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Tarping and mulching effects on crop yields, profitability, and soil nutrients in a continuous no-till organic vegetable production system

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Abstract

Small-scale organic vegetable farms need strategies to overcome yield, labor, and economic challenges in transitioning to reduced and no-till practices. However, the production tradeoffs associated with different scale-appropriate management practices are not well documented for these operations. We evaluated crop yields, labor, profitability, and soil nutrients over four continuous years of management in Freeville, NY. Cabbage (Y1 and Y3) and winter squash (Y2 and Y4) were managed in permanent beds under four contrasting tillage systems: conventional rototilling to 20 cm depth (CT), shallow rototilling to 10 cm (ST), no-till (NT), and no-till with tarping (NTT), in which an impermeable, black polyethylene tarp was applied to the soil surface between crops. Within each tillage treatment, we compared three mulching systems: rye mulch (RM), compost mulch (CM), and no mulch (NM), where mulches were applied annually to each crop. Crop yields did not vary by tillage, except in RM, where yields were highest in CT and reduced in ST and NT over four years. Mulch treatments were a significant driver of crop yields. When compared to NM, RM reduced crop yields in the first two years and CM increased yields after the first year. Overall, RM systems had the lowest net returns and CM returns were equivalent to NM despite greater yields. No-till consistently required the greatest pre-harvest labor investment, up to two times greater than tilled systems with NM, and the lowest net returns. Labor requirements for NTT were greater than CT but up to 41% lower than NT, and profitability was equivalent to CT. Shallow tillage performed similar to CT across yield, labor, and profitability measures, except when combined with the use of RM. Compost mulching led to dramatic changes in soil properties after four years, including a 49% increase in total soil carbon, a 31% increase in total soil nitrogen, and a 497% increase in extractable phosphorus. Small farms adopting NT practices should: 1) consider the potential tradeoffs associated with annually applied organic mulches, and 2) integrate tarping to increase the profitability of NT over consecutive production years.

Introduction

Organic vegetable farmers typically rely on frequent tillage to manage weeds, prepare seedbeds, and to warm and loosen soil for planting (Lowry and Brainard, 2019b). On very small 'market' farms, operations commonly less than 2 ha, the consequences of intensive, repeated tillage on soils can be magnified by land constraints that limit fallow periods and extensive cover cropping. Challenges to adopting reduced tillage (RT) and no-tillage (NT) practices in organic vegetable systems include greater weed competition (Baker and Mohler, 2015; Bietila et al., 2017; Testani et al., 2019), difficulties with plant residue management, low soil temperatures and fertility (Lilley and Sánchez, 2016), and reduced crop establishment and/or lower yields (Jackson et al., 2004; Delate, Cwach and Chase, 2012). Strategies to reduce tillage in organic vegetable production often focus on the use of specialized equipment, including strip tillage and NT roller crimper applications, and cereal-legume cover crop mixtures (Jokela and Nair, 2016a, 2016b; Lowry and Brainard, 2019a; Robb et al., 2019; Maher et al., 2021). These practices are generally rotational and targeted to specific crops and planting windows. However, small organic vegetable farms maintain highly diverse cropping systems that need labor-efficient, scale-appropriate NT strategies that can be applied over consecutive years to balance production, financial, and soil health goals.

Recently, small-scale organic vegetable farmers in North America have combined organic mulches and tarping approaches to design novel NT systems specific to their farm goals, skills, and resources (Mefferd, 2019; Mays, 2020; O'Hara, 2020; Frost, 2021). Organic mulches, including straw and hay, have well-known soil quality and production benefits: preventing erosion (Crowley et al., 2018), conserving soil moisture during prolonged dry periods (Schonbeck and Evanylo, 1998a), improving biological activity in soils (Schonbeck and Evanylo, 1998b), suppressing annual weeds (Schonbeck, 1999; Brown and Gallandt, 2018), and increasing crop yields (Schonbeck and Evanylo, 1998a; Brown and Gallandt, 2018). However, applying straw mulch has also been shown to delay crop establishment and growth, which is often attributed to cooler soil temperatures (Schonbeck and Evanylo, 1998a) and nitrogen immobilization with high C:N ratio in mulch residues (Black and Reitz, 1972; Sarrantonio, 2003), while also being labor intensive to apply (Brown, Hoshide and Gallandt, 2019). In contrast to straw and hay, research on compost applied as a surface mulch has lagged behind farmer interest and adoption. Compost mulch (CM), with annual application rates often ranging widely (from 3–10 cm depth), could be a component of a scale-appropriate NT production system that rapidly improves soil tilth, increases crop yields, and suppresses weeds when maintained with minimal soil disturbance over time. In on-farm studies (six farms ranging from 0.2 to 8 hectares), CM (leaf-based; one-time application up to 5 cm layer) was shown to increase overall yields in tomatoes and reduce weeds, though not as well as hay mulch (Schonbeck and Evanylo, 1998a). In the same trial, hay mulch reduced the subsequent time for hand weeding or hoeing compared to an unmulched control, compensating for the time required to apply the mulch (Schonbeck, 1999). In another on-farm study (Feldman, Holmes and Blomgren, 2000), CM (manure-based; annually applied 10 cm layer) on permanent beds over 3 years increased crop yields in cabbage and melons compared to no mulch (NM) or landscape fabric. This yield increase was associated with dramatic changes in soil quality, including an increase in organic matter, soil moisture moderation and conservation, and greater nutrient concentrations. Despite the high yield potential, compost at mulching rates can be difficult to source, labor intensive to apply (Schonbeck, 1999; Feldman, Holmes and Blomgren, 2000), costly to import (which may reduce overall profitability; Law et al., 2006), and lead to excessive P and N loading (Small, Shrestha and Kay, 2018; Small et al. 2019). Each of these challenges with CM management could limit farmer adoption.

Tarping has become a popular weed and soil management practice for small farms in North America since the publication of *The Market Gardener* (Fortier, 2014). Tarping involves the application of reusable opaque black polyethylene sheeting (5–6 mil) to the soil surface for a period of days to weeks between crop plantings. Tarps can be applied in a range of field applications, prior to both transplanted and direct-seeded crops, and with duration extending several months (overwinter periods or over sod) depending on field conditions and management goals. They are commonly applied after tillage, warming soils and moderating soil moisture, to create a stale seedbed and reduce weed emergence in the following crop (Birthisel et al., 2019; Birthisel and Gallandt, 2019; Kinnebrew et al., 2022). Tarps can also be used in NT applications to overcome some of the common barriers to NT adoption. Tarping has shown to effectively terminate living weeds and cover crops prior to planting (Lounsbury et al., 2020; Rylander et al., 2020a), increase soil nitrogen availability (Rylander et al., 2020a), reduce weed competition for the following crop, and increase crop yields (Rylander et al., 2020b; Lounsbury et al., 2022). Farmers often cite tarps' weed suppression benefits while acknowledging their labor and logistical challenges (Kinnebrew et al., 2022), but the effects of tarping on labor requirements and profitability in NT systems are not well-documented. Tarping studies in continuously managed permanent bed systems and in combination with other soil management practices are needed to support farmer decision-making in the transition to NT production.

While NT tarping and mulching practices are most applicable to small-scale farms, there are few crop budget analyses that are appropriately scaled to these operations (Hendrickson, 2005; Wiswall, 2009; Conner and Rangarajan, 2009) and they do not compare the economics of adopting various cropping systems with different levels of tillage. Brown, Hoshide and Gallandt (2019) performed a crop budget analysis in onions (one year) under varying physical weed management practices, and found the greatest yields in hay mulch, attributed to improved weed control, which also led to a favorable net income despite having the greatest total labor expenses. In a longer-term study under a four-year rotation, Chan et al. (2011) used flexible, dynamic crop budgets to compare profitability of four organic vegetable cropping systems and found that a RT system using ridge tillage incurred intermediate outcomes between intensive and 'bio-extensive' production systems, in terms of gross income and net return per hour of total labor. These crop budget analyses have shown that net returns are highly sensitive to crop yields, which emphasizes the importance of developing NT practices that can overcome potential yield gaps.

This study was designed to identify the potential tradeoffs associated with tillage, organic mulches, and tarping practices to support farm transitions to RT and NT management. Both tillage and organic mulching practices can have legacy effects on soil fertility (Feldman, Holmes and Blomgren, 2000) and weed seedbanks (Jernigan et al., 2017; Brown and Gallandt, 2018; Mohler et al., 2018), which need to be accounted for through long-term, continuously managed studies. To this end, we established a permanent bed vegetable production system to compare the performance of four tillage systems, including conventional, shallow, NT, and NT with tarping, using different organic mulches (compost, rye, and no mulch) over four consecutive years of management. We hypothesized that: (1) crop yields, labor, and profitability would vary based on tillage intensity and mulch applications, (2) mulches would improve outcomes in NT systems by providing additional weed management benefits, (3) tarping would increase the profitability of a NT system across mulches through greater crop yields and labor efficiencies, and (4) organic inputs in mulches would strongly affect soil parameters after four years.

Methods

Site description and experimental design

The experiment was located at the Homer C. Thompson Vegetable Research Farm in Freeville, NY (42.523204, −76.326472). The soil type is mapped as Howard gravelly loam, a well-drained loamy-skeletal, mixed, active, mesic Glossic Hapludalf. The experiment was established in the fall of 2014, where the previous crops (cabbage and broccoli) were mowed and harrowed, and the entire field was amended with manure-based compost (22 Mg ha^{-1} fresh weight). The experiment was designed as a permanent bed management system, with treatments established and implemented in the same plots over four consecutive production years: 2015 (Y1), 2016 (Y2), 2017 (Y3) and 2018 (Y4). Equipment wheels and foot traffic were confined to the same between-bed pathways for the full duration of the experiment.

This experiment used a split-plot randomized complete block design with four replications. Main plot treatments included four tillage systems: conventional rototill (CT), shallow depth rototill (ST), no-till (NT), no-till with tarping (NTT; Table 1). Main plots were 22.8 m long and 5.5 m wide, consisting of three 1.2 m wide beds with 0.6 m wide pathways. CT was performed with a 1.2 m wide tractor-mounted rototiller (Maschio Fresa; Dewitt, IA) set to its maximum depth of 20 cm. For ST, the same implement was adjusted to operate at minimum depth, resulting in a tillage depth of 7.5–10 cm. NT employed no primary tillage, and hand tools (e.g., wheel hoes) were used to undercut weeds for hand removal and to prepare beds for planting. NTT used 6 mil black polyethylene tarps (Husky; Grand Prairie, TX) applied to the soil surface and removed prior to planting with minimal to no soil disturbance thereafter. Tarps were impervious to water and sized to cover the entire main plot. They were applied and removed by hand and held in place with sandbags placed at 2–3 m intervals along the tarp perimeter, with additional bags placed in two pathways down the length of the tarp to maximize contact with the bed surface and secure from wind. In Y1 and Y3, tarps were applied in mid-April and left in place for 7–8 weeks prior to crop planting. For Y2 and Y4, tarps were applied in mid-November the previous fall and left in place over winter until planting in early June (>6 months).

Within each tillage treatment, three mulch treatments were established as subplots: rye mulch (RM), compost mulch (CM), and no mulch (NM) (Table 2). Each mulch subplot was 5.5 m wide (3 beds) and 7.6 m long. Mulch treatments were first applied in September 2014, to establish treatments prior to Y1. In NM, an oat (*Avena sativa*) cv. 'Kame' and field pea (*Pisum sativum*) cv. '4010' cover crop mixture was drilled at 112 kg ha^{-1} oats and 56 kg ha^{-1} peas using a 1.8 m wide grain drill (Kasco EcoDrill; Shelbyville, IN) in August of Y1 and Y3, after cash crop harvest. No cover crop was planted in Y2 and Y4.

RM and CM treatments were applied annually to each crop. Wheat straw was initially used for RM in Y1, which resulted in volunteer wheat plants. For Y2 to Y4, the mulch source was switched to rye, made by mowing and baling cereal rye during flowering to contain no viable grain seed and minimal weed seeds. RM was applied by hand across the entire field area (beds and pathways) to attain a depth of approximately 7.5–10 cm. Field application rates varied based on the year: 15.7 Mg ha^{-1} at fall 2014 establishment, 7.9 Mg ha^{-1} in Y1, 9.4 Mg ha^{-1} in Y2, 15 Mg ha^{-1} in Y3, and 15 Mg ha^{-1} in Y4. In early May of each year, rye from the previous year was raked off the beds into the pathways prior to tillage (CT and ST) and hand labor (NT) operations (Table 3). In NTT, tarps were applied directly over RM, which was then raked after tarp removal and prior to planting. In Y1, RM was applied after bed preparation (e.g., tillage, fertilizer applications) and prior to transplanting, and the crop was transplanted into the mulch. In Y2 to Y4, mulching was delayed until 17–19 days after planting, shortly after the first cultivation, to facilitate mechanical transplanting and improve early crop establishment.

Compost treatments used a 3–4 cm layer of compost applied as mulch. Compost was organically approved (Cornell University Farm Services; Ithaca, NY) and manure-based with primary feedstocks including horse and dairy manure and bedding and forage materials. Compost was tested annually after application (UME Analytical Lab; Orono ME). When averaged across years, compost on a dry matter basis had a pH of 7.3, 238 g total C kg^{-1}, 13.5 g total N kg^{-1}, 6.1 g total P kg^{-1}, and 7.3 g total K kg^{-1}. Compost was applied using a tractor-mounted manure spreader (H&S 80; Marshfield, WI) modified with plywood shields that restricted material from spreading onto pathways and directed compost onto the bed surface. Actual field application rates of compost were measured in micro-plots using a 0.87 m^2 tarp placed on the soil prior to application and rates varied by year. Dry weights were 89 Mg ha^{-1} in the fall establishment year; 83 Mg ha^{-1} in Y1; 82 Mg ha^{-1} in Y2; 77 Mg ha^{-1} in Y3; and 43 Mg ha^{-1} in Y4. These application rates are reported based on the amount applied to the bed surface (1.2 m) which excludes the between-bed pathways (0.6 m) that did not receive compost, so the total quantity applied on a per hectare basis was 33% less (five-year average rate of 50 Mg DM ha^{-1}). After compost was spread mechanically, it was raked to provide a uniform coverage over the bed. Compost was applied prior to crop planting with timing based on the tillage treatment: after the first primary tillage event in CT and ST, after hand weeding in NT, and after tarp removal in NTT.

Cabbage (*Brassica oleracea* var. *capitata*) 'Farao' and winter squash (*Cucurbita pepo*) 'Bush Delicata' were grown in alternate years. Cabbage (Y1 and Y3) was planted three rows per bed at 0.3 by 0.5 m spacing, and squash (Y2 and Y4) was spaced at 0.6 m apart in single rows. Both crops were transplanted in early June each year. In Y1, all treatments were planted by hand; in Y2 to Y4, a mechanical transplanter was used in NM and RM, where soils were bare at planting, and CM was hand planted to minimize disturbance of the compost layer. Certified organic seed was used for all crop years and transplants were grown in a certified organic greenhouse. NM and RM treatments

Table 1. Summary of primary tillage, cultivation, and hand weeding events in tillage and mulch treatments over four years

Tillage	Tillage description	Primary tillage			Crop cultivation			Hand weeding[a]		
		NM	CM	RM	NM	CM	RM	NM	CM	RM
		# of events								
CT	Rototill to 20 cm	8	4	8	8	0	3	8	8	7
ST	Rototill to 10 cm	8	4	8	8	0	3	8	8	7
NT	No-till with hand tools	0	0	0	8	0	3	19	19	18
NTT	No-till with tarping	0	0	0	8	0	3	12	12	11

Mulch (no mulch, NM; compost mulch, CM; and rye mulch, RM).
[a]Hand weeding includes in-row hoeing at time of cultivation (all treatments), using wheel hoes to kill and remove weeds prior to planting (NT only), and hand removal of large weeds after crop harvest (NT and NTT only).

Table 2. Summary of organic mulch treatments applied annually to each crop within each tillage treatment

Mulch	Mulch description	Mulch depth	Annual mulch application[b]	Total applications in mulch (5 year sum)[c]			Total applications in fertilizer (4 year sum) [d]	
			Mg DM ha^{-1} yr^{-1}	Mg C ha^{-1}	Mg N ha^{-1}	Mg P ha^{-1}	Mg N ha^{-1}	Mg P ha^{-1}
NM	No mulch; oat-field pea cover crop[a]	-	-	-	-	-	0.53	0.16
CM	Compost mulch, manure-based	3–4 cm	75	85	4.5	1.9	-	-
RM	Rye mulch, early cut cereal rye	7.5–10 cm	12	29	0.35	0.14	0.53	0.16

[a]Cover crop planted in Y1 and Y3 after cash crop harvest.
[b]Average application over five years, including the year prior to the first crop, and annual applications to each crop (Y1-Y4); dry matter (DM) basis with rates reported as applied to the planting bed.
[c]Total carbon (C) and nitrogen (N) and phosphorus (P) in compost based on annual analysis of compost sampled at the time of application. In RM, values are based on estimates of 47% C, 0.6% N, and 0.24% P.
[d]Based on annual fertilizer applications of pelleted chicken litter (5-4-3) at 2240 kg ha yr^{-1} to each crop.

Table 3. Management timeline of field operations for tillage and mulch treatments over four years

Field operation	Mulch NM	Mulch CM	Mulch RM	Year 1 Date	Year 1 DAT[a]	Year 2 Date	Year 2 DAT	Year 3 Date	Year 3 DAT	Year 4 Date	Year 4 DAT
Tarp applied to NTT	X	X	X	4/15	−48	11/16/15	−203	4/14	−56	11/21/17	−197
Rake RM to pathways[b]			X	5/11	−22	5/6	−31	5/9	−31	5/2	−35
First tillage in CT and ST	X	X	X	5/14	−19	5/10	−27	5/11	−29	5/2	−35
First NT bed preparation	X	X	X	5/15	−18	5/13	−24	5/10	−30	5/3	−34
Fertilizer application[b]	X		X	5/19	−14	6/1	−5	5/31	−9	5/30	−7
Second NT bed preparation	X	X	X	5/20	−13	6/1	−5	6/1	−8	5/31	−6
Compost mulch applied[b]		X		5/21	−12	5/19	−18	6/6	−3	6/4	−2
Second tillage in CT and ST	X		X	5/20	−13	6/2	−4	6/2	−7	5/31	−6
Tarp removed in NTT	X	X	X	5/28	−5	5/31	−6	5/26	−14	6/4	−2
Cash crop transplanted	X	X	X	6/2	0	6/6	0	6/9	0	6/6	0
First between-row cultivation	X		X	6/19	17	6/20	14	6/22	13	6/20	14
Rye mulch applied			X	5/26	−7	6/24	18	6/26	17	6/25	19
Second between-row cultivation	X					7/7	31	7/5	26	7/6	30
Third between-row cultivation	X					7/18	42				
First hand weeding	X	X	X	6/17	15	6/20	14	6/22	13	6/20	14
Second hand weeding	X	X	X	7/24	52	7/13	37	7/5	26	7/9	33
Hand weed NT and NTT	X	X	X	10/6	126	9/19	105	8/7	59	9/17	103
Crop yield and quality assessment	X	X	X	8/10	69	10/4	120	8/22	74	9/12	98
Post-harvest tillage in CT and ST	X			8/25	84			8/29	81		
Cover crop seeded	X			8/27	86			8/30	82		
Cover crop mowed	X			11/3	154			11/15	159		

Tillage (conventional, CT; shallow, ST; no-till, NT; and no-till with tarping, NTT); Mulch (no mulch, NM; compost mulch, CM; and rye mulch, RM).
[a]DAT, days after transplanting.
[b]For NTT, the timing of raking in RM, application of CM, and fertilizer applications occurred after tarp removal and prior to planting.

were fertilized at planting with 2240 kg ha^{-1} of 5-4-3 pelleted chicken litter (Kreher Family Farm; Clarence, NY). Fertilizer was incorporated via rototilling in DT and ST plots, wheel hoeing at bed preparation in NT, and tine weeding in NTT. No fertilizer was applied to CM plots because nutrients in the compost exceeded fertilizer recommendations.

The frequency and timing of hand weeding and cultivation varied by treatment and year (Table 3), and was maintained as similarly to grower practice as possible. Plots were hand weeded twice annually, with additional hand weeding at or after crop harvest in NT and NTT based on grower practice of mitigating potential seed rain from large, seed-bearing weeds (Armour,

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personal communication). Both CM and RM plots were hand weeded at a similar frequency to NM to manage any weeds emerging through the mulch during the season. Additionally, NM plots were cultivated between rows 1–3 times annually with tractor-mounted beet knives, and RM plots were cultivated once prior to mulch application (Y2 to Y4). CM plots were not tractor cultivated, so as to minimize disturbance of the compost layer on the soil surface. Pathways between NM and CM beds were cultivated with tractor-mounted sweeps as needed to manage weeds throughout the season. All crops were mowed after harvest with a 1.2 m rotary mower (John Deere 48; Moline, IL).

Pests and diseases were monitored over the season and organic pesticides were applied uniformly to all treatments when needed. Approved organic insecticides were applied according to standard scouting methods in cabbage to manage flea beetle (Entrust SC; 0.29 L ha^{-1}) and imported cabbage worm (Dipel DF; 2.24 kg ha^{-1}), and in winter squash for striped cucumber beetle (Surround; 28 kg ha^{-1} in Y2). In Y4, floating row covers were applied at planting to all treatments to control striped cucumber beetles and removed after four weeks. Crops were watered in at transplanting and overhead irrigation was applied uniformly to all plots based on crop needs annually, with no supplemental irrigations in Y1, five in Y2, one in Y3, and one in Y4.

Crop yields

Cabbage was harvested in mid-August of Y1 and Y3 from two 3.1 m row sections (Y1) and three 3.1 m row sections (Y3). Heads were weighed fresh and rated for pest and disease damage for marketability. Winter squash was harvested from a 3.1 m section of each plot at maturity, counted, and weighed in mid-September (Y4) and early October (Y2). Immature and defective fruit were sorted and weighed separately. All harvest data were collected from the center bed of each plot. After data sampling, all remaining crops were harvested and removed from the experiment to simulate a commercial harvest.

Pre-harvest labor

Pre-harvest labor hours were calculated based on the sum of all hand labor and equipment labor hours required for crop production, excluding harvest, washing, and packing. Harvest and post-harvest labor were not included in this estimate to clarify the effects of each management system on labor efficiency for crop production, independent of crop yields. While farmers strive to reduce pre-harvest labor, they generally accept higher harvest labor that is directly associated with greater yields. All hand labor operations were timed and recorded in the field, including hand weeding, handling mulch (application and raking), handling tarps (tarp application, removal, and adjustment), fertilizer application, transplanting, and other tasks. All equipment operations were recorded, including rototilling, pathway cultivation, between-row crop cultivation, compost application, and pesticide application. Estimates for equipment time for each task were based on Hendrickson (2005), Wiswall (2009), and Pike (2016) and adjusted according to field observations. Setup and turn-around times were included to make values appropriate for small-scale farms. Our estimates of the labor needed to perform these tasks assumes that farms (<2 ha) have access to some level of mechanized equipment, otherwise the time associated with tasks may be higher for those operations that perform a greater percentage of labor by hand (e.g., transplanting, compost application).

Crop budgets

Crop budgets were created to compare the economic performance of each treatment using marketable yields and estimated costs for various field operations (Chan et al., 2011). Costs and receipts were based on a small-scale farm (<2 ha) with some mechanization, where the operator performs all labor and markets at retail prices. Net returns were calculated based on crop sale receipts, minus machinery costs, material costs, marketing costs, and fixed costs (land, building, and equipment). For parameters and assumptions used to derive economic variables, the same values were used in all years. Costs for materials (fertilizer, compost, and transplants) were based on local prices, and the cost of tarps was amortized over a six-year lifespan (Table 4). Based on the Maine Organic Price Report (Maine Organic Farmers and Growers Association. Organic Price Reports, 2015–2018), the retail price for organic cabbage and winter squash was set at \$3.30 kg^{-1}. The fuel cost was \$0.79 $liter^{-1}$. The proportion of crop sold was set at 90% of marketable crop yields to account for marketing fluctuations and the marketing cost was estimated at 20% of crop cash sales based on input from farmer advisors in previous work (Stoner, 2008). Fixed overhead costs were based on Hendrickson (2005) and Stoner (2008). Equipment ownership cost was estimated at \$647 (0.1 ha^{-1}) and land and building load was \$507 (0.1 ha^{-1}). To estimate harvest labor, the harvest rate was set at 114 kg $hour^{-1}$ and a wash and pack rate was set to be 273 kg $hour^{-1}$ for both crops. Many of these assumed values are high relative to published budgets because they are based on small-scale scenarios. Net returns are reported per total labor hour (including equipment, hand, and harvest labor) which represents a key metric on small farms and serves as a useful measure of labor-efficiency, especially for farmer-owners who often perform all or the majority of the labor for their own operation (Weil et al., 2017).

Soil analyses

Soil cores (0–30 cm) were collected from CT, NT, and NTT plots (each mulch treatment) in the fall of Y4 to document treatment effects on total carbon (TC), total nitrogen (TN), and extractable

Table 4. Material costs associated with each mulch treatment averaged over four years

	Four year average costs		
Materials	NM	CM	RM
	------Dollars 0.1 ha^{-1}-------		
Transplants	\$350	\$350	\$350
Compost mulch	-	\$660	-
Rye mulch	-	-	\$326
Cover crop seed	\$49	-	-
Pesticides	\$49	\$49	\$49
Fertilizer	\$61	-	\$61
Tarps[a]	\$58	\$58	\$58
Total materials	\$510	\$1059	\$787

Mulch (no mulch, NM; compost mulch, CM; and rye mulch, RM).
[a]Tarp costs apply to the no-till tarp tillage treatment only and are shown for comparison. They are not displayed in total material costs for each mulch.

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phosphorus (P). Six cores (2.2 cm dia) collected from beds of each plot (excluding pathways) were separated into 3 depths (0–10, 10–20, and 20–30 cm), composited, subsampled, and air-dried at 45°C. Soil bulk density samples were collected separately by taking one larger diameter soil core (6.5 cm dia) from each plot, divided into similar depth increments, dried at 105°C and weighed. Soil nutrient analyses were conducted using modified Morgan soil nutrient extraction (Dairy One Laboratory, NY). Total carbon and nitrogen concentrations were determined using a combustion analyzer (Elementar CN; CNAL Laboratory, NY), and stocks (kg m^{-2}, 0–30 cm) were calculated based on the bulk density of each soil layer with corrections for coarse fragments (Throop et al., 2012), where coarse fragments averaged 23% of total soil mass.

Statistical analyses

All data were analyzed using RStudio (R Core Team, 2020). Where necessary, data were log transformed. The 'lme4' package was used to create linear mixed models for assessing the fixed effects of tillage system and mulch (Bates et al., 2015). Treatment effects were determined via Type III Sums of Squares tests, where treatment differences were deemed significant at $P < 0.05$. Post-hoc pairwise comparisons were made using 'emmeans' and likewise were considered significantly different at $P < 0.05$ (Lenth, 2020). In an effort to clarify trends in marketable crop yields, pre-harvest labor, and cash returns per labor hour over the four-year duration of the experiment, values were normalized to the standard practice (CT + NM = 1.0) within each year. These four-year relative values were then compared to account for year-to-year and crop-to-crop variability and summarize treatment effects over the duration of the four-year experiment.

Results and discussion

Marketable crop yields

Tillage affected cabbage yields in both years (Y1 and Y3) and had no effect on winter squash yields (Table 5). In Y1, tillage effects on yield varied by mulch. Cabbage yield in NTT was 37–40% greater than in tilled systems within NM and CM, and greater than NT within CM. Yield differences between tillage systems within RM were variable and not significant. In Y3, cabbage yields in CT were 13% greater than NT. In contrast, yields in NTT were either greater than or equal to CT across all years. Lower yields in NT organic vegetable systems are often attributed to greater weed densities (Delate, Cwach and Chase, 2012; Lilley and Sánchez, 2016; Rylander et al., 2020a, 2020b; Lounsbury et al., 2022). However, multiple crop cultivations and hand weeding events were performed to minimize crop-weed competition (Table 1), including a zero-seed rain approach (Brown and Gallandt, 2019) within NT and NTT systems. This suggests that NT yields in Y3 cabbage were likely limited by soil-related factors (e.g., N availability) rather than weed competition. When averaged over four years, yields in NT and NTT were equivalent to CT in NM and CM; NT yields were reduced in RM (Table 6). Yields in ST were equivalent to CT, except for RM, suggesting that farmers could maintain CT yields and reduce tillage intensity by approximately 50% with relatively small adjustments in the operating depth of tillage equipment (from 8 cm to 4 cm).

Mulch effects on crop yields varied by tillage in Y1 and were consistent across tillage treatments thereafter (Table 5). In Y1, cabbage yield in RM was reduced by 57–87% relative to NM and CM with the greatest yield decrease within NT. In contrast, yields in RM were greater than and equal to NM in Y3 and Y4, respectively. Reduced yields in RM were likely related to a

Table 5. Marketable crop yields for tillage and mulch treatments over four years

Tillage	Year 1, Cabbage			Year 2, Winter squash			Year 3, Cabbage			Year 4, Winter squash		
	NM	CM	RM	NM	CM	RM	NM	CM	RM	NM	CM	RM
	Marketable yield, kg 0.1 ha^{-1}											
CT	3211	3376	1380	1663	1618	1243	5687	6749	6557	1506	1905	1893
	Ba	Ba	b									
ST	3248	3230	896	1479	1953	810	5574	6199	6161	1612	2030	1353
	Ba	Ba	b									
NT	4081	2832	648	1368	2009	593	5052	5862	5579	1465	1829	1496
	Aba	Bb	c									
NTT	4479	4608	1085	1491	1903	641	4765	6561	5866	1438	1957	1767
	Aa	Aa	b									
T		**			ns			*			ns	
								CT > NT				
M		***			***			***			**	
					CM > NM > RM			CM = RM > NM			CM > NM = RM	
TxM		*			ns			ns			ns	

Tillage (conventional, CT; shallow, ST; no-till, NT; and no-till with tarping, NTT); Mulch (no mulch, NM; compost mulch, CM; and rye mulch, RM).
Main effects are not shown where interaction effects are significant.
Differences in means are shown between tillage systems within a mulch (column; capital letters) and between mulches within tillage (row; lower case letters) for each year. Letters are only shown where treatment means are significantly different ($P < 0.05$).
ns, *, **, *** Nonsignificant or significant at $P < 0.05$, 0.01, or 0.001, respectively.

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Table 6. Four-year average crop yields, pre-harvest labor hours, and net returns per total labor hour for tillage and mulch treatments relative to conventional practice (CT+NM)

Tillage	Relative crop yields			Relative pre-harvest labor hours			Relative net returns		
	NM	CM	RM	NM	CM	RM	NM	CM	RM
	------------------------------------Relative to CT + NM---------------------------------								
CT	1.00	1.13	0.90	1.00	1.30	1.49	1.00	0.83	0.57
	ab	a	Ab	Cc	Bb	Ba	Aa	ABab	Ab
ST	0.99	1.16	0.69	1.04	1.27	1.63	0.97	0.97	0.21
	a	a	Bb	Cc	Bb	Ba	Aa	ABa	Bb
NT	0.99	1.09	0.61	2.11	1.97	1.97	0.63	0.68	0.16
	a	a	Bb	Aa	Ab	Aab	Ba	Ba	Bb
NTT	0.99	1.26	0.71	1.25	1.36	1.65	0.86	1.03	0.27
	b	a	ABc	Bb	Bb	Ba	ABa	Aa	ABb
T		*			***			**	
M		***			***			***	
TxM		*			***			*	

Tillage (conventional, CT; shallow, ST; no-till, NT; and no-till with tarping, NTT); Mulch (no mulch, NM; compost mulch, CM; and rye mulch, RM).
Differences in means are shown between tillage systems within a mulch (column; capital letters) and between mulches within tillage (row; lower case letters) for each year. Letters are only shown where treatment means are significantly different ($P < 0.05$).
ns, *, **, *** Nonsignificant or significant at $P < 0.05$, 0.01, or 0.001, respectively.

combination of adverse weather conditions and greater pest pressure. In Y1, RM was applied prior to cabbage planting and likely delayed crop establishment and early growth in a wet spring, especially in NT systems. In Y2, warm and dry conditions after winter squash establishment coincided with a severe striped cucumber beetle infestation and heavy plant feeding in RM plots. Applying RM favored these pests and contributed to stand loss, which averaged almost 50% (data not shown). Improved crop yields in RM in Y3 and Y4, similar to or greater than NM, suggests the timing of mulch application (2–3 weeks post-transplanting) and other cultural practices (e.g., row cover for winter squash) could help farmers reduce the likelihood of crop losses in this system. Others have found that cultivation after crop planting and prior to mulch application can improve crop yields (Law et al., 2006), and have suggested the importance of delaying hay mulch application until after crop establishment to allow for soil warming (Schonbeck and Evanylo, 1998a).

CM increased crop yields across tillage systems after Y1. Yields in CM were greater than NM in Y3, and greater than both NM and RM in Y2 and Y4. Sustained yield improvements with CM after Y1 could be related to changes in soil organic matter, nutrient availability, structural properties, and biological factors associated with applying compost at mulching rates (see Table 7). On average across all four years, tarping increased relative yields in CM (27% greater than NM and 77% greater than RM; Table 6). Surprisingly, within other tillage systems, yields in CM did not differ significantly from NM, though they trended higher. Tarps have been shown to moderate soil moisture (Lounsbury et al., 2020) and increase plant-available soil N for the following crop (Rylander et al., 2020a, 2020b). It is likely that the use of tarps in a NTT + CM system improved soil conditions for crop growth through a combination of changes in the planting zone, including increasing moisture availability, concentrating crop-available nutrients, lowering soil bulk density, and enhancing weed suppression. Given the high nutrient loading in a CM system, tarping in this system may function to retain soil inorganic N and mitigate the potential for N leaching, especially when applied overwinter and early spring.

Pre-harvest labor hours

Pre-harvest labor hours for cabbage ranged from 89–170 hours 0.1 ha^{-1} in Y1 and 63–118 hours 0.1 ha^{-1} in Y3 (Table 8). Generally, winter squash required less labor than cabbage, ranging from 41–115 hours 0.1 ha^{-1} in Y2 and 37–110 hours 0.1 ha^{-1} in Y4. Tillage and mulch had strong effects on labor requirements, and there was a significant interaction between these factors in all years. Labor hours for CT and ST did not differ in any year or across mulches. NT required significantly more labor than tilled systems, especially in NM, with an average of 31–57% more labor for cabbage and 137–201% more labor for winter squash. In NM, tarping reduced pre-harvest labor required for NT by an average of 27% in cabbage and 48% in winter squash. While tarping reduced NT labor requirements in cabbage, NTT required more labor than tilled systems in winter squash (Y2 and Y4). Over four years, tarping reduced labor for NT by 41% but required 25% more labor than conventional tillage (CT + NM; Table 6).

Organic vegetable farmers typically rely on tillage to terminate weeds and prepare seed beds prior to planting without herbicides. We found that winter annual weeds (primarily common chickweed, *Stellaria media*) were well established by spring and NT required significant labor to remove these weeds by hand and create an adequate bed for planting. This hand labor accounted for as much as 40% of the total pre-harvest labor in NT + NM systems when averaged over four years (data not shown). Tarping eliminated this particular labor requirement for NT planting and created a bed free of living weeds without soil disturbance. However, our results also show that tarping can add significant labor, including the application and removal of tarps, such that a

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Table 7. Total carbon (TC), total nitrogen (TN), and extractable phosphorus (P, modified Morgan) by depth after four years of continuous management under tillage and mulch treatments

Tillage	Mulch	0–10 cm			10–20 cm			20–30 cm			0–30 cm		
		TC	TN	P	TC	TN	P	TC	TN	P	TC	TN	P
		-- g kg^{-1}--		mg kg^{-1}	--g kg^{-1}--		mg kg^{-1}	--g kg^{-1}--		mg kg^{-1}	--Mg ha^{-1}--		kg ha^{-1}
CT	NM	23	2.0	22	21	1.8	14	19	1.7	8	54	4.7	36
				b	b	b							
	CM	66	4.5	138	49	3.7	104	27	2.3	31	90	6.8	167
				Ba	Aa	Aa							
	RM	23	1.9	21	21	1.9	14	22	1.7	13	57	4.8	41
				b	b	b							
NT	NM	23	2.1	18	21	1.8	8	19	1.7	6	61	5.3	28
				b	b	b							
	CM	86	5.8	311	34	2.5	60	22	1.9	15	85	6.4	179
				Aa	Ba	Ba							
	RM	25	2.1	29	19	1.6	11	18	1.5	7	58	5.0	41
				b	b	b							
NTT	NM	23	2.0	25	20	1.7	7	19	1.6	5	59	5.0	32
				b	b	b							
	CM	84	5.6	409	34	2.6	56	22	1.8	11	84	6.4	213
				Aa	Ba	Ba							
	RM	25	2.1	32	20	1.7	11	20	1.6	8	64	5.4	47
				b	b	b							
T		ns	ns	*	**	***	***	ns	ns	***	ns	ns	ns
							[a]			[a]			
M		***	***	***	***	***	***	***	**	***	***	***	***
		[b]	[b]				[b]	[b]	[b]	[b]	[b]	[b]	[c]
TxM		ns	ns	*	*	**	ns	ns	ns	ns	ns	ns	ns

Tillage (conventional, CT; shallow, ST; no-till, NT; and no-till with tarping; NTT); Mulch (no mulch, NM; compost mulch, CM; and rye mulch, RM).
Differences in means are shown between tillage systems within a mulch (column; capital letters) and between mulches within tillage (row; lower case letters) for each year. Letters are only shown where treatment means are significantly different ($P < 0.05$).
ns, *, **, *** Nonsignificant or significant at $P < 0.05$, 0.01, or 0.001, respectively.
Main effects are not shown where interaction effects are significant.
[a]CT > NT = NTT.
[b]CM > RM = NM.
[c]CM > RM > NM.

NTT system required an average of 25% more labor than CT + NM over four years (Table 6). The labor to fix and adjust wind-blown tarps can also contribute to added labor hours, especially in overwinter tarping periods where they remain in place for longer durations. Farmers will need to plan for these labor needs and develop strategies to streamline tarp management logistics. It is also important to consider that tarping can occur in the shoulder seasons, when other field activities are minimal or restricted by adverse field conditions (e.g., wet soils), and this labor benefit is not quantified in our measure of total pre-harvest labor hours. The added management flexibility and 'placeholder' function of tarping is often cited by farmers as a major benefit (Kinnebrew et al., 2022).

Using mulches greatly increased pre-harvest labor hours, especially in tilled systems. CM added significant labor in tilled systems relative to NM, ranging from 36–46% more labor in CT (Y2-Y4) and 41–43% in ST (Y2 and Y3). Compost mulching had a smaller effect on labor hours within NT (16–18% increase in Y2 and Y4, and 34% decrease in Y4) and increased labor for NTT in only one of four years (by 47% in Y3). RM had a more consistent effect on pre-harvest labor across tillage systems and years. Across all years, RM required more labor than NM within tilled systems, ranging from 46–88% more labor for cabbage and 41–52% for winter squash. Within NTT, RM required an average of 48% more labor than NM in cabbage and led to a smaller increase (25% in Y2) or no effect (Y4) in winter squash. Using RM added less labor for NT relative to other tillage treatments, where it added 20% more labor for cabbage and had either no effect (Y2) or required less labor for winter squash (reduced 34%, Y4). Labor required by CM was either less than or equal to RM, except within NT in Y2. Based on four-year averages among tilled systems, NM had the lowest labor requirements,

Table 8. Pre-harvest[a] labor hours for crop production for tillage and mulch treatments over four years

Tillage	Year 1, Cabbage			Year 2, Winter squash			Year 3, Cabbage			Year 4, Winter squash		
	NM	CM	RM	NM	CM	RM	NM	CM	RM	NM	CM	RM
	--Pre-harvest labor hours, 0.1 ha^{-1}------------------------------											
CT	97	90	142	42	60	59	63	92	96	37	50	56
	Bb	Bb	Ba	Cb	Ba	Ba	Bb	ABa	Ba	Cb	Ba	Ba
ST	98	89	143	41	58	60	63	89	118	42	48	62
	Bb	Bc	Ba	Cb	Ba	Ba	Bc	Bb	ABa	BCb	Bb	ABa
NT	152	138	170	99	115	95	91	107	116	110	71	72
	Ab	Ac	Aa	Ab	Aa	Ab	Ab	Aa	Aa	Aa	Ab	Ab
NTT	106	99	158	55	58	69	69	95	101	53	54	60
	Bb	Bb	ABa	Bb	Bb	Ba	Bb	ABa	ABa	B	B	B
T		***			***			***			***	
M		***			***			***			*	
TxM		***			***			**			***	

Tillage (conventional, CT; shallow, ST; no-till, NT; and no-till with tarping, NTT); Mulch (no mulch, NM; compost mulch, CM; and rye mulch, RM).
Differences in means are shown between tillage systems within a mulch (column; capital letters) and between mulches within tillage (row; lower case letters) for each year. Letters are only shown where treatment means are significantly different ($P < 0.05$).
NS, *, **, *** Nonsignificant or significant at $P < 0.05$, 0.01, or 0.001, respectively.
[a]Pre-harvest labor hours include hand and equipment labor hours required for crop production, excluding harvest, washing, and packing.

RM required the most labor, and CM was intermediate. Trends in NTT were similar to tilled systems, where RM significantly increased labor and CM was not different from NM. In contrast, mulching in NT either had no effect (RM) or reduced pre-harvest labor hours (CM).

Mulching effects on pre-harvest labor hours can be associated with several management factors, including the time required to apply the mulch, effects on the efficiency of transplanting (hand planting vs mechanical), and effects on weed suppression and subsequent labor hours for weed management (Schonbeck, 1999, Brown, Hoshide and Gallandt, 2019). In tilled systems, greater labor needs in mulch treatments were largely the result of the time invested in mulch application. For example, the hand labor to apply RM accounted for an average of 36% of total pre-harvest labor over four years, outweighing any labor savings associated with a reduction in equipment operations (see tillage and cultivations in Table 1) or time spent hand weeding. Similar results were evident in CM, where the labor saved via fewer equipment operations was outweighed by the time spent applying compost, though CM applications were generally more efficient than RM and comprised a smaller percentage of total pre-harvest labor hours (13% averaged over four years). The mechanized compost application method used in this study likely contributed to some labor efficiency so these differences are conservative, and small-scale farms relying on hand application of compost at mulching rates would likely have greater labor investments.

RM required more labor than CM averaged over four years (Table 6), which was largely due to the intensive hand labor requirements associated with transplanting cabbage by hand in Y1. In that year, RM was applied prior to planting which interfered with planting operations and required a greater labor investment to plant within the mulch. After Y1, RM application was delayed until several weeks after planting, which enabled more efficient mechanical transplanting and reduced labor differences between mulches. CM was planted by hand in all years to avoid disturbance of the compost surface layer with the transplanter. However, hand planting in CM was generally more efficient and less labor intensive than hand planting into RM.

Mulches had a relatively small effect on hand weeding time within the crop, which contrasts with other studies in hay and straw mulch (Schonbeck, 1999; Brown, Hoshide and Gallandt, 2019). More important in this study, where NT treatments were managed over consecutive years, we found that both CM and RM required significant hand weeding labor to prepare beds for planting the next crop, as winter annual weeds (primarily chickweed) emerged through the mulch the following spring. RM was more effective at suppressing these weeds than CM and required approximately half as much labor to prepare the bed for planting (data not shown). This labor savings was generally outweighed by the high labor requirements associated with RM application. While CM required more hand weeding labor than RM for bed preparation, less labor was required for application given our mechanized approach. As a result, when accounting for all hand weeding and application labor, mulches offered little to no labor savings for NT when averaged across four years (Table 6). However, we found that combining tarping with mulching provided significant labor efficiencies for NT, especially in CM. Applying tarps directly over mulches killed weeds that emerged through mulch and created a weed-free bed for planting with little to no soil disturbance. Farms considering the transition to these integrated NT systems should develop methods to reduce the labor necessary for handling tarps and mulch application to increase farm profitability.

Net returns per total labor hour

Net returns for cabbage ranged from negative (−5) to 49 dollars labor $hour^{-1}$ in Y1 and increased across all systems to 54–78 dollars labor $hour^{-1}$ in Y3 (Table 9). Winter squash returns were lower and more similar between years, ranging from −8 to 25

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Table 9. Net returns per total labor hour for tillage and mulch treatments over four years

Tillage	Year 1, Cabbage			Year 2, Winter squash			Year 3, Cabbage			Year 4, Winter squash		
	NM	CM	RM	NM	CM	RM	NM	CM	RM	NM	CM	RM
	---Dollars labor hour^{-1}---											
CT	36	35	4	25	12	8	78	71	69	28	26	27
ST	36	34	−3	18	21	−8	77	67	61	29	31	10
NT	35	21	−5	9	14	−8	60	58	54	12	20	14
NTT	49	49	0	17	21	−12	65	68	62	19	27	22
T		**			ns			***			*	
		NTT > NT						CT = ST > NT			CT > NT	
M		***			***			*			*	
		NM = CM > RM			NM = CM > RM			NM > RM			CM > RM	
TxM		ns			ns			ns			ns	

Tillage (conventional, CT; shallow, ST; no-till, NT; and no-till with tarping, NTT); Mulch (no mulch, NM; compost mulch, CM; and rye mulch, RM).
Differences in means are shown between tillage systems within a mulch (column; capital letters) and between mulches within tillage (row; lower case letters) for each year. Letters are only shown where treatment means are significantly different ($P < 0.05$).
ns, *, **, *** Nonsignificant or significant at $P < 0.05$, 0.01, or 0.001, respectively.
Main effects are not shown where interaction effects are significant.

dollars labor hour^{-1} in Y2 and 12 to 31 dollars labor hour^{-1} in Y4. Net returns were significantly affected by tillage in three of four years, wherein NT was generally the least profitable. Net returns between CT and ST did not differ in any year. No-till was less profitable than CT by 21% in Y3 and 44% in Y4. Interestingly, net returns in NTT were equivalent to tilled systems in all years, and 91% greater than NT in Y1. Relative four-year net returns of the NT system were 37% less than CT + NM, and NTT produced intermediate returns.

Tillage treatment effects on net returns were largely attributable to differences in labor requirements, except for RM where yields were reduced by ST and NT. The profitability of NT was reduced by the additional labor costs for hand weeding and spring bed preparation prior to planting. Tarping increased the net returns of NT by reducing pre-plant labor for weed management such that it became equally profitable as CT. Despite the added labor associated with tarp management, these results show how tarping could improve the profitability of NT production for organic farmers who have few options for suppressing and killing living weeds without tillage.

Mulch had a significant effect on net returns in all years, with RM consistently the least profitable. Both NM and CM produced greater net returns than RM in three of four years. RM generated negative returns in Y1 and Y2, while NM and CM averaged 37 and 17 dollars hour^{-1} in Y1 and Y2, respectively. Returns in RM were more similar to other mulches after Y2, but remained significantly lower than NM in Y3 and CM in Y4. There was no difference in net returns between NM and CM systems in any year. When averaged across all four years, RM relative net returns were consistently lower than NM across all tillage systems (Table 6). The profitability of RM in ST, NT, and NTT ranged from 73 to 84% lower than CT + NM. Within CM, the NTT system produced 35% greater relative returns than NT, suggesting that tarping can significantly improve the profitability of this system.

Very low, and sometimes negative, net returns in RM for the first two years were reflective of very poor crop yields in those years. Dramatic yield improvements in RM in Y3 and Y4 were likely due to changes in management to improve crop establishment, including post-transplant mulch application (cabbage) and the use of row covers (winter squash). The sensitivity of RM profitability to these relatively small changes in crop management underscores the significance of the learning curve for farmers and the potential risks associated with adopting a RM system. Despite producing greater RM yields in Y3 and Y4, decreased profitability relative to NM (Y3) and CM (Y4) demonstrated that such yield gains may not outweigh labor costs required by RM. This contrasts the findings of Brown, Hoshide and Gallandt (2019), where in a tilled system, the yield benefits associated with improved weed management outweighed the labor hours required to apply the mulch.

Surprisingly, net returns of NM and CM systems were not different despite consistently higher yields in CM after Y1. The increased labor associated with CM, as well as the expense of purchased compost inputs, could be a constraint for farmers considering this system. For example, Law et al. (2006) found that the expense of purchasing CM (8 cm depth) outweighed any yield gains. CM was most profitable when used in a NTT system, where yields were up to 25% greater than CT + NM. This suggests that tarping with CM can provide the NT yield increases that are needed to compensate for the additional costs of mulch management. Further, after a NTT + CM system is established, it may be possible to reduce compost applications and increase net returns in future years.

Total soil carbon, nitrogen, and extractable phosphorus

Mulch systems significantly impacted soil total carbon (TC), nitrogen (TN), and modified-Morgan extractable phosphorus (P) concentrations, and their distribution in the soil profile (Table 7). As expected, CM had greater TC and TN concentrations relative to both NM and RM, and these differences varied by soil depth and tillage treatment. At the soil surface (0–10 cm), TC and TN in CM were 3 times and 2.6 times greater than in NM, respectively. While there was no difference in TC or TN between tillage treatments at this depth, soil organic matter concentrations in NT and NTT with CM were 41% greater than

CT with CM (144 vs. 102 g kg $^{-1}$; data not shown). At 20–30 cm, TC concentrations in CM ranged from 1.6 to 2.7 times greater than other mulch treatments and TN was 1.4 to 2.5 times greater. Conventional tillage led to a greater concentration of TC and TN at this 20–30 cm depth. There were no differences in TC or TN between NM and RM at any depth.

Phosphorus concentrations followed similar trends to TC and TN. CM increased extractable soil P across all tillage systems and soil depths. At 0–10 cm, P concentrations were 10–17 times greater than NM and RM treatments, with the greatest concentrations in NT and NTT. CM also led to greater P concentrations at 10–20 cm, where tillage in CT increased P relative to NT and NTT. The effect of CM at 20–30 cm was smaller, although P concentrations remained elevated compared to NM and RM and were greatest in the CT treatment.

Soil bulk density was lowest on the soil surface and increased with depth, ranging from 0.46–0.99 g cm^{-3} at 0–10 cm, 0.97–1.35 g cm^{-3} at 10–20 cm, and 1.37–1.5 g cm^{-3} at 20–30 cm (data not shown). Surprisingly, no differences in bulk density were detected across tillage treatments. However, mulch affected bulk density at both 0–10 cm and 20–30 cm depths. Bulk density of CM at 0–10 cm was about half that of NM and RM (0.43 vs. 0.87 and 0.94 g m^{-3}). At 10–20 cm, this difference was reduced, but still significant (1.09 vs. 1.28 and 1.33 g m^{-3}). Bulk density did not differ by treatment at the 20–30 cm depth. When adjusted for bulk density, tillage treatments had no effect on the mass of TC, TN, or P across the 0–30 cm soil profile (Table 7). However, CM led to 49% more TC, 31% more TN, and 497% more P than NM.

It is important for the increasing number of farmers using CM in NT production to recognize the dramatic changes in soil properties that can develop, as these changes have major consequences for crop production and nutrient management. Compost mulching to achieve a depth of 3–4 cm required an average rate of 75 Mg DM ha^{-1}, equivalent to a total application of 50 Mg DM ha^{-1} when calculated on an area basis that includes between-bed pathways. At this rate, compost can lead to greater crop productivity, driven by changes in soil physical, chemical, and biological properties, including reduced bulk density, soil water retention, and greater crop nutrient supply (Feldman, Holmes and Blomgren, 2000; Law et al., 2006). Data on the effects of contrasting tillage systems over time is limited and this study shows that NT + CM can contribute to the stratification of soil properties, leading to a greater concentration of these nutrients on the soil surface.

Despite benefits to crop production, however, overapplication of compost is known to contribute to excess soil P (Reider et al., 2000) and applying at a mulch rate dramatically increases this surplus. Average annual P applications in compost applied in this study, 374 kg P ha^{-1}, far exceeded recommended rates, at nearly 10 times the P applied in NM, and rendered P vulnerable to losses to the environment (Small et al., 2019). As farmers consider using CM to advance NT production goals, they can expect low nutrient use efficiency and high potential for both P and N leaching as applications far exceed crop demand and uptake (Small, Shrestha and Kay, 2018). They may also need to consider nutrient management regulations that restrict P applications. In the case of N, despite an over 8-fold increase in total N applied in CM when compared to NM, we found a much smaller accumulation in total soil N after four years (31% increase) which shows the potential for significant N losses from the planting bed (0–30 cm) and the need to further document N cycling and movement in a CM system. Nutrient loading with CM and the associated environmental risks will depend on compost application rate and frequency and material feedstocks. Using compost without manure feedstocks and reducing compost rates over time may be a strategy to provide NT yield improvements while reducing these risks.

The fate of soil TC in a CM system is also not well documented. Annual CM applications contributed a total of 85 Mg C ha^{-1} (over 5 years) to the planting bed area and led to the accumulation of 29 Mg C ha^{-1} when compared to NM (49% increase), which shows both the magnitude of soil C inputs in a CM system as well as the potential for C losses through soil respiration processes. In contrast to CM, RM did not result in greater TC than NM despite annual inputs of 5.8 Mg C ha^{-1}. This could be attributed to our RM management practices, where mulch that was applied the previous year was raked from beds into between-bed pathways to minimize soil incorporation and N immobilization, facilitate planting without residue interference and help suppress pathway weeds. Our study did not account for any changes in soils in these pathways and the potential movement of nutrients to these between-bed areas, which comprised one-third of the total field area. Management practices in pathways, including mulching and cultivation methods, are an important consideration for farmers adopting a permanent bed management system as they can present an additional set of soil and weed management conditions.

Conclusions

Small-scale, organic vegetable farms need to consider the agronomic, economic, and environmental sustainability of adopting NT practices. Scale-appropriate tools and strategies that are suitable for diversified farms with intensive rotations and optimize labor efficiency can facilitate the transition from conventional tillage. Results from this study suggest that reducing tillage on these farms could be as accessible as adopting shallow tillage practices (from 8 cm to 4 cm) with relatively small equipment adjustments to standard crop production methods. Alternatively, tarping can increase the viability of organic NT production by reducing labor costs and providing a weed-free planting environment with minimal soil disturbance. While tarping saved labor for NT production, we found that the profitability of tarping in NT was also limited by the labor associated with tarp management. These costs could be mitigated to the extent that farmers develop management plans to streamline tarp logistics and improve the timeliness of labor use by applying them at either non-peak management times or when other operations are constrained by field conditions. While this research was focused on transplanted and mulched crops, tarps could provide a complementary strategy for direct-seeded crops, which are also commonly grown in rotation on small vegetable farms and for which mulching is neither practical nor appropriate. Using NT in combination with organic mulches, may provide additional soil health benefits such as protecting soils from erosion and enhancing soil physical and biological functions. However, both compost and rye mulching add significant labor and materials expenses, especially when applied annually, that can reduce the profitability of these practices. Our results also suggest that there are other management tradeoffs specific to each mulch strategy. Rye mulching decreased crop yields in some years; management changes that improve early crop establishment and reduce sensitivity to pests can improve crop productivity in this system. Compost mulching can confer greater yield potential, especially when combined with NT and tarping practices, and lead to rapid increases in soil organic matter, but can also lead to excessive nutrient loading. Further work that integrates tarping and mulching practices in vegetable rotations over time and documents legacy effects of these practices will support farmers in overcoming NT production challenges.

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