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Sustainability of Corn Stover Harvest Strategies in Pennsylvania

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Abstract Pennsylvania farmers have a long history of harvesting corn (*Zea mays* L.) stover after grain harvest for animal bedding and feed or as a component of mushroom compost, or as silage for dairy cattle feed. With the shallow soils and rolling topography, soil erosion and carbon losses have been minimized through extensive use of cover crops, no-till, and organic matter additions from animal manure. Our objective was to determine the effect of harvesting corn stover as a feedstock for bioenergy production in continuous corn or corn–soybean [*Glycine max* (L.) Merr.] rotations on corn grain and stover yields, soil carbon, nitrogen, phosphorus, potassium, and the potential for cover crops to mitigate negative impacts of stover harvest. Although there was not a significant effect of stover harvest on corn grain yields in continuous corn, stover harvest tended to increase yields in years with wet springs but decreased them in dry years. Under the corn soybean rotation, 100 % stover removal always resulted in lower grain yields. The harvest index (HI) varied from 0.45 to >0.6 over the 5-year period with the lowest HI values being in response to a late summer drought and highest values being associated with an early summer drought. In most cases, 60 % soil cover was maintained in fall and spring with 50 % harvest of corn stover. Without a rye (*Secale cereale* L.) cover crop, surface residue for 100 % stover harvest ranged from 20 to 30 %, whereas it was greater than 40 % when rye was established promptly in the fall. Soil carbon was similar across stover removal levels, crop rotations, and cover crops, as were soil nitrogen, phosphorus, and potassium concentrations, since nutrient removal by the grain and stover were replaced with fertilizer additions. Based on the crop yield, surface cover, and soil nutrient responses, partial stover removal could be sustainable under typical climate and management practices in Pennsylvania.

Keywords Bioenergy · Corn stover · Soil carbon · Soil cover · Sustainability

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Introduction

Crop residues are an important component in the US supply of biomass feedstock required to meet the RFS2 goals for ethanol production [1]. Within that supply wheel, corn is the most widely planted crop in the US farm landscape and generates the most crop residue. However, corn stover already provides many environmental benefits including reducing soil erosion losses, maintaining soil carbon, and reducing evaporative water losses, which can be critical during periods of drought. All of these factors can affect crop yields, leading to concern that excessive removal of stover may jeopardize these functions [2].

Nationally, corn yields have increased 40 % over the last 25 years [3]. In Pennsylvania, corn yields have increased at a similar rate, from 6.5 to 9.3 Mt/ha (103 to 148 bu/acre) since 1989 [3]. The increase in corn yields have resulted in a corresponding increase in stover production. Stover can interfere with planting operations, keep soils wet and cool in the spring,

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immobilize N and increase the need for fertilizer inputs, and harbor pests such as slugs [4] or plant diseases such as fusarium, the causal agent in head scab in wheat [5].

Increasing tillage intensity is a common residue management strategy to mitigate problems of increased residue on subsequent corn yields. Stover removal can also help to mitigate some pest and agronomic issues that have been associated with increasing levels of stover as corn yields have increased in Pennsylvania and other regions. An alternative to increased tillage intensity for managing excess residue is the partial harvest of corn stover which has been shown to reduce the N rates required to achieve optimum yields [6].

To minimize the impacts on soil resources, guidelines have been proposed for stover harvest, targeting high yielding fields and only removing a fraction of stover [7]. Enough residue needs to remain to minimize soil erosion losses; however, additional stover above that needed to minimize soil erosion losses is needed to maintain soil carbon levels. The quantity of stover available for harvest also depends on crop rotation and tillage intensity [7]. In lower yielding environments, these guidelines would only recommend a small amount of stover to be harvested. Ultimately, site-specific corn yields will determine which fields can be sustainably and economically harvested [8, 9].

In Pennsylvania, even in areas with lower yields and sloping soils, stover harvest has been common for other uses such as animal bedding and feed, or compost production [10]. Corn is also harvested for silage production on dairy and livestock farms, where all of the biomass is removed. Farmers in this region have mitigated the impacts of biomass removal on soil carbon losses and erosion by using cover crops, no-tillage, and manure applications. In general, these tactics have proved effective in not only mitigating the impacts of stover harvest, but also increasing soil carbon levels and improving productivity [11]. There is some potential to incorporate no-till, cover crops, and manure or other carbon inputs [12] in conjunction with a partial stover removal strategy to reduce the impact of stover removal in these lower yielding environments with sloping soils. Understanding the impact of these practices on corn yields, soil carbon, and surface residue cover is critical since excessive removal will increase soil erosion and ultimately reduce crop productivity. The objective of this study was to evaluate the impact of stover removal at 3 levels (0, 50, and 100 %) on (1) corn yields in both continuous corn and corn–soybean rotations, (2) soil cover provided by crop residue and cover crops, and (3) soil carbon levels as well as other nutrients removed with stover harvest.

Materials and Methods

Field experiments were conducted near State College, Pennsylvania (40.864060, -77.848484) over a 5-years period from 2008 to 2012 (Table 1). The soils at this site were a mixture of Hagerstown (Fine, mixed, semiactive, mesic Typic Hapludalfs) and Opequon (Clayey, mixed, active, mesic Lithic Hapludalfs). Prior to the initiation of the experiment, the site was managed in no-till corn and soybean production for approximately 15 years and received dairy manure applications almost every year.

The experimental design was a randomized block with four replications and 12 treatments. Individual plot size was 12 rows (9.14 m) wide by 30.48 m long. Treatments consisted of four crop rotation sequences, each with 0, 50, or 100 % corn stover removal in the fall. The four crop rotations were continuous corn, continuous corn with a rye cover crop, and corn–soybean or soybean–corn (each with a rye cover crop). The rye cultivar (“Aroostook”) was planted at 134 kg ha^{-1} immediately following stover harvest and killed with herbicide in the spring one week prior to corn planting.

Fertilizer additions to each treatment were managed to provide optimum levels of nutrients and account for nutrients removed in the harvested stover. Nitrogen was applied to all

Table 1 Monthly average of the mean daily temperature and total precipitation from 2008 to 2012 compared with the 30-year average (1981–2010)

	2008	2009	2010	2011	2012	30-year
Air temperature, C°						
Jan	−1.84	−6.16	−3.46	−5.57	−0.43	−2.7
Feb	−3.15	−1.17	−3.40	−1.57	1.55	−1.3
Mar	1.83	3.86	6.38	2.37	9.72	2.9
Apr	10.44	9.31	11.61	9.68	9.94	9.7
May	12.10	14.42	15.96	16.39	18.08	15.3
Jun	20.19	18.42	20.42	19.80	19.97	20.2
Jul	21.59	19.00	22.80	23.74	23.15	22.3
Aug	19.25	20.79	21.29	20.34	20.19	21.4
Sep	16.94	15.98	13.23	17.02	16.21	17.1
Oct	9.10	9.30	11.15	10.06	11.37	10.9
Nov	3.40	6.52	4.79	7.33	2.65	5.4
Dec	−1.18	−1.81	−3.77	1.74	2.01	−0.3
Precipitation, cm						
Jan	4.11	1.22	6.60	1.02	7.06	6.96
Feb	6.78	2.01	0.23	7.29	3.94	6.43
Mar	13.44	3.16	9.35	10.44	5.41	8.64
Apr	9.78	6.58	3.53	12.95	3.23	8.13
May	10.34	8.92	8.74	14.10	17.07	8.79
Jun	7.70	12.88	5.49	5.41	8.10	10.44
Jul	6.35	12.24	9.80	2.97	5.97	8.94
Aug	3.86	5.82	6.27	14.48	9.65	9.75
Sep	13.46	3.12	5.64	20.32	9.04	9.07
Oct	4.24	8.66	12.37	11.10	10.24	7.70
Nov	3.61	2.79	9.70	8.15	1.14	8.48
Dec	8.26	5.87	4.88	8.81	8.31	7.32

corn plots at a rate to achieve a yield goal of 11.4 Mg ha^{-1}. Continuous corn received a total application of 224 kg N ha^{-1} while corn following soybean received 165 kg N ha^{-1}, assuming a 59 kg N ha^{-1} soybean credit. Nitrogen was applied as a split application with 56 kg N ha^{-1} applied as UAN just after planting and the remainder applied as a dribbled sidedress application between each row at the V6 growth stage. Phosphorus and K were applied to all corn plots at a rate to achieve a yield goal of 11.4 Mg ha^{-1} and account for their removal with corn stover harvest. In both the continuous corn and corn–soybean rotations, where stover was not removed, 56 kg ha^{-1} of P_2O_5 and K_2O were applied prior to corn planting. When 50 % of the stover was removed, 67 kg ha^{-1} of P_2O_5 and 110 kg ha^{-1} K_2O were applied prior to corn planting. With 100 % removal of corn stover, 78 kg ha^{-1} of P_2O_5 and 168 kg ha^{-1} K_2O were applied prior to corn planting. In the corn–soybean rotations, 56 kg ha^{-1} of P_2O_5 and K_2O were applied prior to planting in the soybean.

Corn was planted in late April or early May with a Kinze (Williamsburg, IA) 12-row no-till corn planter at a seeding rate of 74,100 plants per hectare in 76-cm rows. The hybrids varied each year but were all supplied by DeKalb and had 100- to 103-day relative maturities and resistance to the European corn borer [*Ostrinia nubilalis* (Hübner)], Western corn rootworm (*Diabrotica virgifera virgifera*) and glyphosate. Soybean crops were planted in early May as well using a Great Plains (Salina, KS) drill. Soybean varieties also varied between years but were all considered to be early lines ranging in Maturity Group from 2.7 to 2.9.

All plots were harvested with a commercial combine and grain mass was measured with a weigh wagon in the field. Corn stover was harvested from each plot immediately following grain harvest with a Hesston StakHand (Agco, Duluth, GA) harvester equipped with load cells. Harvest height was adjusted prior to stover collection to approximate either 50 or 100 % stover removal. Stover samples were collected from each plot at harvest and dried at 55 °C to determine moisture concentration at harvest. After drying, samples were ground in a hammer mill and then reground to pass a 1-mm screen using a Wiley mill (Thomas Scientific, Swedesboro, NJ). Total N was determined with a Leco FP-528 [13] (LECO Corp., St. Joseph, MI). Phosphorus and potassium were quantified by inductively coupled plasma emission spectroscopy [14] after extraction by acid digestion [15]. The complete dataset is available in the REAP database (nrrc.ars.usda.gov/slreap/#/Home) [16]. Crop residue coverage was estimated using digital photographs that were interpreted with SamplePoint software (http://www.samplepoint.org/) [17] at harvest and in the spring prior to killing the cover crop. The line transect method [18] was used at two samplings and these data were compared to the SamplePoint techniques using regression analyses to develop a relationship between the two methods.

Prior to the initiation of the study, and following the grain harvest in the fifth year, three ~1-m-deep soil cores 4.25 cm in diameter were collected from each plot, and separated into four depth increments, 0 to 5, 5 to 15, 15 to 60, and 60 to 120 cm to assess total N and C and also extractable P and K. Soil samples were weighed before being sieved through a 2-mm screen to remove rock fragments and other debris. Total C and N were assessed by combustion [19, 20]. The Mehlich 3 (ICP) [21] was performed to test for P and K. The complete soil nutrient dataset is also available in the REAP database (nrrc.ars.usda.gov/slreap/#/Home) [16].

Soil variables (N, P, K, and C), crop yield response, and harvest index (HI) were analyzed for treatment effects using SAS® 9.2 generalized linear mixed models (Proc GLIM MIX). We used a randomized block framework with repeated measures where stover removal, crop rotation, and cover cropping were considered main effects, replicates were blocks, and calendar year was considered random (SAS Institute Inc., Cary, NC, USA). Means comparisons were made using Tukey's test (α=0.05).

Results

Corn Yields

There were large differences in precipitation over the five study years, ranging from 2009 where timely precipitation resulted in record yields, to 2 years of drought with temporal differences leading to different effects of corn grain and stover yields (Table 1). There was not a significant effect of corn stover removal on corn grain yields (P>0.05). However, in a year with a wet spring (2009) with continuous corn there was a trend for higher corn yields with stover harvest (Fig. 1a). Under early (2010) or late season (2011) drought, the trend was the opposite, with 100 % stover harvest resulting in the lowest yields (Fig. 1a). Under the corn–soybean rotation, 100 % stover removal always tended to have lower grain yields (Fig. 1b). Corn yields were not different between rotations, as there was no increase in corn yields following soybean in the corn–soybean rotation compared to those in the continuous corn rotation (P>0.05).

Corn and soybean yields are highly correlated with July and August precipitation. In 3 out of 5 years, there was below average July precipitation (Table 1). In 4 of 5 years there was below average August precipitation. Thus compared to average conditions corn and soybean yields in this study, were probably lower than expected over the long term. Higher corn and soybean yields would likely result in even less impact on soil carbon and soil cover than reported in our study. May precipitation was at or above average every year. In 2009, the wet June and July carried the corn through a dry August,

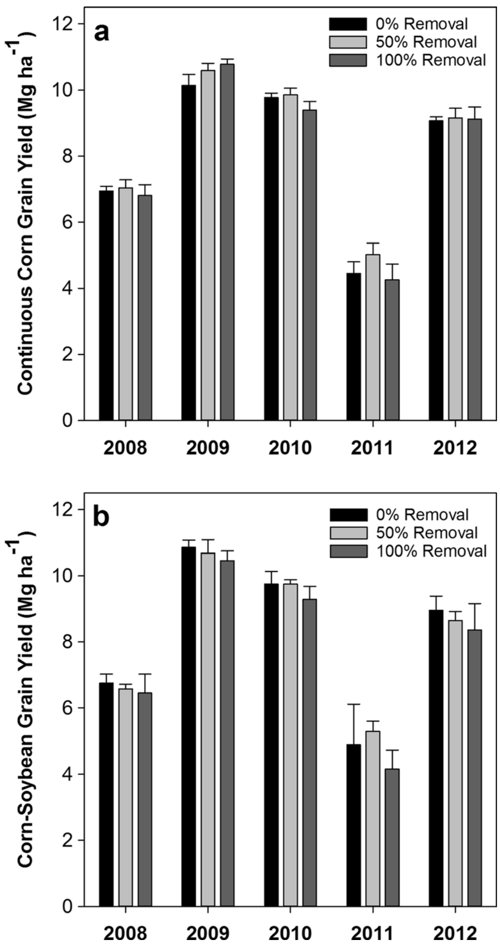


Fig. 1 Corn grain yields (dry weight) from 2008 to 2012 in either (**a**) continuous corn or (**b**) corn–soybean rotation. *Vertical bars* denote±SE

whereas in 2011 June and July were very dry with wet period occurring at end of August.

Harvest index varied from 0.45 to >0.6 over the 5-year period with the lowest HI occurring following a year with a late summer drought (2011) and highest in a year with an early summer drought (2010) (Fig. 2). The variation in the harvest index affected corn stover yield. In our environment, where corn is sometimes subject to early season drought stress due to the shallow soils, vegetative growth is limited, and this can result in high harvest indices with good corn yields and lower than expected stover yields.

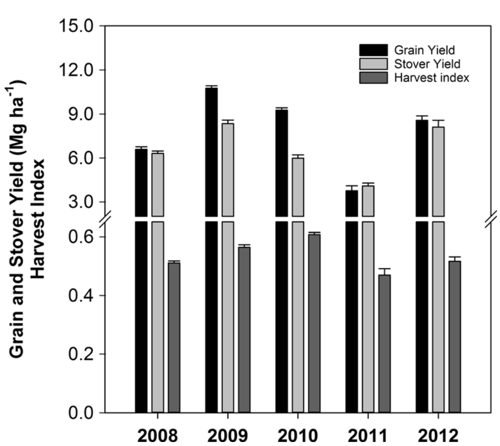


Fig. 2 Harvest index and annual mean grain (dry wt) and stover yields from 2008 to 2012

The use of a rye cover crop did not have a significant effect on corn yield (P=0.2550). The rye cover was killed with herbicide 1 week prior to corn or soybean planting to reduce interference with the following crop. Because of the late establishment in the fall and early kill in the spring, rye yields in this study were relatively low. Rye yields measured in three out of five years were 600±60 kg dw/ha. These relatively low yields may have limited any potential benefits of cover cropping on subsequent corn yields or soil carbon levels.

Soil Cover

Under continuous corn, in the fall, soil cover was above 60 % in all years for the 50 % stover removal treatment and above 90 % for the no stover removal treatment (Fig. 3a). With 100 % stover removal, in some years, cover was less than 20 %. Rye growth was not sufficient to add to soil cover in the fall (Fig. 3b). In the spring, soil cover generally decreased less than 10 % over winter. While soil cover remained above 75 % for 50 % stover harvest, it dropped to less than 30 % for 100 % stover harvest (Fig. 3c). With timely establishment of a rye cover in the fall, soil cover remained above 40 % for 100 % stover removal in the spring; however, in 2009, late establishment of rye led to little improvement of soil cover in the spring (Fig. 3d). Although soil cover was generally greater than 75 % following soybean harvest, no till planting of rye reduced soil cover by 50 % and is not captured in the fall data (Fig. 4a, b). This suggests that in some cases, late fall planting of rye could reduce soil cover and potentially expose soils to increased soil erosion. All rotations alternating corn and soybean had a rye cover crop, resulting in spring soil cover greater than 60 % in all removal treatments except in 2009 following fall corn where there was poor establishment of fall rye (Fig. 4c, d).

All soil cover data were determined using the SamplePoint method [17]. However, the line transect method is the basis for NRCS guidelines (http://efotg.sc.egov.usda.gov/references/public/MI/Line_Transect_%26_Residue_Estimates.pdf). In a spring 2012 comparison of the two methods, we found that the SamplePoint method estimated soil cover about 10 % higher than the line transect method (Fig. 5). So the cover data reported in this study should be reduced by about 10 %, which results in line transect cover estimates for the 100 % stover harvest to be less than the 30 % target cover in NRCS guideline in the spring.

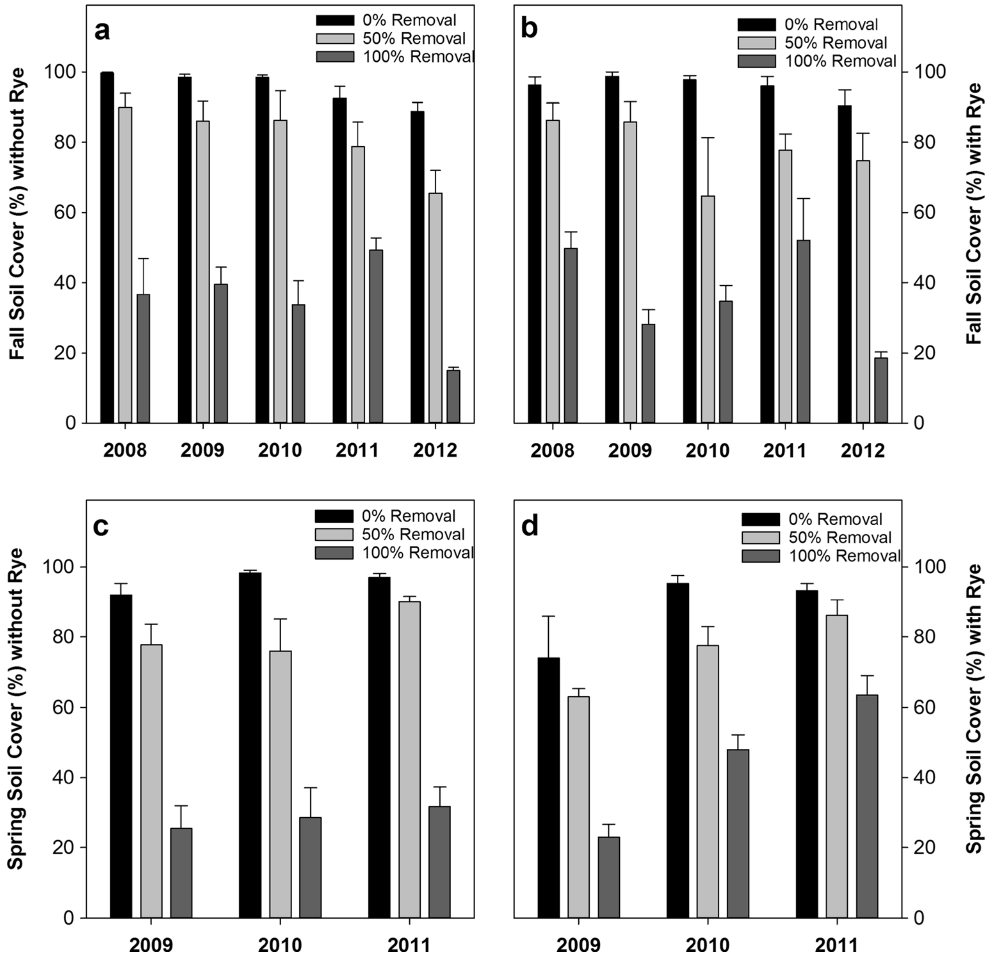


Fig. 3 Soil cover following continuous corn rotation in the fall without (**a**) or with (**b**) rye or spring without (**c**) or with (**d**) rye, from 2008 to 2012. *Vertical bars* denote±SE

Soil Nutrients and Carbon

Corn stover removal did not have a significant effect on any of the soil variables analyzed in our study ($P>0.05$), with Mehlich extractable P a potential exception ($P=0.0512$). Stover removal tended to decrease Mehlich extractable phosphorus in near-surface soils. Soil depth was a significant factor for most soil variables, and nutrients typically decreased with depth. Mean soil nitrogen concentration increased over the 5-year-time period of the study ($P=0.0136$), but total soil nitrogen content did not ($P=0.2996$). Mehlich extractable phosphorus decreased over the study period, but only in near surface soils (0–5 and 5–15 cm) as indicated by the time×depth interaction term in the mixed model ($P=0.0122$). Soil K levels were not affected by removal. This was likely due to our fertilization strategy that compensated for nutrient removal by applying approximately 10.4 kg K/Mg stover removed. Actual removal rates in this study were 11.1 kg K and 1.23 kg P/Mg stover removed. Cover cropping with annual rye had few effects on soil nutrients with the exception of Mehlich extractable phosphorus ($P<0.05$); however, there are other indications that suggest this might represent a type I error. Prior to the beginning of the study, plots designated to have no rye cover crop had higher levels of Mehlich extractable phosphorus compared to plots designated to receive a rye cover crop (cover: $P<0.05$), and over the course of the study period, Mehlich extractable phosphorus decreased (time: $P<0.05$) similarly on plots with and without a cover (cover×time: $P>0.05$). There were no significant differences between the continuous corn and the corn—soybean crop rotations on soil nutrients.

Corn stover removal at the 50 or 100 % levels had no significant impacts on the change in total soil carbon at any depth during the 5-year period of continuous corn or corn–soybean production in the study (Fig. 6). Total soil N was also not impacted by the stover removal treatments at any depth. Cover cropping had no significant impacts on soil C or N, likely due to the low cover crop biomass production in this system.

Stover removal tended to slightly reduce soil P levels in the 0–5 cm depth but unchanged deeper in the profile (Fig. 7). The difference between P applications and removal indicated that usually there was less than about 10 kg/ha P applied than removed (Fig. 8). Soil K levels remained unchanged during the course of the study as the fertilizer strategies we used resulted in a larger positive K balance than with P. Overall,

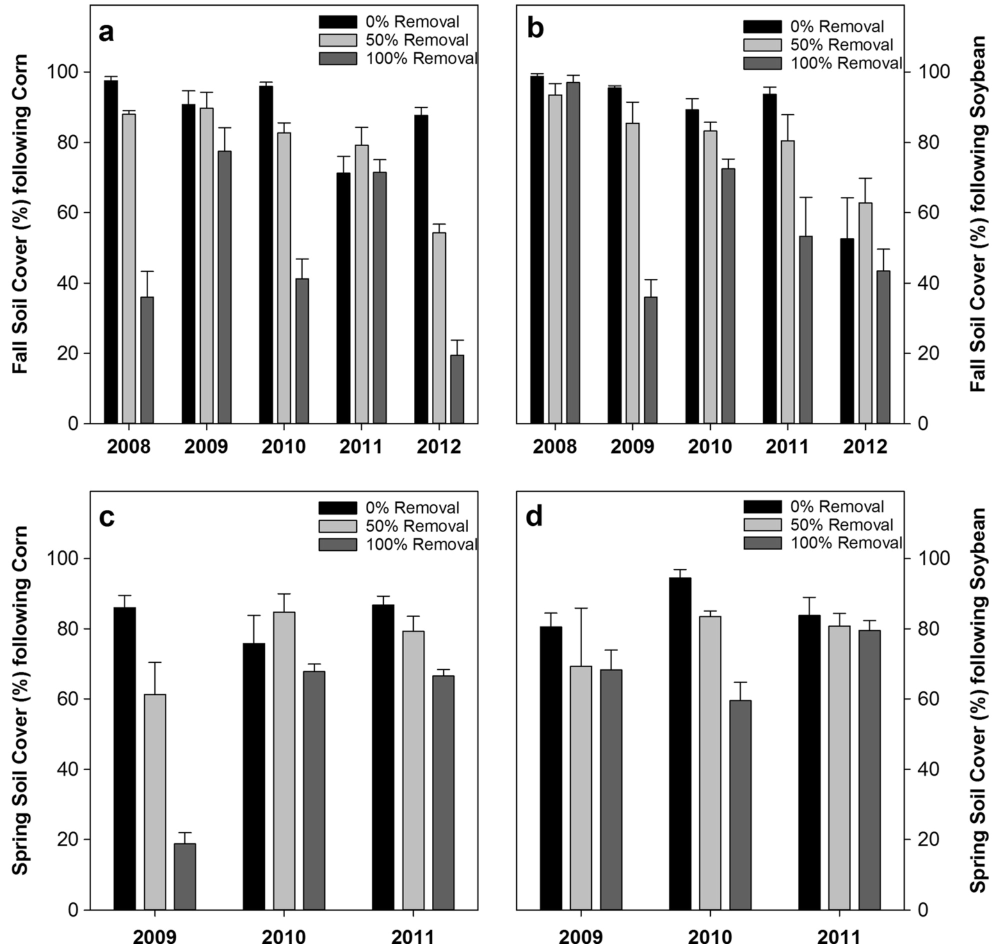


Fig. 4 Soil cover in corn–soybean rotations in the fall following corn (**a**) or soybean (**b**) or spring following corn (**c**) or soybean (**d**), from 2008 to 2012. *Vertical bars* denote±SE. Subtract 10 % from cover estimates (see Fig. 5) which were determined using the SamplePoint method [17], for comparison with the line transect method [18] (basis for NRCS guidelines of maintaining a 30 % cover)

the lack of response to stover removal in soil nutrients in this study is likely due to a fertilization that largely compensated for nutrients removed and to the previous 10 years of no-till management with almost annual manure application that resulted in a resilient soil with high soil carbon levels in the surface 5 cm.

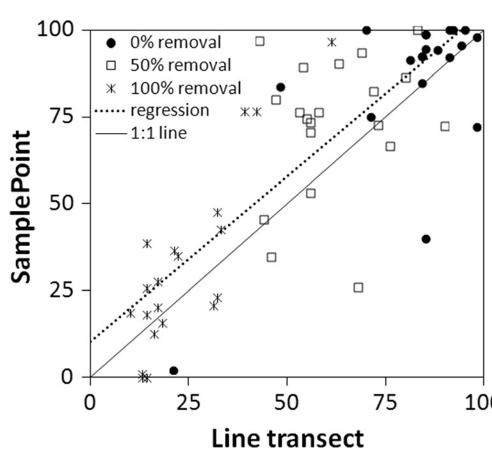


Fig. 5 Comparison of SamplePoint and line transect methods for determining cover of soil by crop residues (regression of SamplePoint and line transect, $y=0.95x+10.46$, $R^2=0.68$)

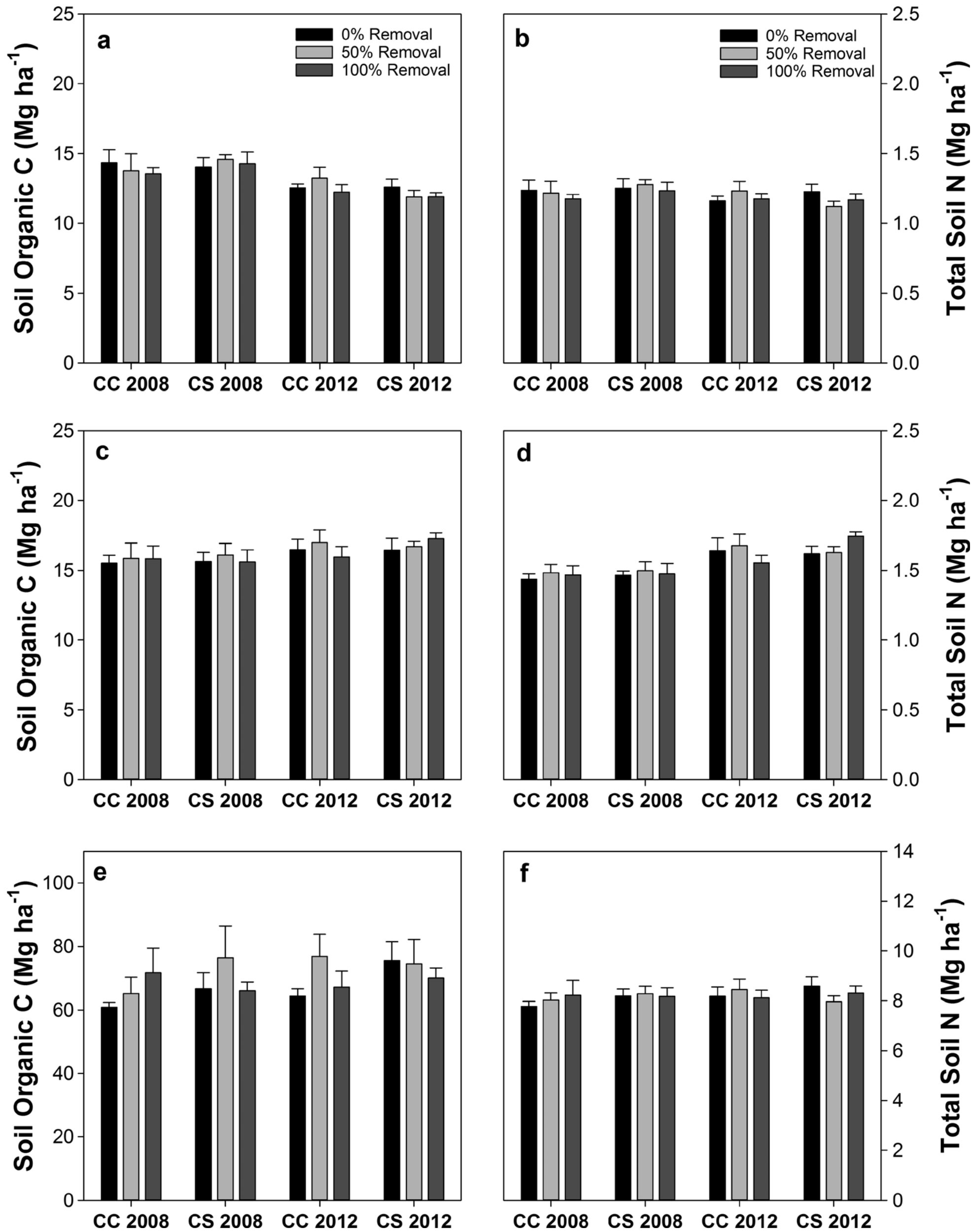
Discussion

Corn Yields

Corn yields were generally not impacted by stover harvest in this study. Subtle positive and negative effects from stover harvesting that have been reported in other studies [22] were observed in our study. As corn yields increase (above 11.3 Mg/ha 180 bu/ac) in cool wet springs, high residue can reduce soil temperatures [23], increase incidence of pests (slugs) and disease problems, all which can reduce yields; corn stover harvest can reduce this potential as in spring 2009. During early or late drought years, crop residue can provide a mulching effect, reducing evaporative soil moisture loses and reduce yield losses [24].

The increased variation in harvest index in this study was likely due to the variation in timing of drought. The harvest index in this region can vary significantly due to shallow soils and the impact of the timing of seasonal droughts on dry matter partitioning between the grain and stover [25]. Soils in this region tend to have lower water-holding capacity compared to the central Corn Belt and subject to periodic short-term midseason drought stress. In years like 2010 when early

Fig. 6 Change in soil organic carbon and nitrogen from 2008 to 2012 by soil depth [0–5 cm (**a**, **b**), 5–15 cm (**c**, **d**), and 0–100 cm (**e**, **f**)], stover removal level, and crop rotation [continuous corn (CC) and corn–soybean (CS)]. *Vertical bars* denote±SE



season precipitation was below average, vegetative growth was limited. However, with above average precipitation later in the summer, plants can recover and produce good grain yield resulting in a high harvest index. These harvest indexes values are based on assessments at harvest, so they may tend to be higher than those obtained in other studies where the assessments were made at physiological maturity.

Soil Carbon

Stover removal has the potential to decrease organic inputs, soil organic carbon, and soil nutrient availability if not carefully balanced with nutrient and tillage management [26]. Previous research has shown that excessive stover removal can lead to rapid decreases in soil organic carbon, decreased soil nitrogen and phosphorus, and that the effects on soil properties increase as more biomass is removed [27]. While others have indicated that the effects of stover removal may be less detrimental and nuanced [28], Wilhelm et al. [26] reviewed the available literature and found that <1 to >9.25 Mg ha^{-1} of stover must be retained in traditional tillage systems to maintain or increase SOC depending on soil and climatic conditions. A recent multisite analysis found that about 6 Mg stover/ha should be returned to the soil to maintain soil carbon level [29]. In our 5-year study, we saw no significant change in SOC in any single depth increment or through the soil profile as a whole for any rotation or stover removal treatment (Fig. 6). It is possible that 5 years of data is not adequate to

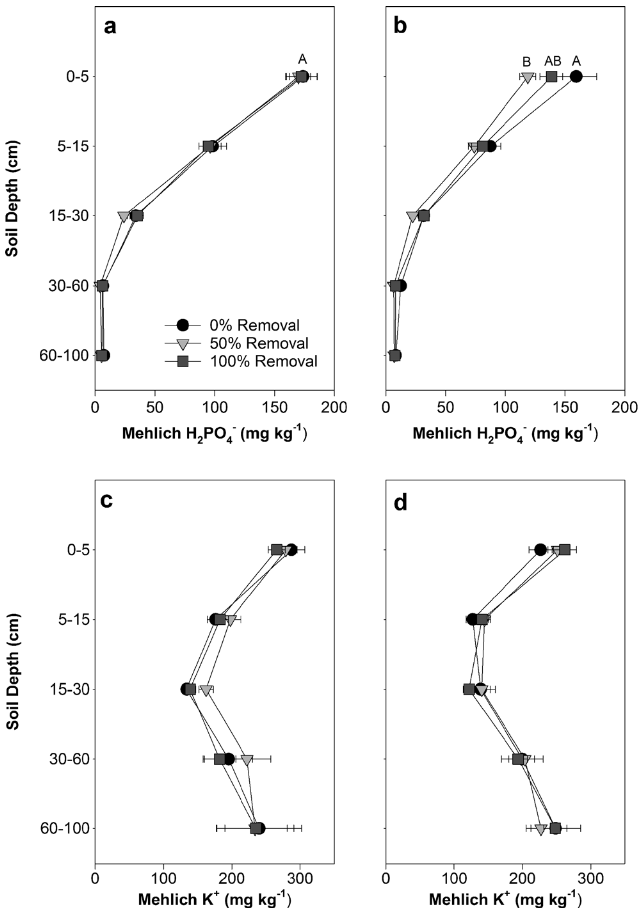


Fig. 7 Change in soil phosphorus and potassium from 2008 (**a**, **c**) to 2012 (**b**, **d**) by soil depth and stover removal levels. *Vertical bars* denote±SE

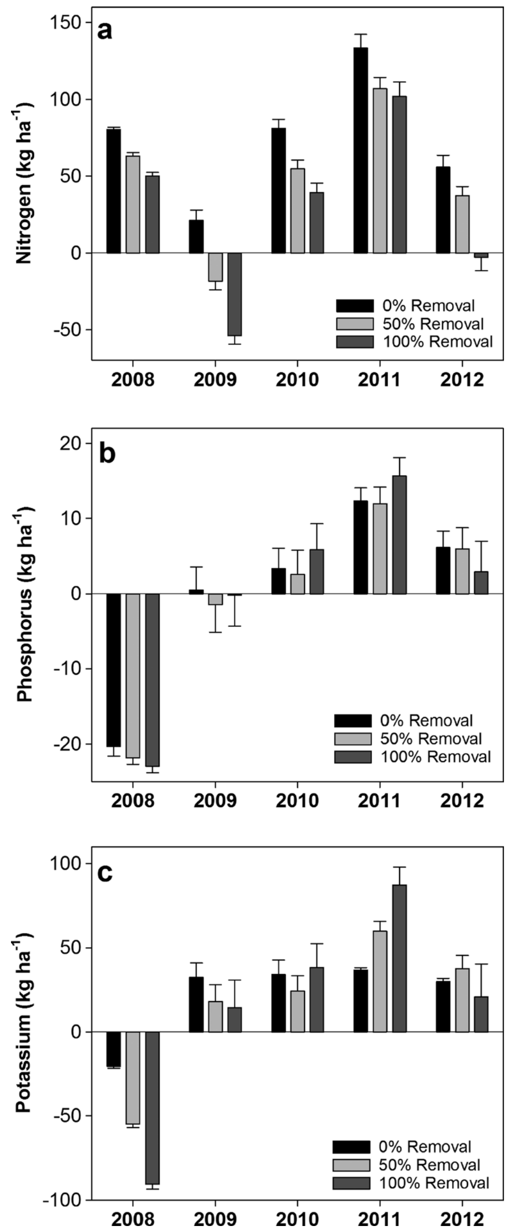


Fig. 8 Difference in amount of **a** nitrogen, **b** phosphorus, and **c** potassium applied and the amount removed in the corn grain and stover. *Vertical bars* denote±SE

accurately capture changes in SOC [30]; however, other researchers have documented significant changes in SOC after only one growing season of stover removal [27]. The research plots had been managed under no-till practices with organic manure amendments for at least 15 years prior to the beginning of this study. Under this management, the system may have achieved its current equilibrium, and under no-till practices belowground C inputs and non-harvestable aboveground C inputs may be adequate to maintain current SOC levels. Previous studies have shown that up to 75 % of new C entering soil was derived from belowground inputs (roots and rhizodeposition) while most aboveground C was lost as CO_2 [31]. Under different climatic regimes, this may not be the case. Climate influences the total change in SOC with humid temperate regions tending to have greater capacity to sequester SOC than arid or warm tropical regions [32]. Warmer temperatures lead to more rapid oxidation of organic matter and can decrease SOC without significant annual inputs. Conversely, cooler climates tend to slow oxidation of organic matter and lower annual inputs are required. Similarly, soil texture influences SOC sequestration because finer-textured soil tend to form stable aggregates that shield SOC from microbial activity, and finer textures soils have higher clay content which may actually chemically adsorb organic matter and prevent decomposition [33]. A recent study of no till systems in Ohio concluded that the effects of stover removal were more pronounced on silt loam soils on 10 % slope than they were on silt loam or clay loam soils on level slopes [34]. Though not discussed thoroughly, it also appears that the time since inception of the no till management influenced the outcome. The site where no till had been in place for more than 35 years showed larger response to stover removal than the sites with 15 and 8 years since adoption of no till management [34]. In our study, conducted on a Hagerstown series soil, the near-surface texture is silt loam (0–40 cm) and the underlying horizons are silty clay loam (40–60 cm) and clay (60+ cm). The climatic regime is characterized by a short warm summer season with mean annual temperature of 10.1 °C and mean annual precipitation of 100 cm (Table 1). Under these conditions, no-till management and minimal residue retention appear adequate to maintain SOC content, as measured over a 5-year period. Continued removal of corn stover may eventually cause a reduction in SOC, but further monitoring would be necessary to determine the long term impacts. There are several other agro-ecosystem services provided by retaining corn residues in the field such as erosion control, weed control and moisture conservation. For these reasons we advocate at least 50 % retention of corn residues.

Soil Nitrogen, Phosphorus, and Potassium

The results for soil nitrogen closely mimic those of soil organic carbon; there were no significant differences caused by cover cropping, crop rotations or rate of corn stover removal. There is far less literature describing N response to stover removal than there is for SOC, and so the reference frame is quite small. Previous studies have reported that removing 100 % of stover under no-till management could reduce total soil N% by 10 to 20 % in the top 20 cm of silt loam soils in OH [34], while others have shown that converting to minimum tillage increased total soil N, but only when at least 33 % of residue was retained [35]. In a study conducted by Karlen et al. [36], doubling the amount of corn residue added to plots increased total soil nitrogen by 30 %, but there were no significant effects from removing residue. The discrepancy between the studies may be explained by fertilizer management. In our study, we attempted to match annual fertilizer rates to average nutrient removal over time. Applied N exceeded N removed in all years for the 0 % removal treatment, 4 of 5 years for the 50 % removal treatment and 3 of 5 years for the 100 % removal treatment (Fig. 8). In all cases, N inputs exceeded N removal over the course of the study. Nitrogen management can be particularly important in agro-ecosystems because of the role N serves in SOC sequestration. The C and N cycles are very closely linked and increasing N can promote carbon sequestration if adequate residue is supplied, but may increase decomposition and decrease SOC if adequate residue is not supplied [28]. Although not specifically addressed in our study, it is important to consider that excess N fertilization may lead to impaired water quality and unnecessary costs for producers [37].

The only soil nutrient that was significantly affected by corn stover removal in our study was Mehlich extractable soil P (Fig. 7). After 5 years, extractable P was unchanged in 0 and 100 % removal plots, but reduced by 30 % in the top 5 cm of 50 % stover removal plots (Fig. 7). This result is due to the fertilizer management employed in the study. There was no phosphorus applied in the first year of the study, and phosphorus was applied in subsequent years to replace the estimated phosphorus removed in residue (Fig. 8). When summed over the 5-year-study period, the ratio of phosphorus removed vs. applied was highest on the 50 % stover removal plots (Fig. 8), and this was the only instance where more nutrients were removed than added in the entire study. Through the course of the study, the reduced phosphorus availability did not appear to impact grain yields (Fig. 1). These findings are consistent with the results from Salinas-Garcia et al. [35] and Blanco-Canqui and Lal [34], but differ from Karlen et al. [36] who found no significant changes in P with stover removal.

Finally, we saw no significant changes in Mehlich extractable potassium over our five year study (Fig. 7). Even though removals exceeded fertilizer inputs in the first year similar to phosphorus, potassium inputs generally exceeded removals for all treatments in subsequent years and appear to have been sufficient to maintain the rather large soil pool (Fig. 8). This is consistent with the results of Karlen et al. [36].

Implications of Corn Stover Harvest on Sustainability

In our study conducted in central Pennsylvania, there were minimal impacts on several key indicators identified as criteria for a sustainable residue harvesting system [2]. There were few impacts of stover removal on soil organic carbon and nutrients after 5 years of residue removal with the exception of soil surface phosphorus. With the 50 % partial stover removal treatment, soil cover was above critical levels throughout the year, reducing potential soil erosion. Cover crops added to the soil coverage in some cases. There were also no consistent negative effects on corn yields with partial stover removal and in some cases there were trends for higher yields when cool conditions or pests associated with high residue levels impacted early season corn growth.

The previous tillage history of the field in no-till for 15 years with frequent manure applications may have also contributed to the lack of impact on corn yields and soil nutrients. On soils with less organic matter in the surface, the impact of stover removal could be more dramatic. The climate of central Pennsylvania is characterized by short warm summers with adequate rainfall, and cool fall, winter, and spring temperatures which reduces microbial oxidation of soil organic carbon. The soils on the study sites are fine texture silt-loam and clay-loams which also tend to retain nutrients and soil organic carbon. It is possible that after several more years of complete stover removal could result in a slow decline in soil organic carbon on these sites so this should be monitored with periodic soil testing.

These results are consistent with other recent studies that were conducted in conjunction with this study as part of a national effort. Karlen et al. [36] reported that over 239 site-years, harvesting an average of 3.9 Mg/ha stover resulted in yield increases at 57 % of the sites. They also reported no-till grain yields were lower than those from conventional tillage but similar when stover was collected. Muth et al. [9] developed a landscape based model to estimate sustainable stover removal using soil characteristics and no-tillage and concluded that 764,000 metric tons of stover could be harvested annually in Pennsylvania.

Overall, our results suggest that on some soils, a strategy of partial (50 %) stover removal, when combined with no-tillage, nutrient replacement, cover cropping, and monitoring of soil nutrients and carbon can sustain soil quality with no impact on corn yields and provide adequate soil cover during the winter months in this region.

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