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RESEARCH ARTICLE

Mechanical termination of a perennial grain crop minimally impacts soil structure, carbon and carbon dioxide emissions

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Abstract

Introduction: Mechanical termination of crops can negatively affect soil biological, chemical, and structural characteristics. Perennial crops do not require annual termination and can improve these same soil characteristics, which has catalysed interest in the development of new perennial crops. Advanced lines of the perennial grass intermediate wheatgrass (*Thinopyrum intermedium* [Host] Barkworth and Dewey; IWG) have been bred for increased seed size and marketed as Kernza® perennial grain, but little is known about how this new crop can be terminated for subsequent annual crop production in rotations that enhance agricultural productivity and environmental sustainability.

Materials and Methods: Five methods of terminating IWG were tested in Minnesota, USA. Treatments included mechanical tillage using a chisel plow (CHI), undercutter (UND), and disc (DSC), along with no-till treatments of glyphosate (GLY) and a repeated-mowing control (CTRL). Treatment effects on IWG mortality, soil carbon dioxide (CO_2) emissions, bulk density, aggregate stability, soil carbon stocks and soybean yield were measured.

Results: Daily CO_2 fluxes differed by treatment ($p < 0.05$) on only one of 19 sample dates, and cumulative soil CO_2 emissions over the course of the growing season did not differ across treatments. Bulk density decreased relative to baseline in all treatments except CTRL. Aggregate stability remained unchanged in all treatments except CTRL, which increased from the baseline. Soil carbon stocks did not change in any treatment. Soybean yield was highest in GLY but was not significantly different from CHI or UND.

Conclusions: Soil structure, soil carbon stocks and soil CO_2 emissions were unaffected by tillage and no-till IWG termination treatments. However, tillage followed by preplanting harrowing proved ineffective at terminating IWG and required subsequent summer herbicide applications. Therefore, additional tillage events may be required to fully terminate IWG when herbicide use is prohibited.

KEYWORDS

greenhouse gas emissions, intermediate wheatgrass, Kernza, soil health, tillage

1 | INTRODUCTION

A history of intensive land disturbance associated with annual agriculture has resulted in degraded soils throughout the Upper Midwest (Thaler et al., 2021). Soil tillage is one such disturbance that is widely used on agricultural lands and is viewed as a key practice to maximise yield, despite evidence that no-till can produce similar yields in certain crops and climates (Pittelkow et al., 2015). Tillage is useful during crop transitions for incorporating plant residues, expediting optimal soil temperature for seed germination, aerating topsoil, and creating a more conducive seedbed for planting (Haddaway et al., 2017). However, tillage could be detrimental to soil biological, chemical and structural characteristics (Baumhardt et al., 2015; Holland & Coleman, 1987; Lützow et al., 2006).

Perhaps the clearest impact of tillage is on soil structure and aggregation. Conventional tillage reduces both the amount of macroaggregates and the concomitant capacity to store particulate organic carbon (C) within aggregates (Beare et al., 1994; Six et al., 1999). This disturbance of aggregate formation increases C mineralisation and contributes to soil carbon dioxide (CO_2) emissions (Balesdent et al., 1990; Reicosky, 1997). However, CO_2 emissions in no-till (NT) systems have been shown to be lower, higher, or not different from conventional tillage (Bhattacharyya et al., 2022). Similarly, the evidence for increasing soil organic carbon (SOC) by limiting tillage is not definitive. Some studies point to NT practices increasing SOC (González-Sánchez et al., 2012; West & Post, 2002), while others find no difference compared to conventional tillage (Dimassi et al., 2014; Powlson et al., 2014). These mixed results demonstrate the importance of soil texture, SOC content, soil moisture and soil temperature as a context within tillage influences on soil carbon dynamics (Bhattacharyya et al., 2022; Franzluebbers & Arshad, 1997).

Conservation agriculture practices that reduce tillage have been shown to improve soil quality and crop yields in some soil types (Nunes et al., 2018). Reducing the intensity of tillage often results in improvements to common soil health indicators, including SOC stocks, microbial biomass and soil respiration (Nunes et al., 2020). As a result, cropping strategies that use minimal tillage during crop transitions are believed to align with agricultural sustainability goals. Further reductions in the use of tillage can be achieved by incorporating perennial crops into crop rotations. Due in large part to their extensive root biomass and continuous living cover, perennial crops have the potential to reduce negative environmental consequences of agriculture (Sainju et al., 2017; Smith et al., 2014). One of the most important improvements over annual crops is the ability of perennial crops to improve key soil health indicators (Rakkar et al., 2023; Ryan et al., 2018).

Intermediate wheatgrass (IWG, *Thinopyrum intermedium*) is a cool-season grass native to Eurasia that has been grown as a forage crop in the United States since the early 1900s and has been the focus of domestication efforts as a grain crop (Bajgain et al., 2020). Recent studies have found improvements in key ecosystem services resulting from IWG production, including soil C. Compared to annual wheat, research has shown increases in SOC concentration beneath IWG at 0–30 cm (Taylor et al., 2023) and 30–60 cm depths (Audu et al., 2022), which has potential to drive soil C storage in IWG (Tang et al., 2023; Wiesner et al., 2022). This increase in carbon can amplify the soil's capacity to execute its essential processes related to nutrient cycling, water retention, gas exchange, soil structure, agronomic outcomes and biological activity (Lal, 2016).

In the upper Midwest, IWG is often grown for 2–5 years before grain yields decline and the crop is terminated to rotate to another crop. Termination options come with varying degrees of physical soil disturbance and associated greenhouse gas emissions and deterioration of soil biology (Nunes et al., 2020). Farmers frequently cite environmental quality benefits as a key reason for adopting IWG specifically (Lanker et al., 2020), or perennial crops more broadly (Adebiyi et al., 2016; Marquardt et al., 2016). Therefore, the termination approach introduces a critical decision for producers: how to ensure complete termination of the established IWG crop without sacrificing the soil health improvements achieved during its production. Taken together, there is a need to understand which termination method effectively terminates IWG with minimal impact on environmental quality benefits, so that an optimal method can be recommended to farmers. IWG is less susceptible to mortality from tillage because disturbed plant crowns can propagate new tillers leading to recruitment of plants after initial termination, making the choice of termination method more difficult. Little research has been done to determine tillage intensity required to completely terminate IWG (Dimitrova Mårtensson et al., 2021). Low-intensity strategies that include chemical herbicides might prove best at meeting this dual-goal of termination while preserving environmental benefits.

Tillage intensity can be defined in various ways including the amount of residue that is buried, tillage depth and degree of horizontal disturbance below the soil surface. Tillage intensity can also vary in terms of the number of passes applied to a field in a single season, or how different implements and approaches can be combined into a schedule between the harvest and planting of crops in a rotation. In addition to mechanical termination methods, chemical treatments are effective approaches to terminate crops in no-tillage systems (Palhano et al., 2018). Glyphosate is a commonly used herbicide for this purpose due to its low cost, wide availability and high effectiveness (Duke & Powles, 2008). This chemical treatment could also serve to maintain beneficial soil characteristics since it does not require soil disturbance. However, glyphosate carries concerns as a possible human carcinogen and environmental pollutant, and overuse can contribute to the rise of herbicide-resistant weeds (Heap & Duke, 2018; Richmond, 2018). Additionally, chemical weed management is prohibited in organic systems, which makes up a significant portion of IWG production.

This study assessed four methods of IWG termination and their impacts on agronomic outcomes, greenhouse gas emissions and soil health indicators. Termination methods included a chisel plow with straight points, a chisel plow with 10 cm horizontal sweeps (undercutter), a disc harrow, and spring glyphosate application. We hypothesised that the most intensive tillage practice, the undercutter, would lead to the greatest decline in soil health indicators, but would effectively terminate IWG and not impact subsequent crop yield. We expected the glyphosate treatment to be optimal for effectively terminating IWG while limiting declines in soil health indicators and ensuring subsequent crop yield. Findings from this project will fill a major research gap and advance the understanding of agronomic best practices for managing perennial grains to support economic viability and ecosystem services.

2 | MATERIALS AND METHODS

2.1 | Location and design

This experiment was conducted on a second-year IWG stand located at the Rosemount Research Outreach and Centre in Rosemount, MN (44°42′35.5″N, 93°04′17.8″W). Soil within 0–15 cm depth is described as Waukegan silt loam with 90 g clay kg^{-1}, 330 g sand kg^{-1}, and 580 g silt kg^{-1}, 40 g organic matter kg^{-1}, 5.98 pH, and contained 17.65 kg N ha^{-1}, 9.25 mg P kg^{-1}, and 79.25 mg K kg^{-1}. Weekly precipitation and average maximum and minimum temperatures were calculated using daily weather data from the Minnesota State Climatology Office and are presented in Figure 1. IWG (MN-Clearwater; Bajgain et al., 2020) was seeded at a rate of 6.2 kg pure live seed ha^{-1} in September 2018 with 45 cm row spacing. The IWG crop was fertilised with 90 kg ha^{-1} of urea in April 2019 and 2020.

2.2 | Treatments and agronomic management

Plots were 9.15 m wide by 22.9 m long and organised in a randomised complete block design with four replicate blocks. Fall tillage was completed on 6 November 2020. Treatments included: chisel plow with straight points (CHI), chisel plow with horizontal 10 cm sweeps for undercutting (UND), disc harrow (DSC), spring glyphosate (GLY) and control (CTRL). The CHI and UND tilled the soil to a depth of approximately 15 cm and left approximately 50% of the residue on the surface. The UND differed from the CHI in that the sweeps added a horizontal disturbance to the tillage in an effort to cleave roots from crowns to more effectively terminate the IWG. The DSC tilled the soil to a depth of approximately 10 cm and left approximately 75% of the residue on the surface. Tillage plots (CHI, UND and DSC) were further prepared for soybean planting using a tandem disc harrow to an approximate depth of 10 cm on 18 May and 26 May 2021. No soil disturbance occurred in CTRL or GLY before planting. Soybean germplasm with tolerance to glyphosate (Pioneer Enlist E3 Variety 71270402) was planted on 26 May 2021 using a six-row planter (John Deere 7100). This planter is not specifically designed for NT planting, but for logistical reasons it was

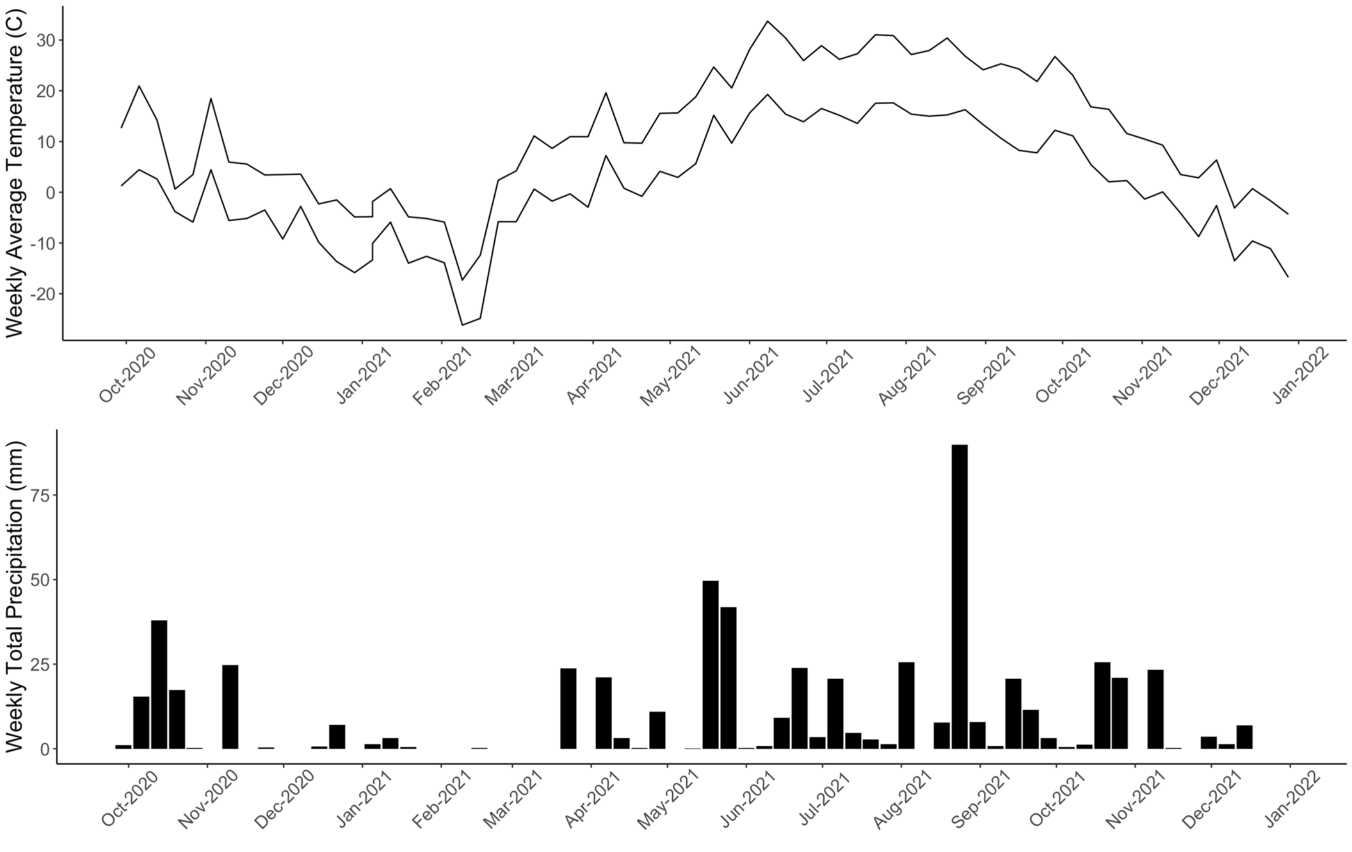

FIGURE 1 Weekly average maximum and minimum air temperature and weekly cumulative precipitation during the study period.

used to plant in all plots, including the NT treatment plots (GLY and CTRL). Glyphosate was applied at 1.12 kg a.e. ha^{-1} to GLY only on May 6. Glyphosate was applied to all plots except CTRL on July 1st at 0.9 kg a.e. ha^{-1}. CTRL was mowed before soybean planting to minimise the growth of the IWG on 29 April, 13 May and 26 May.

2.3 | Soil sampling

Soil samples were collected on 17 October 2020 (baseline) and 9 November 2021 (final) using a probe truck outfitted with a soil probe with a 39 mm diameter (Giddings Machine Co.). Soil was sampled to 60 cm depth and separated into four depth increments for analysis: 0–15, 15–30, 30–45 and 45–60 cm. Baseline samples were collected based on subblock to achieve block average values. Three cores were collected and composited for each plot. Composited samples from three plots were combined to form two subblock samples per block: plots 1–3 and plots 3–5. Separate subblock samples were collected for root biomass and soil analysis. For aggregate stability analysis, three shovels of 0–15 cm soil were collected in each plot and combined in the same subblock scheme described above. Final soil samples included two cores for each plot that were composited and separated into the same depth increments as baseline. Each plot was sampled for aggregate stability in the same manner as baseline samples, by combining three shovels of 0–15 cm soil. At baseline and final timepoints, a 100 g air-dried subsample of 0–15 cm soil was analysed by Agvise Laboratories (Agvise Laboratory Inc.) to determine soil fertility, soil texture, organic matter content and pH. Baseline fertility and soil properties are provided in Supporting Information S1: Table S1.

2.4 | Soil analyses

Soil from the field was stored at 4°C until processing. Approximately 10 g of fresh soil was dried at 105°C until reaching constant mass to measure gravimetric moisture content. Bulk density was estimated by dividing the moisture-adjusted weight of soil by the soil core volume based on the diameter of the probe and the height of the increment (15 or 30 cm). To measure aggregate stability, 50 g subsamples were dried in an oven set slightly above room temperature to accelerate drying (30°C). Dried subsamples were placed in the top of a four-sieve shaker stack, saturated at the water surface for 10 min, and then submerged repeatedly for 10 min on an elliptical oscillator (31 oscillations min^{-1}). The four sieve sizes were: 4, 2, 0.25 and 0.053 mm. The resulting aggregate size fractions were then oven dried at 105°C and weighed. Aggregate stability data is presented as mean weight diameter, which is the sum total of the proportion of dried soil mass in each size fraction multiplied by the mean aggregate size of that fraction (Nimmo & Kim, 2002; Rakkar et al., 2023). The soil percent carbon was determined with elemental analysis (Elementar Pyrocube CNS analyser, Elementar Americas Inc.) on ground soil samples that had been dried at 50°C. SOC stocks were estimated using the fixed-depth approach by multiplying the SOC concentration by the bulk density and the height of the depth increment. Particulate organic matter (POM) was quantified by fractionating 5 g of soil using a 53 µm sieve after 18 h of shaking in 0.5% sodium hexametaphosphate solution (Cotrufo et al., 2019). Permanganate oxidisable carbon (POX-C) was quantified using the protocol described in Weil et al. (2003) modified for reading colour development on clear 96-well plates (Biotek Synergy HT, Biotek Inc.). For the reaction, 2.5 g of air-dried soil was suspended in 18 mL distilled deionized water to which 2 mL of 0.2 M $KMnO_4$ solution was added. All while limiting light exposure, samples were shaken for 2 min at 120 rpm, allowed to settle for 10 min, and 0.5 mL of supernatant was added to 49.5 mL distilled deionized water. This solution was inverted to mix, pipetted into plate wells, and the absorbance was read using a spectrophotometer at a wavelength of 550 nm.

2.5 | Crop analysis

Plant counts were measured using the grid method described in Vogel and Robert (2001) at three time points: once before soybean planting (April 30) and twice after (June 8 and July 1). A 1 × 1 m grid with 25 cells was placed at two locations in each plot. The presence or absence of a weed plant, a soybean plant, or an IWG plant was recorded for each cell in the grid. The total number of cells containing each plant type were summed to compare population of each type. The two grid totals were averaged for each plot for analysis. The grids on 8 June 2021 were placed so that one soybean row was in the middle of the grid. The grids on 1 July 2021 were placed between two soybean rows to estimate weeds and remaining IWG plant populations. Additionally, on 22 June 2021, the number of soybean seedlings were counted in three 1.5 m transects in each plot to estimate soybean population. Soybean yield samples were collected on 15 October 2021. Three 1.5 m rows of soybeans were harvested and composited to constitute a single sample for each plot. Edges and rows where foot traffic led to poor plant stands were avoided. Samples were dried in a 60°C oven until constant mass. Soybean grain was then threshed to determine yield.

2.6 | Soil carbon dioxide emissions

Soil respiration was measured using a portable Gasmet DX4040 Fourier Transform Infra-red Spectroscopy gas analyser (Gasmet Technologies Oy). Typically, respiration was measured bi-weekly, though sampling was more frequent around management events that involved soil disturbance (Table 1). A stainless-steel anchor pan (13.97 cm by 50.17 cm) was installed to a soil depth of approximately 8 cm in each plot. Pans were only removed for management events that may risk damage to the pan and would be re-installed at least 24 h before the next sampling event. To sample CO_2 emissions, a chamber that was connected to the DX4040 was fixed to the preinstalled anchor pan. The total chamber volume was 6250 cm^3.

TABLE 1 Management event dates by treatment.

Treatment	Fall tillage	Herbicide	Mowing	Preplant harrow	Soybean planting	Soybean harvest
CHI	06 November 2020	01 July 2021	-	18 May 2021, 26 May 2021	26 May 2021	05 October 2021
DSC	06 November 2020	01 July 2021	-	18 May 2021, 26 May 2021	26 May 2021	05 October 2021
UND	06 November 2020	01 July 2021	-	18 May 2021, 26 May 2021	26 May 2021	05 October 2021
GLY	-	06 May 2021, 01 July 2021	-	-	26 May 2021	05 October 2021
CTRL	-	-	29 April 2021, 16 May 2021, 26 May 2021	-	26 May 2021	05 October 2021

Note: Treatments included: chisel plow with straight points (CHI), chisel plow with horizontal 10 cm sweeps for undercutting (UND), disc harrow (DSC), spring glyphosate (GLY) and control (CTRL).

Each plot was sampled for 6 min with gas concentration measurements occurring every 20 s. Soil CO_2 fluxes were estimated by calculating the slope of a linear model with chamber CO_2 concentration as the response and time as the predictor. This slope—the change in CO_2 concentration over time—is referred to as the CO_2 flux. Units were converted from ppm CO_2 cm^{-3} to μg CO_2 cm^{-3} using methods and coefficients described in Venterea (2010). The chamber height was then used to remove the vertical dimension and convert to units of C mass per unit area per unit time, which was then used in statistical modelling and total emissions calculations. These models tested data from a subset of sampling days where the timing of management events could trigger treatment-related differences in CO_2 fluxes. Total emissions over a management related period (e.g., from soybean planting through the end of season) or over the entire sampling period were calculated by trapezoidal integration in R using the *pracma* package.

2.7 | Statistical analysis

All statistical analysis and data visualisation were completed using R Studio (R Core Team, 2021). Linear mixed effect models were constructed using the *nlme* package, with termination treatment set as a fixed effect and treatment blocks included as random effects. Tukey's HSD was used to test differences in means across treatments using the *multcomp* or *emmeans* packages, with statistical differences identified at $p < 0.05$ or adjusted for multiple comparisons. Treatments with statistically similar means were grouped using compact letter display.

Changes in soil health indicators, including bulk density, SOC stocks and aggregate stability, were calculated by subtracting baseline from final values. When analysis of variance results indicated that the change in a response was significant from zero, summary statistics determined the direction and magnitude of the change for each treatment. Crop response variables included soybean yield, and weed, IWG and soybean plant counts.

3 | RESULTS

3.1 | Soil carbon dioxide emissions

Carbon dioxide (CO_2) fluxes were similar among treatments throughout the sampling periods (Figure 2). The primary tillage events in November 2020 did not lead to significantly different CO_2 fluxes among the tillage treatments or compared to the untilled treatments. Differences in daily flux were only observed on one date in late May (Figure 2). On this date (24 May), which was 6 days following initial field preparation disking, UND had a greater flux of CO_2 compared to glyphosate ($p = 0.02$). Cumulative CO_2 emissions were not different among treatments ($p > 0.05$). However, the GLY trended towards the lowest CO_2 cumulative emissions compared to other treatments (Figure 3).

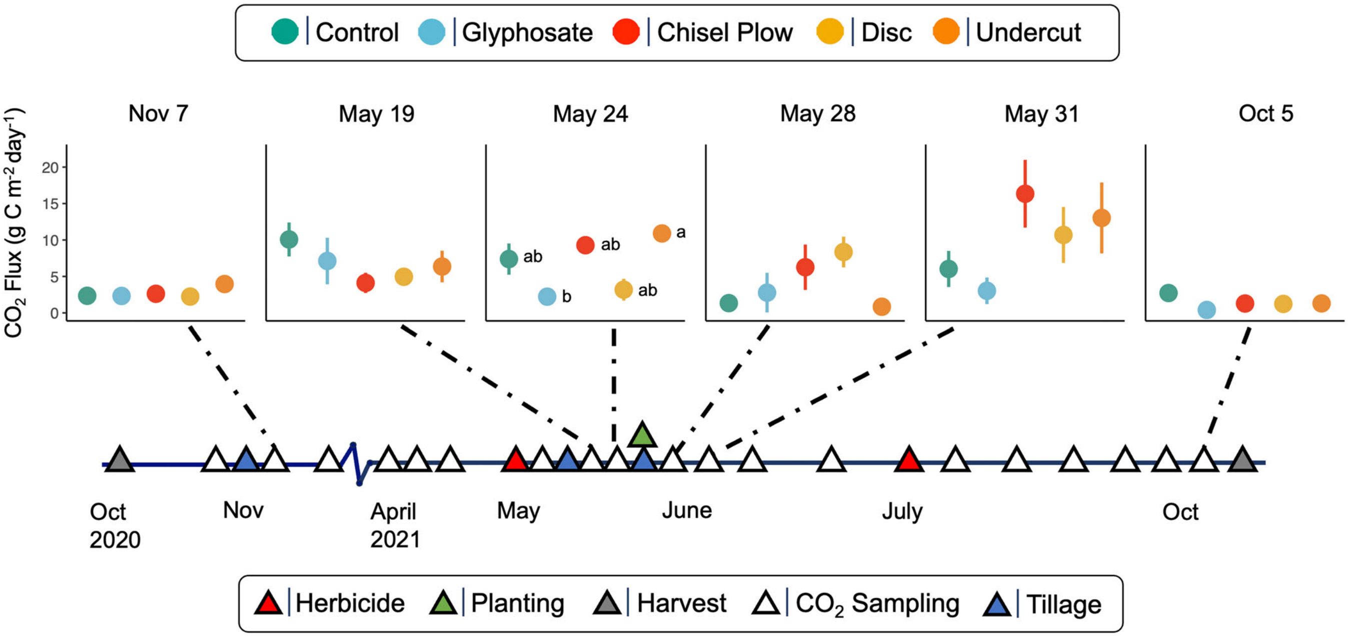

FIGURE 2 Soil CO_2 flux averaged by treatment at select CO_2 emissions sampling dates that aligned with field cultivation or management dates. Different letters within a panel represent statistically significant differences in CO_2 flux based on Tukey's HSD. Panels with no letters represent dates where no significant differences were found.

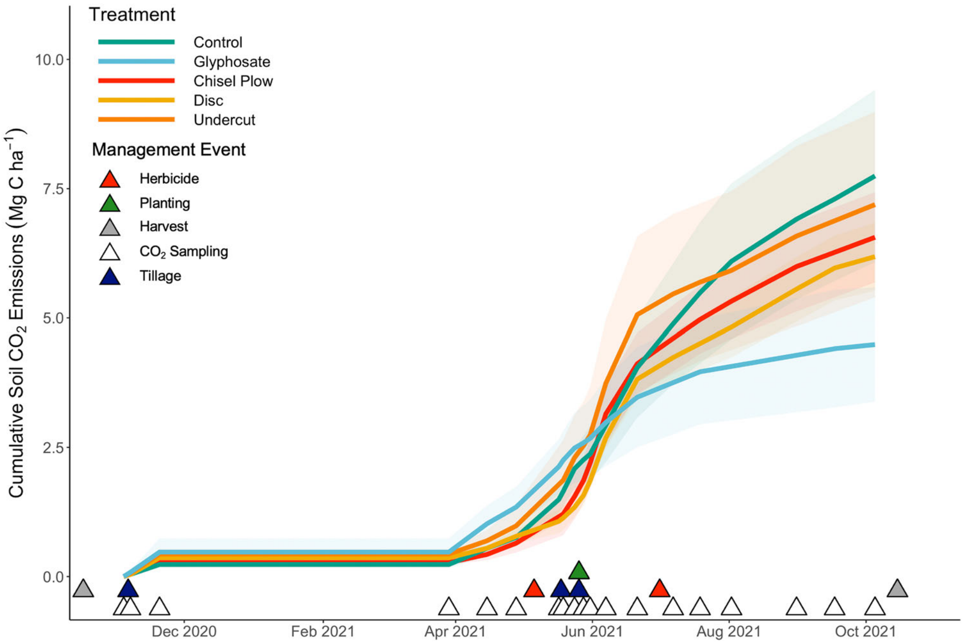

FIGURE 3 Accumulation of CO_2 emissions during study period. Shading shows standard error. Triangles represent the date that management events occurred.

3.2 | Crop responses

Fall tillage practices on their own were ineffective at terminating IWG (Table 2). All tillage treatments (CHI, UND and DSC) had similar IWG plant counts at the first plant count sampling on 30 April relative to the CTRL and GLY–the no-till treatments which had not yet been applied (Table 2). In May, after the glyphosate and mowing treatments were applied, CHI, UND and DSC were disked before planting soybeans and plant counts were measured again on 8 June. IWG plant counts were zero in GLY, ranged from 2 to 3 in other noncontrol plots, and were close to 10 times greater in CTRL. On 1 July, IWG populations in all non-control plots had declined to mean

TABLE 2 Crop responses by treatment.

	Grid plant count (plants grid^{-1})							Transect plant count (plants transect^{-1})	Seed yield (Mg ha^{-1})
	30 April		8 June			1 July		22 June	15 October
	IWG	Weeds	IWG	Weeds	Soybean	IWG	Weeds	Soybean	Soybean
CTRL	25 ± 0a	1.25 ± 0.41a	24.75 ± 0.16c	3.5 ± 0.6a	3.63 ± 0.26a	13.38 ± 1.25b	10.64 ± 1.51a	14.92 ± 1.54a	0.53 ± 0.03a
GLY	25 ± 0a	2.13 ± 0.64a	0 ± 0a	3.13 ± 1.76a	3.63 ± 0.46a	0.13 ± 0.13a	5.5 ± 2.33a	14.92 ± 2.09a	5.76 ± 0.42c
CHI	23.75 ± 0.49a	1 ± 0.19a	2.25 ± 0.49b	3.63 ± 2.26a	4.88 ± 0.13b	0.88 ± 0.23a	5 ± 1.87a	31.08 ± 1.86b	4.98 ± 0.30bc
DSC	24.63 ± 0.18a	1.88 ± 0.64a	3 ± 0.68b	3.5 ± 2.08a	4.75 ± 0.16ab	1.13 ± 0.35a	6.75 ± 2.75a	33.25 ± 1.2b	4.81 ± 0.12b
UND	23.88 ± 0.48a	1.25 ± 0.37a	3 ± 0.46b	3.25 ± 2.14a	4.5 ± 0.19ab	0.38 ± 0.18a	5.38 ± 1.98a	32.92 ± 1.33b	5.20 ± 0.29bc

Note: Means and standard errors of plant counts from grid surveys (1 × 1 m sample area), transect samples (1.5 m of sown crop rows), and soybean grain yield during the 2021 growing season by intermediate wheatgrass (IWG) termination treatment. Letters represent statistically significant differences based on Tukey's HSD. Treatments included: chisel plow with straight points (CHI), chisel plow with horizontal 10 cm sweeps for undercutting (UND), disc harrow (DSC), spring glyphosate (GLY) and control (CTRL).

values of 1 plant or fewer per grid. Also on 1 July, IWG plant counts in CTRL were over 50% lower compared to the previous sampling date. Weed populations remained similar across treatments at all sampling times.

Two weeks after planting (8 June), soybean plant counts varied by treatment ($p = 0.03$), and CTRL and GLY had fewer soybean seedlings than CHI. Four weeks after planting (22 June), soybean plant counts showed a continuation of this trend ($p < 0.001$). There were approximately half as many soybean seedlings in the CTRL and GLY as in the other treatments. This is likely due to the lack of tillage in CTRL and GLY, which led to poor soybean seed-to-soil contact in these plots. Soybean yields varied by treatment ($p < 0.001$) and were higher in the GLY than in DSC or CTLR (Table 2).

3.3 | Soil outcomes

Soil variables measured in this study remained largely unchanged across termination treatments, with only soil physical characteristics responding to treatment. Bulk density changed relative to baseline in the 0–15 cm increment (Figure 4), where it decreased in all treatments except for CTRL ($p = 0.01$). There were no changes in bulk density in the deeper depths. There were few changes in aggregate stability: CTRL increased in mean weight diameter ($p = 0.003$) and in the proportion of aggregates in the 250 µm size class ($p = 0.04$) relative to baseline. There were no changes in soil carbon stocks, and POM or POX-C did not differ across treatments (data not shown).

4 | DISCUSSION

4.1 | Soil CO_2 emissions

We hypothesised that intensive tillage termination methods would lead to the greatest declines in soil health indicators, including higher CO_2 emissions, but our results largely found this to not be the case. Different methods to terminate a second-year stand of intermediate wheatgrass did not lead to differences in cumulative soil CO_2 emissions either during termination or in the subsequent growing season. Moreover, we only observed differences in daily fluxes on one of 19 sampling dates. Our results show that tillage can be used in a termination procedure without increasing soil CO_2 emissions relative to NT approaches. It is important to note that the tillage treatments (i.e., CHI, UND and DSC) differed by the initial implement used for termination, but subsequent management was the same. Our cumulative CO_2 emissions results are similar to other long-term, multi-site comparisons of tilled and NT systems where no differences in CO_2 emissions were detected (Álvaro-Fuentes et al., 2008). However, other studies have found elevated short-term (<70 days) CO_2 emissions in tilled systems compared to NT systems (Akbolat et al., 2009; Toderi et al., 2022). While both of these

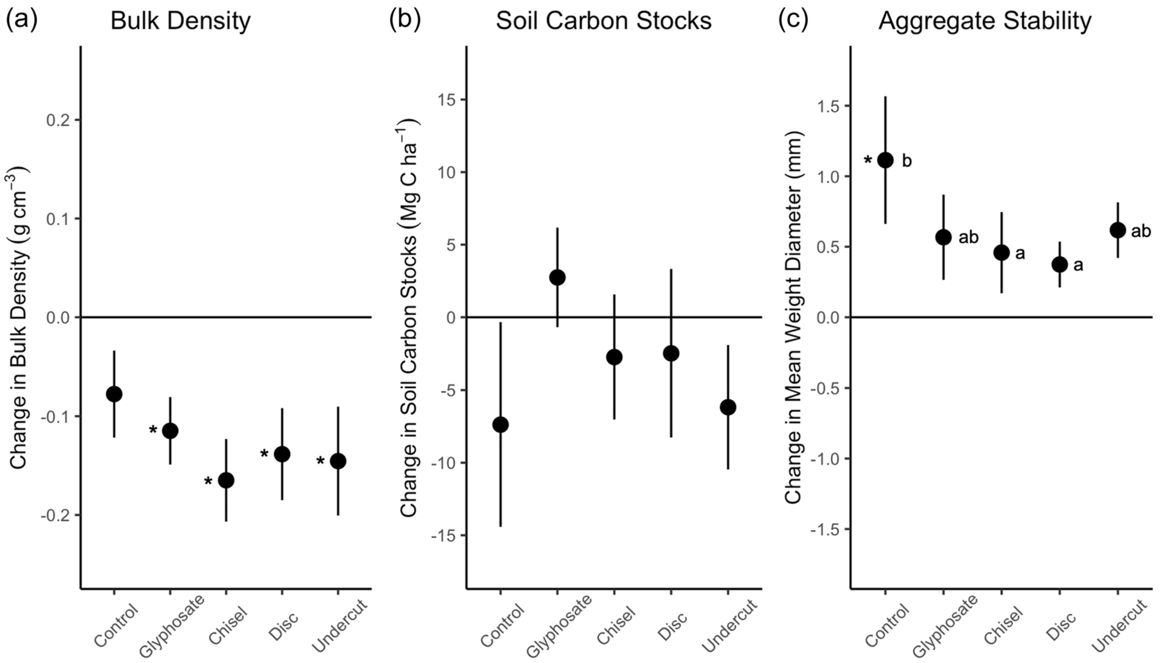

FIGURE 4 Changes in soil properties at 0–15 cm relative to baseline as measured after soybean harvest. Asterisks represent a significant difference from zero and letters represent statistically significant differences based on Tukey's HSD.

short-term studies found treatment differences in either mean CO_2 efflux (Akbolat et al., 2009) or total CO_2 emissions (Toderi et al., 2022), they had similar results to our study in that they reported multiple individual sampling dates with no treatment differences.

There are three possible explanations for the lack of a treatment effect on CO_2 emissions in our study. The first being simply that the high degree of spatial and temporal variability associated with chamber-based soil CO_2 emissions measurements made it difficult to detect treatment differences (Parkin & Kaspar, 2004). While our method has the benefit of allowing for sampling of all plots within a short timeframe, there are logistical limitations to how many chambers can be sampled each day and the sampling frequency. Perhaps given these limitations, our sampling frequency and a single chamber in each plot was insufficient to detect treatment differences. Second, it is possible that relatively cold soil temperatures at the time of the primary tillage event in early November suppressed soil microbial activity and thereby limited emissions. On the date of tillage (November 6), soil temperatures ranged from 5.4 to 11.6°C during daytime hours at 5 cm depth in a nearby field. Agricultural soils could have low levels of respiration at these temperatures, but they are far below empirical temperature optimum for respiration of >45°C (Pietikäinen et al., 2005; Schipper et al., 2019). Therefore, based on our results, tillage occurring when low soil temperatures limit microbial activity may not lead to substantial CO_2 emissions. Lastly, the lack of a treatment effect could be a function of our sampling dates relative to the timing and duration of tillage-derived CO_2 emissions. Reicosky (1997) found that CO_2 emissions measured using chamber-based methods are highest in the minutes immediately following tillage and the flux declines sharply before stabilising after 1 h. If this pattern were the dominant one present in our experiment, it is possible that we did not capture the initial burst of mineralised C that occurs rapidly following soil disturbance. However, using eddy covariance methods, Baker and Griffis (2005) showed that CO_2 fluxes remain elevated for 3–4 days following tillage, suggesting that our approach would have been adequate to capture the resulting CO_2 emissions. Moreover, Toderi et al. (2022) detected differences between tillage and NT practices in CO_2 flux for approximately 30 days. The duration of mineralisation is likely dependent on multiple soil and weather-related factors including SOC pool size, soil temperature and soil moisture. In our study, soil CO_2 emissions were measured either 1- or 2-days following tillage events. Thus, we may have not captured an initial burst of CO_2, but tillage-derived differences in emissions would likely have persisted through our initial post-tillage sampling event especially given the relatively cold conditions for microbial respiration at the time of primary tillage.

GLY trended towards emitting the lowest cumulative CO_2. There are two counteracting mechanisms likely contributing to this result: (1) the lack of tillage that could otherwise increase microbial activity and drive respiration loss of C and (2) an increase in CO_2 emissions directly resulting from glyphosate use. Lower CO_2 emissions in NT compared to tilled systems is well-documented (Akbolat et al., 2009; Baker & Griffis, 2005; Chi et al., 2016; Moraru & Rusu, 2012; Toderi et al., 2022; but see Elder & Lal, 2008; Gelybó et al., 2022; Hendrix et al., 1988). Therefore, the trend toward lower CO_2 emissions in GLY is likely tied to the lack of tillage and physical exposure of soil organic matter to oxygen and conditions suitable for microbial activity and associated C mineralisation. On the other hand, multiple studies have demonstrated that glyphosate application stimulated C mineralisation and elevated CO_2 respiration (Araújo et al., 2003; Haney et al., 2000; Lane et al., 2012). This increase in evolved CO_2 following glyphosate application does appear to be dependent on the application concentration, microbial community composition, and historical use of the product on a given soil (Lane et al., 2012). Additionally, the effectiveness of glyphosate at eliminating the vegetation between soybean rows in noncontrol treatments could also have led to lower autotrophic respiration derived from remaining IWG plants compared to CTRL. Our chambers were placed adjacent to the soybean row, which was either bare soil or included plants depending on the IWG termination effectiveness. These plant-derived CO_2 emissions could have been an important contributor to measured emissions as they are major C sources (Kuzyakov & Larionova, 2005; Pausch & Kuzyakov, 2018). Parsing out the mechanisms that affect emissions in herbicide-dependent NT production is an important area for future research.

4.2 | Crop response

Contrary to our hypothesis, we found that the intensive tillage methods were unable to terminate IWG effectively. On their own, the primary tillage events in November were ineffective at terminating IWG based on April 30 plant counts, which show that CHI, UND and DSC had similar IWG populations as CTRL and GLY. It was not until the two additional disking cultivation events in late May that considerable reductions in IWG plant populations were observed. Disking in late May contributed to an 87%–90% reduction in IWG plant counts between April and June values. Additionally, tillage treatments did receive glyphosate on July 1 to manage weeds and IWG populations, and therefore these results should not be considered as the results of tillage-based management alone. Previous work has also found that repeated tillage passes were required to reach adequate termination of IWG (Dimitrova Mårtensson et al., 2021). While July 1 soybean plant counts suggest that non-control treatments had similar crop establishment and that living IWG did not compete with the next crop in rotation, visually it was clear that GLY achieved a far superior level of IWG termination (Supporting Information S1: Figure S1).

For logistical reasons, we were not able to use a planter specific for NT seeding of soybeans in CTRL or GLY. This likely contributed to lower soybean establishment success in those plots, as shown in June 22 transect counts. Despite this, GLY recorded the highest soybean yield, though it was not significantly different from CHI or UND. Soybeans can compensate for low populations by increasing branching and thus reduce yield losses related to poor establishment (Carpenter & Board, 1997). This result aligns with our hypothesis that the most intensive tillage treatments (CHI and UND) and GLY would best support subsequent crop yield.

4.3 | Soil properties

We hypothesised that the tillage treatments would lead to greater declines in soil properties. However, we found only limited differences in soil properties between treatments that involved soil disturbance and those that did not (GLY and CTRL). Soil carbon stocks did not change from baseline and did not differ among treatments. This is perhaps unsurprising given that the substantial size of the bulk SOC pool makes it challenging to detect differences within a short timeframe (Lal, 2009; Smith, 2004). The soils on which this study was conducted are also relatively high in organic matter, which would make it difficult to detect smaller changes. We expected that the active carbon pools (POM and POX-C) would have varied among treatments as these are believed to be sensitive indicators of changes in SOC resulting from differing land management practices, especially those involving tillage (Plaza-Bonilla et al., 2014). However, we did not detect treatment differences suggesting that a single crop transition is not sufficient to impart detectable changes in SOC. This finding is in agreement with previous studies that found that occasional tillage in long-term NT systems does not reduce SOC stocks and has limited effects on soil physical properties (Blanco-Canqui and Wortmann, 2020). Although, there is a general lack of studies that explore short-term (1–3 year) shifts in C pools following changes in management.

Two measurements of physical soil health—bulk density and aggregate stability—also showed limited treatment effects. While bulk density decreased in tillage treatments relative to baseline, the same occurred in the no-till GLY. In CHI, UND and DSC, tillage implements disturbing soil likely aerated the soil and mitigated compaction, thereby reducing bulk density (Osunbitan et al., 2005). In GLY, the mechanisms underlying a decrease in bulk density are less clear, especially given the lack of a change in CTRL. It is possible that the greater soybean productivity in GLY had an associated higher degree of root growth that loosened soil. Interestingly, tillage did not significantly impact aggregate stability. A combination of factors associated with IWG roots could have contributed to the maintenance of aggregate stability despite tillage. Roots and fungal hyphae facilitate aggregate formation by enmeshing soil particles (Tisdall & Oades, 1982). Root exudates and the microbial community that they cultivate also contribute chemical binding agents, including extracellular polymeric substances (EPS; Amézketa, 1999). Moreover, the microbial production of EPS has been shown to be enhanced under perennial crop cultivation (Sher et al., 2020). Additionally, our experiment was carried out on silt loam soils with relatively high organic matter, which offer positive conditions for aggregate formation (Haynes & Swift, 1990; Tiemann & Grandy, 2015; Tisdall & Oades, 1982). Perhaps these factors moderated the effects of tillage on the deterioration of aggregate stability. Alternatively, a single crop transition involving tillage could have been insufficient to create detectable differences between tillage and NT treatments. Wright et al (1999) showed that differences in aggregate stability between NT and plowed maize were not significantly different after the first year, but were in the second and third year. However, in previously uncultivated soils, Grandy et al. (2006) found that mean weight diameter in cultivated plots remained lower relative to control for over 2 years following tillage.

While the mean weight diameter was not different between GLY and CTRL, aggregate stability in CTRL did increase relative to baseline, whereas GLY did not. This is potentially a result of the persistence of the IWG stand in CTRL. With the additional year of IWG growth, its roots could have continued enhancing soil structure through the mechanisms described above. On the other hand, GLY was highly effective at terminating IWG, and therefore the lack of root and associated biological activity could have contributed to stalled aggregate formation (Tisdall & Oades, 1982). While soil biological measurements can be sensitive indicators of soil health (Bastida et al., 2008), there is evidence that IWG cultivation can improve physical soil structure more strongly than soil biology (Rakkar et al., 2023). Rakkar et al. (2023) showed that after 2 years of cultivation, IWG led to soils containing a greater proportion of large aggregates compared to an annual grain rotation across three sites.

5 | CONCLUSION

Our study was the first to investigate the impacts of crop rotation from a perennial grain to an annual crop on soil structural properties, soil CO_2 emissions, and the subsequent crop response. Our results show that producers have multiple options for terminating IWG that will have limited effects on the soil environment or future crop yield when rotating to soybean. However, an important finding is that the tillage treatments as we executed them were only nominally effective at terminating IWG, and that additional tillage passes are likely required to achieve an acceptable level of termination without herbicides. More intensive tillage in terms of frequency and depth compared to the treatments tested here could lead to further impacts to soil structure, carbon and CO_2 emissions. These outcomes are largely dependent on soil type, weather, existing SOC stocks, and topography. We recognise that this study is limited by a single year of data, and believe further longer-term research with additional sites will aid in exploring these topics. With these caveats in mind, it appears that a single termination event is not sufficient to impart considerable setbacks to ecosystem benefits accrued through short-term IWG cultivation. Therefore, termination methods involving tillage could be viewed as an option that, when used in moderation and in combination with chemical methods, need not diminish the environmental gains achieved through IWG production.

AUTHOR CONTRIBUTIONS

Jake Kundert: Formal analysis and investigation; writing—original draught preparation; writing—review and editing; **Manbir Rakkar**: Conceptualisation; methodology; formal analysis and investigation; writing—review and editing; funding acquisition; **Jessica Gutknecht and Jacob Jungers**: Conceptualisation; methodology; formal analysis and investigation; Writing—original draught preparation; writing—review and editing; funding acquisition; resources; supervision.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The datasets generated during and/or analysed during the current study are available from the corresponding author upon reasonable request.

ETHICS STATEMENT

All authors have adhered to the ethical policies of the journal.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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