following order: macroaggregates > microaggregates > silt-and-clay fraction (Table 3). Only the low-input rotation diverged from this expected trend, as the mean residence time of the macroaggregates was the lowest, but not significantly different from the two other fractions.

Nitrous oxide emission measurements

A cropping system effect on N_2O–N emissions was found for two successive measurements taken after the second fertilization of the conventional plot. At the May gas sampling event, N_2O–N emissions from the conventional cropping system (8.3 g N ha^{-1} d^{-1}) were greater than fluxes from both the low-input (2 g N ha^{-1} d^{-1}) and organic (no N_2O–N flux) systems ($p < 0.05$; Fig. 4). When soil moisture content was included as a covariate, significantly greater N_2O–N fluxes were observed in the conventional system (14.5 g N ha^{-1} d^{-1}) than in the low-input (no N_2O–N flux) and

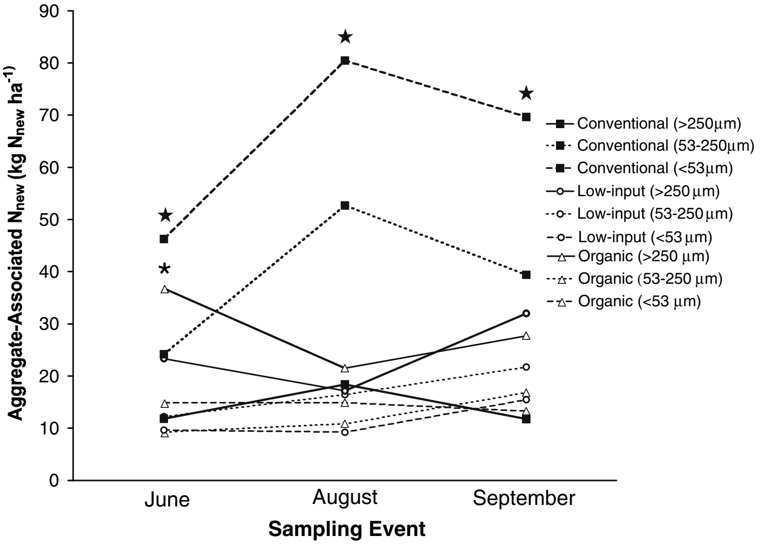

Fig. 3 Cover crop- and synthetic fertilizer-derived N (N_{new}) in the macroaggregate, microaggregate, and silt-and-clay fractions of the conventional, low-input, and organic maize–tomato cropping systems during the 2004 maize season at the Center for Integrated Farming Systems site (Davis, CA, USA). Data points with a '★' contained significantly greater N_{new} than the other fractions within one sampling event ($p < 0.05$). Data points with a '★' indicate significantly higher in N_{new} concentration in the organic cropping system than the low-input cropping system, within a sampling event ($p < 0.05$)

Table 3 Mean residence times of aggregate-N within the conventional, low-input, and organic maize–tomato cropping systems

Cropping system	Mean residence time (months)		
	Macroaggregate (>250 μm)	Microaggregate (53–250 μm)	Silt-and-clay (< 53 μm)
Conventional	$24.1^{a,x}$	$9.30^{b,y}$	$2.61^{b,y}$
Low-input	$9.61^{a,x}$	$17.4^{a,b,x}$	$14.5^{a,x}$
Organic	$31.9^{a,x}$	$31.8^{a,x}$	$18.3^{a,x}$

Values with letters 'a and b' are significantly different among the cropping systems ($p < 0.05$). The mean residence times within a cropping system, shown with letters 'x and y', indicate a significant difference for values among aggregate fractions, within a cropping system ($p < 0.05$)

organic (0.6 g N ha^{-1} d^{-1}) systems at the June sampling event ($p < 0.05$; Fig. 4). With a cumulative N_2O–N emission of 453.9 g N Mg N^{-1} (normalized with the soil N level of the cropping system), the conventional rotation showed the highest flux of N_2O–N in comparison to the low-input (255.1 g N Mg N^{-1}) and organic (102.6 g N Mg N^{-1}) systems. Although greater than the organic system, cumulative N_2O–N fluxes from the conventional and low-input systems were not different ($p < 0.05$; data not shown).

Whole soil carbon and nitrogen sequestration

At the first soil sampling event, both the SOC and soil N concentrations of the organic system (20.2 Mg SOC ha^{-1} and 2.15 Mg N ha^{-1}) were greater than SOC and soil N levels in the conventional (15.6 Mg SOC ha^{-1} and 1.49 Mg N ha^{-1}) and low-input systems (15.3 Mg SOC ha^{-1} and 1.49 Mg N ha^{-1}) ($p < 0.1$ and $p = 0.01$ for SOC and soil N comparisons, respectively; see Table 4 for soil N values only). Moreover,

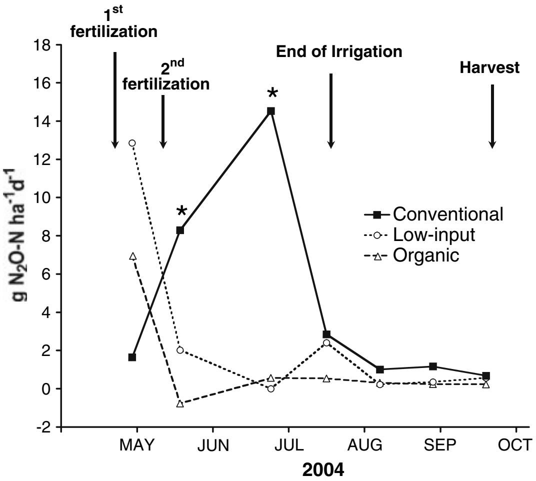

Fig. 4 Effects of cropping management on nitrous oxide (N_2O–N) emissions from the conventional, low-input, and organic maize–tomato rotations at the Center for Integrated Farming Systems site (Davis, CA, USA). Arrows indicate approximate timing of fertilization events, the termination of irrigation, and the maize harvest. The N_2O–N fluxes paired with a '*' were significantly higher among the cropping systems, within that sampling event ($p < 0.05$)

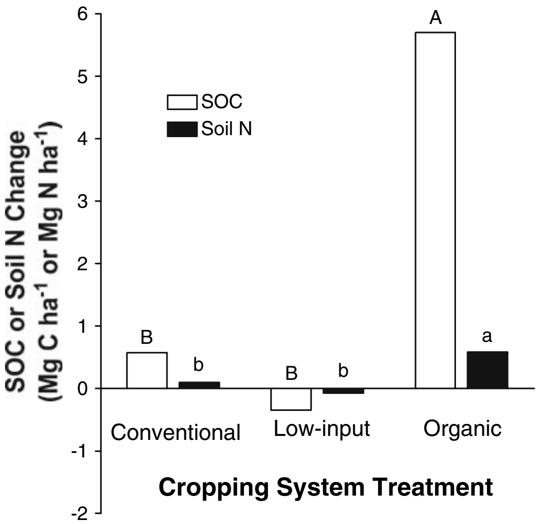

Fig. 5 Soil organic carbon (SOC) and soil nitrogen (N) sequestered in the conventional, low-input, and organic maize–tomato cropping systems at the Center for Integrated Farming Systems site (Davis, CA, USA) after 11 years of crop management. Data bars with different capitalized letters refer to significant differences between the amount of SOC sequestered ($p < 0.1$), while data bars with different lowercase letters refer to significant differences between the amount of soil N sequestered ($p < 0.1$)

after 11 years of continuous crop management, soil N sequestration in the organic rotation (590 kg N ha^{-1}, as measured at the first soil sampling event) was greater than soil N sequestration in the conventional and low-input rotations (100 and –70 kg N ha^{-1}, respectively; $p < 0.05$; Fig. 5). The amount of SOC sequestered in the organic system (5.70 Mg SOC ha^{-1}) was also greater than the SOC sequestered by the conventional and low-input systems (570 and –340 kg SOC ha^{-1}, respectively), at the $p < 0.1$ significance level (Fig. 5). No differences in the SOC and soil N stocks of the conventional and low-input cropping systems were found after 11 years of crop management (Fig. 5). Despite changes in SOM levels in the cropping systems, no significant fluctuations in bulk density were measured (data not shown); hence, the calculation of SOC and soil N concentrations on an area basis were not affected by the effect of changes in SOM on bulk density.

Table 4 Whole soil N and N_{new} concentrations at the March (first) and September (last) soil sampling events in 2004, for the conventional, low-input, and organic maize–tomato cropping systems (0–15 cm) at the Center for Integrated Farming Systems site (Davis, CA, USA)

Cropping system	Soil sampling event		
	March Total N (Mg ha^{-1})	September Total N (Mg ha^{-1})	September N_{new} (kg ha^{-1})
Conventional	$1.49^{b,y}$	$2.07^{b,x}$	$190^{a,x}$
Low-input	$1.49^{b,x}$	$1.89^{b,x}$	$80^{a,x}$
Organic	$2.15^{a,y}$	$2.65^{a,x}$	$50^{a,x}$

Values with letters 'a and b', within one sampling event and N component, indicate significant difference among the cropping systems ($p < 0.05$). Total N and Nnew values shown with letters 'x and y', indicate a significant difference for values between the two sampling events ($p < 0.05$)

Whole system ^{15}N recovery

At the end of the growing season, less fertilizer-derived N was recovered in the whole soil of the conventional (36.5% ^{15}N recovery) than in the low-input and organic systems (90.0% and 83.8% ^{15}N recovery, respectively) ($p < 0.05$; Table 2). Cumulative recoveries of the fertilizer or cover crop-derived N in the conventional, low-input, and organic systems (i.e., ^{15}N recovery in above-ground maize biomass plus whole soil) were 44.2%, 98.9%, and 92.5% ^{15}N recovery, respectively.

Discussion

Soil organic nitrogen flows as governed by aggregate dynamics

Tisdall and Oades (1982) presented a hierarchical model, which suggested that classes of organic matter (e.g., persistent, transient, and temporary) are associated with different physical soil fractions. One outcome from this aggregate hierarchy is that SOM-C concentration increases with increasing aggregate-size class because large aggregate-size classes are composed of small aggregate-size classes plus organic binding agents (Elliott 1986). The macroaggregate fraction has been shown to be sensitive and responsive to management, with the breakdown of this fraction resulting in the release of labile SOM (Elliott 1986; Six et al. 2000). Therefore, it was not surprising that a majority of changes in aggregate-associated SOM-N in this study were observed in the macroaggregates. In contrast, the lack of change in the levels of soil N associated with the microaggregates and silt-and-clay fractions, between the beginning and end of the season, for the three cropping systems reflects the lower capacity for N retention and nutrient supply of these smaller fractions.

As hypothesized, mean residence times of the aggregate fractions were generally shortest in the conventional, intermediate in the low-input, and longest in the organic system (Table 3). Our data suggest that synthetic fertilizer-N input led to faster turnover of the silt-and-clay fraction in the conventional system in comparison to the low-input and organic rotations, where incorporation of the ^{15}N-labeled cover crop generally resulted in longer mean residence times (i.e., greater stabilization) of the residue within all aggregate fractions. The substantial concentration of synthetic fertilizer–^{15}N recovered in the silt-and-clay fraction of the conventional system, suggested that the synthetic N moved easily through the soil and that N, not lost from top 15-cm of the soil profile, was retained only by interaction with silt-and-clay particles. In contrast to the conventional system, the potential for soil N stabilization was greater in the low-input and organic systems as the majority of the cover crop-N in the low-input and organic systems was stored in the macroaggregate fraction. We expected rates of incorporation of the ^{15}N-labeled cover crop into the aggregate fractions of the organic system to be slower than into the low-input system due to comparatively greater whole SOC and soil N levels in the organic system, yet incorporation rates were similar between these two alternative systems (Fig. 3).

Although the mean residence times of the aggregates associated with the low-input and organic systems were not significantly different, the trends observed for N stabilization and flow through aggregates in the conventional, low-input, and organic systems showed that N turnover was generally fastest in aggregates of the conventional system, intermediate in the low-input system, and slowest in the organic system. This corroborated our hypothesis that the alternating applications of synthetic fertilizer and organic amendments to the low-input system would induce an intermediate level of aggregate-associated N turnover (i.e., mean residence time) relative to conventional and organic cropping systems.

^{15}N use efficiency

Earlier studies have shown that crops take up a greater proportion of N from synthetic fertilizer than from cover crop-derived N (Ladd and Amato 1986; Bremer and van Kessel 1992; Harris et al. 1994). The greater N_{new} concentration in the grain of the conventional rotation than in the low-input and organic grain appears to corroborate earlier findings that N from the synthetic fertilizer is more plant-available than N derived from the cover crop. However, NUE values for the aboveground maize biomass were similar in all three cropping systems (Table 2). Consequently, our hypothesis that the intermediate aggregate turnover in the low-input system would lead to greater N use efficiency was not corroborated. Our finding is in agreement with other long-term studies that found comparable NUE from organic or synthetic ^{15}N sources across conventional, legume, and manure-based cropping systems (Harris et al. 1994; Glendining et al. 1997; Kramer et al. 2002b). Also, several researchers have shown that the growth and incorporation of annual legumes can unequivocally provide adequate N for subsequent cash crops under conventional tillage regimes (Mitchell and Teel 1977; Touchton et al. 1984; Sarrantonio and Scott 1988; Stivers and Shennan 1991; Drinkwater et al. 1998). Furthermore, recent meta-analyses, which compared crop yields between conventionally managed systems and those using cover crops, found that yields (i) increased due to leguminous cover crop-N in the absence of synthetic fertilizer-N (Miguez and Bollero 2005) or (ii) were not different between conventional systems and systems with cover crop management, under certain levels of leguminous cover crop-N (Tonitto et al. 2006). The similar grain-N contents of the three cropping systems in this study, despite the low plant-availability of the cover crop-N in the low-input and organic systems, suggest that the soil N pool was supplementing plant-available N in both the low-input and organic systems.

Losses of fertilizer and cover crop-derived N

The large N_2O fluxes measured shortly after the second fertilization event of the conventional system (Fig. 4) suggest that synthetic fertilizer N is an important driver of N_2O–N efflux and corroborate results from studies that found the input of chemical fertilizers to agricultural soils to be an important source of N_2O (van Kessel et al. 1993; Kroeze et al. 1999; Akiyama et al. 2004). Our results show that synthetic fertilizer N was not stabilized within the soil matrix, which led to low mean residence times across the different aggregate fractions. It is likely that the synthetic N not stabilized in the soil served to stimulate the microbial-driven processes of nitrification and denitrification, during this hot (~35–43°C) and heavily irrigated period, which can lead to elevated N_2O production. Moreover, the cumulative N_2O effluxes from each rotation (normalized for soil N concentration) logically correspond to the average mean residence time of the aggregate fractions of each cropping rotation (i.e., shorter mean residence time, higher cumulative N_2O fluxes). However, inherent variability associated with trace gas flux measurements may have reduced our ability to detect differences both among cumulative N_2O–N fluxes and in mean comparisons of N_2O–N fluxes from cropping systems at each gas sampling time.

Similar to other studies (Ladd and Amato 1986; Clark et al. 1999; Kramer et al. 2002b), we found that the fate (i.e., N recovery) of the organic-N from the cover crop residues resided in the soil (i.e., 83–90% ^{15}N recovery), rather than in the maize crop. More specifically, cover crop-N was primarily protected from N losses within macroaggregates. The high recovery of the cover crop-N was likely because the cover crop was incorporated within the sampling depth as fresh, organic residue and had yet to undergo substantial decomposition during the period of this study. Unlike the aforementioned and studies reviewed in Seo et al. (2006), a majority of N inputs from the synthetic fertilizer in this study were not recovered in the maize crop. The significant proportion of synthetic fertilizer-N that was not recovered by either soil or maize in the conventional system (~55%) illustrates the inefficiency of this cropping system, as nearly half of the synthetic fertilizer N input was likely lost from the sampling profile (0–15 cm) as either leachate or volatile gas.

Crop management effects on carbon and nitrogen sequestration

Increased N fertilization has been correlated to increased SOC sequestration (Campbell et al. 1991; Dumanski et al. 1998), which can lead to better plant growth and increased crop productivity (Allison 1973). Despite receiving a relatively high N fertilization rate and producing the largest maize yields and vegetative biomass (i.e., greater maize stover returned to the system), the conventional system showed neither the greatest SOC nor soil N stocks of the three cropping systems after 11 years of cropping. This supports findings from recent studies showing that, while synthetic fertilizer-N may increase crop residue returns, N fertilization has a net negative effect on SOC sequestration (Omay et al. 1997; Halvorson et al. 2002; Russell et al. 2005). Moreover, our data imply that N-fertilizer type plays a role in long-term SOC and soil N sequestration. The conventional and organic systems both received high rates of N additions (280 kg N ha^{-1} yr^{-1} and 473 kg N ha^{-1} yr^{-1}, respectively), yet the organic system, where solely organic amendments were applied, sequestered disproportionately more SOC and soil N after 11 years of crop management. The greater long-term protection and stabilization of N derived from the cover crop within aggregate structures may have fostered the gradual accumulation of a large pool of soil N in the organic system compared to the conventional and low-input cropping systems. Clark et al. (1998) and Kramer et al. (2002a) showed that, over several seasons of alternative farm management, the gradual development of a slowly releasing soil N pool was notably beneficial to sustaining plant production while minimizing N losses to the environment.

The combined application of organic amendments and synthetic fertilizers in low-input cropping systems has been shown to contribute N from both N sources in temporally distinct patterns (Palm et al. 2001; Kramer et al. 2002a), which might lead to N synchrony. Finding a trend of greater PFP_N in the low-input system than in the other systems corroborates our hypothesis that the application of synthetic fertilizer-N in alternate years increases the total N use efficiency of the system in the short term. Yet, the similarity between the conventional and low-input systems with regards to whole soil-N concentrations, aggregate-N levels, and the amount of SOC and N sequestered after 11 years of continuous cropping, suggests that the use of synthetic fertilizers may have negated the positive, long-term effects of organic amendments on soil C and N sequestration. Palm et al. (2001) and others (e.g., Vanlauwe et al. 2002; Seo et al. 2006) have proposed that a system, where synthetic and organic resources are added in combination, can meet crop N needs and also conserve soil N. It has been pointed out that N immobilization due to an available C source (Sakala et al. 2000; Vanlauwe et al. 2002) prior to the peak in N demand by the plants, can be beneficial to plant productivity because it reduces N losses by leaching and/or denitrification (Robertson 1997; Scow 1997). Our findings suggest that more research is needed to elucidate the interaction between synthetic fertilizer-N, organic amendments, and aggregate-SOM dynamics, especially with regard to short-term plant N uptake versus long-term SOC and soil N stabilization in cropping systems.

Conclusions

This study has successfully shown that soil aggregate dynamics form a mechanistic linkage between fertilizer type, N uptake by crops, and long-term SOM stabilization in different cropping systems. The lack of difference in SOC and soil N sequestration between the conventional and low-input systems after 11 years of cropping implies that the use of synthetic fertilizers may have decreased the positive, long-term impact of organic amendments on SOC and soil N sequestration. Our hypothesis that the low-input management practice results in an intermediate level of aggregate-N turnover relative to conventional and organic cropping systems was corroborated. However, our hypothesis that the intermediate level of aggregate-N turnover in the low-input rotation leads to the greatest N use efficiency of the three systems was not corroborated. Nevertheless, the low-input system showed the greatest PFP_N value, which suggests that alternating applications of synthetic-N may improve total N use efficiency. Similar NUE values in aboveground biomass among the three cropping systems, coupled with the short mean residence times of the synthetic fertilizer-N in the silt-and-clay fraction and the trend of higher cumulative N_2O–N fluxes in the conventional system, indicate that the greater grain-N_{new} in the conventional system likely occurred due to rapid aggregate-N cycling and at the expense of greater N loss to the environment in comparison to the alternative cropping systems. These results illustrate how nutrient management practices dictate the tradeoffs among long-term SOM stabilization, N availability for plant uptake, and N susceptibility to loss.

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