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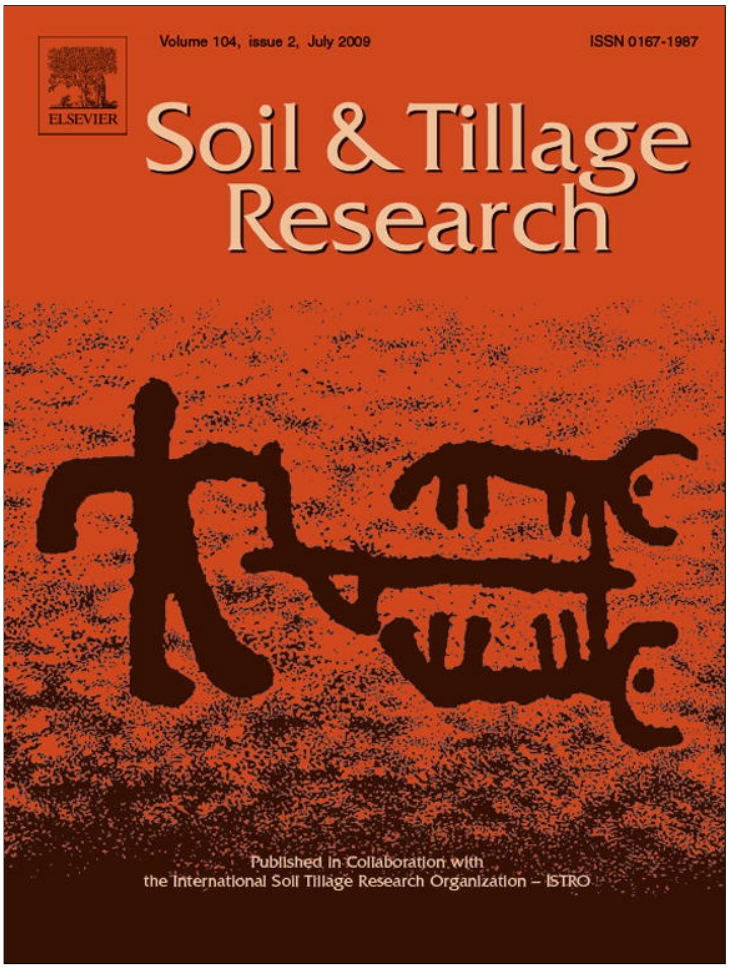

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Transitioning from standard to minimum tillage: Trade-offs between soil organic matter stabilization, nitrous oxide emissions, and N availability in irrigated cropping systems

Angela Y.Y. Kong *, Steven J. Fonte, Chris van Kessel, Johan Six

Department of Plant Sciences, University of California, Davis, One Shields Avenue, Davis, CA 95616, USA

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ABSTRACT

Few studies address nutrient cycling during the transition period (e.g., 1–4 years following conversion) from standard to some form of conservation tillage. This study compares the influence of minimum versus standard tillage on changes in soil nitrogen (N) stabilization, nitrous oxide (N_2O) emissions, short-term N cycling, and crop N use efficiency 1 year after tillage conversion in conventional (i.e., synthetic fertilizer-N only), low-input (i.e., alternating annual synthetic fertilizer- and cover crop-N), and organic (i.e., manure- and cover crop-N) irrigated, maize–tomato systems in California. To understand the mechanisms governing N cycling in these systems, we traced ^{15}N-labeled fertilizer/cover crop into the maize grain, whole soil, and three soil fractions: macroaggregates (>250 μm), microaggregates (53–250 μm) and silt-and-clay (<53 μm). We found a cropping system effect on soil N_{new} (i.e., N derived from ^{15}N-fertilizer or -^{15}N-cover crop), with 173 kg N_{new} ha^{-1} in the conventional system compared to 71.6 and 69.2 kg N_{new} ha^{-1} in the low-input and organic systems, respectively. In the conventional system, more N_{new} was found in the microaggregate and silt-and-clay fractions, whereas, the N_{new} of the organic and low-input systems resided mainly in the macroaggregates. Even though no effect of tillage was found on soil aggregation, the minimum tillage systems showed greater soil fraction-N_{new} than the standard tillage systems, suggesting greater potential for N stabilization under minimum tillage. Grain-N_{new} was also higher in the minimum versus standard tillage systems. Nevertheless, minimum tillage led to the greatest N_2O emissions (39.5 g N_2O–N ha^{-1} day^{-1}) from the conventional cropping system, where N turnover was already the fastest among the cropping systems. In contrast, minimum tillage combined with the low-input system (which received the least N ha^{-1}) produced intermediate N_2O emissions, soil N stabilization, and crop N use efficiency. Although total soil N did not change after 1 year of conversion from standard to minimum tillage, our use of stable isotopes permitted the early detection of interactive effects between tillage regimes and cropping systems that determine the trade-offs among N stabilization, N_2O emissions, and N availability.

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1. Introduction

Adoption of conservation tillage practices, which include no-tillage and several forms of reduced/minimum tillage, is a means to increase soil organic matter (SOM), mitigate CO_2 emissions, and partly address the mounting environmental problems associated with modern agricultural practices. Despite a 300% increase in the implementation of conservation tillage across the Midwest and in other parts of the U.S., conservation tillage is practiced on less than 0.3% of California farmlands (Mitchell et al., 2000). The slow adoption of minimum tillage by Californian growers may be related to the sparse information surrounding the many variants of reduced tillage that are practiced on the myriad of crop types grown under mostly irrigated conditions in California [e.g., coastal vegetables: Jackson et al. (2004), Sacramento Valley rice (*Oryza sativa* L.): Linquist et al. (2008), San Joaquin Valley cotton (*Gossypium* spp.)-tomatoes (*Lycopersicum esculentum* L.): Veenstra et al. (2007) and Mitchell et al. (2008)].

Reluctance among growers to adopt conservation tillage stems partly from the chance that conservation tillage can alter both crop demand for N, due to changes in yield potential, as well as the N supply, due to changes in N cycling and losses. According to Pekrun et al. (2003), net N immobilization can occur with slow SOM turnover during the transition period from standard to conservation tillage. Peigné et al. (2007) suggests that N availability for crops is lower under conservation tillage than under standard tillage. Moreover, others have found that higher inorganic fertilizer rates can be beneficial to crop N uptake during a transition period

* Corresponding author. Tel.: +1 530 752 6309; fax: +1 530 752 4361.
E-mail address: aykong@ucdavis.edu (Angela Y.Y. Kong).

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from standard to minimum tillage to account for lower N mineralization rates (Franzluebbers et al., 1995; Malhi et al., 2001).

Clark et al. (1998) found that cropping systems which combined decreased levels of synthetic N fertilizer with organic N inputs were more efficient at storing excess N than conventional systems. Management that combines synthetic fertilizer and organic N inputs may also synchronize N availability with crop N uptake better, which can lead to more optimal yields (Kramer et al., 2002). Recently, it has been shown that combining reduced tillage with organic and low-input cropping management has synergistic effects on nutrient cycling and availability, leading to crop yields that are comparable to conventionally managed systems (Drinkwater et al., 2000; Veenstra et al., 2007). Hence, more research exploring the full potential benefits of merging reduced tillage practices and alternative crop nutrient management to optimize yields and reduce negative effects on the environment is needed.

Our aim in this study was to test the hypothesis that tillage reduction in conjunction with the joint application of synthetic fertilizer-N and organic amendments in an irrigated, low-input cropping system would establish an optimal balance between SOM stabilization, N_2O flux, and N-availability for crop nutrient uptake (i.e., greater C sequestration, lower N_2O emissions, and N availability synchronized with crop N needs).

The specific objectives of this study were to: (1) assess at the whole cropping system scale how tillage and cropping system management (conventional, low-input, and organic) interact to influence N stabilization and loss and (2) use a soil physical fractionation approach to elucidate the underlying mechanisms of short-term N cycling during the early transition stage from standard to minimum tillage in irrigated cropping systems.

2. Materials and methods

2.1. Experimental study site and treatments

Our field study took place at the Russell Ranch experimental site (Davis, CA, USA; 38°32′24″N 121°52′12″W), which is located in a region with a Mediterranean climate regime, characterized by wet winters and hot, dry summers. Two soil types are found at the site: (i) Yolo silt loam (fine-silty, mixed, nonacid, thermic Typic Xerorthent) and (ii) Rincon silty clay loam (fine, montmorillonitic, thermic Mollic Haploxeralf). Three maize-tomato (*Zea mays* L.–*L. esculentum* L.) cropping systems ($n = 3$), which varied in nutrient inputs, were selected for this study: *conventional* (annual synthetic N fertilizer applications), *low-input* (synthetic N fertilizer applied in alternate years with cover crop-N incorporated the years without synthetic N fertilization) and *organic* (annual addition of composted manure- and cover crop-N). Since 1993, all cropping systems at the Russell Ranch were under standard tillage. In the spring of 2003, each maize-tomato cropping system plot (0.4 ha) was split down the center into two tillage regimes: *standard* (12–15 tractor passes) and *minimum* (5–10 tractor passes; see Table 1). The experiment was designed as a completely randomized-split plot, with the main plot as cropping system and tillage as the subplot. One experimental plot (1.5 m × 1.0 m) was established in each tillage regime, within each cropping system, for a total of 18 experimental plots in which our study took place.

2.2. Stable isotopic labeling plus crop management practices

From January through March 2004, *Vicia dasycarpa* and *Pisum sativum* plants (i.e., legume cover crop) were grown under greenhouse conditions and labeled with 99 at.% $(^{15}NH_4)_2SO_4$. On April 16, composted manure was incorporated into the organic cropping system at a rate of 373 kg N ha^{-1} and, subsequently, the ^{15}N-labeled above- and belowground biomass of the greenhouse-grown legume cover crop was manually incorporated into experimental plots in both the low-input and organic systems (100 kg N dry weight ha^{-1}; 7.34 kg ^{15}N dry weight ha^{-1}). Maize was direct-seeded into the low-input and organic cropping systems in early May. Within the experimental plots, six rows of maize were planted 25 cm apart.

Maize was direct-seeded into the conventional plots in mid-March (at the same density as the low-input and organic systems), following an herbicide application. Shortly after, experimental plots in the conventional systems received two separate bed-top applications of urea mixed with $(^{15}NH_4)_2SO_4$ (99 at.%). The first fertilization, applied on April 22 as urea–N in solution with a phosphorus–potassium starter fertilizer at a rate of 60 kg N ha^{-1} (3.91 kg ^{15}N ha^{-1}), and the second fertilization, an application of 220 kg urea–N ha^{-1} (13.0 kg ^{15}N ha^{-1}) on May 12, yielded an overall fertilization of ~6.5 at.% ^{15}N.

Throughout the maize growing season, the plots were furrow-irrigated and simulations of field cultivation were done by hand within the experimental plots. After harvest, the maize stover was returned to each system. With the exception of applying a solution form of the fertilizer to the surface of the experimental plots in the conventional cropping system, all field operations on the experimental plots mirrored those taking place at the field-scale.

2.3. Soil and crop sample collection and processing

Soil samples (4 cm diameter; 0–15 cm) were collected at maize harvest (September 21). Two soil cores, one from the center and one immediately adjacent to a maize plant, were obtained from each of the experimental plots. Upon return to the laboratory, soil cores were weighed, composited, and sub-samples were taken for determination of moisture content and bulk density. The remaining soil was 8 mm sieved, air-dried, and then fractionated by wet

Table 1
Description of standard and minimum tillage practices across conventional (CONV), low-input, and organic cropping systems. A check mark indicates a separate instance of each tillage operation during the 2004 maize growing season.

Operation	Standard tillage			Minimum tillage		
	CONV	Low-input	Organic	CONV	Low-input	Organic
Bed disc	✓✓✓	✓✓✓✓✓	✓✓✓✓✓		✓✓	✓✓
Rip beds	✓	✓	✓			
Shape beds	✓	✓	✓	✓		
Landplane	✓✓	✓✓	✓✓			
List beds	✓	✓	✓	✓✓✓✓	✓✓✓✓✓	✓✓✓✓✓
Roll beds	✓	✓✓	✓✓		✓	✓
Perfecta	✓	✓✓	✓			
Mulch beds		✓	✓			
Cultivate	✓✓		✓			✓✓
Total number of tractor passes for tillage	12	15	15	5	8	10

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sieving into three aggregate size classes [macroaggregates (>250 μm), microaggregates (53–250 μm), and silt-and-clay (<53 μm)] according to Elliott (1986). Briefly, 80 g air-dried soil samples were submerged in deionized water on top of a 250 μm sieve for 5 min, effectively slaking the soil (Kemper et al., 1985). Water-stable aggregates were separated by moving the sieve in an up-and-down motion 50 times over a period of 2 min. The material remaining on the 250 μm sieve (macroaggregates) was backwashed into an aluminum pan. The soil–water solution that passed through the 250 μm sieve was transferred onto a 53 μm sieve and wet-sieved, according to the procedure outlined above, to separate the microaggregates (material remaining on the 53 μm sieve) from the silt-and-clay fraction. The three aggregate fractions produced from the wet sieving were oven-dried at 50 °C in aluminum pans and then stored for analysis. Mean weight diameter (MWD) was used as an index of aggregate stability and was calculated by summing the weighted proportion of each aggregate fraction obtained from a whole soil sample.

On September 21, maize plants (grain and vegetative biomass) were harvested from the experimental plots, weighed, and oven-dried at 50 °C. Maize grain and vegetative biomass were later subsampled for elemental and isotopic N measurements.

2.4. Nitrous oxide sampling and measurement

After maize seeds were sown, 20.3 cm diameter polyvinylchloride (PVC) rings (15 cm tall) were installed to a depth of 10 cm at the northern end of each experimental plot, equidistant between the maize rows. Nitrous oxide (N_2O) fluxes were measured at 3-week intervals, starting at the first fertilization event (mid-March) until the maize harvest (late September), using closed chambers modeled after the design by Hutchinson and Mosier (1981). 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 and then stored in 10 mL Exetainers (Labco, Inc.) for later analyses with a Hewlett Packard 6890 Series Gas Chromatograph (Palo Alto, CA). 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. Nitrous oxide-N flux rates 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 basis.

2.5. Elemental and isotopic N analyses

Sub-samples of whole soil, aggregate fractions, grain, and vegetative maize biomass were ground and analyzed for elemental and isotopic N concentrations using a PDZ Europa Integra C-N isotope ratio mass spectrometer (Integra, Germany). The proportion of soil N derived from ^{15}N-labeled cover crop or ^{15}N-labeled synthetic fertilizer (f) was calculated using the equation:

$$f = \frac{{}^{15}N_{sample} - {}^{15}N_{natural\ \ abundance}}{{}^{15}N_{labeled\ \ material} - {}^{15}N_{natural\ \ abundance}} \quad (1)$$

where $^{15}N_{sample}$ = ^{15}N atom% for the sample of interest, $^{15}N_{labeled\ material}$ = ^{15}N atom% of cover crop or synthetic fertilizer, $^{15}N_{natural\ abundance}$ = ^{15}N atom% of the equivalent sample taken before the addition of ^{15}N material. Total N concentrations were multiplied by f to obtain the concentration of N derived from the ^{15}N-labeled fertilizer or cover crop-^{15}N (N_{new}). All elemental and isotopic N measurements for the soil samples were converted to an area (m^2) basis using bulk density measurements. Nitrogen use efficiency (NUE) of the maize 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.

Mean residence times (MRT) of soil N were calculated by taking the reciprocal of the estimated rate constant (k), obtained from the following first-order decay equation:

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

where A_t = 1 − proportion of N_{new} of the soil sample, A_0 = 1 − proportion of N_{new} immediately before ^{15}N incorporation (i.e., zero), k = decay rate constant, and t = time between the 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; see Kong et al., 2007 for further details about the MRT calculations].

2.6. Statistical analyses

Whole soil N_{new}, mean weight diameter, aggregate N_{new}, NUE, and N_2O emission measurements among the three cropping systems were analyzed using analysis of variance (ANOVA) for a split-plot, completely randomized design by the PROC MIXED procedure of the Statistical Analysis System (SAS; SAS Institute, 2002). Differences between means were calculated based on least significant difference tests, with the PDIFF option of the LSMEANS statement. All differences discussed were significant at the $p < 0.05$ probability level, unless otherwise stated.

3. Results and discussion

3.1. Stabilization of whole soil N_{new}

By measuring soil N 6 years after conservation tillage adoption, Wright et al. (2008) estimated ~4% annual increase in soil N due to tillage reduction. In the current study, after 1 year of transitioning from standard to minimum tillage, there were no differences in soil N levels between the different tillage systems (Table 2). Nor did we detect interactive effects between cropping system and tillage on total soil N. Our results were similar to those of McCarty et al. (1998) who also found that total C and N pools in the surface soils

Table 2
Total soil organic carbon (C), nitrogen (N), and aggregate stability (shown as mean weight diameter) values for the conventional, low-input, and organic cropping systems. Mean weight diameter and grain yield values followed by a different letter, within one column, are significantly different between cropping systems ($p < 0.05$). Values of soil organic C and N followed by a different uppercase letter are significantly different than the other cropping systems in that column.

Cropping system	Standard tillage				Minimum tillage			
	Mg C ha^{-1}	Mg N ha^{-1}	Mean weight diameter (mm)	Grain yield (Mg ha^{-1})	Mg C ha^{-1}	Mg N ha^{-1}	Mean weight diameter (mm)	Grain yield (Mg ha^{-1})
Conventional	18.6^{B}	2.08^{Y}	1.35^{x}	13.6^{a}	18.6^{B}	2.12^{Y}	1.35^{x}	9.25^{a}
Low-input	18.2^{B}	1.89^{Y}	1.24^{x}	4.14^{b}	17.5^{B}	1.84^{Y}	1.17^{x}	6.70^{b}
Organic	23.6^{A}	2.65^{X}	1.76^{x}	4.76^{b}	22.9^{A}	2.57^{X}	1.69^{x}	6.73^{b}

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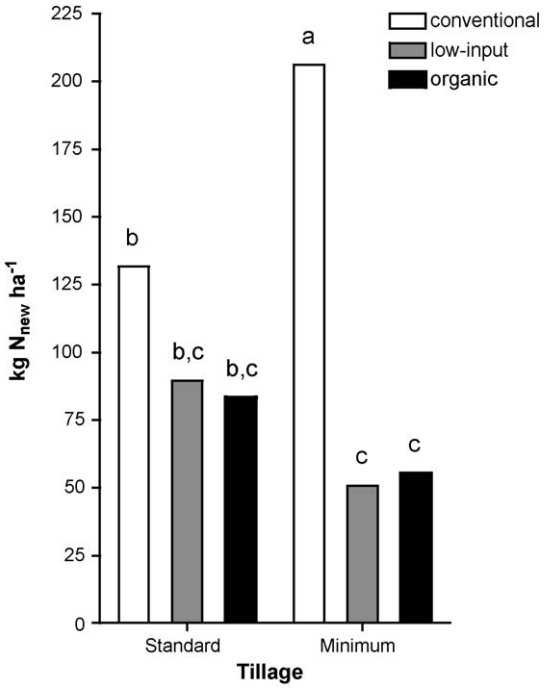

Fig. 1. Soil nitrogen derived from ^{15}N-labeled cover crop (in the low-input and organic cropping systems) or ^{15}N-labeled synthetic fertilizer (in the conventional cropping system; N_{new}) under minimum and standard tillage. Means with different letters are significantly different ($p < 0.05$).

did not respond rapidly to the transition from standard to conservation tillage.

Although there were no significant differences in total soil N, we found differences in soil N_{new} levels among cropping systems as well as a tillage × cropping system interaction ($p < 0.1$; Fig. 1). Both standard and minimum tillage in the conventional system received nearly 2.3 times more ^{15}N inputs compared to the low-input and organic systems under the respective tillage regimes, yet the conventional-minimum tillage (214.7 kg N_{new} ha^{-1}) and conventional-standard tillage systems (131.2 kg N_{new} ha^{-1}) had 77% and 31% greater N_{new} than their low-input and organic system counterparts, respectively. In addition, 1 year after tillage conversion, minimum tillage showed higher N_{new} compared to its standard tillage counterpart in the conventional system. The latter agrees with many studies that have evaluated the effect of tillage on N cycling and have concluded that higher N mineralization is associated with no-tillage compared to standard tillage (e.g., Doran, 1987; Kandeler et al., 1999; Kristensen et al., 2000).

However, N_{new} (i.e., cover crop-derived N) in the low-input and organic systems were not affected by tillage reduction. Among the three cropping systems, the relative reduction of tillage operations from standard to minimum tillage was greatest in the conventional system, intermediate in the low-input and lowest in the organic system (Table 1). The disparities in the degree to which tillage operations were reduced could have been a factor in how tillage reduction affected N_{new} levels in the cropping systems. Additionally, differences in N mineralization may have caused the observed differences in tillage effects on N_{new} among the cropping systems. Many studies have shown that differences in biochemical characteristics of soil amendments can lead to differences in N mineralization (e.g., Herman et al., 1977; Vanlauwe et al., 1996). Therefore, differences in N input quality as well as in quantity between the synthetic-N fertilizer applied to the conventional system and the cover crop residue-N incorporated into the low-input and organic systems may have led to differences in N mineralization and how tillage affected soil N_{new} among the cropping systems.

3.2. Fertilizer- or cover crop-derived grain-N and N use efficiency

No effect of tillage was found on maize grain yield (Table 2), whereas, grain-N_{new} was higher in the minimum than in the standard tillage systems (11.9 and 5.01 kg N_{new} ha^{-1}, respectively), with the highest grain-N_{new} observed in the minimum tillage-conventional cropping system (25.8 kg N_{new} ha^{-1}). Nitrogen use efficiency (NUE) of aboveground biomass (i.e., grain + vegetative biomass) was also higher under minimum than standard tillage (Fig. 2). Moreover, we found a significant tillage × cropping system effect on NUE, in which NUE for the conventional-minimum tillage system was the highest (18.0%), whilst NUE for the conventional-standard tillage system was the lowest (5.7%; Fig. 2). The latter suggests that tillage reduction can enhance maize NUE in conventional N management systems. In contrast, NUE's for the minimum and standard tillage regimes of the low-input and organic systems were not different, indicating that the rate of decomposition of organic N amendments, compared to the availability of synthetic-N fertilizers for plant uptake, might be less affected by tillage reduction. Our data agree with findings that crop NUE in conservation tillage systems are the same or higher compared to standard tillage systems (Habtegebrial et al., 2007; Teal et al., 2007).

Total N recovery (soil + grain + vegetative biomass) in the standard and minimum tillage systems averaged 83% and 74%, respectively. This indicates that a large majority of the ^{15}N applied to the experimental plots was recovered. The N that could not be accounted for might have leached past the 15 cm sampling depth or was lost via volatilization.

3.3. Aggregate-N_{new} accumulation

Soil aggregation was greatest in the organic system and lowest in the conventional system (Table 2). However, the differences in aggregation across the cropping systems were not likely a direct

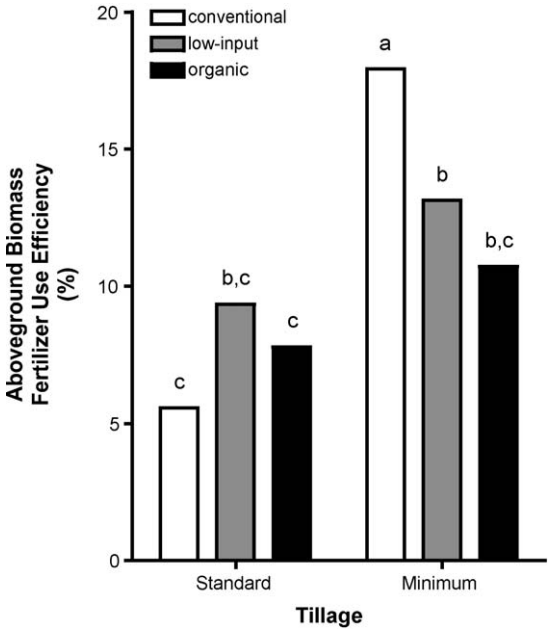

Fig. 2. Nitrogen use efficiency (NUE) in aboveground maize biomass (grain + vegetative biomass) collected at harvest from the conventional, low-input, and organic cropping systems under both standard and minimum tillage. Means with different letters are significantly different at the $p < 0.05$ level.

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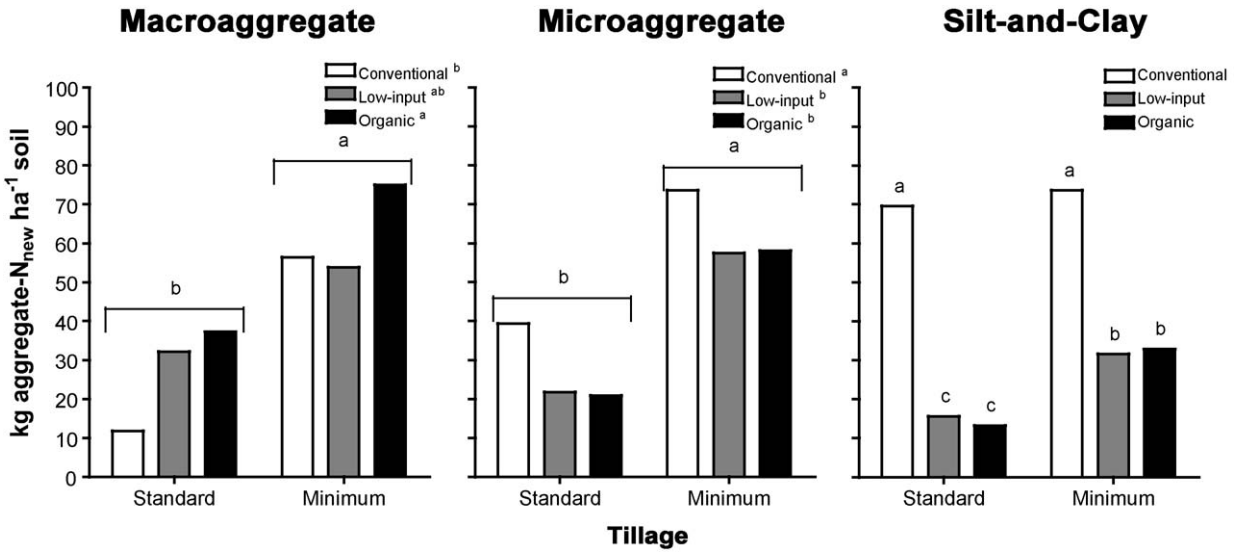

Fig. 3. Cover crop- and synthetic fertilizer-derived ^{15}N (N_{new}) in the macroaggregate (>250 μm), microaggregate (53–250 μm), and silt-and-clay (<53 μm) fractions of the conventional, low-input, and organic cropping systems under standard and minimum tillage regimes. Groupings with different letters, within a soil fraction, indicate significant differences between tillage regimes ($p < 0.05$), while differences among cropping systems are indicated with different letters in the legends for each panel in the graph. Differences due to a significant tillage × cropping system effect were only found in the silt-and-clay fraction and are indicated by different letters above the means.

result of the experimental manipulations employed in this study, but are attributed to long-term, continuous crop management (see Kong et al., 2005). Aggregation did not differ between the minimum and standard tillage systems, contrary to results from other studies that found increased SOM and reduced soil disturbance in no-tillage systems promote soil aggregation through the enhanced binding of soil particles (Puget et al., 1995; Jastrow, 1996). The lack of differences in aggregation between the minimum and standard tillage regimes is not surprising as the measurements were taken only 1 year after the transition to minimum tillage.

Recoveries of fertilizer- or cover crop-derived N in the macro- and microaggregates were greater under minimum than standard tillage (Fig. 3). Macroaggregate- and microaggregate-N_{new} (61.8 and 63.0 N_{new} ha^{-1}) under minimum tillage were 56.0 and 56.6% higher than their standard tillage counterparts, respectively. Our data, taken 1 year after adoption of minimum tillage, agrees with other studies that have found that tillage reduction can increase SOM stabilization in aggregates, particularly macroaggregates (Beare et al., 1994) and more specifically microaggregates occluded within macroaggregates (Six et al., 1998). Also, a cropping system effect on N_{new} in the macro- and microaggregates was observed, while silt-and-clay-N_{new} showed a tillage × cropping system interaction (Fig. 3). With a greater concentration of fertilizer-^{15}N recovered predominantly in the silt-and-clay fraction of the conventional system compared to the low-input and organic systems (Fig. 3), it is probable that the synthetic N, not lost beyond the sampling depth, moved easily through the soil matrix and was retained by interaction primarily with silt-and-clay particles. Because accrual of organic matter in macroaggregates is crucial to SOM stabilization in cultivated soils (Beare et al., 1994; Six et al., 1998), the predominance of N_{new} in the silt-and-clay of the conventional system is not likely to be stabilized in the long-term.

3.4. Loss of N: nitrous oxide flux

At the peak of N_2O emissions during the May and June gas sampling events, differences were found both between tillage regimes and amongst the cropping systems (Fig. 4). In mid-May, the emissions were 28.9 g N_2O–N ha^{-1} day^{-1} or 43% greater in the minimum tillage than the standard tillage soils, averaged across the three cropping systems. At the June sampling event, the N_2O emissions measured from the minimum tillage-conventional system were the highest emissions recorded in the season (39.5 g N_2O–N ha^{-1} day^{-1}). Rochette (2008) attributed the higher rates of N_2O flux from minimum versus standard tillage to greater soil compaction, poor soil drainage, reduced gas diffusivity and air-filled porosity. The N_2O–N spikes, measured shortly after the second fertilization event in the conventional system, support findings that show excess synthetic fertilizer-N, along with sufficient soil moisture (via irrigation) in conservation tillage soils, usually lead to restricted aeration and higher denitrification rates than in conventionally tilled soils (Palma et al., 1997). After the cessation of irrigation, emissions from all the cropping system-tillage plots were similarly low, averaging <2.0 g N_2O–N ha^{-1} day^{-1}. Although conservation tillage has not been consistently shown to either increase or decrease N_2O fluxes

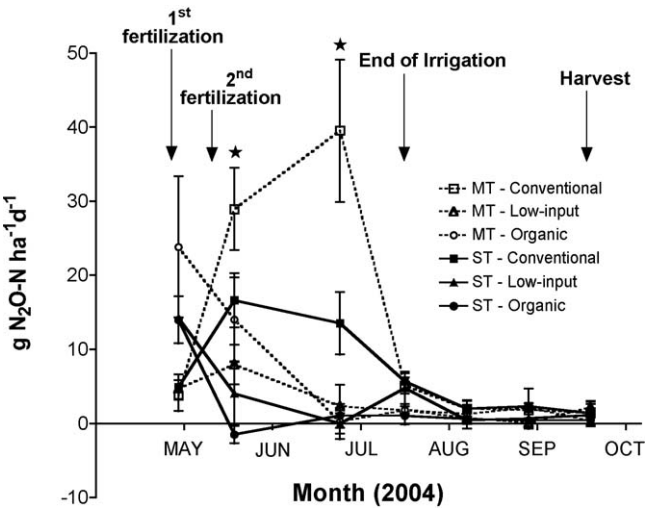

Fig. 4. Nitrous oxide (N_2O–N) emissions from the conventional, low-input, and organic rotations under standard (ST) and minimum tillage (MT), across the 2004 growing season. Arrows indicate approximate timing of fertilization events, termination of irrigation, and harvest. The N_2O–N fluxes paired with a '★' were the highest within that sampling event ($p < 0.05$).

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Table 3
Mean residence times of soil-N derived from ^{15}N-labeled synthetic fertilizer (in the conventional cropping system) or ^{15}N-labeled cover crop (in the low-input and organic cropping systems) under standard and minimum tillage. Different letters indicate significant differences at $p < 0.05$ among the cropping systems.

Cropping system	Mean residence time (years)	
	Standard tillage	Minimum tillage
Conventional	4.69[c]	3.35[c†]
Low-input	8.66[b]	17.0[b†]
Organic	15.0[a]	19.0[a†]

† Significant differences at $p < 0.1$ between tillage regimes.

compared to standard tillage, our data agree with those studies showing increased N_2O–N emissions due to tillage reduction (e.g., Baggs et al., 2003; Rochette et al., 2008). Even so, N_2O fluxes from minimum tillage observed in this study may be short-lived, as Six et al. (2004) concluded that increased N_2O emissions under no-tillage generally decrease after 10+ years of continued tillage reduction.

3.5. Trade-offs at the whole cropping system scale

We found that the high soil N_{new} and NUE (Figs. 1 and 2, respectively) measured in the conventional system, especially under minimum tillage, occurred despite the greater N_2O emissions from this cropping system. The conventional cropping system not only showed the fastest N turnover (Table 3) and more fertilizer-N incorporation into the less stable silt-and-clay fraction (Fig. 3), but also the highest N_2O fluxes among the three cropping systems (Fig. 4). It can be surmised that the greater N emissions were encouraged by the high N fertilization rates applied to the conventional system (280 kg N ha^{-1} year^{-1}) and that minimum tillage stimulated N cycling in this system, particularly crop N uptake and denitrification.

Contrastingly, long mean residence times of soil N, low N_2O–N fluxes, and lower NUE likely led to the organic cropping system accumulating the most soil N of all the systems over the last 11 years of continuous management. While N_2O emissions and the amount of N_{new} incorporated into the organic cropping system were similar to that of the low-input system, the latter received the lowest N inputs (~100 kg N ha^{-1} year^{-1}) of the three cropping systems, whereas annual N input to the organic system was the highest (473 kg N ha^{-1}). In spite of receiving the least N additions, the low-input cropping system showed intermediate levels of NUE and intermediate levels of macroaggregate- and microaggregate-N_{new}. When combined with minimum tillage practices, our data suggests that the low-input system can achieve the optimum balance between SOM stabilization, N_2O emissions, and N availability for plant uptake; whereas, the combinations of reduced tillage with either conventional or organic cropping practices failed to realize the full benefits of minimum tillage.

4. Conclusion

Although whole soil N dynamics were largely unchanged, the use of ^{15}N in this study revealed that tillage reduction already had an impact on N cycling within the first year of transition from standard to minimum tillage and that interactions between tillage and management practices determine the trade-offs among N stabilization, N_2O emissions, and N availability. Among the cropping systems, soil N_{new} in the conventional system was found mostly in the microaggregate and silt-and-clay fractions, whereas N_{new} mainly resided in the macroaggregates of the low-input and organic systems. Minimum tillage systems showed greater aggregate fraction-N_{new} than the standard tillage systems, suggesting that there is greater potential for N stabilization under minimum tillage. However, the combination of minimum tillage and conventional crop management led to the highest N_2O emissions of all the tillage-cropping system combinations, despite showing greater relative soil N_{new} levels. In contrast, minimum tillage combined with the low-input system produced intermediate N_2O emissions, adequate soil N_{new} concentrations, and appreciable N use efficiency. Hence, our hypothesis that tillage reduction coupled with low-input nutrient management would establish an optimal balance between SOM stabilization, N_2O flux, and plant-available N was corroborated. These results provide a greater understanding of the mechanisms governing N cycling in the early transition period from standard to minimum tillage and have the potential to aid growers in developing management practices that maximize the benefits of minimum tillage while mitigating greenhouse gas emissions and maintaining yields.

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