Effects of Strip Tillage and Production Inputs on Soil Biology across a Spatial Gradient

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Strip tillage results in soil disturbance levels similar to those of conventional tillage systems in the row locations (strip) and properties of no-till in the interrow (between-row) locations. In this study, biological and physical soil properties in the region spanning the row to interrow were investigated and results were compared among strip–tillage systems utilizing different inputs (conventional fertilizer and pesticides vs. USDA-approved organic inputs) and rotation regimes (continuous tomato [*Lycopersicon esculentum* Mill.] vs. a 3-yr vegetable rotation). Bulk density was significantly greater in the interrow locations. Soil respiration potential was greatest in the interrow and least in the row locations, and greater in treatments receiving organic inputs relative to synthetic inputs. No differences in soil N mineralization potential were determined. Microbial biomass C and N were greatest in interrow and least in row locations. Total soil C and N values did not vary from row to interrow locations or as a result of synthetic vs. organic inputs. The data suggest that organically managed production systems are less biologically stratified than conventional input systems under strip-tillage management. Although net C mineralization was similar between chemical and organically managed systems, greater microbial biomass values in the organic treatment systems may have been the result of continuous additions of weed biomass during the summer. The hypothesis of a gradient effect for biological activity in strip-tillage systems from row to interrow appears to be true in systems managed with synthetic fertilizers and pesticides, but not true of organically managed systems.

Abbreviations: MBC, microbial biomass carbon; MBN, microbial biomass nitrogen.

SOIL BIOLOGY & BIOCHEMISTRY

Strip tillage is a conservation tillage practice that isolates soil tillage to a narrow band, generally 15 to 45 cm in width, using a specialized tillage implement. Strip tillage incorporates the environmental and crop growth benefits of no-till systems with the improved root environment associated with tillage practices (Coolman and Hoyt, 1993). Hill (1990) and Vyn and Raimbault (1993) described the challenges for conventional and no-till management systems on different soil types, drainage classes, and cropping systems. By combining the properties of conventional tillage in the seed bed area and no-till in the interrow area, strip tillage creates a soil matrix with an intermediate level of disturbance relative to these two practices and provides unique soil physical properties that can potentially maximize crop production and increase profitability while reducing soil erosion. The degree of soil structure disruption is highly variable, depending on the type of strip-tillage instrument used.

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The positive effects of strip tillage related to plant growth include factors associated with an improved seed bed and rooting environment, decreased surface bulk density, disruption of hard pans in the strip, and increased moisture content and erosion control between rows. Soil resistance to the negative effects of heavy equipment traffic, reduced fuel requirements, efficient placement of fertilizer, and potentially increased yields are other advantages of strip tillage relative to conventional tillage. Potential crop benefits related to soil fertility have also been reported and include a more readily mineralizable pool of N and more plant-available P compared with conventional tillage (Kingery et al., 1996). Al-Kaisi and Hanna (2002) reported that strip tillage can improve the seedbed environment in poorly drained soils due to increased soil moisture evaporation and increased soil temperature in the row compared with no-till practices. From an environmental perspective, strip tillage effectively reduces wind and water erosion and increases C sequestration compared with conventional clean tillage. As Al-Kaisi and Yin (2005) summarized, "Although tillage effects on soil CO_2 emission are complex and often vary (Mosier et al., 1991; Lauren and Duxbury, 1993), conservation tillage is regarded as one of the most effective agricultural practices for reducing soil CO_2 emission to the atmosphere from agricultural soils (Kern and Johnson, 1993; Reicosky and Lindstrom, 1993; Lal and Kimble, 1997)."

Other agricultural management practices that have become widely adopted for a variety of reasons are organic production systems and crop rotations. The market for organic produce has seen tremendous growth in the past 15 yr. Since the implementation of the National Organic Standard by the USDA in

2002, U.S. sales of organic foods have grown at 20% or more per year, with the fresh produce sector constituting the largest sector of the organic food industry (Oberholtzer et al., 2005). Interest in rotation cropping has also grown in recent years. In 1997, 82% of the 79 million ha of total U.S. cropland was in some type of rotation system (Padgitt et al., 2000). Interest in the value of crop rotation is particularly high the southeast United States, where continuous tobacco (*Nicotiana tabacum* L.) is being replaced with high-value vegetable and horticultural crops (i.e., rotation is becoming more diverse), and throughout the Corn Belt as corn (*Zea mays* L.) acreage increases and more land is dedicated to continuous corn production (i.e., rotation is becoming less diverse). Crop rotation, which can be considered the planned diversity of an agricultural system (Matson et al., 1997), influences the composition and abundance of the biological community in the soil system. Although it is doubtful that alternative production systems such as reduced tillage, organic inputs, and vegetable rotations will altogether replace conventional methods of production in the foreseeable future, there is potential for these systems to become an accepted and integrated part of the conventional vegetable production system in the southeast United States.

The soil biological community is responsible for many critical crop growth processes including nutrient cycling, soil structural change, and organic matter accumulation and degradation. Therefore, it is important to monitor and assess biological differences between conventional cropping systems and newly adopted systems (i.e., strip tillage, organic inputs, and crop rotations). The biological consequences of alternative management systems have not been studied on a long-term scale in vegetable cropping systems (Hummel et al., 2002). The extent to which strip tillage, organic inputs, and crop rotation affect areas of a crop field other than the row location (i.e., the interrow area) is also largely unexplored. It has been demonstrated that soil biological community composition and biomass vary widely from the rhizosphere to the bulk soil, resulting in significant differences in microbial activity and processes related to soil function, which include soil C sequestration, N dynamics, plant nutrient availability, and litter decomposition (Söderberg and Bååth, 2004). More specific differences in soil biological activity and composition between a large area of residue coverage (i.e., interrows) and a relatively smaller area of select vegetation (i.e., row areas), as seen in strip-tillage systems, is not known. Measurements made for agroecological investigations in conservation tillage studies have been primarily limited to the crop row or crop root zone area. Since the virtues researchers often extol regarding the advantages of conservation tillage revolve around the fact that reduced tillage systems leave cover crops or previous crop residues on the soil surface, however, it is of some importance to characterize the ecosystem of the entire field. Included in a full-field analysis would be the interrow areas, which are frequently cited as the source of environmental and crop-related benefits (e.g., increased C retention, biological activity, and moisture holding capacity). We hypothesized that there is a radius of influence extending from the perimeter of the strip, creating an ever-decreasing gradient of biophysical effect, into the interrow region. Characterizing the biological and physical differences between these regions could provide more accurate and higher resolution information about the environmental benefits associated with strip-tilled systems.

The objective of this study was to examine the spatial gradient of biological, physical, and chemical properties in strip-tillage systems encompassing the region spanning the center of the crop row to midway between crop rows. Parameters of interest included soil respiration during a 24-d laboratory incubation period, N mineralization during a 28-d laboratory incubation period, total C and N, microbial biomass C and N, and soil bulk density.

MATERIALS AND METHODS

Field Preparation and History

This field experiment was established in the fall of 1994 and had been in production for 10 years when this study was initiated. Based on measurable and visible differences in soil physical properties, crop yield differences, and weed community structure among treatments, it is believed that sufficient time had elapsed to allow the biological communities to approach a steady-state condition within each treatment. Our observations of stable states in the aboveground biological community after 10 yr is further substantiated by the work of Monreal and Janzen (1993), who determined that they obtained stable management effects after about 10 yr. Other studies have determined that less time, just 3 to 4 yr after initiation of conservation tillage, is required before more favorable porosity in the 0- to 15-cm soil zone is measured relative to continuous moldboard plowing (Voorhees and Lindstrom, 1984).

The field site is located at the Mountain Horticultural Crops Research Station in Fletcher, NC. The field is situated on a Delanco fine sandy loam (fine-loamy, mixed, semiactive, mesic Aquic Hapludult) with 2 to 7% slopes. The land is gently sloped, moderately well drained, and formed on old alluvial deposits. The site is situated on an old stream terrace subject to infrequent flooding.

A randomized complete split-plot design was used, with agricultural input (conventional chemical fertilizer and pesticide inputs vs. organic inputs) as the whole-plot treatment and vegetable rotation vs. continuous tomato as the split-plot treatment. The 3-yr vegetable rotation split-plot treatment consisted of sweet corn (*Zea mays* L. subsp. *mays*)–fall cabbage (*Brassica oleracea* L.), cucumber (*Cucumis sativus* L.)–fall cabbage, and tomato for Years 1 to 6 (two full 3-yr rotations) and bell pepper (*Capsicum annuum* L. var. *annuum*), yellow squash (*Cucurbita maxima* Duchesne)–fall broccoli (*Brassica oleracea* L.), and staked tomato for Years 6 through 9, respectively. The continuous tomato treatment was planted in staked fresh market tomato every year (same cultivar as Year 3 in the rotation treatment). The year that this study was conducted (Year 10), the rotation treatment was planted with bell pepper. Tomato was planted in single rows 46 cm apart, and bell pepper was planted in double rows (30-cm row and 30 cm between double rows); both crops were planted with 1.5 m between rows. All treatments were trickle irrigated to supply at least 6.2 cm ha^{-1} wk^{-1} of water. There were eight plots consisting of two treatments and four replicates. Each plot measured 12.2 by 24.4 m (0.03 ha). There was an area of at least 12.2-m separation between plots to minimize fertilizer and pesticide drift and pest and pathogen migration between plots.

A winter cover crop of wheat (*Triticum aestivum* L.) and crimson clover (*Trifolium incarnatum* L.) was planted for all treatments. The aboveground biomass of this cover crop was measured in the spring before killing using 0.25-m^2 frames to remove all biomass above the soil surface in the given area, which was then dried (50°C) and weighed. Cover crop growth was terminated in the organic treatment by flail chopping and with a systemic herbicide (glyphosate [*N*-(phosphonomethyl)glycine]) in the synthetic treatment. The conservation tillage treatments (both organic and synthetic) were strip-tilled with a Bush Hog RoTill (Bush Hog, Selma, AL) (producing 30–45-cm-wide strips) and vegetable transplants were planted by hand. Past seeded crops (sweet corn) were planted with a John Deere MaxEmerge no-till planter. Crops were seeded or transplanted during the second to fourth week in May each year.

The strip location was the same every year, being marked at the end of harvest to use as a guide for strip placement for the following season. The Bush Hog RoTill strip-tillage implement has a subsoil shank, which was adjusted to a depth of 20 to 23 cm to shatter compaction directly under the row within the root zone (Coolman and Hoyt, 1993), and strips were 20 to 30 cm wide at the surface. By lifting the soil up and dropping it, the Bush Hog RoTill strip-till implement loosens compaction without inverting the soil or disrupting the structure to the same extent as moldboard plowing. Rather than inversion, as in moldboard plowing, the strip-tillage implement used in this study fractured soil along the length of the subsoil shank, breaking up compaction and creating a finer bed for seeding or transplanting. Residue from the cover crop or weed biomass as well as fertilizer placed within the band was incorporated into the soil by the action of the shank to a depth of about 10 to 15 cm, allowing for increased decomposition and nutrient mineralization in the strip. When these soils were sampled in mid-July, the effect of residue mixing and soil disturbance had diminished relative to what is expected directly after a tillage event.

Fertilizers were applied on the same date for all treatments, which occurred directly after the initial strip tilling. In the synthetic fertilizer and pesticide treatment, 224 kg N ha^{-1} was applied as NH_4NO_3. Nitrogen was applied as a band in the strip-till row. Soil test recommended P and K were surface broadcast over the entire plot each fall when the winter cover crop was planted. For synthetic treatments, P was applied as triple super phosphate (0–20.1–0) and K was applied as KCl (0–0–49.8). Weed, plant disease, and insect control in the synthetic treatments were applied as needed, with materials recommended by the Center for Integrated Pest Management (2004).

In the organic treatments, N, P, and K fertilizers were applied as follows: soybean [*Glycine max* (L.) Merr.] meal at 224 kg N ha^{-1} (assuming 100% availability during the vegetable growing season) was surface applied in the row before planting. Phosphorus as rock phosphate (0–13.1–0, assuming 3% solubility) and K as K–Mg sulfate (0–0–18.3) were surface broadcast at winter cover crop planting as recommended by soil test reports. Plant disease and insects were controlled with materials approved for organic production and weeds were controlled by mowing, hoeing, and hand pulling. After fertilization of both input treatments, an additional pass of the strip-till implement was applied to incorporate the fertilizer and create a smoother surface.

Organic treatment plots were mowed continuously throughout the summer to reduce weed competition around the borders and between rows. Grass clippings were left on the soil surface and should be considered as an additional labile pool of recycled nutrients for plants and soil organisms that the synthetic treatment did not receive.

Soil Sampling and Analyses

Samples were taken 12 to 13 July 2004. Samples were taken later in the growing season to allow the initial effects of tillage, namely N mineralization and organic matter oxidation, to subside and allow the soil to physically settle during the growing season to obtain less extreme measurements of parameters. Bulk density was determined by taking a Uhland core sample (7.5-cm diameter, 7.5-cm length) from each of the three field locations (in the strip, the edge of the strip, and the interrow) in each rotation subplot. Uhland cores were stored at room temperature until bulk density was determined. Soil samples were collected in plastic bags using a 6-cm-diam. push probe to a depth of 15 cm from respective field locations by taking four cores along the length of each row in each location and compositing the cores. Samples were gently sieved through a 6-mm screen and stored at 4°C until respiration, mineralization, and biomass studies were initiated. All biological measurements were initiated within 10 d after the soils were sampled. Gravimetric soil moisture content was measured on the day that soil samples were sieved, within 1 d of being collected from the field.

Total soil C and N were analyzed by combustion of subsamples of the whole soil sample that had been oven dried at 105°C overnight and ground to pass through a 1-mm sieve using a PerkinElmer PE 2400 CHN Elemental Analyzer (PerkinElmer, Norwalk, CT).

The microbial biomass analyses (microbial biomass C [MBC] and microbial biomass N [MBN]) provide a means to examine total microbial biomass values and to compare them among treatments. These analyses were conducted using the chloroform fumigation and extraction technique (Hu et al., 1997; Vance et al., 1987), using a microbial C extraction efficiency factor of 0.33 after Sparling and West (1988). The MBN procedure was conducted using the alkaline persulfate oxidation digestion method of Cabrera and Beare (1993) with a microbial N extraction efficiency factor of 0.54 as per Brookes et al. (1985). All values were calculated by subtracting an unfumigated control value from the fumigated measurements.

Potential microbial activity was assessed by determining soil CO_2 respiration and potentially mineralizable N in laboratory incubations. Soil respiration (mineralizable C) was measured using the NaOH base trap technique for 24 d. A 10-mL aliquot of 0.2 mol L^{-1} NaOH was added to each base trap and lids were sealed to begin the incubation study. Traps were collected and titrated on Day 24 with 0.1 mol L^{-1} HCl. Moisture content was determined at the beginning of the experiment and all measurements were calculated on an oven-dry soil mass basis. Ten milliliters of deionized water was added to the bottom of air-tight jars to maintain a relatively high humidity and the initial moisture content of the soil.

Potentially mineralizable N was evaluated by measuring the N concentration in unamended soils for 28 d. Approximately 10.5 g fresh weight (9.85 g dry-weight average) of soil was weighed into a vial and placed in a 0.95-L air-tight Mason jar. On the extraction date, vials were removed from the jars and the soil was reweighed into plastic snap-top vials. A 0.5 mol L^{-1} K_2SO_4 solution was used to extract the potentially mineralizable N from the soil by shaking on a rotary oscillator for 30 min. Samples were filtered and frozen until they were analyzed for NO_3^- and NH_4^+ concentrations using a N analyzer fitted with a Cd–Cu reduction column (Lachat N Analyzer, Lachat Instruments, Milwaukee, WI). Temperatures were recorded daily for both the respiration and mineralization studies and corrections were made to assure that broad fluctuations in temperature did not occur. Temperatures ranged from 24 to 30°C during these experiments.

Data Analyses

Analysis of variance was conducted to examine the relationships between individual biological measurements and the respective treatments using SAS software (SAS Institute, Cary, NC). Mean compari-

Table 1. Summary of statistical *P* values for main treatment effect and interactions. Analyses were based on measurements for bulk density (BD), soil moisture content (MC), total C (TC), total N (TN), soil respiration, potentially mineralizable N (PMN), microbial biomass C (MBC), and microbial biomass N (MBN). Italicized values indicate significance level, $p < 0.05$.

Treatment or interaction	BD	MC	TC	TN	Respiration	PMN	MBC	MBN
Location†	*<0.0001*	0.2788	0.5918	0.8048	*0.0359*	0.3886	*0.0001*	*0.0002*
Input‡	0.8430	0.3711	0.5736	0.1469	0.0894	0.4202	0.1367	0.1912
Rotation§	*0.0159*	0.2592	0.4535	0.4919	0.2419	0.8891	0.3100	*0.0100*
Location × input	0.4065	0.6540	*0.0045*	*0.0083*	0.2524	0.5372	0.4759	0.8725
Location × rotation	0.7710	0.0660	*0.0018*	*0.0003*	0.8733	0.0805	0.1404	0.1489
Input × rotation	0.1476	0.2812	0.8960	0.7118	0.3811	0.2186	0.1777	*0.0073*
Location × input × rotation	0.5394	0.5533	0.6234	0.6398	0.7371	0.6030	0.1367	0.7567

† Row, edge, or interrow sampling locations.

‡ Synthetic (chemical fertilizers and pesticides) or organic production practices.

§ Continuous tomato or vegetable rotation.

son procedures, such as least significant difference, are not appropriate for analysis of these data due to thefactorial design of the experiment, the limited number of levels with in factors, and the expected differences among treatments. The *P* values were determined to be the most appropriate statistic to communicate significant differences and interactions within and between treatments (Table 1). Biological activity measurements were analyzed by principle components analysis (PCA) using CANOCO software Version 4.5 (Microcomputer Power, Inc., Ithaca, NY) and SAS software. The PCA data were standardized by dividing biological and physical values by the standard deviation.

RESULTS AND DISCUSSION

Soil Bulk Density

Soil bulk density was significantly greater in the interrow position than the row (Table 1, Fig. 1). Bulk density was not affected by input but was affected by rotation, being generally greater in the vegetable rotation treatment. The differences observed between density values in the vegetable rotation vs. the continuous staked tomato treatments were small (Fig. 1) and can be attributed to additional tractor traffic that occurs during double-crop years (when a spring and fall crop were included) in the rotation treatment schedule. It should be noted that machinery traffic was confined to the interrow areas and therefore sites for bulk density measurement were taken from the most highly trafficked portion of the field (the interrow), as well as from the least-trafficked portion of the field (the row). Results from this study indicate that soil bulk density can vary depending on location and rotation within a strip-tillage system and whether controlled traffic patterns are implemented. Results additionally support previous research, anecdotal evidence, and Extension recommendations stating that controlled traffic patterns create compaction where it is useful for improving traction and reduce it where it is least desirable, i.e., in the crop row, where it could reduce crop emergence and stand establishment.

Soil Moisture Content

There were no significant moisture differences among treatments (Table 1, data not shown) due to a rainfall event 1 d before sampling. Input and rotation did not affect the moisture content of the soil at different field locations for the sampling event measured in this study. The effect of tillage activities on the soil water characteristic has not been conclusively determined (McVay et al., 2006) and data from studies reporting tillage effects on water characteristic frequently conflict. Removal of residue from the row location in a strip-tillage system has been observed to reduce soil moisture in the strip while conserving interrow soil moisture (Licht and Al-Kaisi, 2005).

In a tillage study similar to this one conducted at the same research station in 1985, moisture was measured gravimetrically to a depth of 4 cm throughout the summer and found to be generally lower for conventional moldboard tillage relative to strip tillage (Hoyt and Konsler, 1988). Soil water measurements from the between-row region from conventional tillage treatments were significantly lower than in the strip-tillage treatments for the same area in all but one sampling period occurring in mid-July. They reported lower soil water measurements in the row location compared with the between-row location in the strip-tillage treatments.

Total Soil Carbon and Nitrogen Content

Because there are no mineral carbonates in these highly leached, acidic soils, total C can be equated with total soil organic C. No simple treatment effects were sufficient to explain the variation among total soil C and total soil N values. Surprisingly, total C and total N did not differ significantly among row locations

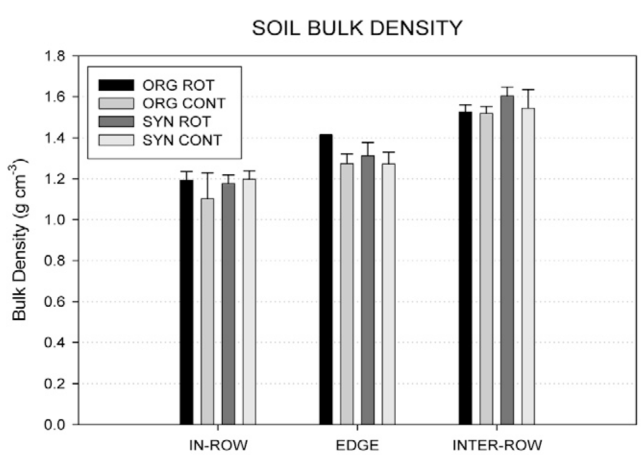

Fig. 1. Bulk density from three different locations in the strip-tillage treatment (ORG ROT, organic inputs–rotation; ORG CONT, organic–continuous cropping; SYN ROT, synthetic inputs–rotation; SYN CONT, synthetic–continuous cropping). Rotation subplot treatment was included because differences were significant between rotation and continuous cropping treatments. Error bars indicate standard error.

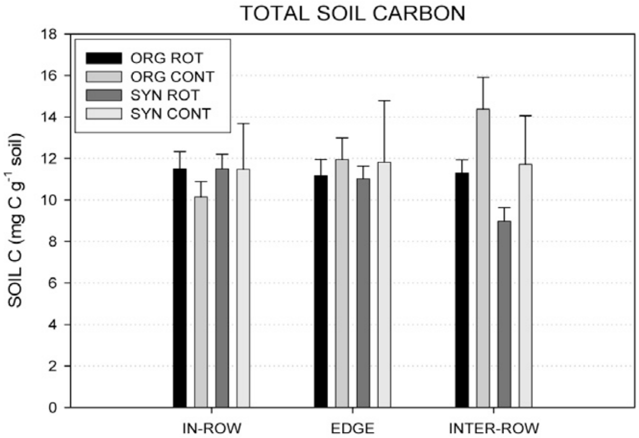

Fig. 2. Total soil C from three different locations in a strip-tillage field (ORG ROT, organic inputs–rotation; ORG CONT, organic–continuous cropping; SYN ROT, synthetic inputs–rotation; SYN CONT, synthetic–continuous cropping). Rotation treatment is included because significant treatment interactions were observed. Error bars indicate standard error.

in the strip-tillage environment (Table 1, Fig. 2 and 3). The location × input interaction and the location × rotation interaction were strongly significant variables in both the total C and total N ANOVA models (Table 1). There was little difference among soil C levels in the row and edge positions, but the interrow location displayed greater C values in the organic than the synthetic treatment, and in the continuous compared with the rotation treatment (Fig. 2). In the row location, where organic and synthetic fertilizers were banded before incorporation, there was no difference in total soil C between the organic and synthetic treatments. Apparently, soybean meal added as an organic N input did not significantly increase the amount of total C in organically managed soils compared with soil taken from the synthetic fertilizer treatment. This is partially explained by the 44% increase in C respired as CO_2 determined in laboratory incubations for the organic treatment relative to the synthetic treatment in the row location (Fig. 4). There was about 50% greater C present as microbial biomass in the row location in the organic treatment relative to the synthetic treatment (Fig. 5). In order for total C values to remain approximately equal, it is likely that other soil organic matter fractions, such as root exudates or sloughed root cells, were greater in the synthetic treatment relative to the organic treatment, but this can only be speculated since these soil organic C pools were not measured directly. Most of the root biomass was removed by screening during sample processing, and so is not accounted for in total soil C and N measurements.

Total soil N did not differ significantly between the row, edge, and interrow locations (Table 1, Fig. 3). Similar to results from the total C data, the interrow yielded greater N content in soils in the organic compared with the synthetic treatment and in the continuous tomato treatment relative to the vegetable rotation treatment. The nonsignificantly greater levels of total C and, especially, N observed in the row locations for the rotation treatment relative to the continuous tomato treatment may be affected by the additional fertilizers applied during double-cropped years in the rotation treatment, which were not received in the continuous tomato treatment. Samples were analyzed on a mass basis, not a volume basis, so bulk density should not be a factor in the soil C and N values presented here.

Cover Crop Biomass

Cover crop biomass was measured in mid-May before being flail chopped (organic treatment) or chemically killed (synthetic treatment). There were statistical differences between the rotation and continuous cropping treatments, with the rotation treatment having more biomass than the continuous tomato treatment (data not shown), so the input effect on aboveground biomass was analyzed separately for those treatments. There was significantly greater biomass for the synthetic inputs relative to the organic input treatment for the rotation strip-tilled plots (14,844 kg ha^{-1} for synthetic vs. 11,388 kg ha^{-1} for organic). In the continuous staked tomato treatment, however, the trend reversed and there was a nonsignificant increase in the organic aboveground biomass relative to the synthetic aboveground biomass.

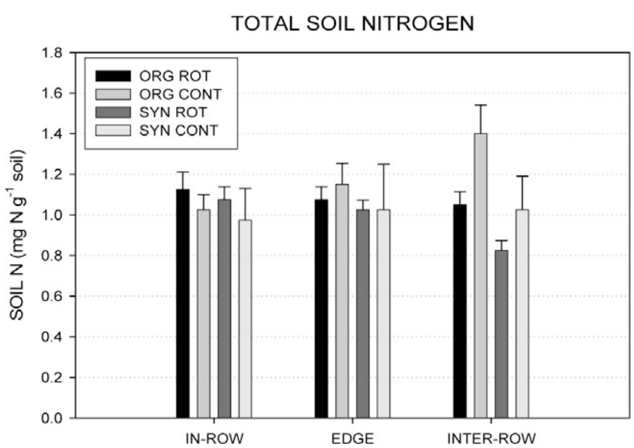

Fig. 3. Total soil N from three different locations in the strip-tillage field (ORG ROT, organic inputs–rotation; ORG CONT, organic–continuous cropping; SYN ROT, synthetic inputs–rotation; SYN CONT, synthetic–continuous cropping). Rotation treatment is included because significant treatment interactions were observed. Error bars indicate standard error.

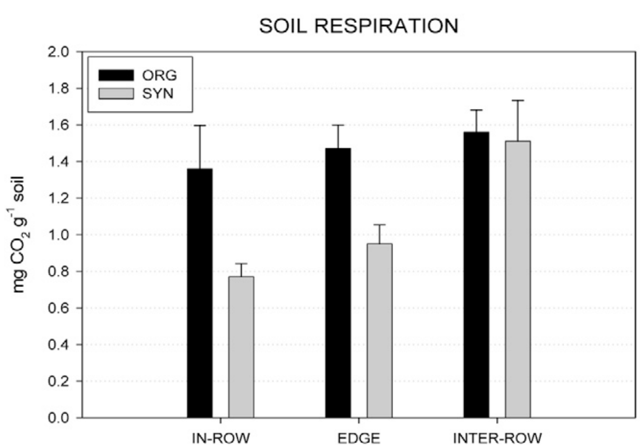

Fig. 4. Soil C mineralization (respiration) at three different field locations, net CO_2 evolution during 24 d (ORG, organic inputs; SYN, synthetic inputs). Rotation subplot treatment was averaged across main plot treatments (tillage and inputs) because no statistical differences were found. Error bars indicate standard error.

Soil Respiration

Many researchers have acknowledged that increased CO_2 emission from soils under more intensive tillage, especially immediately after tillage activities, is due to the combined effects of biological and physical factors (Jackson et al., 2003; Roberts and Chan, 1990; Reicosky and Lindstrom, 1993). The biological factor is explained by increased soil biological activity from soil flora and fauna, including plant roots, and thus greater respiration rates of soil organisms, after tillage events. The physical factor is due to increased gas exchange with the bulk atmosphere in disturbed soils, allowing the inherently elevated soil CO_2 levels to be released to the bulk atmosphere after tillage. Reicosky et al. (1999) expanded on the concept of the physical factor by attributing the reduction of soil CO_2 emission observed in systems with greater residue cover to the roles that residues play in physically blocking CO_2 emission from the soil to the atmosphere, reducing the crop residue decomposition rate (by reducing the introduction of residue to the soil biological environment), and lowering soil temperature. Measurements of CO_2 evolution conducted in situ estimate the combined effects of biological and physical factors. Traditional in situ measurements do not allow discrimination of these two factors. By measuring potential CO_2 evolution in a controlled incubation study in which soil samples from all treatments and locations were equally disturbed, the physical factor was effectively removed, allowing direct measurement of biological activity on soil CO_2 evolution in a controlled environment in which temperature and moisture, disturbance, and residue mixing were made constant across treatments (input and rotation) and locations (row, edge, and interrow). By eliminating most plant roots through sieving, potential biological activity was limited to soil microorganisms and microinvertebrates.

In this study, soil respiration was significantly different ($P = 0.0359$) among row locations (Table 1), being greatest in the interrow and least in the row position regardless of input treatment (Fig. 4). Since rotation was not a significant treatment factor, it was dropped from the model and averaged across the main plot treatment (inputs). The input treatment was significant at the 0.10 significance level ($P = 0.0894$). The observation of a gradient between the row and interrow locations for CO_2 emission is much more apparent when synthetic fertilizers were applied relative to organic inputs (Fig. 4). The lower relative metabolic activity level of soils treated with synthetic inputs relative to organic inputs indicates a more even distribution of biological activity in an organic system relative to a conventional fertilizer and pesticide system.

What may be most significant about respiration measurements in organic vs. synthetic management when viewed from the whole field perspective is that respiration values remained constant from row to interrow regions in the organic treatment while the respiration level doubled from the row to the interrow region in the synthetic treatment. Calculated as a percentage of the total soil C present, net CO_2 evolution in the organic treatment differed very little from row to edge to interrow (12.32, 12.71, and 12.36%, respectively); however, values for CO_2 evolution from the synthetic input treatment expressed as a percentage of total soil C changed dramatically from row to edge to interrow (7.36, 9.34, and 14.72%, respectively). The increase in respiration observed in the row location of the organic input treatment compared with the synthetic treatment (Fig. 4) was probably most influenced by the soybean meal (2439 kg ha^{-1}, 46% C content) banded in the row in the organic treatment compared with the NH_4NO_3 fertilizer banded row in the synthetic treatment. Because of the high C and N content, soybean meal decomposition would support higher levels of microbial respiration in the row position relative to the inorganic fertilizer sources applied to the synthetic treatments. Because pest-control chemicals were applied with a tractor boom that sprayed the interrow and row areas evenly, if there had been a treatment effect due to pesticide application, we would expect to see the influence of these chemicals in both the row and interrow regions. The fertilizers, on the other hand, were banded in the row and incorporated with the strip-till implement; therefore, treatment effects isolated to the row locations for the input treatment could probably be attributed to the influence of organic vs. synthetic fertilizers, to the exclusion of pesticides applications. Since net C mineralization in the interrow region did not differ between organic and synthetic treatments (1.56 and 1.51 g CO_2 kg^{-1} soil, respectively), but did differ strongly in the row, we conclude that the effect of chemical pesticides was not a strong influence on net C mineralization in this study. The input effect in this study, then, can be attributed to the addition of organic inputs as fertilizer and weeds vs. inorganic fertilizer inputs. If we accept that the interrow region of a strip-tilled field is only marginally affected by organic vs. synthetic pesticides, and provided that inputs are banded within the cropped row, then the hypothesis of a gradient effect for biological activity from row to interrow appears to be true in systems managed with conventional fertilizers and pesticides, but is not true (or is less true) of organically managed strip-tillage systems.

The increased level of respiration (and microbial biomass) observed in the interrow for both organic and synthetic input treatments may be explained by the highly labile C source added as cover crop residue remaining on the soil surface. Fortin et al. (1996) and other researchers have measured greater soil CO_2 emissions in no-till treatments relative to conventional-tillage treatments, indicating that, in general, areas of greater residue will display greater net C mineralization. Net C mineralization can show a different response pattern to tillage than the rate of C flux, which is generally greater under conventional tillage directly after a tillage event, but greater under reduced tillage later in the growing season (Fortin et al., 1996; Jackson et al., 2003).

Although it did not significantly affect total soil C levels (Fig. 2), management of the organic treatment probably resulted in greater availability of highly labile C sources since cover crops were killed organically by flail chopping (leaving more cover crop biomass lying on the soil surface compared with the synthetic treatment, where it was sprayed with glyphosate and left standing). Because of the increased weed presence in the organic treatment, weeds were flail chopped, along with cover crop biomass, and left to decompose in the interrows or were incorporated by the action of the strip-tillage implement in the tilled area (row). In conclusion, the addition of soybean meal, weeds, and cover crop mulch, although none of it was incorporated in the interrow region, did have greater soil contact and was highly labile as a C source to support larger microbial communities, which would be expected to result in

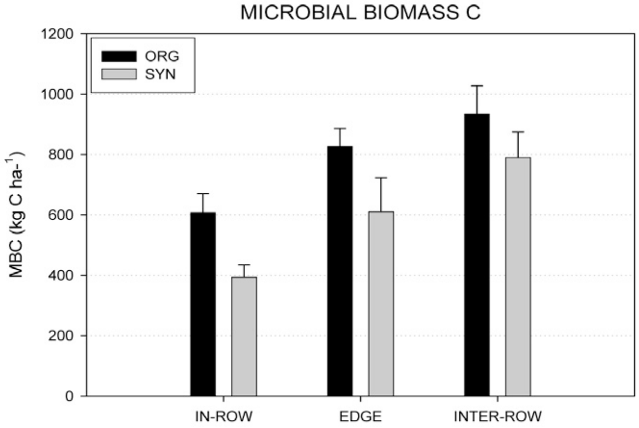

Fig. 5. Microbial biomass C (MBC) from three different locations in the strip-tillage field (ORG, organic inputs; SYN, synthetic inputs). Rotation subplot treatment was averaged across main plot treatments (tillage and inputs) because no statistical differences were found. Error bars indicate standard error.

greater potential respiration than the treatment managed with synthetic fertilizers and pesticide inputs.

It was not the objective of this research project to study soil C sequestration potential among different tillage types, but rather to study the difference in potential biological activity among tillage types; nevertheless, measurement of soil CO_2 emission may be a more sensitive measurement of soil C sequestration potential than low-resolution indicators such as total or organic C values (Fortin et al., 1996; Grant, 1997). As such, these data may provide other researchers (e.g., Al-Kaisi et al., 2005) with information to better predict soil C sequestration potential and C dynamics for strip-tillage systems given the obvious differences determined between field locations (and management treatments) for CO_2 evolution and differences in microbial biomass, despite the similar values across the strip-tilled field for total C.

Soil Nitrogen Mineralization

No significant treatment effects ($P = 0.05$) were determined for net N mineralization based on a 28-d incubation and extraction with 0.5 mol L^{-1} K_2SO_4 (data not shown). Although net N mineralization was greater for organic than synthetic input treatments for the edge and interrow field locations, differences were not significant, as indicated by the lack of a significant interaction factor in the ANOVA. For the row location, net mineralizable N values differed by less than 1 kg ha^{-1} between the synthetic (47.099 kg N ha^{-1}) and organic (46.344 kg N ha^{-1}) treatments. Since fertilizer sources, i.e., soybean meal and NH_4NO_3, were only added to the row area (strip), these data suggest that under laboratory incubation conditions the organic soybean meal released N at the same rate as the mineral N source, NH_4NO_3. The significant differences observed for total soil N between location and input and location and rotation, reflecting the trend for the organic treatment to have greater amounts of total N than synthetic treatments in the row location, did not translate into greater amounts of N mineralized in the organic treatment relative to the synthetic treatment.

Soil Microbial Biomass Carbon and Nitrogen

Microbial biomass C and N were strongly dependent on location (Table 1). No other treatment effects were significant for MBC and so data for the rotation subplot treatment were averaged across the main plot treatment (Fig. 5). The greatest MBC values were observed in the interrow locations followed by the edge, and the lowest values came from the row location. The MBC values demonstrate the most distinctive differences among locations relative to other measurements made in this study. It is obvious that MBC was reduced in the row relative to the interrow, suggesting that the reduced disturbance and increased level of year-long residue cover present in the interrow enhanced the size of the biological community being supported in that region. In contrast to C mineralization measurements, both organic and synthetic inputs demonstrated greater levels of MBC in the interrow than the row, suggesting that MBC levels responded positively to reduced disturbance and greater residue levels present in the interrows. Since the organic treatment consistently produced greater MBC than the synthetic treatments in all row locations and the magnitude of difference between organic and synthetic values did not change greatly from row to interrow, we suggest that the difference between organic and synthetic MBC values can be partially attributed to more than simply the increased C input in the row location with the application of soybean meal. The reduced levels of MBC observed in the edge and interrow locations (as well as the row location) in the synthetic input treatment compared with the organic input treatment is probably the result of chopped weed biomass (from mowing) placed evenly across all regions (row to interrow) in the organic treatment throughout the summer. This pattern contrasts with that for respiration measurements, which showed little difference between organic and synthetic values other than directly in the strip (row).

Rotation and the input × rotation interaction were significant treatment effects for MBN, in addition to the location effect mentioned above (Table 1). In the row location, organic inputs produced greater MBN values than synthetic inputs and crop rotations produced greater MBN than the continuous tomato treatments (Fig. 6). At the edge of the strip, treatment values for MBN were similar, with the exception of the synthetic–rotation treatment, which was about 25% less than other treatment values. In the interrow, the continuous tomato treatment yielded greater MBN than the vegetable rotation treatment, and the synthetic–rotation treatment combination was again lower than other treatment values.

Relationships among Locations and Activity Measurements

Principle components analysis was used to examine multivariate relationships among treatment effects, field locations, and soil parameters. This analysis included measurements of moisture content at the time of soil sampling, total C, total N, potentially mineralizable N, soil respiration, microbial biomass C, and microbial biomass N. Because most measurements did not demonstrate an effect due to rotation treatment, this treatment was not included in the ordination process for determining site scores, although the samples are labeled with the rotation treatment in the biplot (Fig. 7). The first principle component axis accounted for 45.7% of the cumulative variance in the measurement data set. The second axis accounted for an additional 24.2% of the cumulative variance, for a combined explanation of 69.9% of the total data set variance.

As seen in the biplot, the row locations, indicated by square symbols, are oriented on the left side of Principle Component 1 (labeled PC1). The interrow samples, identified by circular symbols, are most heavily distributed on the right side of PC1. The edge-of-row samples, indicated by triangular symbols, are distributed between the other two locations, being oriented about the origin of PC1. The eigenvectors for each measurement are oriented in the direction of increasing values for that measurement and the length of the eigenvector is proportional to the contribution that the measurement makes to the correlation matrix explained by the two principle components. In the biplot, all measurements are increasing to the right side of PC1. The coarser measurements of biological activity (i.e., moisture content, total C, and total N) are increasing in the upward direction of Principle Component 2 (PC2) and the more direct measurements of biological activity (i.e., potentially mineralizable N, respiration, MBC, and MBN) are oriented in the downward direction of PC2. Bulk density is the only physical parameter measured in this study, and it is also oriented in the downward direction of PC2. By examining the relative distribution of samples (represented by symbols) and biological measurements (represented by arrows), we can recognize trends and treatment responses. The interrow treatments, which have already been identified as the most biologically active from individual ANOVA, are oriented in the direction of increasing values for potentially mineralizable N, respiration, MBC, MBN, and bulk density. This descriptive statistical procedure illustrates that the interrow location displayed the greatest values for biological measurements relative to the row and edge-of-row locations.

CONCLUSIONS

The similar values for C mineralization in the organic input system across row locations, relative to the more divergent values observed for the synthetic system, suggests that organically managed production systems may be less biologically differentiated among row locations than conventional input systems under strip-tillage management using soybean meal in the crop row. Conventional input systems using synthetically produced mineral fertilizers and chemical pesticides do not directly provide a C source to the biological community outside of the additional growth provided in the crop row from crop plants and weeds. With conventional broadcast application of organic manures, composts, and meals, the organic inputs present in the fertilizer source support the typically C-limited biological community more readily than conventional fertilizer systems, which supply little C to the row area.

The determination of lower metabolic activity and a smaller biological community in agricultural production systems using conventional fertilizers and pesticides relative to organic production systems is an indication of reduced functioning of the whole biological community in conventional systems under strip-tillage management. Despite greater input of C as soybean meal fertilizer in the strip (row location), there was not a corresponding increase in total C observed for the organic compared with the synthetic treatment. The greater

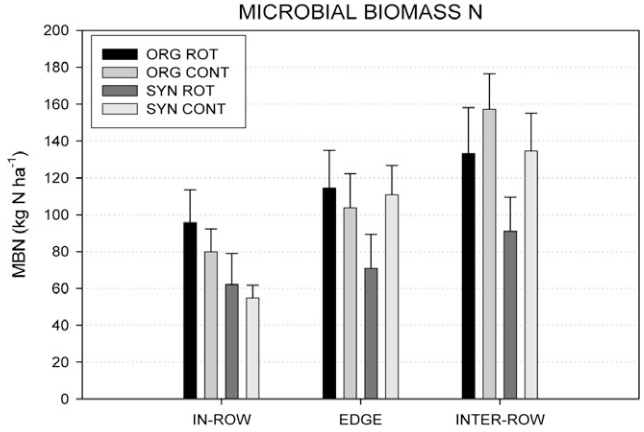

Fig. 6. Microbial biomass N (MBN) from three different locations in the strip-tillage field (ORG ROT, organic inputs–rotation; ORG CONT, organic–continuous cropping; SYN ROT, synthetic inputs–rotation; SYN CONT, synthetic–continuous cropping). Rotation subplot treatment was included because differences were significant between rotation and continuous cropping treatments. Error bars indicate standard error.

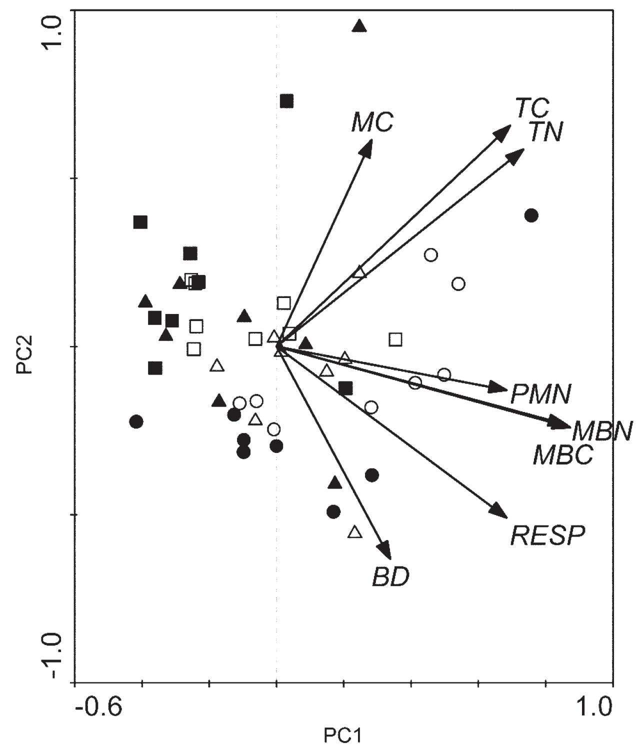

Fig. 7. Biplot of data produced from principle components analysis of all biological parameters and bulk density measurements. First principle component is represented on the horizontal axis and second principle component is represented on the vertical axis. The first principle component explained 45.7% of the total variance in this data set and the second principle component explained an additional 24.2% of the variance, for a cumulative representation of 69.9% of the data set variance. Organic input treatments are represented by open symbols and synthetic input treatments are represented by closed symbols. Row locations are squares, edge-of-row locations are triangles, and interrow locations are circles. Measurements are indicated by arrows: moisture content (MC), total C (TC), total N (TN), potentially mineralizable N (PMN), soil respiration (RESP), microbial biomass C (MBC), microbial biomass N (MBN), and bulk density (BD). Species are centered and standardized. Data were not transformed.

respiration rate measured in the organic relative to the synthetic treatments in the row location partially normalized the increased C input from the organic fertilizer, with the final result being no difference in total soil C between organic and synthetically managed systems.

Had soils been sampled soon after strip tillage, it is probable that the biological activity measurements would have been higher in the strip relative to the interrow. In contrast, given the later sampling date for this study, potential soil respiration and N mineralization measurements revealed greater potential activity from the less-disturbed interrow region, which had greater soil residue cover. Likewise, microbial biomass was greater in the interrow region as well. Total soil C and total soil N values, however, did not vary from the row to interrow locations in the strip-tilled field.

Although it is difficult to distinguish reduced biological activity and biomass values in synthetic systems resulting from the use of synthetic fertilizers vs. synthetic biocide use, the difference in placement of the fertilizer (row only) vs. that for the pesticides (evenly across the entire row to interrow region), allows certain inferences to be made. These data suggest that although potential net C mineralization was not affected strongly by the use of pesticides, reduced microbial biomass values may have been affected by the application of synthetic biocides. The addition of weed biomass by mowing between rows during the summer growing season may have contributed to the higher microbial numbers found in the organic treatment system compared with the chemical system.

Mineralizable N results from this study indicated no difference in N release from the row areas under laboratory conditions for the soybean meal and NH_4NO_3 fertilizer. Differences, of course, would be anticipated for N availability of an organic fertilizer source in a soil under field conditions and the timing of N mineralization measurement.

Bulk density was significantly greater in the interrow than the row location. The significant rotation treatment effect on bulk density is probably the result of increased equipment traffic in the rotation treatments relative to the continuous treatments. Essentially, principle components analysis indicated that the interrow location displayed greater values for biological measurements, despite displaying greater bulk density values, relative to row and edge-of-row locations in a strip-tilled field.

In summary, although total soil C and N levels did not differ dramatically between the row and interrow locations of the strip-tilled production systems, the microbial biomass and potential biological activity were greater in the interrow area relative to the row area at the time that these soils were sampled in mid-July. These results are counter to our original hypothesis, in which we suggested that there would be an ever-decreasing gradient of biophysical effect extending from the row to the interrow region. We initially suggested that biological activity and biomass would be greater in the row than the interrow since crops would be actively growing throughout the season, creating a zone of root exudates and tissues, and a moisture gradient favoring water movement into the strip, which, we presumed, would enhance biological activity. In contrast to our hypothesis, potential soil respiration and N mineralization measurements revealed greater potential activity from the less-disturbed interrow region, which had greater residue levels on the soil surface. Although we were incorrect about the direction of increase in biological activity in a strip-tilled field, the hypothesis of a gradient effect for biological activity in strip-tillage systems from row to interrow appears to be true in the system managed with conventional fertilizers and pesticides but is not evident based on data from the organically managed system in this study. As Aon et al. (2001) pointed out, the many interactions occurring between and among microbial, biochemical, and physicochemical variables in soil are difficult to distinguish, characterize, and, especially, predict.

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