Soil Amendments Affect Soil Health Indicators and Crop Yield in Perennial Strawberry

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ADDITIONAL INDEX WORDS. **carbon:nitrogen ratio, *Fragaria ×ananassa*, organic matter, tillage depth**

SUMMARY. **Soil amendments with varying carbon:nitrogen (C:N) ratios [grass clippings, wheat (*Triticum aestivum*), straw, sawdust] were pre-plant incorporated into 12 × 15-ft field plots at ≈4 tons/acre in fall and then planted to perennial strawberry (*Fragaria ×ananassa*) the following spring and grown 4 years. These amendments were intended to alter soil biological activity as measured by a suite of soil tests referred to as "soil health indicators" which, in turn, were hypothesized to affect strawberry plant growth and yield. In addition, plots were either tilled deeply or shallowly to determine if intensity of tillage affected soil health indicators. After the first and second years, amendments were reapplied between rows and soil and plant variables continued to be monitored. Soil respiration was consistently higher in plots with higher C:N amendments, with up to a 189% increase in respiration in sawdust-amended plots over unamended plots. The respiration rate was highest in sawdust-amended shallow-tilled plots; however, in most cases, tillage depth had no effect on other soil or plant variables. Potentially mineralizable N was higher in sawdust-amended plots in May both years, but not throughout the rest of the season. Soil moisture and pH were 21% and 2% higher, respectively, between the rows of strawberries than within the rows by September of the planting year, and remained that way throughout the next year. Neither the C:N ratio of the soil nor the foliar nutrient concentration of strawberry leaves was affected by the C:N ratio of the amendments. Most significantly, plant density and yield were depressed up to 42% and 26%, respectively, by planting into straw-amended soil, but planting into other amendments did not have this effect. After the second fruiting year (the third growing season), only straw was incorporated into half of the plots after harvest to mimic winter straw mulch incorporation, and yield was measured again the following spring. However, incorporation of straw between rows after plants were established did not affect yield. This study corroborates the general recommendation to avoid new strawberry plantings in locations that were recently planted to strawberry, as old fields likely harbor pathogens and contain undecomposed straw residue from previous years' mulching that could depress yield. Despite differences in soil health indicators between amendment and tillage treatments, yield differences were not correlated with them. These observations suggest that alternative soil health indicators may be better suited for perennial strawberry.**

The future of food production relies on the ability of soil to support high yields of food crops over the long term. Predicting the ability of soil to sustain high yields requires tests spanning chemical, physical, and biological properties. An aggregation of such tests can be used to assess soil health [sometimes referred to as soil quality in the literature, especially as the concept was first developing (Doran and Parkin, 1994; Harris et al., 1996)]. Yield is an important variable that reflects soil health (Wander and Drinkwater, 2000) and should be correlated with health indicators, especially over time. Farmers and agricultural researchers have been studying soil chemical and physical properties for a long time, but the importance of soil biological functioning is still being understood, and so this is the least clear component of a soil health test (Doran and Zeiss, 2000).

Recommendations for improving soil biological health typically involve reducing tillage and adding organic matter to the soil (Gugino et al., 2009). Both management practices can affect soil microbial activity (Beare et al., 1997; Frey et al., 1999; Lupwayi et al., 1998; Tu et al., 2006). Reduced tillage can slow decomposition of soil organic matter, at least in the top of the soil profile (Kern and Johnson, 1993; Six et al., 2002; West and Post, 2002). Organic matter is important for promoting soil microbial growth, but it is still unclear which organic matter qualities will promote microbial growth that then benefits a specific crop (Trinsoutrot et al., 2000). However, the carbon: nitrogen ratio of mulch clearly affects nutrient availability to the plant (Congreves et al., 2012; Manzoni et al., 2010) and may be one of the most important drivers of microbial communities (Manzoni et al., 2008).

Soil health tests have been developed using a variety of cropping

Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
0.4047	acre(s)	ha	2.4711
29.5735	fl oz	mL	0.0338
0.3048	ft	m	3.2808
0.0929	ft^2	m^2	10.7639
2.54	inch(es)	cm	0.3937
25.4	inch(es)	mm	0.0394
0.4536	lb	kg	2.2046
1.1209	lb/acre	kg·ha^{-1}	0.8922
1.4882	lb/ft	kg·m-1	0.6720
28.3495	oz	g	0.0353
33.9057	oz/yard^2	g·m^{-2}	0.0295
0.001	ppm	mg·g^{-1}	1000
1	ppm	mg·kg^{-1}	1
0.9464	qt	L	1.0567
2.2417	ton(s)/acre	Mg·ha^{-1}	0.4461
(°F – 32) ÷ 1.8	°F	°C	(°C × 1.8) + 32

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systems, but research has focused on annual systems with a slower expansion into perennial systems (Idowu et al., 2009). In preliminary work surveying the soil health of perennial strawberry fields, the biological soil indicators tended to be poor relative to other crops, but the reason why was unclear (Pritts et al., 2014). Our objective was to alter the soil biological properties by providing soil amendments varying in C:N ratios and tilling at two different depths, and then determine if these had an impact on soil health indicators, plant establishment, growth, and yield. We hypothesized that adding soil amendments with a higher C:N ratio would increase microbial activity. In addition, we hypothesized that shallow tilling would lead to less mineralization of soil organic C than deep tilling, increasing activity in the less disturbed soil over time. We also hypothesized that traditional soil health indicators would be correlated with yield. In this article, we refer to individual soil tests as "soil health indicators" because they collectively span chemical, physical, and biological properties of the soil but were not aggregated or scaled into a true "soil health test."

Materials and methods

EXPERIMENTAL DESIGN. A completely randomized 2 × 4 factorial design was used to examine the effects of three soil amendments plus an unamended control treatment, each tilled to two different depths. The field was located in Ithaca, NY (lat. 42°26′30″N, long. 76°28′19″W) on a predominantly Arkport soil (coarse-loamy, mixed, active Lamellic Hapludalf). Each amendment and tillage combination was replicated four times for a total of 32 plots that were 12 × 15 ft each. In Fall 2013, 14.5 kg dry weight of three organic amendments varying in C:N ratios [grass (19:1), wheat straw (93:1), and sawdust (344:1)] were uniformly spread and incorporated into the randomly assigned plots. This rate falls within the recommended amount of between 3 and 6 tons/acre of straw added to a strawberry field for winter protection (Pritts and Handley, 1998). Organic amendments were sourced from university farm services with assurance that no herbicides with residual activity were used in their production. The unamended deep-tilled plots were considered farmer control plots because growers typically do not apply an amendment before planting, but they do deep-till.

'Honeoye' bare root strawberry plants were transplanted on 6 May 2014 at a spacing of 1.5 × 4 ft and allowed to form matted rows. Every third row served as a buffer row for adjacent plots (four row plots with two shared buffer rows) and data were collected only from 2-m center sections of the two inner rows. Plots were either shallow-tilled or deep-tilled for weed control over the course of the season. Shallow-tilled plots were cultivated with both a rotary cultivator (Reigi-weeder; Univerco, Napierville, QC, Canada) and a rototiller (Proline FRT garden tiller; Troy-bilt, Valley City, OH) to a depth of ≈3 inches. Deep-tilled plots were cultivated to a depth of 10 inches with the rototiller. Any remaining weeds in the strawberry plant row were pulled by hand, dried in the sun, and then incorporated back into the soil during the next cultivation event. The field was tilled in Oct. 2013, Apr. 2014, June 2014, twice in July 2014, Aug. 2014, Sept. 2014, June 2015, July 2015, and Aug. 2015. Soil was collected before tilling when both occurred in the same month.

Soil amendments were applied again at the same rate per plot in Fall 2014 and 2015 and then incorporated, but only between the rows because plants were established in the row. Each winter the entire field was protected against cold damage with two layers of 1.5-oz/yard^2 spunbonded polypropylene rowcover (DeWitt Supreme Frost Blanket; Agricultural Solutions, Strong, ME) spread directly over the top of the plants and soil from December until March. All plots were band fertilized twice each summer with 65.2 lb/acre urea for a seasonal total of 60 lb/acre N.

To determine if standard mulching practices using straw mulch incorporation impacted strawberry plants, all plots received straw mulch at the beginning of harvest in Fall 2016 to keep fruit clean. After harvest, half of all the plots had their straw removed so there were two plots from each previous amendment and tillage depth combination that had straw and two that did not. This straw was incorporated in fall and the entire field was again overwintered under rowcover.

To summarize, plant establishment and yield in year 2 (2015) were measured in response to broadcast pre-plant soil amendments the fall before planting (2013) and between-row

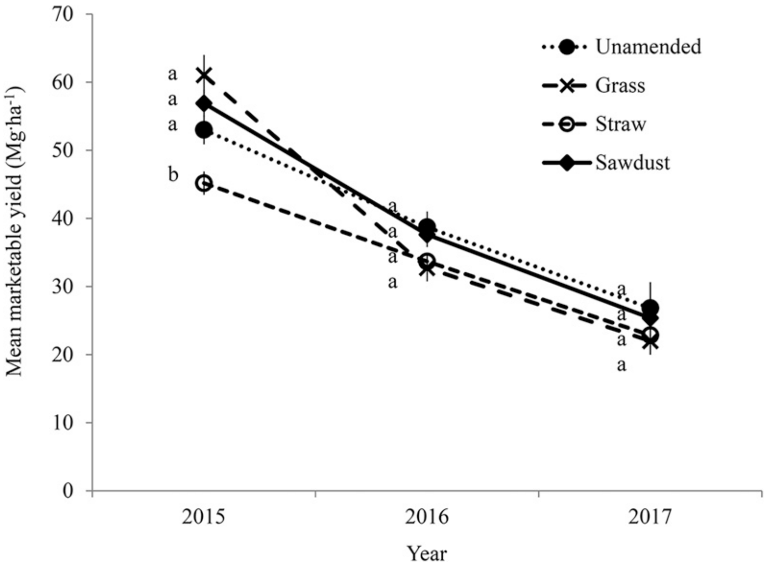

Fig. 1. Mean marketable yield (±SE) of strawberries in unamended plots or amended with sawdust, grass, or wheat straw. Within a year, yields with a common letter are not significantly different ($P < 0.05$) based on a Tukey's honestly significant difference test; 1 Mg·ha^{-1} = 0.4461 ton/acre.

incorporation of amendments in the fall of year 1 (2014). Yield in year 3 (2016) was measured in response to between-row incorporation of these same amendments in year 2 after harvest (2015). Yield in year 4 (2017) was measured in response to +/− straw mulch incorporation between rows after harvest in year 3 (2016).

Soil collection. Soil samples were collected 1 May (before planting), 17 June, and 20 Sept. 2014 and 19 May and 18 Aug. 2015. Unincorporated organic matter was removed and a 20-mm-diameter soil probe (compact soil probe; Oakfield Apparatus, Oakfield, WI) was used to collect the top 6 inches of soil. Within each plot, eight cores were collected and aggregated into two samples: four from between the strawberry rows and four from within the strawberry rows. On 1 May 2014, the strawberry plants were not yet planted, so eight cores were collected and all aggregated into one sample. Soil was stored at 3 °C until analysis.

Soil health indicators. For 2 years, we measured three biological soil health indicators: microbial respiration, potentially mineralizable N (PMN), and the soil C:N ratio, as well as soil pH and soil moisture. We measured PMN using the method from the Cornell Soil Health Test (Gugino et al., 2009). Briefly, ammonium N was measured using the colorimetric method (Mulvaney, 1996) on 2 M potassium chloride (KCl) extracts from two subsamples of 2-mm-sieved field-moist soil. One subsample was extracted after field sampling and the other was incubated under anaerobic conditions for 1 week and then extracted. The difference between the N concentrations, measured on a digital colorimeter (Digital colorimetric AutoAnalyzer III; Bran+Luebbe, Mequon, WI), is the PMN.

Soil respiration was measured using a modified method from Whitman et al. (2014). For 13 d, 10.00 ± 0.05 g of 4-mm-sieved field-moist soil was stored at 3 °C. Then the soil was placed into an air-tight chamber (1 qt jar; Ball, Broomfield, CO) and incubated in a completely dark incubation room held at 30 °C for a total of 20 d. The chamber contained 5 mL of carbon dioxide (CO_2)-free water, 15 mL of 0.09 M potassium hydroxide (KOH), and the

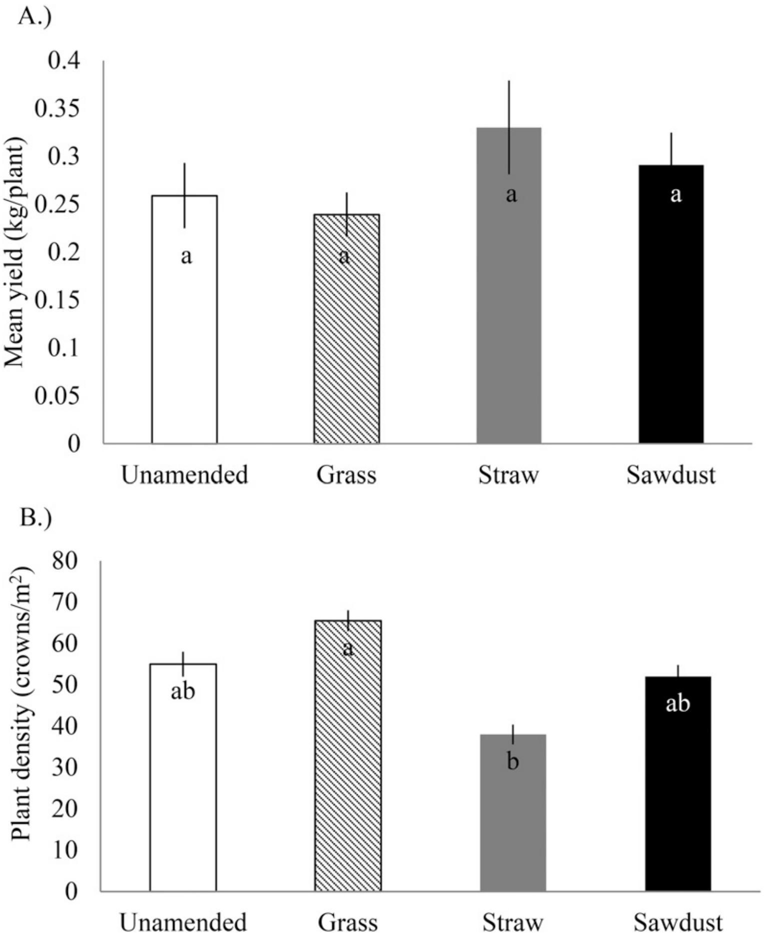

Fig. 2. Mean marketable yield (±SE) per plant of strawberry (A) and strawberry plant density (B) in unamended, sawdust, grass, and wheat straw-amended plots in 2015. Within a year, yields with a common letter are not significantly different ($P < 0.05$) based on a Tukey's honestly significant difference test; 1 kg = 2.2046 lb, 1 crown/m² = 0.0929 crown/ft².

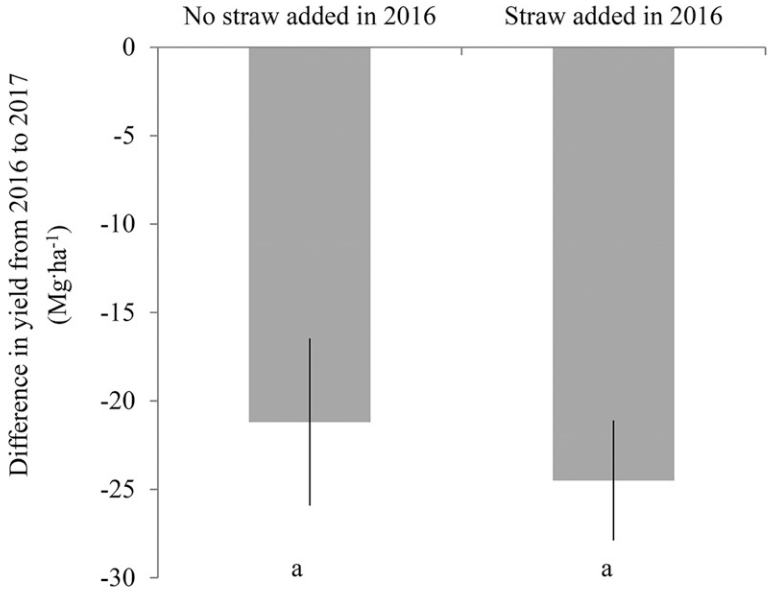

Fig. 3. Mean difference in marketable yield (±SE) from 2016 to 2017 of strawberry in plots with wheat straw mulch incorporation in Fall 2016 and plots without straw. Values were not significantly different ($P < 0.05$) based on a Tukey's honestly significant difference test; 1 $Mg\cdot ha^{-1}$ = 0.4461 ton/acre.

Table 1. Mean foliar nutrient concentrations for leaves collected in Aug. 2014 and before renovation in 2015 and 2017 from a strawberry field in Ithaca, NY. Leaves were from plants grown in plots with four different amendments (n = 8).

Nutrient concn and recommended range[z]	2014				2015				2017			
	Unamended	Grass	Straw	Sawdust	Unamended	Grass	Straw	Sawdust	Unamended	Grass	Straw	Sawdust
Carbon (%)	44	44	44	44	41	41	41	41	44	44	44	44
Nitrogen (%) 2.0–2.8	1.9	2	1.8	2.1	0.9	1.1	0.9	1	2.3	2.5	2.3	2.4
Potassium 1.5–2.5 (%)	1.7	1.5	1.6	1.7	1.8	2	2.1	1.9	1.1	1.2	1.2	1.2
Phosphorus 0.25–0.4 (%)	0.27	0.29	0.31	0.32	0.28	0.29	0.27	0.26	0.38	0.38	0.37	0.38
Calcium 0.7–1.7 (%)	1.7	1.3	1.5	1.4	1.6	1.8	1.8	1.9	0.6	0.6	0.6	0.6
Magnesium 0.3–0.5 (%)	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.3	0.3	0.3	0.3
Boron 30–70 ($mg\cdot kg^{-1}$)	32	31	32	34	33	34	33	32	18	17	16	18
Manganese 50–200 ($mg\cdot kg^{-1}$)	77	67	99	66	68	59	78	53	71	68	73	76
Iron 60–250 ($mg\cdot kg^{-1}$)	138 a[y]	161 ab	251 b	132 a	140	113	194	116	122 b	85 a	114 b	113 b
Copper 6–20 ($mg\cdot kg^{-1}$)	6.6	6.9	6.9	7.1	6	5.8	6.1	5.7	7.2	7.8	8.6	6.8
Zinc 20–50 ($mg\cdot kg^{-1}$)	25	21	23	23	22	22	23	22	23	24	25	24

[z] Pritts and Handley (1998); 1 $mg\cdot kg^{-1}$ = 1 ppm.

[y] Within a row, different letters indicate that nutrient levels are significantly different from each other based on amendment, calculated using a Tukey's honestly significant difference test ($P < 0.05$).

soil. The water, KOH, and soil were each held individually in open-topped glass vials within the chamber. Water kept the environment moist and the KOH reacted with all CO_2 introduced to the system through soil respiration. Electrical conductivity (EC) of the KOH was measured on days 2, 4, 7, 13, and 20 using a conductivity meter (Orion 115A+; Thermo Scientific, Waltham, MA), which was used to calculate the rate of CO_2 added to the system. Each time EC was measured, the water and KOH were replaced. A standard curve was used to calculate CO_2 respired.

Air-dried, 2-mm-sieved, ground soil was analyzed for C and N using an elemental analyzer (NC2500; Carlo Erba, Milan, Italy) coupled to an isotope ratio mass spectrometer (Delta V, Thermo Scientific). No carbonates were detected in the soil using a Bernard calcimeter method (Sherrod et al., 2002), and so all measured C was assumed to be organic C.

Soil pH was measured with a pH meter (Orion 3 Star; Thermo Scientific) on 2-mm-sieved, air-dried soil. A slurry of 10 g of soil in 30 mL of deionized water was shaken for 1 h and left to sit at least 10 min before measuring. The proportion of soil moisture was calculated by subtracting dry weight of a 30-g sample of soil dried at 105 °C for 24 h in a drying oven (model 16 Thelco; Precision Scientific, Chicago, IL) from the total soil weight and dividing by total soil weight.

PLANT VARIABLES. The youngest, fully formed strawberry leaves were collected in Aug. 2014, 2015, and 2017 for nutrient analysis. Leaves were dried in a drying oven (model SPX Blue M Electric; Thermal Product Solutions, New Columbia, PA) at 70 °C for 4 d. Nutrients were measured using microwave-assisted acid digestion of sediments, Environmental Protection Agency method 3051A (U.S. Environmental Protection Agency, 2007) using an automated digestion system (Vulcan 84; Questron Technologies Corporation, Toronto, ON, Canada). The macro- and micronutrient concentrations (other than C and N) were determined by analysis on an inductively coupled plasma spectrometer (Arcos; SPECTRO Analytical

Instruments, Mahwah, NJ). Total C and N for both the strawberry leaves and the soil amendments, which were also dried in an oven at 70 °C for 4 d, were measured using dry combustion as described for soil C and N.

Strawberry plant growth data were taken on 6 July 2015 after the last harvest by randomly placing two 0.25-m squares over representative sections of each row. All strawberry plant material within the squares was cut and dried at 55 °C for 7 d, weighed, and analyzed for nutrients, C, and N as described previously. Once leaves and stems were harvested for nutrient analysis, individual plants were counted and divided by total plot yield adjusted for 0.5 m of row. Plant density and yield per plant were calculated from these numbers.

We monitored strawberry yield in response to soil amendments and tillage depth over 3 years. Strawberry yield data were collected from June to July 2015, 2016, and 2017 from 2-m sections of each of the two middle rows in each plot. Rows were maintained at the standard 18-inch width, with 4 ft between row middles, so that 10,890 ft of strawberry row was equal to 1 planted acre. Yield harvested in kilograms per meter then could be converted to pounds per acre by multiplying by 7.3 or by 8.2 for kilograms per hectare. Fruit was harvested twice per week. Moldy and damaged fruit was weighed separately from marketable fruit.

Statistical analysis. R software was used for all statistical analyses (version 0.98.495, © 2009–13; RStudio, Boston, MA). All non-normal data were log transformed but reported means are back transformed. Results were considered significant if $P < 0.05$. For post hoc comparisons Tukey's honestly significant difference tests were used to determine significant differences between treatments. A linear mixed model was used to assess whether management practices affected soil health indicator tests, with treatments, sampling between or within rows, and their interactions as fixed effects, and individual plots as random effects. A linear model was used to determine if treatments had effects on yield and if there were significant correlations between yield and soil health indicators. A paired *t* test was used to assess changes in yield from 2016 to 2017 between plots receiving and not receiving incorporated straw in 2016.

Results

Strawberry yield. Yields dropped ≈30% in each year of our study despite near optimal field management. There was also ≈20% lower marketable yield in straw-amended plots compared with all other plots in the first fruiting year (2015) (Fig. 1). Yield per plant (as opposed to per unit area) was not significantly different among soil amendment treatments (Fig. 2A), but plant density in straw-amended plots was significantly lower (Fig. 2B) in 2015, resulting in an overall lower yield per unit area. There was no reduction in yield due to soil amendments in the second and third fruiting years (2016 or 2017). After the 2016 harvest, straw mulch was incorporated into half of the plots (n = 16) and the other half had straw removed before tillage. Overall yields decreased from 2016 to 2017, but there was no difference based on straw incorporation (Fig. 3). Tillage depth had no effect on yield in any year.

Leaf nutrient concentrations. All plant nutrient concentrations were within recommended ranges in 2014 and 2017 (Table 1) (Pritts and Handley, 1998). Leaf N did not differ among amendment treatments. Leaf N was lower than recommended in 2015, but this was true for both amended and unamended plots and all levels were within a narrow range (0.9% to 1.2%). Iron, N, and C were the only elements that varied significantly across treatments, but not in any predictable pattern (Table 2). Nutrient data were not collected in 2016.

Soil health indicators. Based on tillage depth, there were no differences in any of the soil health indicator tests we ran: soil respiration, PMN, the C:N ratio, soil moisture, or pH. However, soil respiration, PMN, soil moisture, and pH consistently responded to the organic amendment types or sampling location (Table 3). Soil respiration and

Table 2. Significant type 3 analysis of variance probability values from foliar nutrient concentrations for strawberry leaves collected in Aug. 2014 and before field renovation in 2015 and 2017 from a matted row strawberry field in Ithaca, NY. Leaves were from plants grown in plots with four different mulches tilled deep or shallow (n = 4). There were no significant interactions, but amendment type and tillage depth were occasionally significant ($P < 0.05$).

	2014			2015			2017		
	P value			*P* value			*P* value		
Nutrient	Amendment	Depth	Interaction	Amendment	Depth	Interaction	Amendment	Depth	Interaction
Carbon	NS[z]	NS	NS	0.02	NS	NS	NS	NS	NS
Nitrogen	NS	0.03	NS	NS	NS	NS	NS	NS	NS
Potassium	NS	NS	NS	NS	NS	NS	NS	NS	NS
Phosphorus	NS	NS	NS	NS	NS	NS	NS	NS	NS
Calcium	NS	NS	NS	NS	NS	NS	NS	NS	NS
Magnesium	NS	NS	NS	NS	NS	NS	NS	NS	NS
Boron	NS	NS	NS	NS	NS	NS	NS	NS	NS
Manganese	NS	NS	NS	NS	NS	NS	NS	NS	NS
Iron	0.007	NS	NS	NS	NS	NS	0.0007	0.006	NS
Copper	NS	NS	NS	NS	NS	NS	NS	NS	NS
Zinc	NS	NS	NS	NS	NS	NS	NS	NS	NS

[z] NS = not significant ($P > 0.05$).

Table 3. Mean values and significant probability values for effects of soil amendments, tillage depth, sampling between or within rows, and their interactions on five soil health indicators at each sample date and with all sample dates combined. The five soil health indicators were as follows: carbon dioxide (CO_2) from soil respiration, potentially mineralizable nitrogen (PMN), carbon:nitrogen (C:N) ratio, soil moisture, and pH. At the first sample date, no strawberry plants had been planted, so there was no sample location treatment. When appropriate, non-normal data were log transformed to satisfy the assumption of normality of residuals.

		Soil health indicator tests				
Sample date		Soil respiration [CO_2-C ($mg\cdot g^{-1}$)][z]	PMN ($mg\cdot g^{-1}$ soil-N)	C:N	Soil moisture (% w/w)	pH
1 May 2014	Mean values	0.32	2.03	14.2	16.2	7.1
	Amendment	<0.0001	0.008	NS	0.05	NS
	Tillage depth	NS[y]	NS	NS	NS	NS
	Amendment: Tillage	NS	NS	NS	NS	NS
17 June 2014	Mean values	0.31	1.79	13.7	7.1	7.1
	Amendment	<0.0001	NS	NS	NS	NS
	Tillage depth	NS	NS	NS	NS	NS
	Sample location	NS	NS	NS	NS	NS
	Amendment: Tillage	NS	NS	NS	NS	NS
	Amendment: Sample location	NS	NS	NS	NS	NS
	Tillage: Sample location	NS	NS	NS	NS	NS
24 Sept. 2014	Mean values	0.27	0.87	13.8	12.2	7.0
	Amendment	NS	NS	NS	NS	NS
	Tillage depth	NS	NS	NS	NS	NS
	Sample location	NS	NS	NS	<0.0001	<0.0001
	Amendment: Tillage	0.01	NS	0.02	NS	NS
	Amendment: Sample location	0.04	NS	NS	NS	NS
	Tillage: Sample location	NS	NS	NS	NS	NS
19 May 2015	Mean values	0.34	0.75	14.0	15.5	6.9
	Amendment	<0.0001	0.01	NS	NS	NS
	Tillage depth	NS	NS	NS	NS	NS
	Sample location	NS	NS	NS	NS	0.0002
	Amendment: Tillage	NS	NS	NS	NS	NS
	Amendment: Sample location	0.03	NS	NS	0.02	NS
	Tillage: Sample location	NS	NS	NS	NS	NS
19 Aug. 2015	Mean values	0.32	0.73	13.9	12.1	6.8
	Amendment	NS	NS	NS	0.002	NS
	Tillage depth	NS	NS	NS	NS	NS
	Sample location	NS	0.01	NS	<0.0001	<0.0001
	Amendment: Tillage	NS	NS	NS	NS	NS
	Amendment: Sample location	NS	NS	NS	NS	NS
	Tillage: Sample location	NS	NS	NS	NS	NS
Overall average	Mean values	0.31	1.23	13.9	12.2	6.9
	Amendment	<0.0001	NS	NS	NS	NS
	Tillage depth	NS	NS	NS	NS	NS
	Sample location	NS	NS	NS	<0.0001	<0.0001
	Amendment: Tillage	0.02	NS	NS	NS	NS
	Amendment: Sample location	NS	NS	NS	NS	NS
	Tillage: Sample location	NS	NS	NS	NS	NS

[z] 1 $mg\cdot g^{-1}$ = 1000 ppm.

[y] NS = not significant ($P > 0.05$).

PMN were primarily affected by amendment, with sawdust-amended soil having the highest respiration rate at every sampling date and with unamended soil having the lowest PMN every spring (Table 4). Soil moisture and pH were higher between the rows than within the rows (Fig. 4). Soil C:N ratio was unaffected by any of the amendments or tillage depth.

When soil health indicator data from each sampling date were averaged, soil respiration increased with increasing amendment C:N ratio, but this increase was more pronounced in shallow-tilled plots than deep-tilled plots (Fig. 5). When PMN and soil C:N data from each sampling date were averaged, the effect of amendment was not significant (Table 3).

SOIL HEALTH INDICATORS AND YIELD CORRELATIONS. Neither soil respiration nor PMN were significantly correlated with marketable yields in 2015, 2016, or 2017 (Table 5).

Discussion

The respiration rate and, in May, the PMN rate, responded to soil amendment additions in a predictable

Table 4. Mean carbon dioxide (CO_2) from soil respiration and potentially mineralizable nitrogen (PMN) at each sample date based on soil amendments added to a strawberry field. Within a sample date, respiration rates or PMN with a common letter are not significantly different ($P < 0.05$) based on a Tukey's honestly significant difference test and columns with no letters indicate no significant differences. When necessary, non-normal data were log transformed to satisfy the assumptions of normality of residuals, but back transformed means are reported here.

	May 2014	June 2014	Sept. 2014	May 2015	Aug. 2015
		Soil respiration [CO_2-C ($mg \cdot g^{-1}$ soil carbon)]^z			
Unamended	0.19 a	0.19 a	0.25	0.25 a	0.22 a
Sawdust	0.55 c	0.38 bc	0.28	0.50 b	0.53 b
Grass	0.28 b	0.26 b	0.27	0.30 a	0.25 a
Straw	0.28 ab	0.44 c	0.27	0.31 a	0.26 a
		PMN ($mg \cdot g^{-1}$ soil-N)			
Unamended	1.5 a	1.5	0.8	0.5 a	0.6
Sawdust	2.7 b	1.8	0.9	0.8 ab	0.9
Grass	1.8 a	1.9	0.9	0.8 ab	0.8
Straw	2.1 ab	1.9	0.9	0.9 b	0.6

^{z}1 $mg \cdot g^{-1}$ = 1000 ppm.

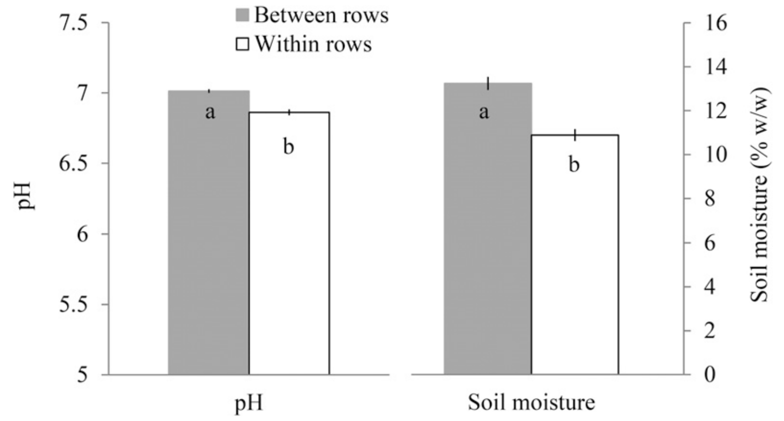

Fig. 4. Soil moisture and pH (±SE) of soil sampled from between strawberry rows or within strawberry rows. Values within a panel with a common letter are not significantly different ($P < 0.05$) based on a Tukey's honestly significant difference test.

way. Greater respiration rates with more added C are consistent with Monaco et al. (2008), who also reported increased soil potential respiration and PMN when organic C amendments were added to farm soil as compared with bare soil or inorganic N additions. These researchers also found that respiration rates were highest with straw, the highest C:N ratio amendment in their study. Soil nutrient stoichiometry has been shown to affect the soil microbial community (Chen et al., 2014). Stoichiometry may also explain the effect of the interaction between soil amendments and tillage depth on the combined soil respiration (over all sample dates). A review by Cleveland and Liptzin (2007) found common C:N:phosphorous (C:N:P) ratios in the soil of 186:13:1. If we assume higher N and P levels near the soil surface than deeper in the soil profile, soil microbial communities in the top of the profile may have enough native soil N and P to metabolize any added C. The respiration rate would be highly correlated with added C because the stoichiometric limit would be much higher. However, communities deeper in the soil profile would use up the native soil N and P more quickly, and then additional incorporated soil C would increase respiration at a slower rate as it reached a nutrient limitation. Treonis et al. (2010) also found greater increases in microbial activity higher in the soil profile, but that tilling increased the depth that these increases were noticed. They found different soil bacterial community biomarkers when they added soil amendments and either tilled or did not till, indicating shifts in community structure.

The higher pH in soil between than within rows may be a result of ion exchange during plant nutrient uptake. As plants take up cations they release hydrogen (H^+) ions, decreasing pH over time (Randall et al., 2006; Wang et al., 2006). Also, urea, which was used to fertilize this strawberry field, acidifies the soil (Cai et al., 2014; Jiang et al., 2014) and was band applied to the planted row.

Changes in measured soil health indicators responded in ways consistent with current understanding of soil biological activity; however, they did not correlate with yield. Plant tissue analysis was also not predictive of yield, as it mostly stayed within recommended ranges. In 2015, leaf N was lower than recommended but this was true for both amended and unamended plots and levels still remained within a narrow range, so it did not seem to be the primary reason for the reduced marketable yield. Because yield per plant was not depressed in straw-amended soil, only yield per hectare, the lower yield in straw-amended plots seemed to be the result of poor plant runnering and growth of daughter plants, resulting in low plant density. Stolon development in June-bearing strawberries occurs during long photoperiods and high temperatures (Heide, 1977); however, this should have been unaffected by straw amendments. From a subsequent greenhouse experiment, there was no evidence of herbicidal or allelopathic activity in the straw that would have inhibited plant establishment (Gannett, 2016). However, strawberry stolon number is lower and their length longer in low nutrient environments (Tworkoski et al., 2001). Amendment particle size does affect decomposition and the rate and timing of N immobilization (Angers and Recous, 1997; Tarafdar et al., 2001). Perhaps the timing of N immobilization in our straw-amended plots corresponded with stolon production and therefore decreased first year yield.

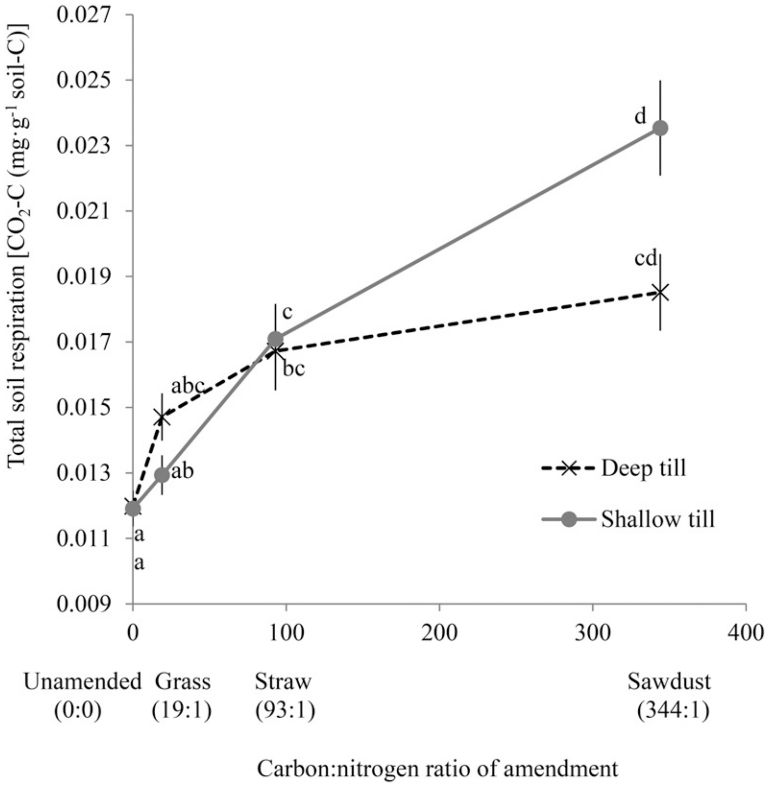

Fig. 5. Mean total carbon dioxide (CO_2) from soil respiration (±SE) of soil from plots that were unamended or amended with grass, wheat straw, or sawdust, which have increasing carbon:nitrogen (C:N) ratios, and either deep-tilled or shallow-tilled. Points with a common letter are not significantly different ($P < 0.05$) based on a Tukey's honestly significant difference test; 1 mg·g^{-1} = 1000 ppm.

Yearly declines in matted row strawberry yield are typical, as the berry size decreases each year (Pritts and Handley, 1998). Therefore, a typical perennial strawberry planting will only be in production for 4 years (three fruiting seasons) before it is replanted (Pritts and Handley, 1998). Growers are advised to change the location of their strawberry field when they replant and to stay out of strawberry in the original location for 2 to 5 years unless they fumigate the soil (Funt et al., 2004). Fungal pathogens, especially verticillium wilt (*Verticillium dahliae*) and *Fusarium* wilt (*Fusarium oxysporum*), accumulate in the soil and cause strawberry diseases and decreased yield (Fang et al., 2012; Subbarao et al., 2007). Weed seed populations also build up, so rotating with a cover crop can improve weed management and increase strawberry plant density and yield (Portz and Nonnecke, 2011). Decreases in yield when a farmer does not rotate the field are collectively known as strawberry replant disorder. Another factor that may play a role in strawberry replant disorder, based on our findings, is planting into straw residue that remains after the last strawberry crop. It is unclear how long straw residue must decompose before it does not impact strawberry plant establishment.

Although planting into incorporated straw residue was detrimental for strawberry establishment, there was no measurable impact of straw incorporation into the row middles once plants were established. Because growers only incorporate straw between rows in established plantings, any negative effect might be spatially separated from the active rhizosphere.

Although the soil health indicators used in this experiment were responsive to amendments, they were unable to predict yield. Future soil health indicators designed for perennial strawberry will need to measure processes that link soil functioning and yield. Early stolon production is highly correlated with yield, so it might be a good response variable to use for assessing soil health indicators in perennial strawberry.

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Table 5. Significant probability values from correlations between soil health indicator tests and marketable strawberry yield in 2015, 2016, and 2017.

Sample date	Respiration	PMN[z]	C:N[z]	Soil moisture	pH	Respiration	PMN	C:N	Soil moisture	pH	Respiration	PMN	C:N	Soil moisture	pH
	2015					2016					2017				
1 May 2014	NS[y]	NS	NS	NS	NS	NS	NS	NS	0.009	NS	NS	NS	NS	NS	NS
Between															
17 June 2014	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Between															
Within	0.01	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
24 Sept. 2014	NS	0.006	NS	NS	NS	NS	0.003	NS	NS	NS	NS	NS	NS	NS	NS
Between															
Within	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	0.01	NS	NS	NS
19 May 2015	NS	NS	NS	NS	NS	NS	0.03	NS	NS	NS	NS	NS	NS	NS	NS
Between															
Within	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
19 Aug. 2015	NS	NS	NS	0.01	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Between															
Within	NS	NS	NS	NS	0.03	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Overall	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

[z] PMN = potentially mineralizable nitrogen, C:N = carbon:nitrogen ratio.

[y] NS = not significant ($P > 0.05$).

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