Integrated weed management with strategic tillage can maintain soil quality in continuous living cover systems

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Maximizing living cover and minimizing soil disturbance with no-till are key strategies in regenerative row-crop production. Although living cover and no-till can increase beneficial soil carbon and water stable aggregates (WSA), annual crops in rotation with perennials often rely on herbicides to control weeds and terminate perennials. Integrated weed management (IWM) reduces reliance on herbicides by employing multiple weed control strategies including tillage and/or cultivation. However, many no-till growers are reluctant to implement some soil disturbance due to concerns about negative impacts on soil health. For that reason, we hypothesized that compared to continuous no-till and standard herbicides (NT-SH), a strategic inversion tillage in IWM (ST-IWM) would result in lower soil carbon and WSA in the year following the tillage event. We also hypothesized that soil carbon and WSA would not differ between the two systems when sampled after cover cropping and 2 years of perennials. We tested these hypotheses within a 6-year, diverse, dairy crop rotation initiated in 2010 in central Pennsylvania in a channery silt loam soil. The systems were compared in split-plots in a full crop entry experiment, where the six phases of the crop rotation were planted every year in a randomized complete block design, replicated four times. We compared the soil health indicators in spring 2010 prior to the start of the experiment and in 2013 and 2019 following inversion tillage (ST-IWM) or herbicide termination (NT-SH) of the perennial forage in the first year of the rotation. We also compared these indicators in the sixth year of the rotation after 3 years of annual and cover crops and 2 years of perennial forage. We sampled at two depths: 0−5 and 5−15 cm for total carbon and bulk density, 0−5 cm for labile carbon and 0−15 cm for WSA. Results indicate that despite initial smaller soil health values in the ST-IWM system following inversion tillage, all properties except labile carbon were similar to the NT-SH system in the sixth year of the rotation.

Introduction

Annual crop production that fulfills the regenerative agriculture goals of enhancing soil carbon without tillage but with continuous plant cover often relies on herbicides to terminate cover and perennial crops and to control weeds. No-till equipment places crop seeds into soil without plowing or disking, reducing soil disturbance and leaving previous crop residues on the surface, thus reducing soil erosion and maintaining soil structure (Jarecki and Lal, 2003; Baker et al., 2007). Besides saving fuel and protecting soil from erosion, no-till farming conserves soil carbon near the soil surface by slowing the decomposition of residues on or near the surface relative to soils that are mixed through tillage (Stubbs et al., 2004; Kan et al., 2021) and is therefore considered an important management tool for conserving soil and improving key components of soil health. When cover crops and perennial crops are integrated into no-till cropping systems, farmers typically apply herbicides to terminate the crops that provide continuous cover and control weeds. This reliance on herbicides for crop and weed termination can contribute to the evolution of herbicide resistant weeds (Quincke et al., 2007; Green and Siehl, 2021; Heap, 2022). Concerns that herbicide use can adversely affect humans (Sanborn et al., 2007; Zhang et al., 2019; Stradtman and Freeman, 2021), aquatic ecosystems (Hunt et al., 2017), wildlife (Freemark and Boutin, 1995), soil organisms (Gaupp-Berghausen et al., 2015) and soil health, present a conundrum for no-till farmers. No-till also increases nutrient stratification in the soil because it allows fertilizers, lime and residues from terminated crops to accumulate near the surface (Scheiner and Lavado, 1998). This stratification can be detrimental to crop production and the environment (Baker et al., 2017; Norton, 2020). These issues have led to the consideration of using strategic disturbance events, such as occasional inversion tillage and shallow cultivation to terminate perennials or cover crops, reducing the frequency and rate of herbicide applications and incorporating nutrients into the soil profile (Kettler et al., 2000; Dang et al., 2015; Summers et al., 2021).

In a 2017 survey by the USDA, 67% of crop acreage in Pennsylvania was managed with no-till and 24% with cover crops [National Agricultural Statistics Service (NASS) USDA, 2017]. Organizations such as the Pennsylvania No-Till Alliance have played an important role in advocating for these conservation practices and are often averse to using any type of tillage that may destroy the soil health benefits gained from continuous no-till (PA No-Till Alliance, 2022). Multiple studies have documented the negative effects of tillage on soil health, with soil health indictors tending to decline with increased tillage intensity (Jarecki and Lal, 2003; Bhardwaj et al., 2011; Cates et al., 2016; Nunes et al., 2020; Sprunger et al., 2021).

A nationwide meta-analysis compared the effects of moldboard plowing, chisel plowing, no-till, and perennial systems on soil organic carbon, permanganate oxidizable C

(POXC or active C), soil respiration, microbial biomass C and N, soil protein, and beta-glucosidase activity (Nunes et al., 2020). The authors found that converting from moldboard to chisel plowing improved soil organic carbon, microbial biomass carbon and soil respiration in the first 0–15 cm of soil, however converting from moldboard plowing to no-till improved all seven soil health indicators at 0–15 cm. Additionally, compared to moldboard plowing, perennial systems had improved soil health indicators at all depths sampled (0–40 cm). The authors concluded that combining cover crops and minimizing crop residue removal along with no-till improved soil health indicators more than switching to no-till alone (Nunes et al., 2020).

The addition of cover crops, perennials and increased crop diversity in cropping systems also enhances soil health indicators, such as SOC and water stable aggregates (Angers and Caron, 1998; Salvo et al., 2014; Congreves et al., 2015; King and Blesh, 2017; Basche and DeLonge, 2019; Sprunger and Martin, 2020). In a Wisconsin study, particulate organic matter (POM) and aggregate C and N were the soil health indicators assessed across six cropping systems ranging from continuous maize with yearly chisel plowing to more diverse rotations with less frequent chisel plowing and perennial forages, to never-tilled perennial pasture (Cates et al., 2016). Although the authors' hypothesized that soil health would be reduced in proportion to tillage intensity they found that the systems that were tilled every year had POM and aggregate C levels similar to the crop rotation tilled every 3 years that included significant crop residues from corn stover and perennials (Cates et al., 2016). The integration of crop residues and perennials also diversifies weed control strategies and can reduce reliance on herbicides with diverse crop lifecycles that interrupt weed lifecycles and mechanical weed control *via* frequent harvests of perennial forages (Cavigelli et al., 2008; Davis et al., 2012; Summers et al., 2021).

One-time tillage, also referred to as strategic tillage, occasional tillage, and single inversion tillage, etc., is a potential alternative to continuous no-till; however, disagreement exists as to the efficacy of one-time tillage on otherwise no-till land. Some studies report little to no effect of one-time tillage on soil health (Salvo et al., 2014; Dang et al., 2015; Blanco-Canqui and Wortmann, 2020), whereas others report a persistent decrease in soil health following tillage (Wortmann et al., 2010; Stavi et al., 2011). For instance, one-time tillage was effective at reducing herbicide dependence and controlling downy brome (*Bromus tectorum* L.), an annual grassy weed, in a 20 year NT winter wheat (*Triticum aestivum* L.)-fallow system in Nebraska (Kettler et al., 2000). The authors compared a one-time tillage using a moldboard plow with secondary tillage (disking, chisel) and rod weeding to a no-till control treatment. Tillage reduced the downy brome densities and wheat yield increased; although 5 years after the tillage event SOC

at 0–7.5 cm depth was still 20% less than in continuous no-till. However, in the 7.5–15 cm depth, SOC was 15% greater compared to the continuous no-till treatment, suggesting that carbon was redistributed through tillage rather than lost from the soil profile (Kettler et al., 2000). In grain-crop systems in Northeastern Australia, Dang et al. (2015) also evaluated strategic or occasional shallow tillage in 14 sites and found weed populations were reduced the year following tillage, without reducing soil TOC. Although bulk density and soil water availability decreased for the first 12 months at some sites, most appeared to recover after 24 months except in high clay soils (Dang et al., 2015).

By contrast, integrating perennials into an annual crop rotation with some tillage has been reported to maintain SOC that was similar to an annual crop rotation with no-till and some tillage (Cates et al., 2016) or 100% no-till management of the same crop rotation of perennials and annuals (Salvo et al., 2014). For instance, Salvo et al. (2014) found that at the end of 9 years of integrating a few years of perennial pasture into annual crop rotations with tillage maintained total SOC at levels similar to no-tillage with the same crop rotation. A review by Blanco-Canqui and Wortmann (2020) examined the impacts of occasional tillage on SOC and physical properties. Although results varied from study to study, they concluded that occasional tillage generally does not reduce overall SOC content but can affect its vertical distribution, with effects lasting up to 2 years following tillage. Additionally, occasional tillage was effective at reducing nutrient stratification and suppressing weed populations for several years. Blanco-Canqui and Ruis (2020) concluded that the benefits of occasional tillage depend on the type, timing, depth, and frequency of the tillage and that the ideal type of one-time tillage will vary. These findings explain the variability in the results of other studies but are encouraging for the use of one-time tillage when occasionally integrated. Though many studies include one-time tillage or cover crops and perennials as a factor, a research gap exists concerning the interaction between one-time tillage and continuous cover with cover and perennial crops (Osterholz et al., 2021).

We undertook this study because we wanted to assess the effects of strategic tillage on soil health indicators. Although farmer cooperators frequently point out that increased water infiltration is a major benefit of no-till, a recent meta-analysis of 89 field trial studies reported that no-till had no significant effect (5.7 ± 9.7%) on infiltration rates even with residue retention (Basche and DeLonge, 2019). Instead, the use of either perennials or cover crops across those studies was found to increase mean infiltration rates by 59.2 ± 20.9 and 34.8 ± 7.7%, respectively. Moreover, recognition is growing that no-till management by itself is not a consistently effective means to increase soil carbon, because soil carbon accrual can vary, due to differences in climate, soil texture, organic mineralization rates, and carbon saturation (Ogle et al., 2012;

Powlson et al., 2014; Daryanto et al., 2020). Thus, farmers are more likely to recognize the utility of weed control provided by strategic tillage combined with the integration of perennials and cover crops that can be more effective for sequestering soil carbon than no-till alone (Mary et al., 2020).

In this study, we assessed the effects of one-time tillage in a 6-year annual and perennial crop rotation with continuous cover by measuring soils across crop rotation years for total organic carbon (TOC), permanganate oxidizable carbon (POXC), and water-stable soil aggregates (WSA). We chose POXC as an indicator of soil carbon dynamics because it is a good proxy for labile C (i.e., readily available to soil microorganisms) and has been reported to be more responsive to soil management than TOC (Culman et al., 2012; Hurisso et al., 2016). We also chose WSA as a sensitive indicator of changes in soil structure due to management (Haynes and Swift, 1990). To those ends, we hypothesized that (1) in the spring following an inversion tillage event, the three soil health indicators would be smaller compared to those for continuous no-till soils; and (2) indicator values would return to similar levels observed in no-till soils after returning to no-till with cover crops and 2 years of perennial crops in the sixth year of the rotation.

Materials and methods

The experiment was conducted as part of the Dairy Cropping Systems (DCS) project established in 2010 at the Pennsylvania State University Russell E. Larson Agronomy Research Farm near Pennsylvania Furnace, PA (40.72°N, −77.92°W). The project aimed to simulate a confinement 97-ha dairy farm at 1/20th the scale (4.86 ha) that could produce all forage and grain needed for a simulated 65-cow dairy herd while minimizing off-farm inputs and environmental impacts. We sampled soils from a 6-year crop rotation of annual and perennial crops comparing two weed control systems: (i) continuous no-till with standard herbicides (NT-SH) and (ii) strategic tillage and integrated weed management that reduced herbicide applications (ST-IWM). The crop sequence (Figure 1) consisted of: (1) winter canola (*Brassica napus* L.) or canola plus oats followed by a rye cover crop (2) soybean [*Glycine max* (L.) Merr.] followed by a rye (*Secale cereale* L.) cover crop (3) corn grain or corn silage (*Zea mays* L.) followed by (4–6) 3 years of perennial forage. The perennial forage in the ST-IWM system was alfalfa (*Medicago sativa* L.) and orchard grass (*Dactylis glomerata* L.) planted with a companion small grain (for species over the 9 years, see Summers et al., 2021) (Table 1), while the NT-ST system was alfalfa as the perennial crop until 2016 when orchardgrass was added so that the perennial forage systems would have the same species that were harvested for hay and silage. The practice of harvesting perennial forages grown in rotation with annual crops to feed a total mixed ration to cattle in
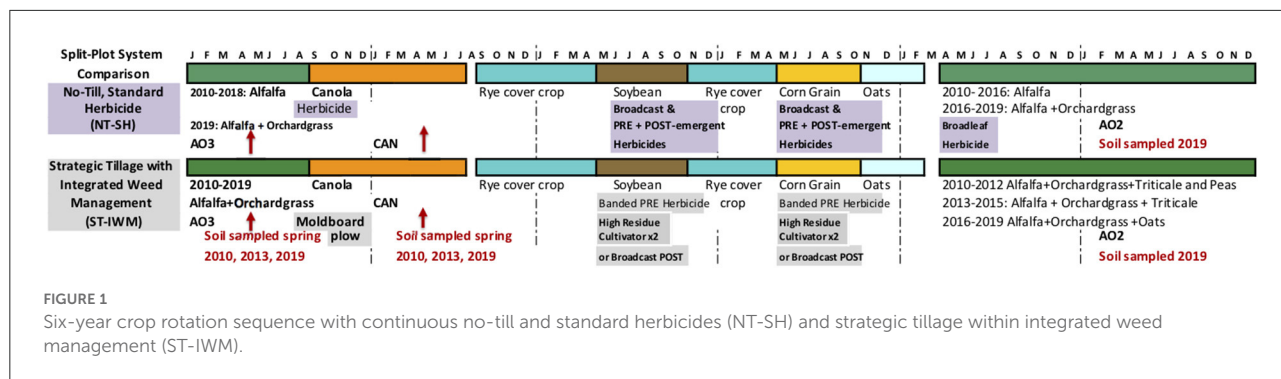
FIGURE 1
Six-year crop rotation sequence with continuous no-till and standard herbicides (NT-SH) and strategic tillage within integrated weed management (ST-IWM).

TABLE 1 The main crops in the rotation sequence, the abbreviation used within the paper, and which soil analyses was conducted in each crop.

Main crop name	Abbreviation	Annual/ perennial	Indicators analyzed
Canola	Can	Annual	All
Soybean	n/a	Annual	None
Corn grain/silage	n/a	Annual	None
Alfalfa-orchardgrass	AO (2 or 3)	Perennial	Second-year: TOC and bulk density by volume Third year: all

confinement is typical for dairy farms of this size in Pennsylvania (Holly et al., 2019).

Experimental design

Every crop phase of the 6-year rotation was present every year in randomized main plots (37 by 27 m) replicated four times, and the two weed control systems were split-plots (18 × 27 m) within each crop entry. A winter rye cover crop was present on the entire experiment when the experimental plots were established in spring 2010. Agronomic production details (ex. crop varieties, seeding rates, planting dates, herbicides, etc.) are described in Summers et al. (2021). Most relevant to this study, the NT-SH system received standard herbicide application rates to control weeds and terminate perennial crops without any tillage. To terminate the perennial alfalfa or alfalfa-orchardgrass in fall 2018 prior to planting winter canola, 0. 9 kg ae ha^{-1} of glyphosate (N-[phosphonomethyl]glycine), 0.5 kg ae ha^{-1} 2–4-D LV4, and 0.3 kg ae ha^{-1} dicamba was applied in late August. Pre- and post-emergence herbicides were broadcast as part of the NT-SH system weed management strategy (see Summers et al., 2021).

By contrast, in ST-IWM prior to fall planting or winter canola, the perennial crops (alfalfa-orchardgrass) were terminated with a moldboard plow followed by secondary tillage (disk, a S-tine chisel and cultimulcher) in late August

followed by planting winter canola. For the corn and soybean row crops, pre-emergent herbicide was banded over only corn and soybean rows, a high residue shallow-disk cultivator was used to control weeds between the row crops twice early in the season, instead of postemergence herbicide from 2010 to 2012 (Summers et al., 2021). From 2013 to 2018 the corn and soybean crop plots were split into two nested split-split (9 by 27 m) plots, one nested split-plot received the shallow-disk cultivation, the other nested split plot received a post-herbicide application instead of the high residue cultivation as described in Summers et al. (2021). Soil samples from both of these nested split-split plots were combined in 2019 for the ST-IWM. Herbicide reduction in the ST-IWM varied over the 9 years and by crop entries, with the exception of when the perennial forage was terminated with tillage and herbicide was eliminated or reduced 100%. For the other crops, burndown herbicide applications were the same in both systems, and the STM-IWM system herbicide reductions occurred in the pre-emergent and post-emergent herbicide applications and were calculated as kilograms per hectare of active ingredient. Compared to the NT-SH system, over the 9 years the STM-IWM herbicide reduction averaged 18% in soybean, 37% in corn and 37% in the establishment year of the perennials. Herbicides were not applied to either treatment in the second and third years of the perennial forages or when the winter canola was planted (Summers et al., 2021).

The predominant soil series at the experimental site is Murrill (Fine-loamy, mixed, semiactive, mesic Typic Hapludults). Manure management practices were chosen to reflect best on-farm practices. When soil was managed without tillage (NT-SH), manure was injected following perennial termination prior to planting winter canola, and before planting a rye cover crop (Figure 1). Manure was broadcast and incorporated by the tillage in the ST-IWM system prior to planting canola.

Soil sampling

Prior to any experimental field operations, soils were sampled in spring 2010 to establish baseline values. In spring

2013 and 2019, soils were sampled from plots containing winter canola (planted the previous fall) and the third year of the perennial crop. In the ST-IWM system, the canola plots followed the full fall tillage event, while the third year perennial plots were in the sixth year after tillage. In the NT-SH system, neither the canola nor perennial crops had received any tillage. In 2013, the NT-SH system had been in only alfalfa, while the ST-IWM had alfalfa and orchardgrass. In 2019, both the NT-SH and ST-IWM plots were planted in alfalfa and orchardgrass in 2016. For simplicity, we therefore refer to this crop as alfalfa + orchardgrass (AO3). In 2019, we also sampled soil from the second-year alfalfa orchardgrass (AO2) crop (5 years after tillage) from both the NT-SH and ST-IWM systems for TOC and bulk density measurements.

Ten to 15 soil cores were randomly collected between 4 and 20 of April 2010, on 9 and 10 of April 2013 and 19 March, 2019, when winter canola and perennials had begun greening-up after winter dormancy. Soil cores were split into 0–5 and 5–15 cm depths for separate composite samples. After being air dried and passed through a 2 mm sieve, these samples were measured for TOC and POXC.

Additional soil cores were sampled to 15 cm depth and composited on 20 and 21 May of 2010; on 17, 20 and 21 May, 2013; and on 3 June, 2019, when the canola and the perennials were flowering or beginning to flower. These samples were measured for WSA after storage in cool, airtight containers to minimize microbial activity.

Bulk density

Soil bulk density was sampled on 17 November, 2019, which also allowed the calculation of TOC on a volumetric basis in 2019. Ten to 15 bulk density samples were collected from canola, and the second and third years of alfalfa and orchardgrass (AO2 and AO3, respectively) using a tractor mounted Giddings soil probe (7.5 cm diameter). Following a modified bulk density procedure described by Blake and Hartge (1986), cores were collected in a thin plastic sheath, cut open in the laboratory, and soil was separated into 0–5 and 5–15 cm depths. Soils were air dried, weighed, and passed through a 2 mm sieve. Material collected on the sieve was weighed, washed, and volume determined by water displacement to allow correction of bulk density values for stone content.

Total organic carbon

TOC concentrations at 0–5 and 5–15 cm depths were measured by combustion with a 2,400 CHNS/O Series II Analyzer (Perkin Elmer, Waltham, MA, USA) in 2010 and 2013 and a Vario Max elemental analyzer (Elementar, Langenselbold, Hesse, Germany) in 2019.

Labile carbon (POXC) and water-stable aggregates

Samples (0–5 cm) were tested for POXC using the Weil et al. (2003) method. Briefly, 2.5 g of air-dried soils were mixed with 2 mL stock solution (0.2 M $KMnO_4$ in 1 M $CaCl_2$, pH 7.2) and brought to 20 mL volume with water. Cleared soil suspensions were diluted 1/10 before measuring absorbances at 550 nm in a colorimeter (Hach, Loveland, CO). Standard curves of absorbance values for known $KMnO_4$ concentrations provided the y-intercept (a) and slope (b) in the following equation to calculate soil POXC concentration::

$$POXC \ (mg \ kg-1) \ = \ (0.02 \ Mol/L \ - \ (a+b * absorbance))$$
$$* (9000 \ mg \ C/Mol) \ * \ (0.02 \ L \ soln./0.0025 \ kg \ soil)$$

For water-stable aggregates, field moist soils sampled from 0 to 15 cm were sieved through 2 and 1-mm sieves, with material remaining on top of the 1-mm sieve retained and air-dried. A modified version (Grover, 2008) of the Kemper and Rosenau (1986) method was used with a dispersing solution (2 g of sodium hexametaphosphate in 1 L of deionized water). Four grams of air-dried soils were added to sieve-bottom cups in an 8-cup wet-sieving apparatus (Eijkelkamp Soil & Water Giesbeek, Netherlands). Tins containing deionized water were placed under the sieve-bottom cups, which were lowered to completely submerge the soils. After submersion without disturbance for 5 min, the cupholder was raised and lowered at a rate of 33 times per minute for another 5 min. Tins containing water were replaced with tins containing dispersing solution, and the process was repeated.

Once raised out of the solution, samples in the sieve-bottom cups were gently rubbed with a rubber-tipped rod for 20 s each. Samples were lowered again into dispersing solution and raised and lowered for a final 5 min. The two sets of tins, one containing water and unstable soil fraction and the other containing dispersing solution and the stable fraction, were removed and placed in a drying oven at $110°C$ for 2 days. Any sand, rock, or particulate organic matter remaining in the sieve bottom cup was discarded.

WSA percentage was measured using the equation:

$$[Stable \ Aggregate/ (Stable \ Aggregate \ + \ Unstable \ Aggregate)]$$
$$* 100$$

where stable aggregate refers to the fraction of the soil slaked off in dispersing solution and unstable aggregate refers to the fraction of the soil that slaked off in water.

Two replicates were performed for each plot and a percent difference between replicates was determined using the equation:

$$[(Rep \ 1 \ - \ Rep \ 2)/Average(Rep1, \ Rep2)] * 100$$

If the percent difference between replicates was greater than 29%, a third replicate was performed. This was only necessary for one sample.

Statistical analysis

Because the WSA procedure was carried out by different individuals in 2010, 2013, and 2019, potential variation in individuals' techniques called for separate analyses of 2010, 2013 and 2019 results, and standardized scores were generated for water stable aggregate data within each year. Standardized scores were calculated by subtracting the population mean (all blocks and both systems) from each WSA percentage of each sampled plot and dividing this value by the population standard deviation.

Data were analyzed with PROC MIXED for a split-plot design in JMP Pro 15 by SAS (SAS Institute, Inc. Cary, North Carolina). For TOC, labile carbon, WSA, and standardized WSA, fixed effects were year, system, crop, and the two and three-way interactions between these terms with block, block × crop, and block × year as random effects, with fixed effects separated by the Personality Standard Least Squares test, equivalent to the Satterthwaite approximation. Bulk density and total organic carbon by volume was analyzed for 2019, which was the only year with sufficient bulk density data. Crop and system and the interaction between them were fixed effects and block and the interaction between block and crop were random. The SLICE test, which analyzes simple effects to separate LSmeans within an interaction, was used to test the pre-planned hypotheses, comparing the system within the same crop and year. Means were considered significantly different at $p < 0.05$. We also conducted the SLICE test when there was a significant interaction, with the exception of testing the Year effect. We only conducted the SLICE test to compare 2013 and 2019, the years when crops were planted in the same plots or soil and appropriate to compare between those years.

Results and discussion
Total organic carbon concentration

For TOC at the 0–5 cm depth, "system" showed the only significant effect ($p = 0.00089$), where ST-IWM averaged 14% lower TOC than the NT-SH average. Canola TOC concentration in ST-IWM was 21% less in 2013 ($p = 0.0197$) and 29% less in 2019 ($p = 0.0013$), compared to the NT-SH system (Table 2). Others have also reported a reduction in soil TOC in the upper soil layer following inversion tillage compared to no-till (Kettler et al., 2000; Jarecki and Lal, 2003; Mary et al., 2020).

By contrast, there were no significant differences between systems in the AO3 in any year (Table 2). In 2013 the ST-IWM

AO3 had not yet been exposed to tillage since the start of the experiment, but in 2019 the ST-IWM AO3 had experienced inversion tillage 6 years earlier. The similar TOC concentrations indicated that levels in the ST-IWM system had recovered to those observed in the NT-SH system (Table 2). In Uruguay, Salvo et al. (2014) also found that when rotated to perennial pastures following tillage, SOC was not reduced relative to no-till. In addition, in 14 grain crop locations that were occasionally tilled in Australia, Dang et al. (2015) found that soil organic carbon in the top 0–10 cm did not differ from paired no-till systems three to 24 months after tillage.

For TOC concentration at 5–15 cm depth, none of the fixed effects were significant. And the hypothesis that the systems would differ after tillage in Canola was not true in any year (Table 2), indicating tillage did not have an effect at this depth. It is possible that some TOC was redistributed to a deeper depth than what was sampled in our study, as Kettler et al. (2000) noted a redistribution of carbon to deeper depths following tillage. Because the plow depth is closer to 30 cm, increased TOC from buried residue could be buried in the 15–30 cm layer. Due to channery soils, sampling past 15 cm was not feasible on a wide scale and this possibility was not investigated. The potential for redistribution of a portion of the carbon, rather than loss of carbon due to tillage, would support the idea that occasional tillage does not reverse the benefits of no-till.

Bulk density and calculation of total organic C by volume

In the 2019 bulk density analysis, only crop showed a significant effect in the 0–5 cm depth ($p = 0.00418$), where AO3 had 9% lower average bulk density than the canola and AO2 was not significantly different from either of the other crops (Table 3). Overall, bulk density values at both depths were lower than 1.55 g cm^{-3}, which is the bulk density considered to be root-restrictive for silt loam soils (Kaufmann et al., 2010). Nevertheless, lowered bulk densities are an indication of higher organic matter content, greater porosity, and improved soil hydraulic function (Kaufmann et al., 2010; Bagnal et al., 2022). The lower bulk density after 2 years of perennial forage, regardless of tillage, thus suggested that soils had better structure in support of root growth. As with the TOC concentration results, there were no significant effects observed in the 5–15 cm depth for bulk density (Table 3).

Decreased bulk density following perennial crops was expected as the perennial roots are likely to add organic matter to the soil, as well as improving fungal hyphae and biological activity that promotes soil porosity, making the soil less dense (Angers and Caron, 1998; Blanco-Canqui and Ruis, 2020) and reducing the potential for compaction. This result supports our hypothesis that the lack of disturbance during perennial

TABLE 2 Total organic carbon (g C kg soil^{-1}) at 0−5cm and 5−15 cm, labile carbon by POXC (mg C kg soil^{-1}) at 0−5 cm, water stable aggregates at 0−15 cm and water stable aggregate standard scores, calculated using the means and standard deviation of within-year score compared in 2010, 2013, and 2019.

	TOC (0–5 cm) g C kg^{-1}	TOC (5–15 cm) g C kg^{-1}	POXC (0–5 cm) mg C kg^{-1}	WSA %	WSA standard score
Crop					
Average of Can	1.64a[a]	1.32a	458a	41.3b	−0.43b
Average of AO3	1.62a	1.25a	478a	46.8a	0.46a
System					
Average of ST-IWM	1.51b	1.31a	424b	42.9a	−0.15a
Average of NT-SH	1.75a	1.27a	512a	45.3a	0.19a
Year					
Average of 2010	1.61a	1.23a	495a	35.8b	5.39E − 07a
Average of 2013	1.64a	1.37a	446a	40.7b	−7.03E − 08a
Average of 2019	1.64a	1.27a	462a	55.7a	0.05a
Three-way effect combination					
Can, ST-IWM, 2010	1.57A[b]	1.20A	500A	32.7A	−0.33A
Can, NT-SH, 2010	1.62A	1.28A	473A	32.4A	−0.37A
AO3, ST-IWM, 2010	1.57A	1.22A	515A	36.8A	0.12A
AO3, NT-SH, 2010	1.67A	1.22A	494A	41.1A	0.59A
Can, ST-IWM, 2013	1.47B*a*[c]	1.52A*a*	353B*b*	38.0A*ab*	−0.65A*a*
Can, NT-SH, 2013	1.87A*a*	1.35A*a*	506A*a*	38.8A*ab*	−0.46A*a*
AO3, ST-IWM, 2013	1.59A*a*	1.34A*a*	440A*a*	43.5A*b*	0.68A*a*
AO3, NT-SH, 2013	1.65A*a*	1.25A*a*	486A*a*	42.5A*b*	0.43A*a*
Can, ST-IWM, 2019	1.37B*a*	1.35A*a*	342B*b*	48.0B*a*	−1.17B*a*
Can, NT-SH, 2019	1.94A*b*	1.26A*a*	574A*a*	58.1A*a*	0.40A*a*
AO3, ST-IWM, 2019	1.47A*a*	1.23A*a*	395B*a*	58.2A*a*	0.43A*a*
AO3, NT-SH, 2019	1.76A*a*	1.25A*a*	537A*a*	58.7A*a*	0.53A*a*
Main effect	*p*-value	*p*-value	*p*-value	*p*-value	*p*-value
Crop	0.69561	0.14599	0.48898	**0.03776**	**0.02489**
System	**0.00089**	0.40978	**0.00284**	0.19563	0.19915
Year	0.85648	0.11073	0.12520	**0.00067**	0.98440
System × crop	0.15841	0.68003	0.23882	0.52971	0.37678
System × year	0.09678	0.35064	**0.01134**	0.48342	0.40040
Crop × year	0.88381	0.60267	0.92488	0.91313	0.80845
System × crop × year	0.42148	0.70549	0.64071	0.29173	0.32388
SLICE tests					
Effect of system	*p-value*	*p-value*	*p-value*	*p-value*	*p-value*
Can, ST-IWM, 2010 vs. Can, NT-SH, 2010	0.7770	0.5058	0.6741	0.9383	0.9531
Can, ST-IWM, 2013 vs. Can, NT-SH, 2013	**0.0197**	0.1474	**0.0264**	0.8512	0.7530
Can, ST-IWM, 2019 vs. Can, NT-SH, 2019	**0.0013**	0.4560	**0.0014**	**0.0278**	**0.0194**
AO3, ST-IWM, 2010 vs. AO3, NT-SH, 2010	0.5305	0.9667	0.7505	0.3285	0.4726
AO3, ST-IWM, 2013 vs. AO3, NT-SH, 2013	0.6828	0.4672	0.4842	0.8119	0.6899
AO3, ST-IWM, 2019 vs. AO3, NT-SH, 2019	0.0827	0.8868	**0.0374**	0.9228	0.8795
Effect of year					
Can, ST-IWM, 2013 vs. Can, ST-IWM, 2019	0.4963	0.1479	0.8500	**0.0351**	0.4189
AO3, ST-IWM, 2013 vs. AO3, ST-IWM, 2019	0.4732	0.3560	0.4584	**0.0028**	0.6893
Can, NT-SH, 2013 vs. Can, NT-SH, 2019	0.6275	0.4688	0.2566	**0.0002**	0.1802
AO3, NT-SH, 2013 vs. AO3, NT-SH, 2019	0.4811	0.9541	0.3942	**0.0027**	0.8793

[a]Lowercase letters (a, b) denote differences due to main effects at p <.05.

[b]Uppercase letters (A, B) denote systems that differ at p <.05 within the same crop and year *via* the "SLICE" procedure.

[c]Italicized lowercase letters (a, b) denote years (2013 vs. 2019) that differ at p < .05 within the same system and crop *via* the "SLICE" procedure.

Significant differences of main system and year effects comparing 2013 and 2019 (System and Year) were determined by the SLICE statement in JMP to perform a partitioned F test of least square means (LSMeans) of their interaction. *p*-values < 0.05 are in bold.

TABLE 3 Bulk density and TOC by volume averages at 0−5 and 5−15 cm depths for strategic tillage within integrated weed management (ST-IWM) and continuous no-till with standard herbicide (NT-SH) in canola (Can), second-year alfalfa orchardgrass (AO2) and third-year alfalfa orchardgrass (AO3) crops sampled in 2019.

	BD (0–5 cm) g cm^{-3}	BD (5–15 cm) g cm^{-3}	TOC (0–5 cm) Mg ha^{-1}	TOC (5-15cm) Mg ha^{-1}
System average				
ST-IWM	1.13A	1.26A	8.35B	7.92A
NT-SH	1.09A	1.26A	10.41A	7.84A
Crop average				
Can	1.16a	1.26a	9.58a	8.18a
AO2	1.11ab	1.26a	10.03a	8.00a
AO3	1.06b	1.27a	8.53a	7.47a
System × crop				
ST-IWM, Can	1.17a[a]A[b]	1.23aA	7.97aB	8.30aA
ST-IWM, AO2	1.13abA	1.26aA	9.09aB	8.01aA
ST-IWM, AO3	1.08bA	1.28aA	8.00aA	7.46aA
NT-SH, Can	1.15aA	1.28aA	11.18aA	8.06aA
NT-SH, AO2	1.09bA	1.25aA	10.97aA	7.98aA
NT-SH, AO3	1.03bA	1.27aA	9.07bA	7.48aA
Factor	*p-value*	*p-value*	*p-value*	*p-value*
Crop	**0.00418**	0.859	0.07343	0.22671
System	0.07235	0.80057	0.00012	0.84223
System × crop	0.64693	0.43808	0.06324	0.96056
SLICE tests	*p-value*	*p-value*	*p-value*	*p-value*
Effect of system				
Can, ST-IWM vs. Can, NT-SH	0.6596	0.2078	**0.0003**	0.7152
AO2, ST-IWM vs. AO2, NT-SH	0.2353	0.7452	**0.0078**	0.9659
AO3, ST-IWM vs. AO3, NT-SH	0.1058	0.7459	0.0844	0.9820

[a]Different lowercase letters (a, b) indicate that crops differ at p < .05.
[b]Different uppercase letters (A, B) indicate that systems differ at p < .05.
Significant differences of the main effects of system (system) and crop (Crop) were determined by the SLICE function in JMP to conduct a partitioned F-test of LSMeans of the interaction of System x Crop. *p*-values < 0.05 are in bold.

growth would lead to improvement in soil health indicators. Interestingly, the bulk density did not increase significantly following tillage as there was no difference between the two systems in the canola crop. This did not support our first hypothesis that strategic tillage would cause an initial decrease in soil quality. Tillage has been shown to decrease bulk density in the short term but increase it in the long-term (Logsdon and Karlen, 2004; Dang et al., 2015). However, we did not detect a difference in systems or following tillage in the canola.

The TOC by volume (Mg/ha) showed similar trends to the TOC concentration in both sampled depths. System had a significant effect in the 0–5 cm depth ($p = 0.00012$), with TOC by volume 20% smaller in ST-IWM compared to the NT-SH. The canola had 29% less ($p = 0.0003$) and AO2 had 17% less TOC by

volume ($p = 0.0078$) in ST-IWM compared to NT-SH (Table 3). There were no significant differences however, between the two systems in AO3 (Table 3), indicating that following strategic tillage, 2 years of the perennial forage were required for TOC to increase to the same level as the no-till system. At the 5–15 cm depth, there were no significant differences in TOC by volume between systems or crops (Table 3). In summary, TOC by volume decreased significantly following tillage, but was similar between systems following 3 years of annuals and cover crops and 2 years of perennials.

Labile carbon

In the analysis of POXC, system showed a significant effect ($p = 0.00079$), where ST-IWM averaged 17% lower than NT-SH. Compared to NT-SH, canola POXC in ST-IWM was 30% less in 2013 ($p = 0.0264$) and 40% less in 2019 ($p = 0.0014$, Table 2). However in 2019, POXC in AO3 of the ST-IWM system was 26% less than in the NT-SH system ($p = 0.0374$), indicating that POXC had not increased to similar levels in ST-IWM 6 years after tillage. In 2013, AO3 in the ST-IWM system hadn't yet experienced tillage, while in 2019, the AO3 in that system had been tilled 6 years before. Quincke et al. (2007) also noted a significant decrease in labile carbon following tillage in the top few centimeters of soil, but found increased labile carbon in deeper layers that essentially offset the carbon lost from the more superficial layer, suggesting that labile carbon had been redistributed by moldboard plow rather than lost. In our study, POXC was only analyzed at the 0–5 cm depth, and it may have been possible that a similar redistribution of carbon occurred at deeper soil depth. Kettler et al. (2000) and Mary et al. (2020) also noted a redistribution of carbon to deeper depths following tillage.

Water stable aggregates

In the analysis of the WSA and standardized WSA scores, only year showed a significant effect on WSA ($p = 0.00067$) while crop had significant effects on both scores ($p = 0.03776$ and $p = 0.02489$, respectively, Table 2). Compared to 2010, the average WSA was 37% smaller than the averages for 2013 and 2019. The larger average WSA values in 2013 and 2019 may be attributed to the combination of cover crops, perennials and lack of disturbance in most years of both systems. The role of different people conducting the WSA analysis also likely explains some of the WSA differences among years. Year-to-year variation was why we used a standardization procedure for raw WSA scores. Compared to the canola, WSA and the standardized score in AO3 averaged 11.8% greater and 1.9 fold greater, respectively (Table 2). Others have also reported that perennial roots and their associated fungal hyphae and soil

microorganisms stabilized soil aggregates regardless of tillage (Angers and Caron, 1998).

Following tillage in 2019, WSA of canola in the ST-IWM system was 17% smaller than in NT-SH ($p = 0.0278$), and the standardized WSA score was also significantly smaller in the ST-IWM system ($p = 0.0194$). However, WSA scores for canola in 2013 did not differ between the two systems when the NT-SH system had not included orchardgrass in the perennial forage prior to herbicide termination. In 2019, by contrast, AO3 in the systems did not differ for either WSA or the standardized scores, indicating that less disturbance with cover crops and 2 years of perennial alfalfa and orchardgrass significantly enhanced the physical soil stability in the ST-IWM. The lack of significant difference following tillage in the 2013 canola, however, may also be explained by the presence of orchardgrass in addition to alfalfa in the ST-IWM system when the NT-SH was planted to only alfalfa. The presence of orchardgrass in the ST-IWM system may have promoted and protected WSA enough to counter the tillage impact. Because perennial grasses have more fibrous roots, it has been suggested that they promote greater aggregate stability than other types of perennials (Miller and Jastrow, 1990; Angers and Caron, 1998; Rachman et al., 2003). In 2019, the NT-SH system also had orchardgrass planted with alfalfa, and the benefits of both no-till and perennial grass roots may have assisted in the formation of stable aggregates.

Other studies that compared occasional tillage to continuous no-till have also reported that occasional tillage often did not reduce soil aggregation, or that it recovered within a year with return to no-till (Dang et al., 2015; Blanco-Canqui and Wortmann, 2020). A 2010 study by Wortmann et al. found no significant differences in water stable aggregates across several tillage treatments, including no-till and moldboard plow tillage, 5 years following tillage. It is possible that ST-IWM might have returned to levels similar to NT-SH after several years without the aid of perennial roots. However, Dougherty et al. (2022) have suggested that only slight differences in soil health indicators can be expected within short timeframes, which may explain the lack of significant differences in the Wortmann et al. (2010) study. Additionally, the Wortmann et al. (2010) study used the water stable aggregate sampling method by Cambardella and Elliott (1994), which involves wet sieving soil and combining weights of three aggregate size classes, which could have accounted for different sensitivities.

Conclusion

Herbicides are typically used to terminate cover and perennial crops and control weeds during no-till management of annual and perennial crop rotations. Reliance on herbicides can lead to herbicide-resistant weeds and negative environmental impacts that conflict with the goals of regenerative agriculture. Integrated weed management employs multiple weed control practices but the use of occasional tillage is often dismissed in minimal tillage systems because of its association with reduced soil health. In this study, we found that most of the negative effects of strategic tillage on soil health indicators (soil carbon at 0–5 cm, water stable aggregates and bulk density) were mitigated in no-till annual and perennial cropping systems after 3 years' growth of annuals and cover crops and 2 years of perennial forages. We also found evidence that integrating perennial forage grasses with legumes is beneficial for promoting water stable aggregates. When compared to the continuous NT system, labile carbon was the only soil indicator that was lower in the ST-IWM system when measured in the third year of alfalfa-orchardgrass (AO3). Further research on the significance of labile carbon for total soil carbon accumulation and the long-term impacts of strategic tillage in these systems would elucidate the implications of this small reduction in labile carbon. Additionally, this study found no effects of the strategic tillage on soil carbon and bulk density at the 5–15 cm depth, implying that tillage did not impact soil health below the 0–5 cm range in this study, although an investigation of soil carbon at lower depths would be worth pursuing.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

DM, HK, and MB contributed to the conception and design of the study. CD advised on data collection. DM generated and organized data. DM and HK performed statistical analysis. DM wrote the first draft of the manuscript. All authors contributed to manuscript revision, read, and approved the submitted version.

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Conflict of interest

Publisher's note

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