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PRODUCTION AND CONSERVATION TRADEOFFS OF VERTICAL TILLAGE IN NO-TILL SYSTEMS

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ABSTRACT

Over the past 40 years, many corn (*Zea mays* L.) and soybean (*Glycine max* L.) growers in Pennsylvania transitioned from conventional tillage to reduced tillage and no-till systems, which reduce soil erosion and promote soil health. However, there are multiple management tradeoffs in long-term no-till cropping systems. The need for effective residue management in no-till cropping systems resulted in the recent adoption of ‘vertical tillage,’ which is primarily a residue management practice characterized by cutting and incorporating crop residue within the top 5-10 cm of soil. Though vertical tillage is widespread, minimal scientific information is available to document crop production and soil conservation tradeoffs related to this practice. Replicated on-farm field trials were conducted over a two-year period in 2021-2022 in southeast Pennsylvania to study the effects of vertical tillage on crop performance, pest management and soil health metrics. Key results of the project, relative to no-till, indicate vertical tillage results in moderate reductions in surface residue cover, winter annual weed cover and the incidence of slug damage. Across strip trial locations, surface residue cover from a previous grain corn crop was reduced 16% on average when employing vertical tillage once annually in the spring. In addition, vertical tillage resulted in surface residue cover reductions below a state conservation program compliance threshold (≥ 60% residue cover) approximately 18% of the time as influenced by equipment type and intensity of use. While vertical tillage may locally influence these factors, depending on field characteristics and weather conditions, the treatment effect is likely not large enough to alter chemical weed management or avoid early season pest problems associated with additional crop residue. Regarding soil health, results suggest

vertical tillage may not alleviate soil test phosphorus or organic matter stratification in long-term no-till cropping systems but may reduce surface compaction while potentially creating a compacted layer below the working depth of these tools. The primary objective of this thesis research was to provide sound scientific data from on-farm trials to improve grower and policy maker decision-making related to whether vertical tillage has a role in conservation agriculture on southeast Pennsylvania farms, which are located within the environmentally sensitive Chesapeake Bay Watershed.

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Prologue

Crop residue management challenges. No-till and other conservation tillage methods have steadily increased in Pennsylvania and the United States over the last 40 years (USDA NASS, 2017). Approximately 67% of cropland acreage in Pennsylvania was under no-till production in 2017 (USDA NASS, 2017). No-till crop production aims to minimize soil disturbance while maintaining at least 60% surface residue cover throughout the year (USDA-NRCS, 2016). No-till crop production practices can reduce operating costs for growers and soil sediment and nutrient losses to surrounding ecosystems. Improvements in soil and water conservation in the Mid-Atlantic are attributable, in part, to widespread adoption of no-till cropping systems (Maguire et al., 2011). However, several management tradeoffs can emerge as a result of no-till crop production.

One tradeoff of no-till cropping systems is an increased reliance on herbicides as the primary method of weed control, which has contributed to the development of glyphosate- and multiple- herbicide resistant weed species, including horseweed (*Erigeron canadensis* L.), Palmer amaranth (*Amaranthus palmeri* L.) and common waterhemp (*Amaranthus tuberculatus* L.; Heap, 2014). A second tradeoff is the potential for pH stratification, where soil is more acidic at the surface and more alkaline at depth (Raeder et al., 2015) due to recurring applications of surface applied nitrogen (N) and sulfur (S) containing fertilizer, acid rain, and chemical soil weathering processes. Soil pH stratification, sometimes referred to as an “acid-roof,” may reduce nutrient and water availability, increase aluminum toxicity, result in poor weed control due to lack of soil-applied residual herbicide persistence, and perhaps reduce soil microbial activity near the surface (Beegle, 1996). Another tradeoff of no-till cropping systems may include nutrient stratification where soil test phosphorus (P) and other nutrients are more heavily concentrated near the soil surface (Beegle, 1996; Sharpley, 2003) due to repeated applications of surface-applied manure and inorganic fertilizer over time. In no-till cropping systems with a history of surface-applied manure applications, increased losses of soluble P in agricultural runoff are observed at times (Maguire et al., 2011). A perceived management tradeoff in no-till cropping systems among a sub-set of growers in Pennsylvania is potential surface compaction and surface crusting, which may limit root growth and decrease crop yield (Duiker, 2002) due to heavy equipment trafficking on wet soil.

One of the most evident management tradeoffs of no-till crop production, however, is the accumulation of previous crop residue on the soil surface, particularly in high yielding grain crop rotations and continuous corn production environments. A conversion to no-till crop production, coupled with increasing corn yields and increased adoption of double cropping and cover cropping, results in corresponding increases in crop residue on the soil surface left from the previous crop (Adler et al., 2015). The average corn grain yield in the U.S. increased 40% over a 25 year period (1990 to 2015) and Pennsylvania average corn grain yields have increased proportionally from about 6.5 to 9.5 Mg/ha (Adler et al., 2015). Corn grain yields among top Pennsylvania corn producers regularly exceed state average yields. In 2021, the average (n = 27) corn grain yield from a Pennsylvania high-yield corn contest was approximately 15.5 Mg/ha (*PA Five Acre Corn Club Contest Report*, 2021). Increasing corn grain yields lead to corresponding increases in corn stover, assuming a harvest index of 0.5 (Jeschke & Heggenstaller, 2012; Lorenz et al., 2010).

In addition to increasing crop yields and conversion to no-till and cover cropping, the adoption of other common management practices may be influencing an increase in corn residue on the soil surface. Past research studies present conflicting results on whether corn stover (i.e., leaves, stalks and cobs) from Bt corn hybrids decompose at a slower rate than corn stover from non-Bt corn hybrids (Flores et al., 2005, Tarkalson et al., 2008). Some of these same reports indicate no difference in biomass fractions (i.e., lignin) in various portions of corn stover in Bt and non-Bt corn hybrids (Tarkalson et al., 2008). Additionally, the application of foliar fungicide in the U.S. to control various corn leaf diseases such as Grey Leaf Spot (*Cercospora zeae-maydis* L.) and Northern Corn Leaf Blight (*Exserohilum turcicum* L.) is increasing (D. Mueller et al., 2013; Munkvold et al., 2008). The effect of applying foliar fungicide on the biomass fractions (i.e., cellulose and lignin content) of various portions of the corn plant, and therefore on the potential rate of decomposition, is not well studied. Limited research suggests applying foliar fungicide at the V5 and VT corn growth stages may increase lignin content of corn stalks (Kalebich et al., 2017), perhaps slowing the decomposition rate of the stover.

Adequate crop residue cover is essential for a functioning no-till system. Residue cover increases water infiltration, soil moisture retention, and soil organic matter. Residue cover provides a habitat for beneficial soil dwelling organisms. However, excess accumulations of crop residue on the soil surface pose several management challenges in no-till cropping systems. Corn residue can interfere with planting operations and can delay planting in the spring season following a substantial grain harvest the previous fall, where no residue management tactic is employed. Excess residue can interfere with stand establishment by keeping soil temperature lower and soil moisture higher in cool, wet spring seasons (Adler et al., 2015). Corn stover with carbon to nitrogen (C:N) ratios from 50:1 to 75:1 (Jeschke & Heggenstaller, 2012) can immobilize large portions of soil nitrogen (N) pools for longer periods of time into the next growing season, increasing the need for inorganic N fertilizer for a corn crop (Burgess et al., 2002). Previous crop residue can also create a favorable environment for crop pests (e.g., slugs) and can harbor inoculum of plant pathogens that affect wheat and corn, such as Fusarium Head Blight (*Fusarium graminearum* L.) and Grey Leaf Spot (*Cercospora zeae-maydis* L.), respectively. In addition to resistant weeds and potential infection from plant pathogens, slugs are an increasing pest management challenge in no-till crop fields and substantial amounts of surface residue, cool temperatures, and ample moisture favor persistence of slug populations in certain spring seasons. In one survey, over 80% of no-till growers in Pennsylvania reported slugs as one of the greatest pest management challenges in their cropping systems (Douglas & Tooker, 2012).

Residue management with vertical tillage. Growers in Pennsylvania, and within similar crop production environments, employ two main residue management strategies. Crop residue is harvested for livestock bedding, livestock feed, or as a substrate for mushroom production, or the residue is managed in place. Alternative tactics for managing crop residue in place include: (1) modifying harvest equipment (i.e., ‘chopping stalk rolls’ and ‘chopping corn heads’) to better process residue in the fall (Wolkowski, 2011), (2) modifying planting equipment (i.e., alterations to row cleaners, removal of no-till coulters, regular replacement of double-disk openers, alterations to the closing wheel system) to better negotiate residue in the spring, (3) mowing residue in the fall or spring, or (4) incorporating residue into the soil in the fall or spring.

A subset of growers in the region practice a form of shallow non-inversion tillage commonly known as 'vertical tillage' by cutting and incorporating crop residue within the top 5-10 cm of soil to speed decomposition (Chen et al., 2016; Schomberg et al., 1994) and prepare the seedbed for planting. This practice accomplishes the growers' primary residue management objective (i.e., adequate seedbed preparation) with less intensive soil disturbance relative to conventional tillage methods such as chisel plowing and disking. Vertical tillage tools may be designed with individually mounted or spring mounted disk blades or coulters, a row of spiked treader wheels, a set of tines, and/or a set of rolling baskets. Vertical tillage for residue management, and ultimately for seedbed preparation, should not be confused with 'sub-soiling' or 'deep ripping' where shanks operate at a depth up to 50 cm to alleviate sub-soil compaction.

Grower adoption of vertical tillage has steadily increased in the last 20 years, especially in high-yield environments in southeast Pennsylvania. Some growers adopt vertical tillage to improve crop stand establishment without having to significantly alter planting equipment to negotiate crop residues, thus off-setting planter upgrade and maintenance costs. Vertical tillage can also negate the need for replacement or after-market modification of existing harvesting equipment to utilize tools designed to cut and distribute residue more efficiently.

A primary objective of vertical tillage in a no-till system is to prepare the seedbed for planting (Chen et al., 2016; Smith & Warnemuende-Pappas, 2015). Growers desire to manipulate the seedbed to reach a specific set of soil and residue conditions most optimum for their planter set-up and operating ability. Growers use vertical tillage to hasten soil drying and warming in wet and cool spring seasons, potentially facilitating earlier or timelier crop establishment. Growers also use vertical tillage to incorporate surface-applied manure or fertilizer and to alleviate surface crusting/compaction caused by heavy equipment trafficking wet soil.

An external policy factor contributing to vertical tillage adoption rates within Pennsylvania was an income tax credit that growers could capture when purchasing "Low-Disturbance Residue Management Equipment," which included popular vertical tillage tools, through the Resource Enhancement and Protection (REAP) Program sponsored by the Pennsylvania State Conservation Commission (PA State Conservation Commission, 2019). From 2015 to 2019, growers purchasing vertical tillage equipment could capture this tax credit for a portion of the purchased cost of eligible vertical tillage equipment. If purchasing a vertical tillage tool through this program, growers had to abide by a set of guidelines when operating the equipment. These guidelines stipulate that qualifying equipment should be set as follows: (1) disk blade angle must not exceed five degrees, (2) disk blades must have no concavity, (3) working depth of equipment must not exceed 10 cm, (4) average working depth of equipment should be 5 cm, and (5) minimum surface residue cover must not fall below 60% throughout the year (PA State Conservation Commission, 2019). However, a recent 2019 policy change removed the tax credit for vertical tillage tools due to grower use of increasingly aggressive tools that produce soil disturbance levels that no longer meet policy thresholds for soil conservation.

Knowledge gap and research needs. Despite this recent policy measure to disincentivize vertical tillage as a soil conservation method, the increased use of vertical tillage in southeast Pennsylvania has led to grower, consultant, and stakeholder questions regarding the impact of vertical tillage on crop production, grower profitability and soil conservation goals within the region. Although vertical tillage is a regionally widespread agronomic practice, little is known regarding its effects, short- and long-term on crop production, pest management, and soil health.

Growers and agronomic consultants are keenly interested in the effects of vertical tillage on several crop production metrics including crop emergence and establishment, and crop yield. Among the grower community, assessing vertical tillage effects on crop yield helps determine return on investment (ROI). Previous studies report mixed results regarding the impact of vertical tillage on crop yield with some studies reporting higher soybean yields with vertical tillage relative to no-till (Watters & Douridas, 2013), while other studies report a yield increase in corn with vertical tillage, but not in soybean (Van Dee, 2005).

The impact of vertical tillage on pest management is also a significant knowledge gap that prevents a broader understanding of management tradeoffs. The use of vertical tillage as an integrated weed management (IWM) tool is largely unexplored. Vertical tillage may provide control of winter annual weed species prior to planting, which could reduce reliance on pre-plant burndown herbicides such as glyphosate and paraquat. By incorporating crop residue into the soil and speeding decomposition, vertical tillage may also mitigate early-season slug abundance in no-till cropping systems. Greater understanding of the impact of vertical tillage on crop and pest management tradeoffs should also inform development of BMPs for effectively integrating vertical tillage into no-till cropping systems.

Soil test P stratification in long-term no-till cropping systems is of environmental concern as soluble (dissolved) P loss from no-till fields with stratified P is a major contaminant impairing ecosystems (Daryanto et al., 2017; Sharpley, 2003; Smith et al., 2017) in the Chesapeake Bay Watershed (Kleinman et al., 2019). Increases in soluble P loss from farms in southeast Pennsylvania remains a major source of agricultural runoff to the bay, and vertical stratification of P in no-till cropping systems is a tradeoff often overlooked by avid promoters of "no-till" (Kleinman et al., 2019). Therefore, whether vertical tillage incorporates P below the top few centimeters of soil is of regional interest to practitioners, stakeholders, and policymakers.

Increases in soil carbon (C) near the surface in no-till systems is well established (West & Post, 2002). As researchers assess soil C stratification in no-till systems, the intensity of soil disturbance and soil mixing necessary to re-distribute accumulations of soil C near the surface to deeper depths in the soil profile is of interest. If a significant portion of these recent near-surface carbon gains are in the labile C pool, and are re-distributed due to vertical tillage, greater C mineralization may occur as a result of soil disturbance (Powlson et al., 2014). Recent research suggests that shallow non-inversion tillage may maintain soil C gains associated with no-till without subjecting labile C fractions to significant mineralization observed when practicing tillage at deeper depths (Cooper et al., 2016).

Assessing compaction alleviation is important as growers determine how to manage perceived increases in soil compaction caused by heavy equipment trafficking on wet soil over time. Quantifying the ability of vertical tillage tools to break up a surface crusting, or alleviating compaction in the zone of soil mixing, by the tillage tool would be valuable. Alternatively, if anecdotal reports on farms in the region with a long-term vertical tillage management legacy of a shallow ‘plow pan’ developing just below the working depth of the tools can be confirmed, this would prove valuable information as it may influence future soil management decision-making.

Greater understanding of the impact of vertical tillage on soil erosion potential and short-term indicators of soil health should also inform soil conservation policy and non-governmental organizations (NGOs) that advocate for ‘zero-tillage’ practices, and actively discourage adoption of vertical tillage. By assessing several key soil biological and physical indicators, the impact of introducing vertical tillage into long-term no-till cropping systems on soil health may be realized.

Chapter 1

Vertical tillage effects on surface residue cover, pest management, and soybean performance in no-till cropping systems

Introduction

No-till and other conservation tillage methods have steadily increased in the Mid-Atlantic over the last 40 years (USDA NASS, 2017). In addition, the average corn grain yield in the U.S. increased 40% over a 25 year period (1990 to 2015), with northern Mid-Atlantic corn grain increasing from approximately 6.5 to 9.5 Mg ha^{-1} (Adler et al., 2015).

One of the most evident management challenges of no-till production in high-yielding corn environments is the accumulation of corn stover left on the soil surface post-harvest (Jeschke and Heggenstaller, 2012; Lorenz et al., 2010). While surface residue cover in no-till systems reduces soil erosion, promotes water infiltration, and reduces evaporation, excess residue may create additional management challenges. In the last two decades, a subset of Mid-Atlantic growers have practiced a form of shallow non-inversion tillage, commonly known as 'vertical tillage' to manage corn stover and prepare seedbeds for planting (Chen et al., 2016; Smith & Warnemuende-Pappas, 2015). Although vertical tillage is now a regionally widespread agronomic practice, little is known regarding its effects, short- and long-term, on soil conservation, crop production, and pest management goals.

Vertical tillage implements are designed to be residue management tools for preparing an adequate seedbed by cutting and incorporating crop residue within the top 5-10 cm of soil to speed decomposition (Chen et al., 2016; Schomberg et al., 1994). To meet policy thresholds for soil conservation incentive programs in the northern Mid-Atlantic region, disk blade angles of vertical tillage tools must not exceed five degrees and have no concavity, working depth must not exceed 10 cm, and surface residue cover must not fall below 60% throughout the year (PA State Conservation Commission, 2019).

The impact of vertical tillage on soil conservation (≥ 60% residue cover), pest management, and crop performance is a significant knowledge gap. For example, the use of vertical tillage as an integrated weed management (IWM) tool is largely unexplored (Bates et al., 2012). Vertical tillage may provide direct control of established winter annual weed species when employed in the spring prior to cash crop planting, which could reduce the reliance on pre-plant burndown herbicides such as glyphosate and synthetic auxins in some cases or increase the efficacy of pre-plant burndown herbicides. For example, if vertical tillage could effectively control fall- or spring-emerged glyphosate-resistant horseweed (*Erigeron canadensis* L.), this could reduce or eliminate the need to apply dicamba (i.e., Xtendtimax or Engenia) or 2,4-D choline (i.e., Enlist) in pre-plant burndown programs, thereby fostering greater stewardship of soybean trait technologies. However, the intensity and working depth of tillage, and the diversity of species within the established weed community at the time of tillage, will likely influence the efficacy of vertical tillage as an IWM tool.

Crop residues can also create a favorable environment for other early season pests common in no-till systems, such as slugs. In one survey, over 80% of no-till growers in Pennsylvania reported slugs as one of the greatest pest management challenges in their cropping systems (Douglas & Tooker, 2012). Slugs favor cool, wet conditions in high-residue environments, feeding on recently emerged soybean and corn plants mostly at night, and using previous crop residues as refuge habitat during the day (Douglas & Tooker, 2012). By incorporating crop residue into the soil and speeding decomposition, vertical tillage may mitigate early-season slug abundance in no-till cropping systems.

Grower reasons for using vertical tillage tools for seedbed preparation include creating a warming and drying effect on the soil conditions. Thus, growers aim to achieve timelier planting and more even crop emergence and establishment in high residue-environments. Assessing the impacts of shallow non-inversion tillage on crop emergence and establishment as well as on crop yield is of keen interest to growers and agronomists. Trends from a small body of research suggest that vertical tillage may impact crop performance, including crop stand establishment and crop yield (Van Dee, 2005).

Greater understanding of the impact of vertical tillage on crop and pest management tradeoffs may inform development of BMP's for effectively integrating vertical tillage into no-till cropping systems while adhering to soil conservation surface residue thresholds. Towards this end, a multi-criteria assessment of vertical tillage was conducted with use of replicated on-farm paired comparisons across two years (2021-2022) within a grain corn to full-season soybean crop rotation in southeast Pennsylvania. Relative to no-till production, we report the effects of spring-implemented vertical tillage on the change in (1) corn residue surface cover; (2) winter annual weed abundance at the time of planting; (3) soybean emergence and establishment; (4) incidence and severity of leaf defoliation due to slug feeding; and (5) soybean yield. It was hypothesized that, relative to no-till, vertical tillage would significantly reduce surface residue cover, winter annual weed abundance and the incidence and severity of slug damage, while improving soybean establishment, stand density, and grain yield.

Materials & Methods

Study location. Crop production and pest management effects of vertical tillage were compared to no-tillage within a grain corn to full-season soybean crop rotation using an on-farm strip trial approach in southeast Pennsylvania (Lancaster and Chester Co.) in the 2021 and 2022 growing seasons. Most of the farms in this study were located on very deep, well-drained soils on uplands, formed in residuum or colluvium from limestone, micaceous limestone, calcareous schist, micaceous schist, siltstone, or shale; rarely phyllite, granitic gneiss, or quartzitic rocks; or similar parent materials (Appendix, **Table A-1**). These silt loam or loam soils in a moderate climate (Appendix, **Table A-2**) coupled with frequent manure applications, and occasional applications of spent mushroom substrate, contribute to relatively fertile and historically high-yielding environments on all cooperating farms.

Twenty paired comparison replicates, hereafter referred to as paired strips, were imposed each year by distributing paired strips across nine farms in 2021 and on 12 farms in 2022 (**Table 1-1**). Cooperating farms consisted of cash grain operations raising corn (*Zea mays L.*) and soybean (*Glycine max L.*) in rotation with other cash crops such as winter wheat (*Triticum aestivum L.*) and winter barley (*Hordeum vulgare L.*).

On each cooperating farm, paired strips were established in fields rotating from grain corn, where corn residue was left unharvested and undisturbed over winter, to full-season soybean. Fields were left fallow in the corn to soybean transition except for two fields in 2021 and one field in 2022, which had a late planted cover crop that was terminated early in the spring of the following year. Two fields in 2022 had cover crops established that were terminated in late spring after vertical tillage was completed. At one location, the cover crop was terminated approximately one week prior to planting.

At a second location, the cover crop was terminated at-planting.

Table 1-1. Crop management overview across strip trial locations including year, farm (Lancaster County (LC), Chester County (CC)), soil management legacy, equipment type (Great Plains Turbo Till (Great Plains), Kuhn-Krause Excelerator (Kuhn-Krause), Salford), vertical tillage (VT) date, soybean planting date, row width, plant population at planting, soybean maturity group, schedule of burndown and in-season herbicide applications.

Year	Farm	Soil Mgmt. Legacy	Equipment type	VT Date	Planting Date	Row Width (cm)	Plant Population (plants m^{-2})	Maturity Group	Herbicide Applications		
									Burndown	Pre-emerge Residual	Post-emerge
2021	LC 1	No-till	Great Plains	5-Apr	23-Apr	38	40	3.3	Yes	Yes	Yes
2021	LC 1	No-till	Great Plains	5-Apr	23-Apr	38	40	3.3	Yes	Yes	Yes
2021	LC 2	No-till	Great Plains	6-Apr	1-May	38	33	2.9	Yes	Yes	Yes
2021	LC 2	No-till	Great Plains	6-Apr	1-May	38	33	2.9	Yes	Yes	Yes
2021	LC 4	No-till	Salford	7-Apr	22-Apr	38	41	3.6	Yes	Yes	Yes
2021	LC 4	No-till	Salford	7-Apr	22-Apr	38	41	3.6	Yes	Yes	Yes
2021	LC 4	No-till	Salford	7-Apr	22-Apr	38	41	3.8	Yes	Yes	Yes
2021	LC 4	No-till	Salford	7-Apr	22-Apr	38	41	3.8	Yes	Yes	Yes
2021	LC 5	No-till	Great Plains	9-May	10-May	76	38	3.3	Yes	Yes	Yes
2021	LC 3	Vertical till	Salford	10-Apr	1-May	38	35	2.9	Yes	Yes	Yes
2021	LC 6	Vertical till	Kuhn-Krause	7-Apr	20-Apr	38	37	2.8	No	Yes	Yes
2021	LC 6	Vertical till	Kuhn-Krause	7-Apr	18-Apr	38	37	3.4	No	Yes	Yes
2021	LC 6	Vertical till	Kuhn-Krause	7-Apr	24-Apr	38	37	3.2	No	Yes	Yes
2021	LC 6	Vertical till	Kuhn-Krause	7-Apr	20-Apr	38	37	2.8	No	Yes	Yes
2021	CC 1	Vertical till	Kuhn-Krause	7-Apr	20-Apr	38	37	2.6	Yes	Yes	Yes
2021	CC 1	Vertical till	Kuhn-Krause	7-Apr	20-Apr	38	37	2.6	Yes	Yes	Yes
2021	CC 2	Vertical till	Great Plains	17-Apr	24-Apr	38	44	3.6	Yes	Yes	Yes
2021	CC 2	Vertical till	Great Plains	17-Apr	24-Apr	38	44	3.6	Yes	Yes	Yes
2021	CC 3	Vertical till	Kuhn-Krause	24-Apr	27-Apr	38	36	3.2	No	No	Yes

2021	CC 3	Vertical till	Kuhn-Krause	24-Apr	27-Apr	38	36	3.2	No	No	Yes
2022	LC 1	No-till	Great Plains	21-Apr	28-Apr	38	37	3.1	Yes	Yes	Yes
2022	LC 1	No-till	Great Plains	21-Apr	28-Apr	38	37	3.1	Yes	Yes	Yes
2022	LC 7	No-till	Great Plains	5-May	11-May	76	42	3.7	Yes	Yes	Yes
2022	LC 7	No-till	Great Plains	5-May	11-May	76	42	3.7	Yes	Yes	Yes
2022	LC 8	No-till	Great Plains	5-May	12-May	76	42	3.1	Yes	Yes	Yes
2022	LC 9	No-till	Kuhn-Krause	15-Apr	30-Apr	76	35	3.4	Yes	Yes	Yes
2022	LC 5	No-till	Great Plains	16-May	17-May	76	38	3.3	Yes	Yes	Yes
2022	LC 10	No-till	Kuhn-Krause	15-Apr	20-May	76	40	3.9	Yes	Yes	Yes
2022	LC 10	No-till	Kuhn-Krause	15-Apr	20-May	76	40	3.9	Yes	Yes	Yes
2022	LC 11	No-till	Kuhn-Krause	25-Apr	29-Apr	76	35	2.9	Yes	Yes	Yes
2022	LC 12	Vertical till	Kuhn-Krause	15-Apr	27-Apr	38	49	2.6	Yes	Yes	Yes
2022	LC 13	Vertical till	Great Plains	16-May	17-May	76	36	2.9	Yes	Yes	Yes
2022	LC 6	Vertical till	Kuhn-Krause	1-Apr	24-Apr	38	37	3.5	Yes	Yes	Yes
2022	LC 6	Vertical till	Kuhn-Krause	1-Apr	24-Apr	38	37	3.5	Yes	Yes	Yes
2022	LC 6	Vertical till	Kuhn-Krause	1-Apr	24-Apr	38	37	3.2	Yes	Yes	Yes
2022	LC 6	Vertical till	Kuhn-Krause	1-Apr	24-Apr	38	37	3.7	Yes	Yes	Yes
2022	CC 1	Vertical till	Kuhn-Krause	20-Apr	22-Apr	38	37	2.7	Yes	Yes	Yes
2022	CC 1	Vertical till	Kuhn-Krause	20-Apr	22-Apr	38	37	2.7	Yes	Yes	Yes
2022	CC 2	Vertical till	Great Plains	11-Apr	24-Apr	38	40	3.3	Yes	Yes	Yes
2022	CC 2	Vertical till	Great Plains	11-Apr	24-Apr	38	40	3.3	Yes	Yes	Yes

Experimental design. Vertical- and no-tillage treatments were imposed in twenty field-length paired strips each year using a nested treatment structure to control for multiple sources of variation (**Figure 1-1**). To account for sources of variation in treatment responses due to baseline soil conditions, a soil management legacy factor (*n* = 2) was nested within each year. Soil management legacy was identified as either (1) long-term no-till practiced for more than 10 years, or (2) vertical tillage occurring annually for at least the previous eight years in one or more phases within crop rotations. To account for farm-level management sources of variation within each soil management legacy factor, cooperating farms were nested within soil management legacy. To account for field-level sources of variation, paired strips were nested within farm. The number of paired strips within farm differed each year due to field limitations, with paired strips replicated across single- to multiple- fields per farm or, in some cases, replicated within larger fields that contained variability in landscape position. In total, 20 paired strips and 40 experimental units were imposed in the 2021 and 2022 growing seasons. In 2021, strip trials occurred on a total of nine farms and in 12 fields. In 2022, strip trials occurred on a total of 12 farms and in 17 fields.

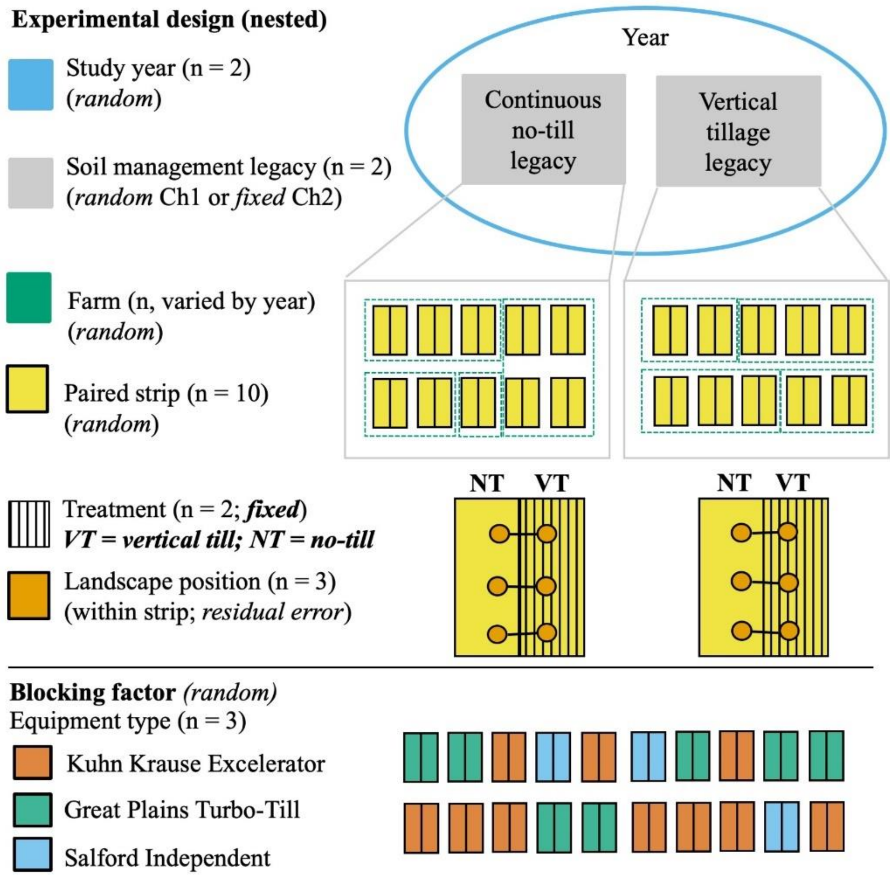

Figure 1-1. Experimental design of project depicting nested treatment structure with fixed effects including tillage treatment (vertical till, no-till) and soil management legacy (continuous no-till, vertical tillage) and random effects including farm and paired strip. Co-located transects are depicted within each strip based on landscape position. Equipment type is included as an additional blocking factor with three brands of tools (Kuhn-Krause Excelerator, Great Plains Turbo Till, and Salford Independent).

Vertical tillage treatment. Crop producers serving as on-farm cooperators employed vertical tillage using owned or rented implements at an average working depth of 5 cm (2 in) to manage corn residue in the early spring (April) prior to establishing full-season soybean (**Table 1-1**). The vertical tillage tools were compliant with standards for "Low-Disturbance Residue Management Equipment" as defined by the Pennsylvania Resource Enhancement and Protection (REAP) Program Guidelines for fiscal year 2019 (PA State Conservation Commission, 2019). Three different vertical tillage tools were used on cooperating farms in 2021, including a Salford Independent (Salford Group, Inc., Salford, ON, Canada), a Great Plains Turbo-Till (Great Plains Manufacturing, Inc., Salina, KS), and a Kuhn-Krause Excelerator (Kuhn North America, Inc., Brodhead, WI). In 2022, cooperating farms used either a Great Plains Turbo-Till or a Kuhn-Krause Excelerator.

Vertical tillage treatments occurred in the spring approximately 14 to 21 days prior to planting in a randomly located field-length strip which created a paired vertical tillage (VT) and no-till (NT) strip. The width of each strip in the field was based on the size of available harvesting equipment so one or two combine passes could be completed within tillage treatment strips. In most site years, vertical tillage was completed once in the spring. At one location in 2022, vertical tillage was conducted twice in the spring prior to planting full-season soybean. At three locations in 2022, corn residue was shredded in the previous fall with a flail mower.

Each cooperating farm implemented their standard fertility, soybean variety selection, and crop protection programs for full-season soybean (**Table 1-1**). A pre-plant burndown and pre-emergence residual herbicide program, along with any post-emergence in-crop herbicide application was implemented at the discretion of the cooperator or their custom pesticide applicator. Most strips in 2021 and all strips in 2022 received a burndown herbicide application, a pre-emergence soil-applied residual herbicide and a post-emerge herbicide. All burndown herbicide applications reportedly occurred after vertical tillage but prior to planting. Due to low weed pressure in the early spring at two locations in 2021, no burndown herbicide was applied after vertical tillage.

Data collection. To account for within-field sources of variation, three data collection transects were established in unique field positions (summit, shoulder, backslope, footslope, toeslope) within each strip and co-located between paired strips (i.e., three paired transects in each strip; six transects per paired strip location). The location of transects was marked using georeferencing software (*QGIS Geographic Information System*, 2022) and a wireless GPS receiver (Garmin GLO Portable GPS and GLONASS Receiver, Garmin Ltd., Olathe, KS) and these waypoints were used for data collection throughout the trial. Hereafter, these transects will be referred to as data collection waypoints to differentiate them from specific transects established at each point for specific measurements.

Soil conservation metrics. Surface residue cover (%) was determined within approximately 21 days after vertical tillage treatments were implemented each spring and just prior to soybean planting (**Table 1-1**). Surface residue cover was quantified using the line-transect method described by the USDA-NRCS standard surface residue cover assessment protocol (*Agronomy Tech Note #MN-19 Estimating Crop Residue Cover*, 1984). Three 15-m transects were established at each data collection waypoint and the presence or absence of corn residue along the transect was recorded every 15-cm lengthwise. Surface residue cover was expressed as a proportion of the total number of observations per transect (n=100).

Pre-plant weed control. Weed abundance was measured after vertical tillage treatments were imposed and just prior to soybean planting to evaluate pre-plant weed control potential. The same transects used to assess surface residue cover were used to collect weed abundance data. The belt-transect sampling method was utilized to assess weed abundance at each waypoint location (*n* = 3) within each strip, so weed abundance could be correlated with surface residue cover. Within each belt transect, the presence or absence of weeds located within 15 cm on each side of the transect were recorded every 15 cm lengthwise. Weed cover was expressed as a proportion of the total number of observations per transect (*n* = 100).

Slug feeding damage incidence. The incidence of slug damage was assessed in late spring at the V1 to V3 soybean growth stage by establishing two separate transects at each data collection waypoint within each strip. Within each transect, the number of soybean plants per three meters of row were counted and assigned a slug damage severity rating based on leaf defoliation (%) via slug feeding where 0 = no apparent damage, 1 = 0-25% defoliation, 2 = 26-50% defoliation, 3 = 51-75% defoliation, and 4 = 76-100% defoliation (Douglas & Tooker, 2012). The number of total plants damaged per three meters of row and the number of plants damaged based on the ordinal scale, were averaged across the six transects assessed within each strip and expressed as a percentage.

Soybean performance. Soybean emergence was assessed in late spring approximately 30 days after planting by measuring the emerged plant population and soybean growth stages, which ranged from the cotyledons expanded (VC) growth stage to the V3 growth stage at the time of assessments. In fields with crop rows spaced 38 cm (15 in) apart, two 5.3 m long transects (0.001 ac) were established at each data collection waypoint within each strip. In fields with crop rows spaced 76 cm (30 in) apart, one 5.3 m long transect (0.001 ac) was established. Emerged soybean plants were counted along transects and soybean stand establishment was expressed on a plants per square meter basis.

Soybean stand uniformity was also assessed at the time of population assessments using the same transect. Twenty plants were counted along the transect, their growth stages recorded, and an average growth stage determined. The growth stages determined at each of the three data collection waypoints within each strip were then averaged.

Crop yield was measured at harvest in the fall using a combine yield monitor or by measuring grain mass harvested from each strip using a weigh wagon or truck scale. All harvest and weighing equipment and infrastructure was provided by the on-farm cooperators. Crop moisture was determined using either a combine yield monitor if collecting yield data using the combine or by a grain moisture tester (Moisture Chek PLUS SW08120, Deere & Company, Moline, IL) if collecting yield data using a weigh wagon or truck scale. Strip length ranged from approximately 130 m to 690 m in 2021 and 2022.

Statistical analysis. The effects of vertical tillage on soil conservation, pest management, and crop performance metrics were analyzed with linear mixed-effects (LME) models using the *lme* package (Bates et al., 2015) in R Statistical Software (v4.2.1; R Core Team, 2022). Prior to analysis, each response variable was expressed as the difference between vertical- and no- tillage treatments measured at paired waypoints within paired strips. The treatment difference (vertical tillage – no tillage) was then modeled using a random intercept model with paired strip nested within farm, farm nested within soil management legacy, and soil management legacy nested within year.

Equipment type was fit as an additional random intercept term to account for sources of variation attributed to the intensity of vertical tillage treatments.

With use of this random intercept model, fixed effects were limited to the population-level intercept, which is an estimate of the average difference between tillage treatments across grouping levels. A one-sided *t*-test ($df = 39$) was used to determine if population-level intercepts were significantly different from zero ($p < 0.05$), thereby providing a statistical test of vertical tillage treatments relative to the no-tillage control strips. Two test statistics were then calculated to describe sources of variation in the model. First, the conditional (R^2c) coefficient of determination was calculated to describe the proportion of the total variance in the response variable attributable to estimated random effects using the MuMin package (Nakagawa and Schielzeth, 2013). Next, variance partition coefficients, or intraclass correlation coefficients (Nakagawa and Schielzeth, 2013) were calculated by extracting variance estimates for each grouping-level from *lme* models using the *VarCorr* function and then expressing each estimate as a proportion of the total variance, or sum of variance parameters. Consequently, variance partition coefficients for each model are used to describe what proportion of the total variance in measured metrics can be attributed to variation within- or between- grouping levels (i.e., year, soil management legacy, farm, equipment, paired strip, and within strip. Finally, conditional means and 95% confidence intervals were extracted from *lme* models for random effects of interest. Conditional means describe the deviation of observations in a group level from the population level effect and can be used to draw inferences about differences between levels within a grouping factor (Harrison et al., 2018).

Results

Results of on-farm strip trials support the hypothesis that vertical tillage impacts surface residue cover and early-season pest incidence, including winter annual weed abundance and slug incidence, but vertical tillage did not influence early-season soybean performance or grain yield.

Surface residue cover. The use of vertical tillage in the spring reduced (t-test = -1.9, df = 39, p = 0.03) surface residue cover in comparison to paired no-tillage strips. Averaged across strips (n = 40), surface residue cover was 16% lower in vertical tillage strips. However, the difference in residue cover between vertical- and no- tillage treatments varied considerably among and within paired strip locations (**Figure 1-2**). Differences in surface residue cover between tillage treatments ranged from a 35% reduction in surface residue cover to no change in residue cover. Random effects included in the model accounted for 77% of the total variation in the difference in surface residue cover between treatments.

Assessing how each of the random components of the model influenced the change in surface residue cover with use of variance partition coefficients revealed that equipment type accounted for 46% of the variance (**Figure 1-3**). The other grouping factors accounted for somewhat less variance with year (12%), farm (9%), strip (6%), and soil management legacy (4%) making up less than half of the variation in surface residue cover, whereas the residual component, which denotes within strip variation accounted for 23% of the total variance.

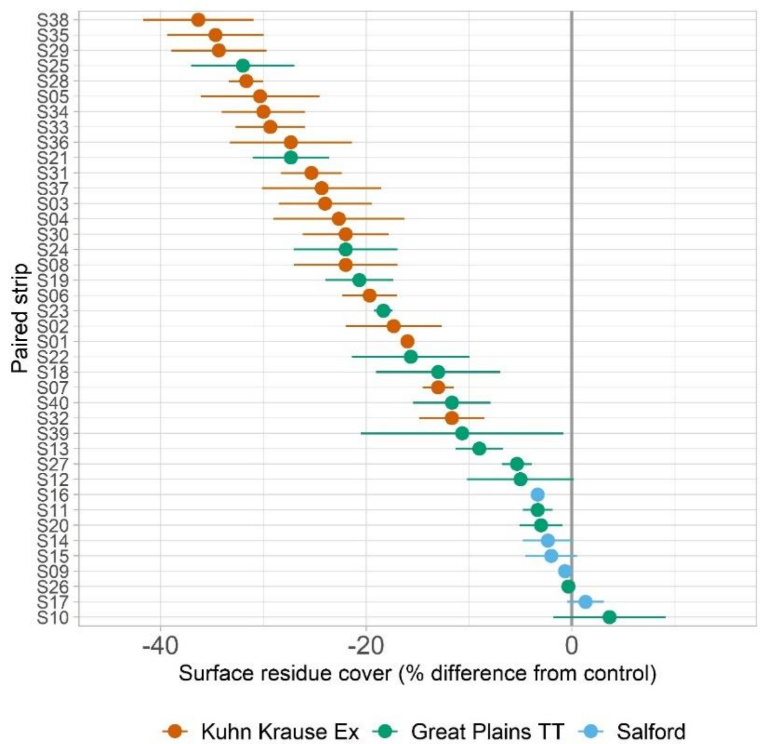

Figure 1-2. Mean (± 1 SE) difference in surface residue cover (%) between paired vertical tillage and no-tillage (control) strips (S1-S40). Mean differences are color-coded by equipment type used at each paired strip location (Kuhn-Krause Excelerator, Great Plains Turbo Till, Salford Independent).

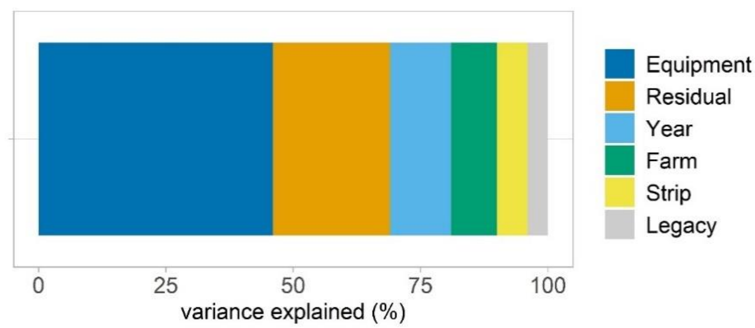

Figure 1-3. Variance explained (% of total) by random effects in analysis of the mean difference in surface residue cover between vertical tillage and no-tillage strips. Variance partition coefficients include, in order of variance explained: equipment type = 46%, residual error = 23%, year = 12%, farm = 9%, strip = 6%, and soil management legacy = 4%.

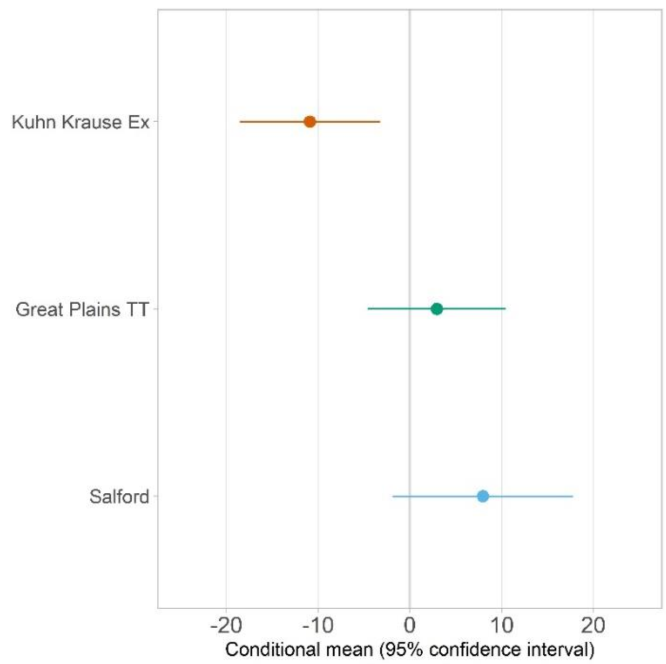

Figure 1-4. Conditional mean (95% confidence interval) difference in surface residue cover between vertical tillage and no tillage by equipment type, including Kuhn-Krause Excelerator, Great Plains Turbo Till and Salford Independent. Conditional means describe the deviation of observations in a random factor from the population level mean.

Analysis of conditional means for equipment type show differences in the magnitude of vertical tillage effects on surface residue cover (**Figure 1-4**). Cooperators using a Kuhn-Krause Excelerator reduced residue cover on average about 24%, which was a significantly greater reduction in comparison to other equipment types. Both the design of these tools, and the way in which cooperators use them, dictates the amount of disturbance created by the vertical tillage operations, and therefore residue levels remaining on the soil surface.

Evaluation of surface residue cover averaged across transects within each strip by equipment type demonstrate the range of baseline surface residue cover in no-tillage treatments and surface residue cover in vertical tillage treatments (**Figure 1-5**). Though baseline surface residue cover was similar among strips subjected to vertical tillage, a greater proportion (32%) of strips had mean surface residue cover levels below a 60% threshold when a Kuhn Krause Excelerator was employed.

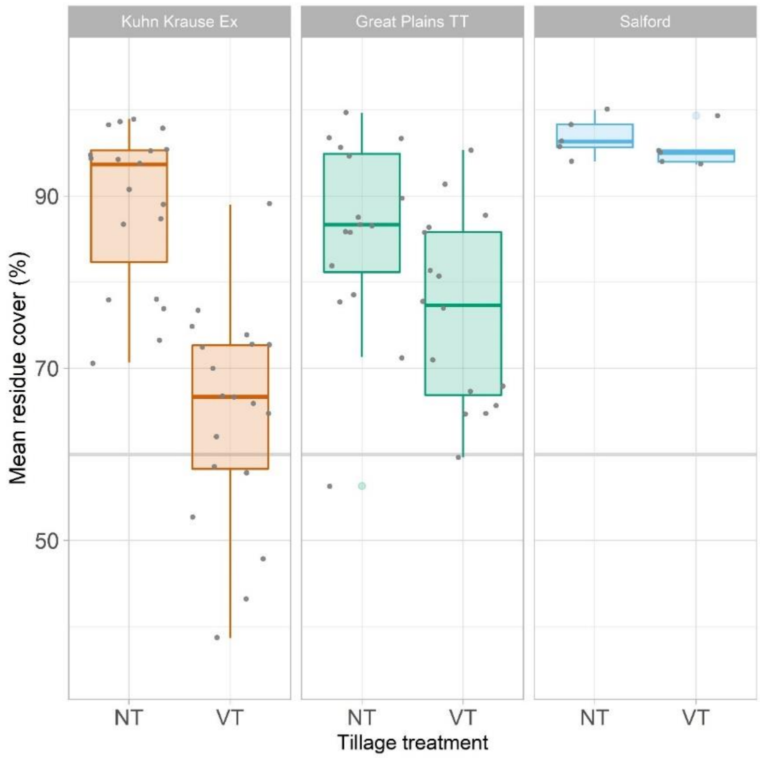

Figure 1-5. Effect of vertical tillage equipment type (Kuhn-Krause Excelerator, Great Plains Turbo Till, Salford Independent) on mean residue cover (%) across tillage treatments (NT = no-till; VT = vertical tillage); REAP compliance surface residue cover threshold marked at 60% surface residue cover

Pre-plant weed control. The use of a single vertical tillage pass in the spring reduced (*t*-test = -2.2, *df* = 39, $p < 0.02$) winter annual weed cover compared to no tillage, with a mean difference of 14% when averaged across strips. The difference in winter annual weed cover between vertical- and no- tillage treatments varied considerably across strips (**Figure 1-6**), ranging from more than 40% less weed cover to no change. Random effects included in the model accounted for 57% of the variation in winter annual cover. Assessing how each of the random components of the model influenced the change in winter annual weed cover revealed that variation between farm (23%), year (19%), and strip (16%) accounted for approximately half of the total variance in winter annual weed cover, whereas soil management legacy and equipment type had a negligible impact (**Figure 1-7**). Though equipment type had a significant effect on the magnitude of change in surface residue cover, it had no impact on the change in winter annual weed cover following vertical tillage (**Figure 1-8**).

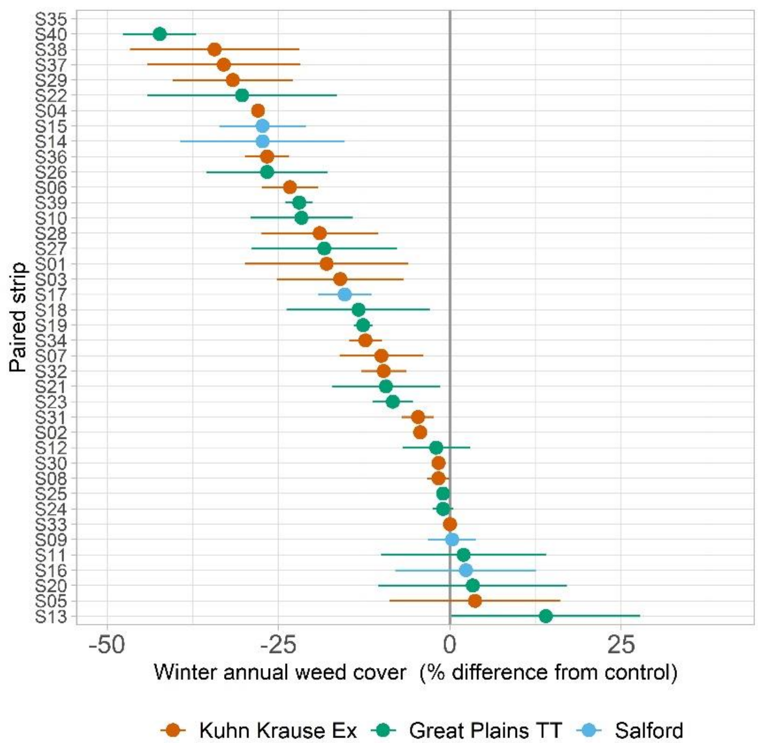

Figure 1-6. Mean (± 1 SE) difference in winter annual weed cover (%) between paired vertical tillage and no-tillage (control) strips (S1-S40). Mean differences are color-coded by equipment type used at each paired strip location (Kuhn-Krause Excelerator, Great Plains Turbo Till, Salford Independent).

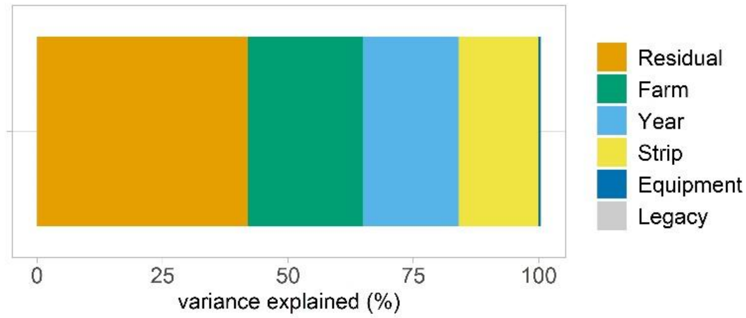

Figure 1-7. Variance explained (% of total) by random effects in analysis of the mean difference in winter annual weed cover between vertical tillage and no-tillage strips. Variance partition coefficients include, in order of variance explained: residual = 42%, farm = 23%, year = 19%, strip = 16%, equipment type = 0.4%, and soil management legacy = 0%.

While the reduction in winter annual weed cover as a result of vertical tillage is statistically significant, the level of weed control observed with use of vertical tillage is not likely to alter chemical weed management programs among most growers in most cases in no-till cropping systems. It should also be noted that, across several sites, initial weed abundance and reductions in weed abundance are quite small which is likely indicative of the within field spatial variability of weed recruitment patterns.

Slug feeding damage incidence. The use of a single vertical tillage pass in the spring reduced (t-test = -4.5, df = 39, $p < 0.001$) the incidence of slug damage by a difference of 9% compared to no tillage across strip trial locations. The difference in slug damage between vertical- and no- tillage treatments also varied considerably among and within strips (**Figure 1-8**) as a few strips had upwards of 35% fewer damaged plants after vertical tillage while other strips had no difference in damaged plants. Random effects included in the model accounted for only 6% of the variation in the incidence of slug damage, whereas within strip variation (residual) accounted for 94% of the total variance in slug damage incidence (**Figure 1-9**).

Though the marginal reduction in the incidence of slug damage is statistically significant, the results may not be biologically significant. Small reductions in incidence of feeding damage (%) by slugs did not seem to impact crop stand establishment in 2021 or 2022 or crop yield in 2021. In both years, across farms and treatments, a low level of soybean leaf defoliation due to slug feeding was observed. In addition to slug damage incidence, the severity of slug damage was quantified based on an estimate of leaf area defoliation (**Table 1-2**).

Table 1-2. Effect of tillage treatment on slug damage incidence and severity as defined by % of plants within a given range of % leaf defoliation due to slug feeding. Significance levels (*p*-value) are based on one-sided *t*-tests (*ns*, non-significant; $p > 0.05$) of the mean difference between treatments.

	Population-level mean		**Population-level mean difference**			
Response variable	**No-till (NT)**	**Vertical till (VT)**	**VT-NT**	**SE**	***t*-test**	***p*-value**
Slug damage incidence	54.2	45.7	-8.5	2.1	-4.5	< 0.001
Slug damage severity (0-25%)	49.6	43.6	-6.0	2.51	-2.7	< 0.005
Slug damage severity (26-50%)	3.9	1.9	-1.9	0.81	-2.4	< 0.01
Slug damage severity (51-75%)	0.7	0.2	-0.5	0.75	-1.2	NS

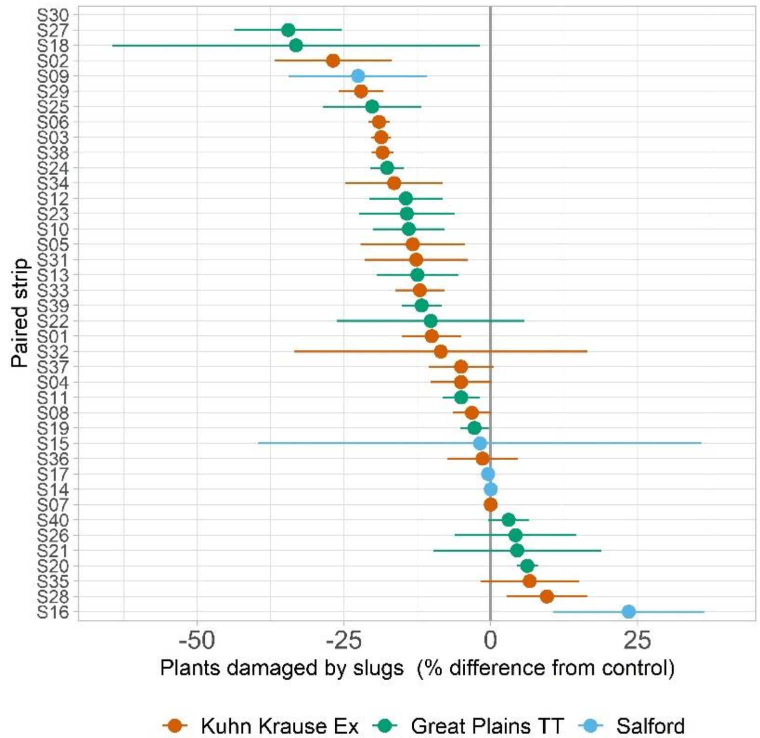

Figure 1-8. Mean (± 1 SE) difference in incidence of slug damage (%) between paired vertical tillage and no-tillage (control) strips (S1-S40). Mean differences are color-coded by equipment type used at each paired strip location (Kuhn-Krause Excelerator, Great Plains Turbo Till, Salford Independent).

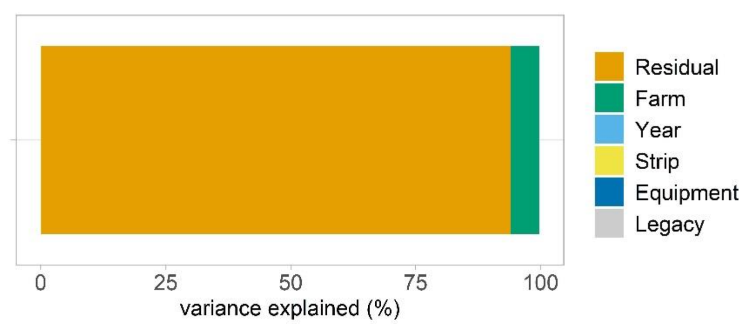

Figure 1-9. Variance explained (% of total) by random effects in analysis of the mean difference in incidence of slug damage (%) between vertical tillage and no-tillage strips. Variance partition coefficients include, in order of variance explained: residual = 94%, farm = 5.7%, year = < 1%, strip = < 1%, equipment type = < 1%, and soil management legacy = 0%.

Soybean establishment and yield. There was no vertical tillage treatment effect on crop establishment in terms of the plant population that emerged after planting, or the crop growth stage assessed in 2021 and 2022 (**Table 1-3**). Additionally, no vertical tillage treatment effect was observed on soybean grain yield in 2021. In 2021, average soybean grain yield across all sites was 5.6 Mg ha^{-1} across no-till treatments and 5.7 Mg ha^{-1} across vertical tillage treatments.

Table 1-3. Effect of tillage treatment on soybean establishment (2021 & 2022) and yield (2021) including plant population, soybean growth stage, and grain yield. Significance levels (*p*-value) are based on one-sided *t*-tests (NS, non-significant; $p > 0.05$) on the mean difference between treatments.

Response variable	No-till (NT)	Vertical till (VT)	Mean difference (VT-NT)	SE	*t*-test	*p*-value
Plant population (plants m^{-2})	28.7	28.4	-0.2	3.59	0.01	NS
Soybean growth stage	1.56	1.62	0.06	0.05	1.2	NS
Grain yield (Mg ha^{-1})	5.62	5.7	0.08	-	-	NS

Discussion

Residue management. Relative to no-till, vertical tillage resulted in moderate reductions in surface residue cover, winter annual weed cover, and incidence of slug damage in 2021 and 2022. High levels of initial residue cover (>70%) were observed across all sites in the spring of 2021 and 2022 prior to any vertical tillage. In some cases, residue levels in high-yielding no-till fields within this study contained 100% surface residue cover at the beginning of each growing season. As this study was completed within relatively high-yielding grain corn fields with stover remaining unharvested, the environment may represent one of the highest residue quantity scenarios currently found in row-crop systems in Pennsylvania. Results from this study found that vertical tillage reduced surface residue cover by approximately 16% on average across strip locations ($n = 40$). Other vertical tillage studies have measured similar levels of baseline residue conditions and subsequent reductions in residue cover in corn-soybean systems after one pass with a vertical tillage tool (Chen et al., 2016; Conley, 2011; Smith & Warnemuende-Pappas, 2015; Whitehair & Presley, 2010).

The extent to which vertical tillage reduced residue cover was dependent on the type of vertical tillage tool used and the intensity of use. At several locations where the Kuhn-Krause Excelerator was used, corn residue cover decreased below the 60% surface residue cover compliance threshold established by the PA REAP program. While the Great Plains Turbo Till did significantly reduce corn residue cover, residue levels remained largely above this REAP compliance threshold. Use of the Salford tool did not reduce corn residue cover.

The Kuhn-Krause Excelerator is designed as a more aggressive tool than the other tools in the study, with disk blades mounted on a gang that can be angled up to five degrees. In comparison, a Great Plains Turbo Till is designed with disk blades mounted on a gang operating at a fixed zero-degree angle, and the Salford Independent is designed with disk blades independently spring-mounted to the frame of the implement fixed at a zero-degree angle. Of these three tools, the Kuhn-Krause Excelerator has the most aggressive design, the Salford Independent has the least aggressive design, and the Great Plains Turbo Till is intermediate. The degree of residue incorporation and soil disturbance can be manipulated by operating the Kuhn-Krause Excelerator at varying depths and disk blade angles. Consequently, the level of disturbance created by an Excelerator can mimic that of a less aggressive Salford tool under certain operating and soil conditions. This likely added to the observed variability in residue cover as on-farm cooperators were instructed to operate the vertical tillage tools per their standard practice. Regardless, the trend in residue cover reduction by equipment type remains consistent across farm and year. Had more stringent instructions been provided to cooperators, regarding the manipulation of settings on vertical tillage and planting equipment, the magnitude of change in residue cover, and perhaps the observed differences related to other metrics such as weed cover or slug damage incidence, may have been greater. In addition, one possible explanation for a lack of significant reduction in surface residue cover across several locations may be partially explained by the high amount of initial residue cover in the spring at these locations. Results under different baseline residue conditions, such as in a soybean or small grain field, likely would have resulted in more substantial surface residue cover reductions.

Integrated weed management. While the reduction in winter annual weed cover across locations in the vertical tillage strips was statistically significant, the magnitude of difference in weed cover following vertical tillage would not alter a chemical weed management program in most cases due to small reductions in total surface weed cover. On most of the farms in this study where vertical tillage is practiced regularly, it is common for growers to apply burndown herbicide in the spring after vertical tillage but prior to planting. This study helps underscore the value of a pre-plant burndown herbicide application in a system which, except for occasional minimum tillage for residue management, largely resembles no-till crop production. The variability of weed cover in response to vertical tillage is likely indicative of the spatial variability of weed recruitment patterns at field scales, which suggests that site-specific precision weed management strategies should be favored over IWM tools that require implementation at a field scale such as vertical tillage.

An additional area of study not fully explored in this experiment is the potential for vertical tillage to increase bioavailability and persistence of soil-applied residual herbicides in high-residue environments (Alletto et al., 2010) by decreasing interception and adsorption of herbicides to surface crop residues (Shaner, 2013). For example, the common soil-applied residual corn herbicide, atrazine (Group 5; triazine), may be more bioavailable when vertical tillage is practiced due to less “tie-up” on surface crop residues (Mueller et al., 2017).

Slug management. The marginal reduction in the incidence of slug damage and within strip variability of vertical tillage effects in 2021 and 2022 is likely indicative of the difficulty associated with capturing the variability in pest feeding across large scale field trials. Additionally, assessing the absolute level of slug damage may be made more challenging as slug feeding in soybean fields can occur on young seedlings close to the soil surface and partially buried by crop residue (Douglas & Tooker, 2012). Though vertical tillage is performed by a subset of growers specifically for improved slug control through residue management, it is challenging to quantify these effects but results from this study suggest that using vertical tillage tools across large acreages solely for slug management may not be tremendously efficacious.

Crop management. No vertical tillage treatment effect was observed on soybean population, crop growth stage, or crop yield. Soybean emergence and establishment may have been impacted by changes in no-till planter adjustment made by operators as they entered a strip that was managed differently than the remainder of the field (i.e., a no-till strip in a vertical tilled field or vice versa). Since adjustments to no-till planters, including (1) aggressivity of row cleaners, (2) amount of down pressure on the row unit, and (3) aggressivity of the closing wheel system, were not controlled in this experiment, this adds additional noise to the assessment of vertical tillage on crop stand establishment. At some locations, however, new planter technology (i.e., automatic, pneumatic adjustment of row unit down pressure) may render the previous concern a non-issue as on-the-go alterations are made based on varying residue and soil conditions. Other studies measuring impact of vertical tillage on crop yield report varying results. In one study, vertical tillage increased soybean yield (Watters & Douridas, 2013), while another study reported increases in corn yield after vertical tillage but not soybean yield (Van Dee, 2005).

Conclusions and future research directions. Results from this two-year study on select farms in southeast Pennsylvania suggest vertical tillage may regularly reduce surface residue cover below state conservation compliance thresholds and may not be a suitable integrated weed management (IWM) or slug management tool. While vertical tillage may locally influence residue cover, weed control and the incidence of slug damage, depending on field characteristics and weather conditions, the effect is likely not large enough to alter chemical weed management or avoid all potential pest problems associated with additional crop residue. In addition, though initial results suggest vertical tillage has no effect on soybean stand establishment or soybean yield improvement, uncontrolled field management factors and soybean cultivar plasticity may confound interpretation. Growers will likely continue to use vertical tillage tools to prepare the seedbed shortly before planting while attempting to achieve timelier crop establishment.

Chapter 2

Vertical tillage effects on soil pH and nutrient stratification, and biological and physical indicators of soil health in no-till cropping systems

Introduction

In the last two decades, shallow non-inversion tillage, commonly known as 'vertical tillage', has been used in conservation tillage systems to manage corn stover and prepare seedbeds for planting (Chen et al., 2016; Smith & Warnemuende-Pappas, 2015). Vertical tillage implements are designed to be residue management tools for preparing an adequate seedbed by cutting and incorporating crop residue within the top 5-10 cm of soil to speed crop residue decomposition (Chen et al., 2016; Schomberg et al., 1994), while meeting policy thresholds for soil conservation incentive programs in the northern Mid-Atlantic region. Short- and long-term effects of vertical tillage on soil pH and nutrient stratification, and biological and physical indicators of soil health, is not well understood, however. Addressing this knowledge gap will improve understanding of soil management tradeoffs associated with vertical tillage within conservation tillage systems in the environmentally sensitive Chesapeake Bay Watershed.

Soil pH stratification, sometimes referred to as an "acid roof," with more acidic conditions at the soil surface and more alkaline conditions at depth (Beegle, 1996), has been perceived as a problem in long-term no-till cropping systems. Reducing soil pH stratification may increase nutrient and water availability, reduce potential aluminum toxicity, or increase soil microbial activity near the soil surface (Beegle, 1996).

Soil nutrient stratification is also an important tradeoff in long-term no-till cropping systems (Beegle, 1996; Sharpley, 2003), as nutrient stratification is accelerated with repeated applications of surface-applied manure and inorganic fertilizer. Soil test phosphorus (P) can become more heavily concentrated near the soil surface in long-term no-till systems (Beegle, 1996; Sharpley, 2003) due to repeated applications of surface-applied manure and inorganic fertilizer over time. Soil test P stratification is of environmental concern as soluble (dissolved) P loss from no-till fields with stratified P is a major water contaminant impairing ecosystems (Daryanto et al., 2017; Maguire et al., 2011; Sharpley, 2003; Smith et al., 2017) in the Chesapeake Bay Watershed (Kleinman et al., 2019). Soluble P loss from farms in southeast Pennsylvania remains a major source of water quality impairment, and stratification of P in no-till cropping systems is a tradeoff with environmental consequences perhaps overlooked by “no-till” producers (Kleinman et al., 2019). Therefore, whether vertical tillage incorporates P below the top few centimeters of soil should be of regional interest to producers, stakeholders, and policymakers.

While studies have been completed in the Midwest investigating the effects of vertical tillage on specific biological and physical soil health metrics (Bates et al., 2012; Daigh et al., 2019; Whitehair and Presley, 2010), the effects remain equivocal. One study reported changes in surface residue cover after use of vertical tillage tools of varying design, operated at different depths in soils with varying texture (Klingberg, 2011). Studies conducted in the upper Midwest and Great Plains reported variable results when comparing soil bulk density, soil aggregate size, and total soil loss between vertical tillage and no-till practices (Whitehair and Presley, 2010) or across a broader range of minimum tillage practices (Daigh et al., 2019). Broad trends from this small body of research suggest that vertical tillage has the potential to impact soil physical properties. In recent years, anecdotal reports from farms in the Mid-Atlantic region with a long-term vertical tillage soil management legacy report a shallow ‘plow pan’ developing just below the working depth of vertical tillage tools. Confirming whether vertical tillage breaks up surface crusting, alleviates compaction in the zone of soil mixing, or creates a compacted layer could better inform future soil management decision-making.

Increases in soil carbon (C) near the soil surface in no-till systems is well documented (West & Post, 2002). As researchers assess soil C stratification in no-till systems, the intensity of soil disturbance and soil mixing necessary to re-distribute accumulations of soil C near the surface to deeper depths in the soil profile is of interest. If a significant portion of these recent near-surface C gains are in the labile C pool, and are re-distributed due to vertical tillage, greater C mineralization may occur as a result of soil disturbance (Powlson et al., 2014). Other research suggests that shallow non-inversion tillage may maintain soil C gains associated with no-till without subjecting labile C fractions to significant mineralization observed when practicing tillage at deeper depths (Cooper et al., 2016). Past research has indicated the quantity of crop residue needed on the soil surface to maintain soil C levels (Johnson et al., 2006; Wilhelm et al., 2007), but how soil disturbance, the breakdown of crop residue, and the subsequent microbial release of CO_2 is impacted by vertical tillage is not clear.

Towards this end, a multi-criteria assessment of vertical tillage was conducted with the use of replicated on-farm paired comparisons across two years (2021-2022) within a grain corn to full-season soybean crop rotation in southeast Pennsylvania.

Relative to no-till production, reported in this study are the effects of spring-implemented vertical tillage on (1) soil pH, nutrient, and organic matter stratification in long-term no-till cropping systems; and (2) biological and physical short-term indicators of soil health including POXC, microbial respiration, wet aggregate stability, and soil penetration resistance. It was hypothesized that, relative to no-till, vertical tillage would reduce soil pH, nutrient, organic matter, and POXC stratification; increase microbial respiration in the fall; reduce aggregate stability; and reduce soil penetration resistance near the surface but increase soil penetration resistance below the working depth of the vertical tillage tools.

Materials & Methods

Study location. Soil fertility and soil health effects of vertical tillage were compared to no-tillage within a grain corn to full-season soybean crop rotation using an on-farm strip trial approach in southeast Pennsylvania (Lancaster and Chester Co.) in the 2021 and 2022 growing seasons. Most of the farms in this study were located on very deep, well-drained soils on uplands, formed in residuum or colluvium from limestone, micaceous limestone, calcareous schist, micaceous schist, siltstone, or shale; rarely phyllite, granitic gneiss, or quartzitic rocks; or similar parent materials (Appendix, **Table A-1**). These silt loam or loam soils in a moderate climate (Appendix, **Table A-2**) coupled with frequent manure applications, and occasional applications of spent mushroom substrate, contribute to relatively fertile and historically high-yielding environments on all cooperating farms.

Twenty paired comparison replicates, hereafter referred to as paired strips, were imposed each year by distributing paired strips across nine farms in 2021 and across 12 farms in 2022. Cooperating farms consisted of cash grain operations raising corn (*Zea mays L.*) and soybean (*Glycine max L.*) in rotation with other cash crops such as winter wheat (*Triticum aestivum L.*) and winter barley (*Hordeum vulgare L.*).

On each cooperating farm, paired strips were established in fields rotating from grain corn, where corn residue was left unharvested and undisturbed over winter, to full-season soybean. Fields were left fallow in the corn to soybean transition except for two fields in 2021 and one field in 2022, which had a late planted cover crop that was terminated early in the spring of the following year. Two fields in 2022 had cover crops established which were terminated in late spring after vertical tillage was completed. At one location in 2022, the cover crop was terminated approximately one week prior to planting. At a second location in 2022, the cover crop was terminated at planting.

Experimental design. Vertical- and no-tillage treatments were imposed in twenty field-length paired strips each year using a nested treatment structure to control for multiple sources of variation (**Figure 2-1**). To account for sources of variation in treatment responses due to baseline soil conditions, a soil management legacy factor (n = 2) was nested within each year. Soil management legacy was identified as either (1) long-term no-till practiced for more than 10 years, or (2) vertical tillage occurring annually for at least the previous eight years in one or more phases within crop rotations. To account for farm-level management sources of variation within each soil management legacy factor, cooperating farms were nested within soil management legacy. To account for field-level sources of variation, paired strips were nested within farm. The number of paired strips within farm differed each year due to field limitations, with paired strips replicated across single- to multiple- fields per farm or, in some cases, replicated within larger fields that contained variability in landscape position. In total, 20 paired strips and 40 experimental units were imposed in the 2021 and 2022 growing seasons. In 2021, strip trials occurred on a total of nine farms and in 12 fields. In 2022, strip trials occurred on a total of 12 farms and in 17 fields.

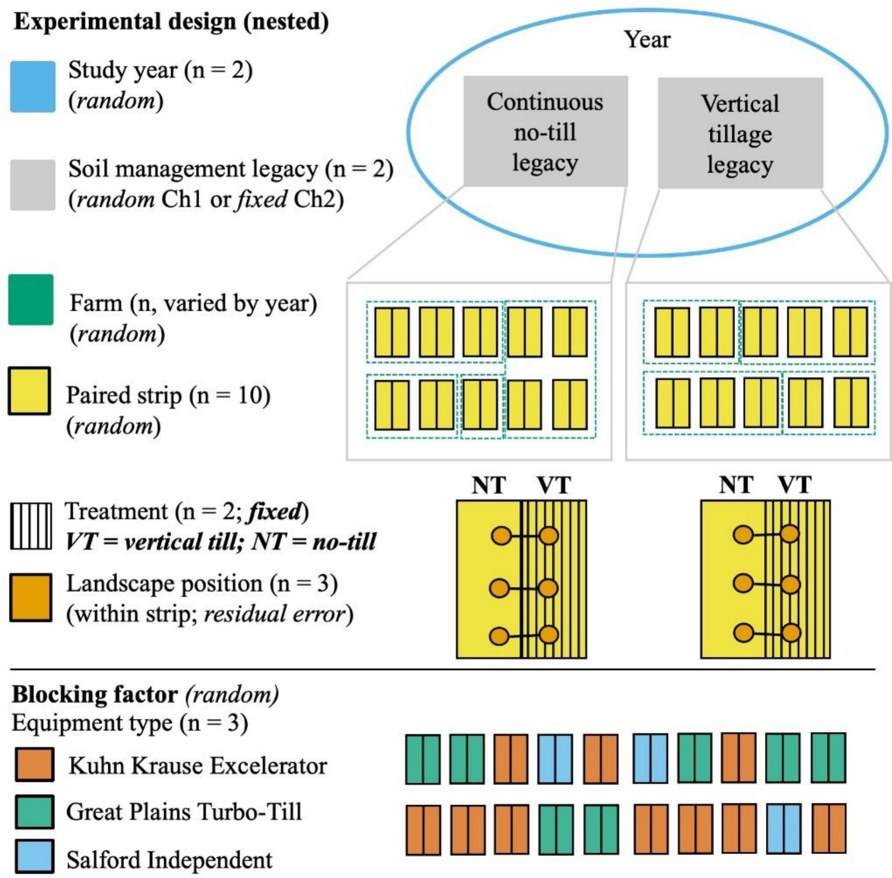

Figure 2-1. Experimental design of project depicting nested treatment structure with fixed effects including tillage treatment (vertical till, no-till) and soil management legacy (continuous no-till, vertical tillage) and random effects including farm and paired strip. Co-located transects are depicted within each strip based on landscape position. Equipment type is included as an additional blocking factor with three brands of tools (Kuhn-Krause Excelerator, Great Plains Turbo Till, and Salford Independent).

Vertical tillage treatment. Crop producers serving as on-farm cooperators employed vertical tillage using owned or rented implements at an average working depth of 5 cm (2 in) to manage corn residue in the early spring (April) prior to establishing full-season soybean (**Table 2-1**). The vertical tillage tools were compliant with standards for "Low-Disturbance Residue Management Equipment" as defined by the Pennsylvania Resource Enhancement and Protection (REAP) Program Guidelines for fiscal year 2019 (PA State Conservation Commission, 2019). Three different vertical tillage tools were used on cooperating farms in 2021, including a Salford Independent (Salford Group, Inc., Salford, ON, Canada), a Great Plains Turbo-Till (Great Plains Manufacturing, Inc., Salina, KS), and a Kuhn-Krause Excelerator (Kuhn North America, Inc., Brodhead, WI). In 2022, cooperating farms used either a Great Plains Turbo-Till or a Kuhn-Krause Excelerator.

Vertical tillage occurred in the spring approximately 14 to 21 days prior to planting in a randomly located field-length strip, which created a paired vertical tillage (VT) and no-till (NT) strip. The width of each strip in the field was based on the size of available harvesting equipment so one or two combine passes could be completed within tillage treatment strips. In most site years, vertical tillage was completed once in the spring. At one location in 2022, vertical tillage was conducted twice in the spring prior to planting full-season soybean. At three locations in 2022, corn residue was shredded in the previous fall with a flail mower.

Each cooperating farm implemented standard fertility, soybean variety selection, and crop protection programs for full-season soybean. A pre-plant burndown and pre-emergence residual herbicide program, along with any post-emergence in-crop herbicide application was implemented at the discretion of the cooperator or a commercial pesticide applicator. Most strips in 2021 and all strips in 2022 received a burndown herbicide application, a pre-emergence soil-applied residual herbicide and a post-emerge herbicide. All burndown herbicide applications reportedly occurred after vertical tillage but prior to soybean planting. Due to low weed pressure in the early spring at two locations in 2021, no burndown herbicide was applied after vertical tillage.

Table 2-1. Soil management overview across strip trial locations including year, farm (Lancaster County (LC), Chester County (CC)), soil management legacy, equipment type (Great Plains Turbo Till (Great Plains), Kuhn-Krause Excelerator (Kuhn-Krause), Salford), tillage depth, coulter angle, soil type, and slope.

Year	Farm	Soil mgmt. legacy	Equipment type	Tillage depth (cm)	Coulter angle (degrees)	Soil type	Soil slope (%)
2021	LC 1	No-till	Great Plains	6.5	0	Bedington silt loam	8-15
2021	LC 1	No-till	Great Plains	6.5	0	Bedington silt loam	3-8
2021	LC 2	No-till	Great Plains	6.5	0	Hagerstown silt loam	3-8
2021	LC 2	No-till	Great Plains	6.5	0	Hagerstown silt loam	3-8
2021	LC 4	No-till	Salford	5	0	Hagerstown silt loam	3-8
2021	LC 4	No-till	Salford	5	0	Hagerstown silt loam	3-8
2021	LC 4	No-till	Salford	5	0	Hagerstown silt loam	3-8
2021	LC 4	No-till	Salford	5	0	Clarksburg silt loam	0-5
2021	LC 5	No-till	Great Plains	10	0	Hollinger silt loam	8-15
2021	LC 3	Vertical till	Salford	5	0	Hagerstown silty clay loam	8-15
2021	LC 6	Vertical till	Kuhn-Krause	5	5	Glenelg silt loam	3-8
2021	LC 6	Vertical till	Kuhn-Krause	5	5	Chester silt loam	8-15
2021	LC 6	Vertical till	Kuhn-Krause	5	5	Chester silt loam	8-15
2021	LC 6	Vertical till	Kuhn-Krause	5	5	Glenelg silt loam	8-15
2021	CC 1	Vertical till	Kuhn-Krause	5	5	Glenelg silt loam	3-8
2021	CC 1	Vertical till	Kuhn-Krause	5	5	Glenelg silt loam	3-8
2021	CC 2	Vertical till	Great Plains	6.5	0	Chester silt loam	3-8
2021	CC 2	Vertical till	Great Plains	6.5	0	Chester silt loam	3-8
2021	CC 3	Vertical till	Kuhn-Krause	7.5	4	Glenville silt loam	3-8
2021	CC 3	Vertical till	Kuhn-Krause	7.5	4	Manor loam	8-15
2022	LC 1	No-till	Great Plains	6.5	0	Bedington silt loam	3-8
2022	LC 1	No-till	Great Plains	6.5	0	Bedington silt loam	3-8
2022	LC 8	No-till	Great Plains	6.5	0	Bedington silt loam	3-8
2022	LC 7	No-till	Great Plains	6.5	0	Bedington silt loam	0-3
2022	LC 7	No-till	Great Plains	6.5	0	Bedington silt loam	0-3
2022	LC 9	No-till	Kuhn-Krause	9	5	Hollinger silt loam	3-8
2022	LC 5	No-till	Great Plains	10	0	Conestoga silt loam	8-15
2022	LC 10	No-till	Kuhn-Krause	6.5	5	Letort silt loam	3-8
2022	LC 10	No-till	Kuhn-Krause	6.5	5	Letort silt loam	3-8
2022	LC 11	No-till	Kuhn-Krause	9	5	Letort silt loam	3-8
2022	LC 12	Vertical till	Kuhn-Krause	4	1	Clarksburg silt loam	0-5
2022	LC 13	Vertical till	Great Plains	10	0	Pequea silt loam	8-15

2022	LC 6	Vertical till	Kuhn-Krause	5	5	Glenelg silt loam	15-25
2022	LC 6	Vertical till	Kuhn-Krause	5	5	Chester silt loam	3-8
2022	LC 6	Vertical till	Kuhn-Krause	5	5	Glenelg silt loam	3-8
2022	LC 6	Vertical till	Kuhn-Krause	5	5	Chester silt loam	3-8
2022	CC 1	Vertical till	Kuhn-Krause	9	5	Manor silt loam	3-8
2022	CC 1	Vertical till	Kuhn-Krause	9	5	Glenelg silt loam	3-8
2022	CC 2	Vertical till	Great Plains	6.5	0	Edgemont channery loam	3-8
2022	CC 2	Vertical till	Great Plains	6.5	0	Chester silt loam	3-8

Data collection. To account for within-field sources of variation, three data collection transects were established in unique field positions (summit, shoulder, backslope, footslope, or toeslope) within each strip and co-located between paired strips (i.e., three paired transects in each strip; six transects per paired strip location). The location of transects was marked using georeferencing software (*QGIS Geographic Information System*, 2022) and a wireless GPS receiver (Garmin GLO Portable GPS and GLONASS Receiver, Garmin Ltd., Olathe, KS) and these waypoints were used for data collection throughout the trial. Hereafter, these transects will be referred to as data collection waypoints to differentiate them from specific transects established at each point for specific measurements.

Soil conservation metrics. Surface residue cover (%) was determined within approximately 21 days after vertical tillage treatments were implemented each spring and just prior to soybean planting. Surface residue cover was quantified using the line-transect method described by the USDA-NRCS standard surface residue cover assessment protocol (*Agronomy Tech Note #MN-19 Estimating Crop Residue Cover*, 1984). Three 15-m transects were established at each data collection waypoint and the presence or absence of corn residue along the transect was recorded every 15-cm lengthwise. Surface residue cover was expressed as a proportion of the total number of observations per transect (n=100).

Soil sampling method: Soil samples were taken in late fall (October and November) after soybean harvest was completed. Within each strip, five randomly located soil cores were collected around each of the three data collection waypoints for a total of 15 cores from each strip. Soil samples were taken with a 1.9 cm diameter soil core to a depth of 15 cm. Each core was then subdivided into three depth increments: 0 - 2.5, 2.5 - 7.5, and 7.5 - 15 cm. Each of the 15 soil cores were homogenized at each of the three depth increments for a total of three soil samples per strip.

Soil samples were air-dried for approximately one week in a 37°C drying oven and then sieved to obtain a subsample of 1-2 mm sized soil aggregates. Approximately 20 grams of soil sieved to a 1-2 mm size fraction was saved for future wet aggregate stability analysis. The remaining portion of each soil sample was then ground to 2 mm size fraction. The sample ground to 2 mm was then split into two subsamples; (1) approximately 50 grams was saved for future active carbon (POXC) and microbial respiration (CO_2-burst) analyses, and (2) the remainder of the sample was sent to the Penn State Agricultural Analytical Services Laboratory (AASL) at University Park, PA for soil fertility and soil organic matter testing.

Soil pH and fertility metrics: Basic soil fertility analyses were conducted at AASL, including soil pH using 1:1 water extracts (Eckert & Sims, 1982), cation exchange capacity (CEC) using summation of cations (Ross & Ketterings, 2011), base saturation using calculation of cations (Sikora & Moore-Kucera, 2014), extractable phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulfur (S), zinc (Zn), and copper (Cu) using a Mehlich-3 (ICP) soil extractant (Wolf & Beegle, 2011), and soil organic matter using loss on ignition (LOI) (Schulte, 2011).

Soil health metrics: Permanganate oxidizable carbon (POXC) was measured using methods described in Weil et al. (2003), where the active carbon fraction of soil organic matter was oxidized with a weak solution of potassium permanganate ($KMnO_4$). The assessment was completed by adding 20 mL of 0.02 M potassium permanganate solution to 2.5 g of air-dry soil placed in a plastic centrifuge tube. The centrifuge tubes were shaken on a mechanical shaker for two minutes at 120 strokes per minute and then were placed in a holding rack for ten minutes while soil particles flocculated and settled on the bottom of the tube. A pocket colorimeter (Pocket Colorimeter II, Hach Company, Loveland, CO) was used to read the absorbance value for the color concentration of the solution with POXC. The lighter the purple color of the solution with POXC, the less absorbance measured by the colorimeter, the more active carbon in the soil sample which was oxidized. POXC is expressed as mg C kg^{-1} soil for each sample.

Microbial respiration was analyzed using methods described in Franzluebbers et al. (2016) to measure the flush of carbon dioxide (CO_2) from a sample of air-dry soil re-wetted to 50% water-filled pore space after a 24-hr aerobic incubation in a dark setting at room temperature. To complete the incubation, 10 g of air-dry soil sieved to 2 mm was placed in a 50 mL plastic beaker and distilled water was added to the top of the beaker to reach 50% water-filled pore space as determined by previously measured sample specific bulk density. The plastic beaker was then placed in a 473 mL (1 pint) glass canning jar sealed with a screw band lid (Ball Corporation, Broomfield, CO) that had a rubber septum installed within the lid and sealed with vacuum grease. After 24 hours, a syringe was used to extract a 1 mL sample of headspace air from the jar and this sample was injected into an infrared gas analyzer (LI-7000 CO_2/H_2O Gas Analyzer, LI-COR Biosciences, Lincoln, NE) where the concentration of CO_2 in the sample air was compared to that of a reference air with a known CO_2 concentration. The concentration of CO_2 in the headspace of the jar was converted to mg C while accounting for the concentration of CO_2 in the ambient air in the room when the jars were sealed at the beginning of the incubation. Microbial respiration estimates are expressed as mg CO_2-C kg^{-1} soil $(1\ d)^{-1}$ for each soil sample.

Wet aggregate stability was assessed utilizing methods described in Kemper et al. (1986), whereby an air-dry soil sample consisting of 1-2 mm sized aggregates was subjected to the disturbance from a wet sieving apparatus and an ultrasonic probe to determine the difference between water stable and water unstable soil aggregates. For wet aggregate stability analysis, 4 g of air-dry soil 1-2 mm in size was placed in a 0.5 mm sieve and subsequently placed in a wet-sieving apparatus (Five Star Scientific, Twin Falls, ID) and into a pre-weighed metal can filled with 75% distilled water. The wet-sieving apparatus was mechanically raised and lowered 1.3 cm at a rate of about 35 times per minute, as eight soil samples, each in their respective sieves and cans, were raised and lowered in water for three minutes. Each soil sample in its respective sieve was then removed from the first set of cans and placed in a second set of pre-weighed metal cans filled partially with distilled water. These sieves now inside a second set of metal cans were placed under an ultrasonic probe as part of a sonifier (Sonifier Cell Disruptor Model W185, Heat-Systems-Ultrasonics, Inc., Plainview, L.I., NY) for approximately 30 seconds that dispersed any remaining soil aggregates into primary particles. Both sets of cans were placed in a 110°C drying oven overnight to evaporate all water from the cans. The mass of both sets of cans were recorded and the mass of the dry soil particles from the first set of cans, representing the portion of water unstable aggregates, and the mass of the dry soil particles from the second set of cans, representing the portion of water stable aggregates, were determined. The percent water stable aggregates (% WSA) in each soil sample were calculated using the following equation:

% WSA = 100 x [Oven dry weight of can B with soil – empty weight of can B] / [(Oven dry weight of can B with soil – empty weight of can B) + (Oven dry weight of can A with soil – empty weight of can A)].

Soil penetration (cone) resistance was also measured at the time of soil sampling in the fall after harvest. A digital recording penetrometer (Field Scout SC 900 Digital Soil Compaction Meter, Spectrum Technologies, Inc., Aurora, IL) was used to measure soil penetration resistance at three locations around each data collection waypoint within each strip (i.e., nine sampling points total per strip). Soil penetration resistance in pound-force per square inch (psi) was measured to a depth of 20 cm at 2.5 cm depth increments: 2.5, 5.0, 7.5, 10, 12.5, 15, 17.5, and 20 cm.

Statistical analysis. All statistical analyses were performed in R Statistical Software (v4.2.1; R Core Team, 2022) using linear mixed-effects (LME) models in the *nlme* package (Pinheiro et al., 2012) for each soil metric. Prior to soil analyses, transect-level data collected within each strip (n = 3) was composited at each sampling depth. Tillage treatment, soil management legacy, sampling depth, and their interactions were fit as fixed effects. Year, farm nested within year, and the paired strip nested within farm were fit as random effects. To account for non-independence between sampling depths, an autoregressive (AR1) variance-covariance structure was fit using a strip-level identifier nested within sampling depth. Mean separation of treatment effects were performed using the *emmeans* package (Length, 2022) when F-tests indicated statistically significant main or interaction effects.

Results

Surface residue cover. Vertical tillage treatment effects on surface residue cover are reported in Chapter 1. Given surface residue cover is an important indicator of short-term soil health impacts, results are briefly reported. Differences in surface residue cover between tillage treatments ranged from a difference of 35% to no change in residue cover, with a mean difference of 16%. Cooperators using a Kuhn-Krause Excelerator reduced residue cover by 24% on average and 32% of strips using this tool had mean surface residue cover levels below a 60% residue cover threshold for no-till systems after implementation. Initial surface residue cover in the spring prior to vertical tillage ranged from 70 – 100%. Residue cover remaining on the soil surface after vertical tillage ranged from 43 – 99%.

Soil pH and fertility. The paired strip comparison of vertical tillage in spring relative to no-till only influenced CEC and potassium (K) base saturation, both of which had a tillage treatment by depth interaction (T x D; **Table 2-2**). However, a soil management legacy by depth interaction (L x D) existed for soil pH, acidity, soil test phosphorus (P), soil test potassium (K), soil test sulfur (S), potassium (K) base saturation, soil test zinc (Zn), and soil test copper (Cu). Soil management legacy main effects were also observed for soil test calcium (Ca) concentration and base saturation. No interactions between soil management legacy and tillage treatments (L x T) were observed for soil pH and soil fertility variables. For soil test magnesium (Mg) concentration and base saturation, only the depth main effect was significant.

Table 2-2. Effect of sampling depth (D), tillage treatment (T), soil management legacy (L) and their interactions on soil pH, soil fertility, and indicators of biological and physical soil health. Significance levels (*p*-value) are based on F-tests (NS, non-significant; $p > 0.05$).

Response variable	Depth	Treatment	Legacy	L x T	L x D	T x D	L x T x D
	------------------------------------ *p*-value ------------------------------------						
Soil pH	< 0.0001	NS	< 0.05	NS	< 0.003	NS	NS
Acidity (meq 100g^{-1})	< 0.002	NS	NS	NS	< 0.003	NS	NS
Soil test P (ppm)	< 0.0001	NS	NS	NS	< 0.01	NS	NS
Soil test K (ppm)	< 0.0001	NS	NS	NS	< 0.005	NS	NS
Soil test Ca (ppm)	< 0.0001	NS	< 0.005	NS	NS	NS	NS
Soil test Mg (ppm)	< 0.0001	NS	NS	NS	NS	NS	NS
Soil test S (ppm)	< 0.0001	NS	NS	NS	< 0.0001	NS	NS
CEC (meq 100g^{-1})	< 0.001	NS	NS	NS	NS	< 0.02	NS
K base saturation (%)	< 0.0001	NS	NS	NS	< 0.003	< 0.04	NS
Ca base saturation (%)	< 0.01	NS	< 0.008	NS	NS	NS	NS
Mg base saturation (%)	< 0.0001	NS	NS	NS	NS	NS	NS
Soil test Zn (ppm)	< 0.0001	NS	NS	NS	< 0.01	NS	NS
Soil test Cu (ppm)	< 0.0001	NS	NS	NS	< 0.05	NS	NS
Soil organic matter (%)	< 0.0001	NS	NS	NS	NS	NS	NS
POXC (%)	< 0.0001	NS	NS	NS	NS	< 0.05	NS
Microbial respiration	< 0.0001	NS	NS	NS	NS	NS	NS
Wet agg. stability (%)	< 0.0001	NS	NS	NS	< 0.003	NS	NS
Penetration resistance (psi)	< 0.0001	NS	NS	NS	< 0.0001	NS	NS

Table 2-3. Interactions of soil management legacy (L) and sampling depth (D) on soil pH, acidity, soil fertility, and wet aggregate stability reported as means (± 1 SE) across sampling depths. Same letters among sampling depths within legacy indicate no significant difference.

Response variable	No-till soil mgmt. legacy			Vertical tillage soil mgmt. legacy		
	0-2.5 cm	2.5-7.5 cm	7.5-15 cm	0-2.5 cm	2.5-7.5 cm	7.5-15 cm
	------------- Mean (+/- SE) -------------			------------- Mean (+/- SE) -------------		
Soil pH	6.9 (0.05)a	6.7 (0.08)b	6.7 (0.07)b	6.3 (0.10)x	6.2 (0.08)y	6.4 (0.05)x
Acidity (meq 100 g^{-1})	0.7 (0.23)a	1.6 (0.32)b	1.4 (0.29)b	2.9 (0.35)x	3.0 (0.24)x	2.4 (0.17)y
Soil test P (ppm)	151 (19.8)a	115 (13.3)b	87 (11.0)b	196 (34.6)x	155 (33.5)y	71 (14.3)z
Soil test K (ppm)	260 (15.5)a	156 (9.4)b	104 (9.5)b	207 (11.7)x	130 (6.4)y	97 (4.2)z
Soil test S (ppm)	14 (0.9)a	13 (0.8)b	11 (0.6)c	17 (0.7)x	14 (0.5)y	11 (0.3)z
K base saturation (%)	6.0 (0.40)a	3.9 (0.29)b	3.0 (0.31)c	4.7 (0.35)x	3.3 (0.15)y	3.0 (0.15)y
Soil test Zn (ppm)	9 (1.0)a	7 (0.4)b	4 (0.3)c	15 (2.4)x	11 (2.1)y	5 (0.7)z
Soil test Cu (ppm)	8 (1.0)a	7 (0.7)a	4 (0.4)b	11 (1.9)x	10 (1.9)x	6 (0.9)y
Wet agg. stability (%)	77 (1.7)a	73 (0.8)b	58 (1.5)c	79 (1.7)x	68 (1.5)y	52 (1.5)z

The effect of sampling depth on soil pH differed among soil management legacy groups ($p < 0.003$). In the no-till legacy treatment, soil pH was higher at the surface 0-2.5 cm compared to the lower soil depth increments, whereas in the vertical tillage soil management legacy, soil pH at the surface was comparable to the lowest depth (**Table 2-3; Figure 2-2**).

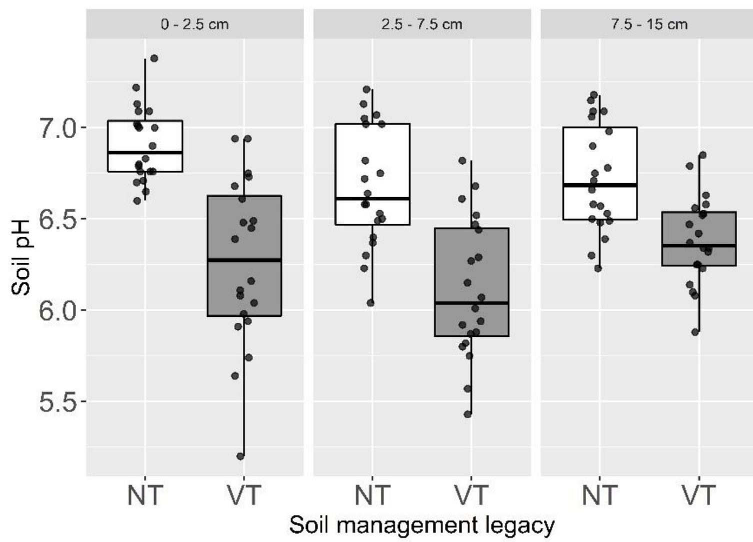

Figure 2-2. Sampling depth (0 - 2.5 cm, 2.5 - 7.5 cm, 7.5 - 15 cm) main effect and soil management legacy (NT = no-till legacy, VT = vertical tillage legacy) by sampling depth interaction for soil pH.

Similarly, a soil management legacy by sampling depth interaction (L x D) was observed for several fertility metrics, including soil test phosphorus (P), potassium (K), and sulfur (S) (**Table 2-2**). Soil test P concentration decreased with depth across both soil management legacies (**Figure 2-3**). However, P stratification was not alleviated, but seemed to be magnified, within the long-term vertical tillage legacy (**Table 2-3**). Similar trends exist for soil test K and soil test S across sampling depths and soil management legacies. A tillage treatment by sampling depth interaction (T x D) was observed in analysis of CEC and potassium (K) base saturation (**Table 2-4**).

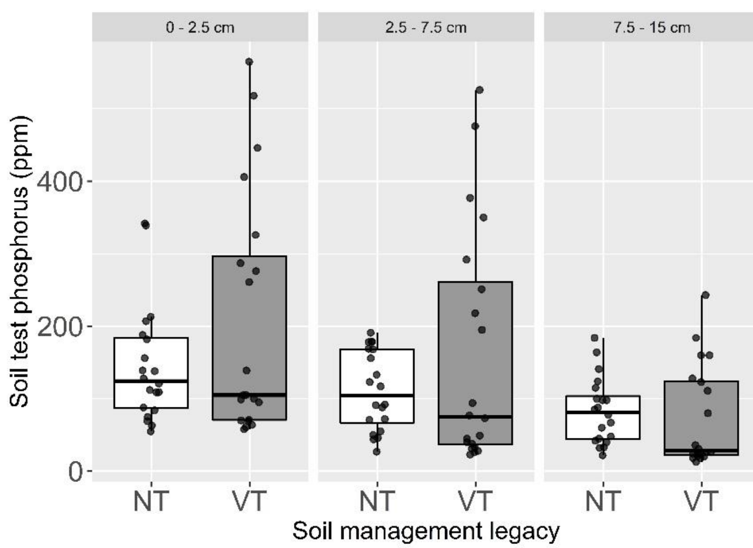

Figure 2-3. Sampling depth (0 - 2.5 cm, 2.5 - 7.5 cm, 7.5 - 15 cm) main effect and soil management legacy (NT = no-till legacy, VT = vertical tillage legacy) by sampling depth interaction for soil test phosphorus (ppm).

Table 2-4. Interactions of tillage treatment (T) and sampling depth (D) on soil cation exchange capacity (CEC), potassium (K) base saturation, and POXC reported as means (± 1 SE) across sampling depths. Same letters among sampling depths within treatment indicate no significant difference.

Response variable	**No-till treatment**			**Vertical tillage treatment**		
	0-2.5 cm	**2.5-7.5 cm**	**7.5-15 cm**	**0-2.5 cm**	**2.5-7.5 cm**	**7.5-15 cm**
	------- Mean (+/- SE) -------			------- Mean (+/- SE) -------		
CEC (meq $100g^{-1}$)	11.8 (0.37)a	10.0 (0.26)b	8.4 (0.22)c	11.2 (0.39)x	10.4 (0.36)y	8.7 (0.22)z
K base saturation (%)	5.0 (0.35)a	3.6 (0.22)b	3.1 (0.22)c	5.6 (0.43)x	3.6 (0.23)y	3.0 (0.23)z
POXC (%)	916 (25.1)a	623 (19.6)b	360 (19.3)c	876 (33.5)a	669 (29.7)b	384 (21.4)c

Biological and physical indicators of soil health. Biological indicators of soil health assessed in this study included soil organic matter, active carbon (POXC), and microbial respiration. There was an interaction between tillage treatment and sampling depth (T x D) for POXC, but only a sampling depth main effect for soil organic matter and microbial respiration (**Table 2-2**).

Significantly higher concentrations of soil organic matter were observed near the soil surface and lower concentrations at a depth of 7.5 – 15 cm. Soil organic matter was found to be approximately 5% on average near the soil surface across tillage treatments and soil management legacies and decreased to approximately 2.6% at a depth of 7.5 – 15 cm (**Figure 2-4**).

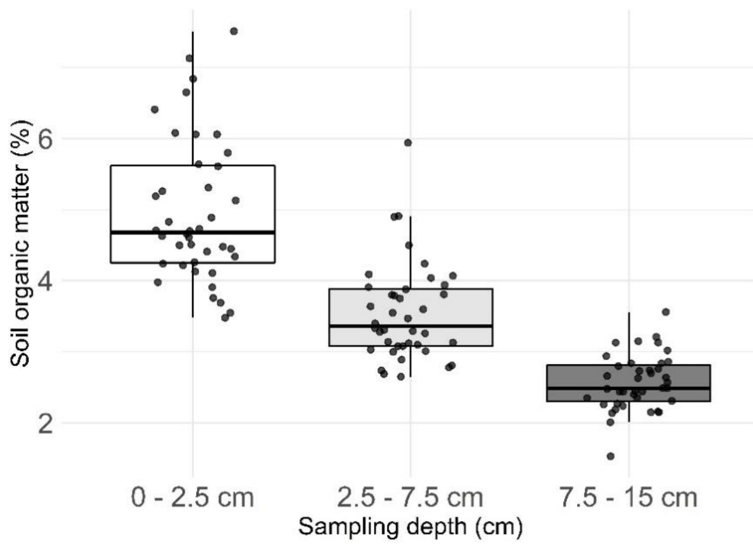

Figure 2-4. Sampling depth (0 - 2.5 cm, 2.5 - 7.5 cm, 7.5 - 15 cm) main effect for soil organic matter (%).

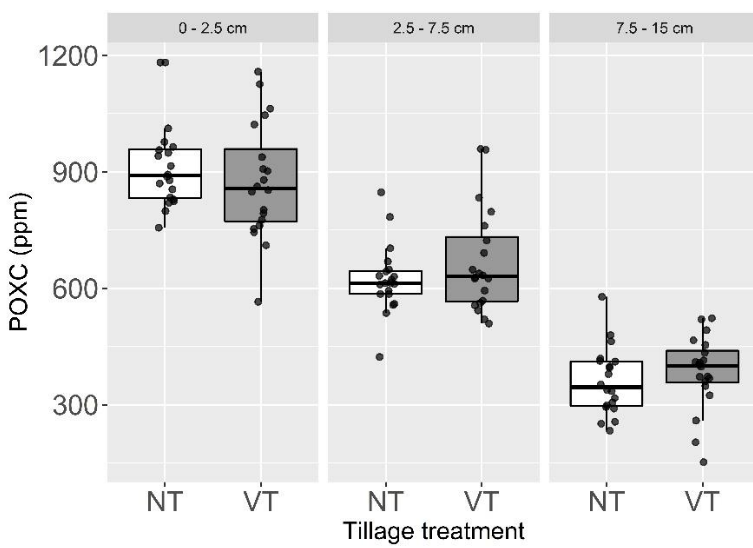

Figure 2-5. Tillage treatment (NT = no-till, VT = vertical tillage) by sampling depth (0 - 2.5 cm, 2.5 - 7.5 cm, 7.5 - 15 cm) interaction for POXC (ppm).

A tillage treatment by sampling depth interaction (T x D) was observed for active carbon (POXC) (**Figure 2-5**). For microbial respiration, only a sampling depth main effect was found to be significant (**Figure 2-6**). Microbial respiration rates were higher near the surface and decreased with depth and this occurred as expected as microbes oxidized greater portions of carbon near the surface were soil organic matter and POXC concentrations were higher.

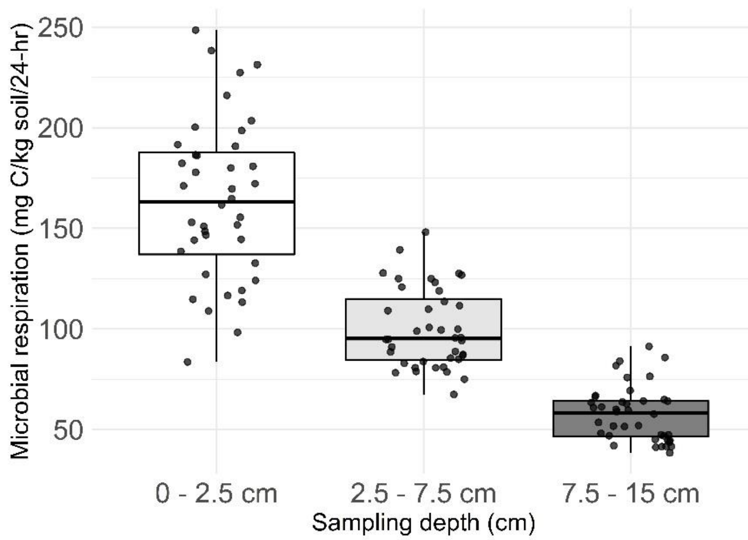

Figure 2-6. Sampling depth (0 - 2.5 cm, 2.5 - 7.5 cm, 7.5 - 15 cm) main effect for microbial respiration mg CO_2-C kg^{-1} soil $(1\ d)^{-1}$.

Physical indicators of soil heath assessed in this study included wet aggregate stability and soil penetration resistance. A soil management legacy by sampling depth (L x D) interaction was detected for both response variables (**Table 2-2**). Wet aggregate stability (%) was lower from 2.5 – 7.5 cm and from 7.5 – 15 cm in the vertical tillage legacy (**Figure 2-7**). These results suggest vertical tillage had a negative effect on aggregate stability within the zone of soil mixing and below the working depth of vertical tillage tools.

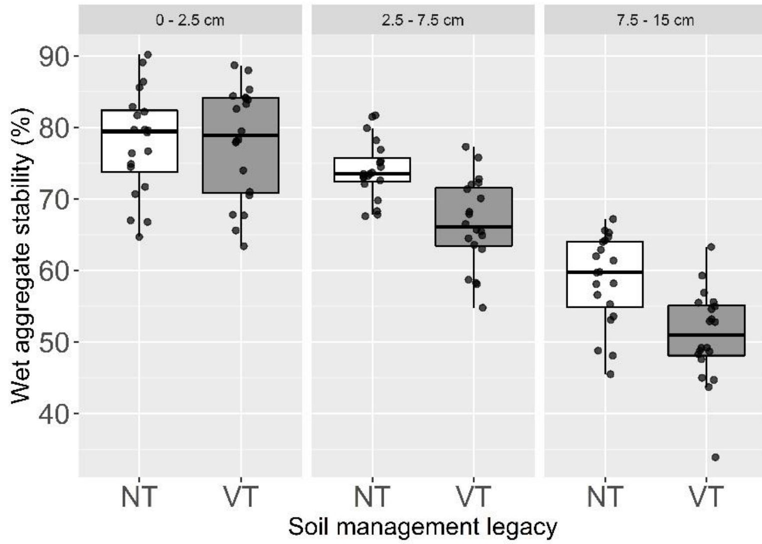

Figure 2-7. Sampling depth (0 - 2.5 cm, 2.5 - 7.5 cm, 7.5 - 15 cm) main effect and soil management legacy (NT = no-till legacy, VT = vertical tillage legacy) by sampling depth interaction for wet aggregate stability (%).

Soil management legacy also influenced soil penetration resistance patterns ($p < 0.0001$) across depth increments (0 to 20 cm; **Table 2-4**; **Figure 2-8**). When interpreting soil penetration resistance values, a generally accepted threshold to indicate soil compaction occurs when values exceed 300 pound-force per square inch (psi; Duiker 2002). In the no-till legacy, penetrometer values remain under 300-psi until the 12.5 cm depth. In the vertical tillage legacy, penetrometer values are lower near the soil surface in the zone of soil mixing performed by the vertical tillage tool but reach the 300-psi threshold at a 7.5 cm depth, shallower than in the no-till legacy. These results suggest that greater compaction occurs below the working depth of vertical tillage tools across legacy vertical tillage farms.

Table 2-5. Interaction of soil management legacy (L) and sampling depth (D) on soil penetration resistance (psi) reported by mean (± 1 SE) across sampling depths.

Soil mgmt. legacy	**Sampling depth (cm)**							
	2.5	**5**	**7.5**	**10**	**12.5**	**15**	**17.5**	**20**
	-- Mean (+/- SE) -------------------- ---------------------------							
No-till	189 (10.2)	255 (14.0)	281 (13.7)	299 (12.5)	303 (11.8)	310 (11.1)	322 (14.1)	324 (13.5)
Vertical tillage	127 (10.7)	228 (10.2)	315 (14.2)	369 (16.3)	384 (15.3)	394 (16.6)	399 (17.9)	378 (13.9)

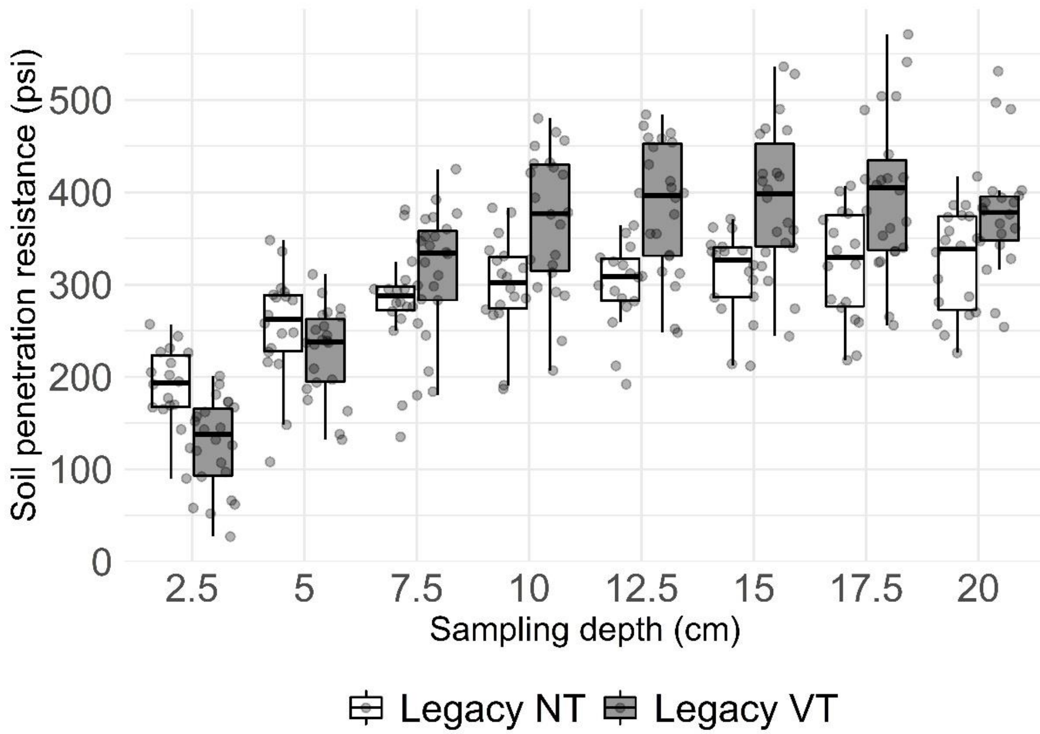

Figure 2-8. Sampling depth (0 – 20 cm) main effect and soil management legacy (NT = no-till legacy, VT = vertical tillage legacy) by sampling depth interaction for soil penetration resistance (psi).

Discussion

Surface residue cover. Relative to no-till, vertical tillage resulted in moderate reductions in surface residue cover in 2021 and 2022. High levels of initial residue cover (>70%) were observed across all sites in the spring of 2021 and 2022 prior to any vertical tillage. Results from this study found that vertical tillage reduced surface residue cover by approximately 16% on average across strip locations (n = 40). Other vertical tillage studies have measured similar levels of baseline residue conditions and subsequent reductions in residue cover in corn-soybean systems after one pass with a vertical tillage tool (Chen et al., 2016; Conley, 2011; Smith & Warnemuende-Pappas, 2015; Whitehair & Presley, 2010).

Soil pH and fertility. While pH stratification across sampling depths and within soil management legacies is statistically significant, it is likely not biologically or agronomically significant due to small differences across depths in the observed fields. Growers participating in this study all maintained regular lime additions, which can alleviate the acid roof symptoms that are sometimes reported in no-till systems. In fact, in this study, legacy no-till farms exhibited the opposite phenomenon, an 'alkaline roof,' where due to recent lime additions, the 0 – 2.5 cm depth segment had a higher soil pH than the lower depth segments. Indeed, prior to the start of the project, several legacy no-till farms applied limestone to the fields which were to be studied. Over time, the soil in this layer would be expected to acidify following the addition of nitrogen fertilizer and due to crop residue decomposition.

No vertical tillage treatment or soil management legacy main effects alleviated nutrient and organic matter stratification found across sampling depths in the no-till and vertical tillage fields in this study. A single vertical tillage pass performed in the spring, or repeated vertical tillage passes over time, did not substantially move soil test P or other nutrients deeper in the soil profile. Nutrient stratification is a potential management tradeoff in no-till systems (Beegle, 1996), which can influence soil nutrient fate in the environment. Results from other no-till and vertical tillage studies affirm soil test P stratification with higher soil test P occurring near the soil surface (Sharpley, 2003). In no-till cropping systems with a history of surface-applied manure applications, increased losses of soluble P in agricultural runoff are observed (Maguire et al., 2011). While decreases in soluble P runoff due to vertical tillage would be beneficial (Smith & Warnemuende-Pappas, 2015), results from this study indicate that shallow non-inversion tillage is not aggressive enough to alter the P stratification observed in the fields in this study.

Differences in several soil fertility response variables measured across depths and soil management legacies is small and perhaps not agronomically significant. Small changes in soil CEC from 12 meq $100g^{-1}$ (no-till treatment; 0 – 2.5 cm) to 11 meq $100g^{-1}$ (vertical tillage treatment; 0 – 2.5 cm) do not generally result in within-field changes to soil fertility programs or other cropping practices. Similarly, practitioners and consultants adhering to the basic cation saturation ratio (BCSR) concept of soil test interpretation (Culman et al., 2021) would likely not change their potassium fertilizer recommendations based on a change in a potassium base saturation from 5% (no-till treatment; 0 – 2.5 cm) to 5.5% (vertical tillage treatment; 0 – 2.5 cm).

Biological and physical soil health. A sampling depth main effect was observed for soil organic matter, active carbon (POXC), and microbial respiration. Higher concentrations of soil organic matter and POXC, and higher rates of microbial respiration, were found near the soil surface and these values decreased with depth. POXC, the fraction of labile carbon often considered to be the readily available carbon pool for utilization by soil microbes, decreased with depth. In the same way, microbial oxidation of carbon was quantified using the CO_2-burst method described earlier, and the quantity CO_2 respired by microbes decreased with depth as well. In addition, a tillage treatment by sampling depth interaction existed for POXC.

Though increases in the total quantity or distribution of soil organic carbon throughout the soil profile is an indicator of improved soil chemical and biological function, this study was not able to confirm that either occurs because of short- or long-term vertical tillage. With escalating public and private interest in evaluating and quantifying on-farm soil health, and burgeoning interest in soil C sequestration, measuring organic matter and carbon stratification, as well as microbial respiration, is pertinent and could guide quantification and verification efforts. As growers begin to receive ecosystem service payments for practices that sequester soil carbon, such as no-till soil management, questions will likely surface whether implementing vertical tillage affects soil carbon sequestration capacity. Results from this study indicate no difference in soil organic matter levels due to soil management legacy. Additionally, POXC should be relatively sensitive to short-term changes in soil management practices such as vertical tillage compared to other soil carbon pools, while organic matter should be indicative of long-term soil management practices.

A soil management legacy by sampling depth interaction was observed for aggregate stability and soil penetration resistance. Aggregate stability decreased with sampling depth and this reduction was greater in the long-term vertical tillage legacy relative to the no-till legacy. The greatest reductions in aggregate stability occurred within the zone of soil mixing and below the working depth of the vertical tillage tools in this study.

Differences in soil penetration resistance were observed across soil management legacies. In the long-term no-till legacy, surface hardness was detected as penetrometer values were higher at shallower depths than in the vertical tillage legacy. When interpreting soil penetration resistance values, a generally accepted threshold used to indicate soil compaction occurs when values exceed 300 pound-force per square inch (psi; Duiker, 2002). In the vertical tillage legacy, penetrometer values were lower near the soil surface in the zone of soil mixing performed by the vertical tillage tool but reach the 300-psi threshold at a shallower depth than in the no-till legacy. These results suggest that a compacted layer or 'hard pan' may be developing below the working depth of vertical tillage tools used in this study and commonly used in the Mid-Atlantic region.

Wet aggregate stability and soil penetration resistance are important physical indicators of soil health as they relate to soil structure and compaction. Past studies indicate a subsurface compaction layer may be created by vertical tillage at or below the working depth of the tool (Gameda et al., 1985). While some studies found inconclusive results related to whether surface crusting is alleviated or created in no-till soils due to vertical tillage (Blanco-Canqui et al., 2009), results from this study suggest vertical tillage may loosen the top few centimeters of soil and create a compacted layer with repeated tillage over time.

Conclusions and future research directions. Results from this study indicate vertical tillage may alleviate soil pH stratification but may not be aggressive enough to alleviate phosphorus or soil organic matter stratification as was hypothesized. Further, vertical tillage did not reduce no-till stratification of active C (POXC) or microbial respiration (CO_2-burst). Additionally, long-term vertical tillage may alleviate surface crusting but may also create a compacted layer at a shallow depth relative to compaction found in soils under long-term no-till management. Growers will likely continue to use vertical tillage tools to prepare the seedbed shortly before planting while attempting to achieve timelier crop establishment. Items of further research could include studying the effects of vertical tillage on soil erosion potential, water and nutrient runoff, water infiltration, as well as early season soil temperature and moisture changes as indicators of soil warming and drying.

Epilogue

Accumulation of crop residue on the soil surface poses several management challenges in long-term no-till cropping systems. Corn residue can interfere with planting operations in the spring season following a substantial grain harvest the previous fall. Excess residue can interfere with stand establishment by keeping soil temperature lower and soil moisture higher in cool, wet spring seasons (Adler et al., 2015). Corn stover with carbon to nitrogen (C:N) ratios from 50:1 to 75:1 (Jeschke and Heggenstaller, 2012) can immobilize large portions of soil nitrogen (N) pools for longer periods of time into the next growing season, increasing the need for inorganic N fertilizer for a corn crop (Burgess et al., 2002). Previous crop residue can also create a favorable environment for crop pests (e.g., slugs) and can harbor inoculum of plant pathogens that affect wheat and corn, such as Fusarium Head Blight (*Fusarium graminearum* L.) and Grey Leaf Spot (*Cercospora zeae-maydis* L.), respectively. Slugs are an increasing pest management challenge in no-till crop fields and substantial amounts of surface residue and ample moisture favor persistence of slug populations.

Residue management strategies to manipulate crop residue in-place include: (1) modifying harvest equipment (i.e., 'chopping stalk rolls' and 'chopping corn heads') to better process residue in the fall (Wolkowski, 2011); (2) modifying planting equipment (i.e., alterations to row cleaners, removal of no-till coulters, regular replacement of double-disk openers, alterations to the closing wheel system) to better negotiate residue at planting; (3) mowing residue; or (4) incorporating residue into the soil with shallow non-inversion tillage commonly known as 'vertical tillage' by cutting and incorporating crop residue within the top 5-10 cm of soil to speed decomposition (Chen et al., 2016; Schomberg et al., 1994) and prepare the seedbed for planting.

Vertical tillage equipment often consists of straight (i.e., non-concave) disk blades or 'coulters,' either individually spring-mounted or collectively gang-mounted, followed by one or more rows of spiked wheels or coil tines, and then followed by a set of rolling baskets. In general, coulters on vertical tillage tools lack concavity, though some equipment brands have slightly concave coulters. Additionally, coulters are usually wavy, but differ in the number of waves per coulter among varying equipment brands. Vertical tillage tools also vary in the angle of the coulters, as some vertical tillage tools have straight coulters while other tools have angled coulters up to at least eight degrees. Variations in equipment design across brands create varying levels of aggressiveness when cutting residue and creating soil disturbance and mixing. When manufacturing of vertical tillage tools first began several decades ago, these tools traditionally limited the horizontal shearing and mixing of soil, instead creating soil disturbance on a vertical rather than a horizontal plane (Chen et al., 2016). Vertical tillage machines are often used at relatively high speeds upwards of 12-16 km h^{-1} (Chen et al., 2016; Wolkowski, 2011) and are typically operated between a 2.5 to 10 cm depth. The fact that growers can operate vertical tillage tools at higher speeds, and therefore cover more ground in a shorter time while managing residue in one pass, has likely driven adoption of vertical tillage and other forms of high-speed, shallow non-inversion tillage by a subset of growers within the Mid-Atlantic region.

It should be noted that a different subset of growers in Pennsylvania, and in the Mid-Atlantic, do not employ the use of vertical tillage to manage previous corn residue prior to establishing a subsequent cash crop. These growers are often avid adopters of no-till and cover crops and use these practices in combination, sometimes along with a relatively new technique gaining popularity known as 'planting green' where a cash crop is planted directly into a living cover crop (Reed et al., 2019).

In addition to managing crop residue, growers use vertical tillage to hasten soil warming and drying in cool, wet spring seasons, potentially facilitating earlier or timely crop establishment. This practice accomplishes the growers' primary residue management objective (i.e., adequate seedbed preparation) with less intense soil disturbance relative to conventional tillage methods such as chisel plowing and disking. In addition, growers use vertical tillage to incorporate manure or inorganic fertilizer and to alleviate potential surface crusting and surface compaction. Growers also use vertical tillage to level the soil surface following a particularly wet season where equipment traffic resulted in uneven field conditions.

Growers practice vertical tillage to resolve perceived problems, and further quantification of the tradeoffs associated with introducing shallow non-inversion tillage into long-term no-till cropping systems is needed to better inform grower decision-making. Management decisions made based on research results rather than anecdotal information and input from ag retail equipment suppliers is a goal to which all growers can subscribe (Wolkowski, 2011).

Ultimately, growers practicing vertical tillage seek to establish a seedbed with soil conditions found on a continuum from wet to dry and from loose to firm and where residue can easily be moved away from the seed furrow at planting. For each grower and each equipment operator and their consultants, decision-making relative to residue management and the search for the ‘ideal seedbed’ to ensure ease of planting and successful crop establishment remains fluid and intangible even to those most familiar with the realities of field preparation and crop production.

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APPENDIX

Additional Materials

Table A-1. Monthly and cumulative annual precipitation (cm) and growing degree days (GDD) in 2021 and 2022 for two locations representing farm sites in northern and southern Lancaster County. [1] = Lancaster County (LC) - North = Lancaster Airport, Lititz, PA. [2] = Lancaster County (LC) - South = Octoraro Lake, Kirkwood, PA. Weather data provided by NOWData from the National Weather Service, NOAA. Additional GDD averages provided by Climate Smart Farming from Cornell University.

	Year	Location	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	Total	15-Year Average	30-Year Average "Normal"
Precipitation (cm)	2021	LC - North	4.2	9.2	6.6	na	7.2	6.8	16.0	19.9	24.3	8.7	2.9	2.0	108	na	107
	2021	LC - South	4.7	10.0	na	na	9.1	na	19.4	21.0	27.2	11.1	na	4.0	107	na	123
	2022	LC - North	5.0	5.5	3.8	8.4	14.1	7.7	10.2	3.6	10.8	na	na	na	69	na	107
	2022	LC - South	8.6	6.6	8.2	13.2	16.6	12.0	17.4	11.6	12.6	na	na	na	107	na	123
Growing Degree Days (base 50°F)	2021	LC - North	0	0	71	157	380	720	819	845	570	363	21	13	3959	3423	3258
	2021	LC - South	0	0	na	na	310	na	768	773	526	335	na	4	2716	3501	3398
	2022	LC - North	3	8	64	108	490	662	874	885	543	na	na	na	3637	3423	3258
	2022	LC - South	3	6	49	95	419	563	786	763	474	na	na	na	3158	3501	3398

Table A-2. Soil taxonomic information across strip trial locations including year, farm (Lancaster County (LC), Chester County (CC)), soil management legacy, soil type, soil taxonomic name, and slope.

Year	Farm	Soil mgmt. legacy	Soil type	Soil taxonomic name	Soil slope (%)
2021	LC 1	NT	Bedington silt loam	Fine-loamy, mixed, active, mesic Typic Hapludults	8-15
2021	LC 1	NT	Bedington silt loam	Fine-loamy, mixed, active, mesic Typic Hapludults	3-8
2021	LC 2	NT	Hagerstown silt loam	Fine, mixed, semiactive, mesic Typic Hapludalfs	3-8
2021	LC 2	NT	Hagerstown silt loam	Fine, mixed, semiactive, mesic Typic Hapludalfs	3-8
2021	LC 4	NT	Hagerstown silt loam	Fine, mixed, semiactive, mesic Typic Hapludalfs	3-8
2021	LC 4	NT	Hagerstown silt loam	Fine, mixed, semiactive, mesic Typic Hapludalfs	3-8
2021	LC 4	NT	Hagerstown silt loam	Fine, mixed, semiactive, mesic Typic Hapludalfs	3-8
2021	LC 4	NT	Clarksburg silt loam	Fine-loamy, mixed, superactive, mesic Oxyaquic Fragiudalfs	0-5
2021	LC 5	NT	Hollinger silt loam	Fine-loamy, mixed, active, mesic Typic Hapludalfs	8-15
2021	LC 3	VT	Hagerstown silty clay loam	Fine, mixed, semiactive, mesic Typic Hapludalfs	8-15
2021	LC 6	VT	Glenelg silt loam	Fine-loamy, mixed, semiactive, mesic Typic Hapludults	3-8
2021	LC 6	VT	Chester silt loam	Fine-loamy, mixed, semiactive, mesic Typic Hapludults	8-15
2021	LC 6	VT	Chester silt loam	Fine-loamy, mixed, semiactive, mesic Typic Hapludults	8-15
2021	LC 6	VT	Glenelg silt loam	Fine-loamy, mixed, semiactive, mesic Typic Hapludults	8-15
2021	CC 1	VT	Glenelg silt loam	Fine-loamy, mixed, semiactive, mesic Typic Hapludults	3-8
2021	CC 1	VT	Glenelg silt loam	Fine-loamy, mixed, semiactive, mesic Typic Hapludults	3-8
2021	CC 2	VT	Chester silt loam	Fine-loamy, mixed, semiactive, mesic Typic Hapludults	3-8
2021	CC 2	VT	Chester silt loam	Fine-loamy, mixed, semiactive, mesic Typic Hapludults	3-8
2021	CC 3	VT	Glenville silt loam	Fine-loamy, mixed, active, mesic Aquic Fragiudults	3-8
2021	CC 3	VT	Manor loam	Coarse-loamy, micaceous, mesic Typic Dystrudepts	8-15

2022	LC 1	NT	Bedington silt loam	Fine-loamy, mixed, active, mesic Typic Hapludults	3-8
2022	LC 1	NT	Bedington silt loam	Fine-loamy, mixed, active, mesic Typic Hapludults	3-8
2022	LC 8	NT	Bedington silt loam	Fine-loamy, mixed, active, mesic Typic Hapludults	3-8
2022	LC 7	NT	Bedington silt loam	Fine-loamy, mixed, active, mesic Typic Hapludults	0-3
2022	LC 7	NT	Bedington silt loam	Fine-loamy, mixed, active, mesic Typic Hapludults	0-3
2022	LC 9	NT	Hollinger silt loam	Fine-loamy, mixed, active, mesic Typic Hapludalfs	3-8
2022	LC 5	NT	Conestoga silt loam	Fine-loamy, mixed, active, mesic Typic Hapludalfs	8-15
2022	LC 10	NT	Letort silt loam	Fine-loamy, mixed, superactive, mesic Typic Hapludalfs	3-8
2022	LC 10	NT	Letort silt loam	Fine-loamy, mixed, superactive, mesic Typic Hapludalfs	3-8
2022	LC 11	NT	Letort silt loam	Fine-loamy, mixed, superactive, mesic Typic Hapludalfs	3-8
2022	LC 12	VT	Clarksburg silt loam	Fine-loamy, mixed, superactive, mesic Oxyaquic Fragiudalfs	0-5
2022	LC 13	VT	Pequea silt loam	Coarse-loamy, mixed, active, mesic Typic Eutrudepts	8-15
2022	LC 6	VT	Glenelg silt loam	Fine-loamy, mixed, semiactive, mesic Typic Hapludults	15-25
2022	LC 6	VT	Chester silt loam	Fine-loamy, mixed, semiactive, mesic Typic Hapludults	3-8
2022	LC 6	VT	Glenelg silt loam	Fine-loamy, mixed, semiactive, mesic Typic Hapludults	3-8
2022	LC 6	VT	Chester silt loam	Fine-loamy, mixed, semiactive, mesic Typic Hapludults	3-8
2022	CC 1	VT	Manor loam	Coarse-loamy, micaceous, mesic Typic Dystrudepts	3-8
2022	CC 1	VT	Glenelg silt loam	Fine-loamy, mixed, semiactive, mesic Typic Hapludults	3-8
2022	CC 2	VT	Edgemont channery loam	Fine-loamy, mixed, active, mesic Typic Hapludults	3-8
2022	CC 2	VT	Chester silt loam	Fine-loamy, mixed, semiactive, mesic Typic Hapludults	3-8

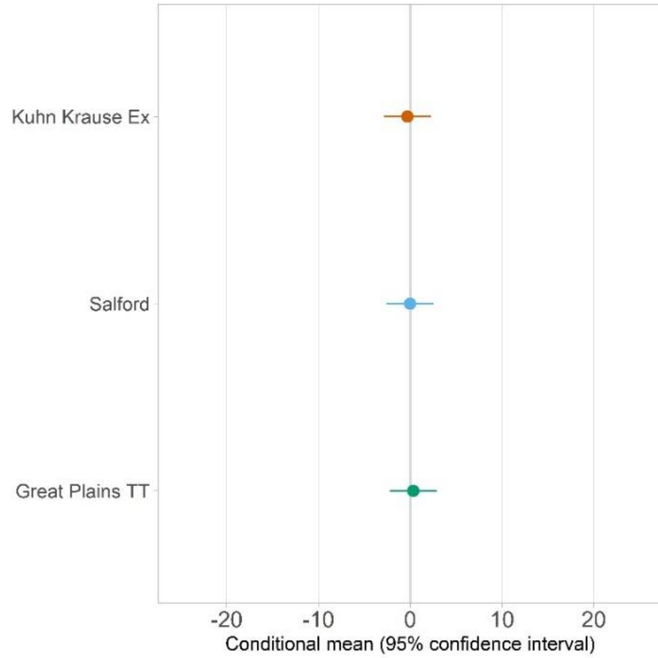

Figure A-1. Conditional mean (95% confidence interval) difference in winter annual weed cover between vertical tillage and no tillage by equipment type, including Kuhn-Krause Excelerator, Great Plains Turbo Till and Salford Independent. Conditional means describe the deviation of observations in a random factor from the population level mean.

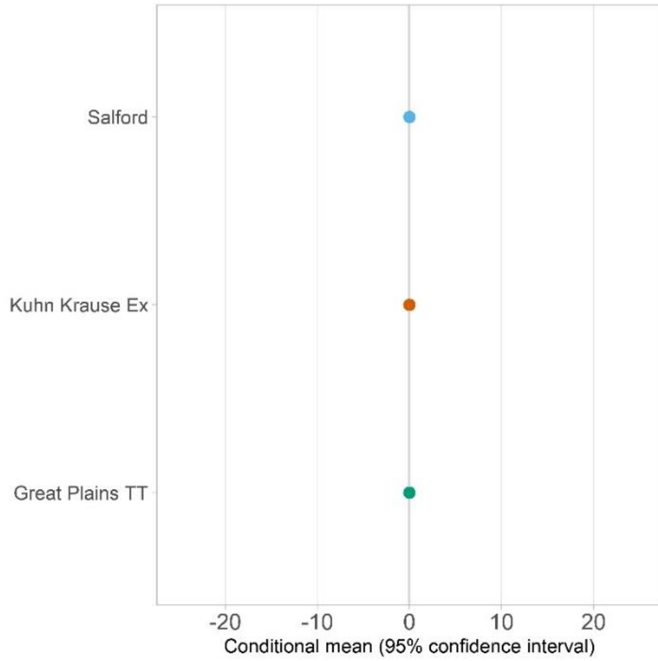

Figure A-2. Conditional mean (95% confidence interval) difference in incidence of slug damage (%) between vertical tillage and no tillage by equipment type, including Kuhn-Krause Excelerator, Great Plains Turbo Till and Salford Independent. Conditional means describe the deviation of observations in a random factor from the population level mean.