Article

Nutrient Accumulation Affected by Corn Stover Management Associated with Nitrogen and Phosphorus Fertilization

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Abstract: Bio-ethanol production from corn stover harvest would change nutrient removal, in particular nitrogen (N) and phosphorus (P), affecting nutrient replenishment and corn development under field-grown conditions. This research was developed to investigate whether stover removal had any influence on the amount of N and P fertilizer required for maximum corn production in the United States (US) Midwest in a stover removal scenario. This study was conducted in Lamberton, MN on a Typic Endoaquoll under continuous corn from 2013 to 2015. The treatments included six N rates (0 to 200 kg N ha⁻¹ in 40 kg increments), five P rates (0 to 100 kg P₂O₅ ha⁻¹ in 25 kg increments), and two residue management strategies (residue removed or incorporated). Residue management was found to have a significant impact on corn response to N and P application. We verified that residue-removed plots yielded more and therefore required more N and P application from fertilizers. Grain yield after residue was removed was greatest with the highest N and P₂O₅ rates, whereas grain yield after residue was incorporated was greatest with intermediate N and P₂O₅ rates in 2013 and 2014. In 2015, residue management did not significantly affect grain yield. Grain N and P accumulation followed a similar behavior as that observed for grain yield. In general, residue removal decreased nutrient availability, while in the residue-incorporated treatment, those nutrients were returned. Although the results of the study showed potential for biomass harvest, it also indicated that nitrogen immobilization and nutrient depletion from the soil could be a limiting factor.

Keywords: corn stover removal; nitrogen application rates; phosphorus application rates; nutrient management strategies; *Zea mays* L.

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1. Introduction

Corn (*Zea mays* L.) is one of the most widespread and oldest cultivated crops in the world [1,2]. According to the United States Department of Agriculture, the United States (US) has produced more than 360 Mt of corn annually in the last five years, accounting for 32% of global corn production [3], with more than 80% of its production occurring in the Midwest. Continuous corn (about 35%) and 2-year corn–soybean rotation (about 65%) are the dominant cropping systems in the US Midwest [4]. In the US, bio-ethanol production is mostly derived from corn grain [5]. The use of plant residues such as corn cobs or stover has the potential to increase bio-ethanol yield per unit of land and also make use of existing bio-ethanol production and distribution infrastructures [6–8].

Corn stover has been identified as potential feedstock for cellulosic bio-ethanol production because of its high cellulosic content, large volume of biomass production, and wide availability around the world [9–11]. However, the removal of stover can lead to a decline in soil quality and, hence, agricultural productivity by decreasing the content of soil organic carbon (SOC) and increasing the risk of soil erosion [12,13]. Conversely, the incorporation of stover into agricultural soil can improve soil quality through a variety of processes, such as the stabilization of soil structure, prevention of soil erosion, maintenance of SOC, nutrient recycling, and provision of energy for soil microbial communities,

among others [10,11,13]. Therefore, the use of corn stover as a renewable energy could reduce greenhouse gas emissions (GHG) from transportation (fuel) with biofuel and the reduced production of fossil fuels. However, the removal of corn stover could increase the carbon footprint/GHG emissions in the process of manufacturing fertilizer and increased application in the field to fulfill the crop nutrient requirements.

Frequent crop residue removal can accelerate the depletion of soil nutrients and lead to the increased need for fertilizer application [14]. Researchers from the state of Minnesota, US reported the N, P, potassium (K), and sulfur (S) removed in 7.5 Mg ha⁻¹ of corn stover (cobs not included) to be 46, 3.5, 76, and 3.7 kg ha⁻¹, respectively [15]. However, the effects could have a more significant impact on crop production as southern MN farms have black and deep soils that are rich in secondary nutrients. Thus, soil nutrient pools may be depleted compared to areas where only grain is harvested [12,16,17]. The balance between stover removed to nutrients returned to the system has to be considered to properly address the nutrient requirement of crops under different scenarios (e.g., removed or incorporated residue management). Under or over N and P fertilizer application can lead to a reduction in crop yield, in addition to creating conditions that favor nutrient losses to the environment and poor plant nutrition [18]. Therefore, there is a need for improved nutrient management strategies, in particular N and P, to properly replace nutrients exported in grain and harvested crop residues, ensuring adequate plant nutrition and greater grain yield [2,19]. Supplemental fertilizer application to agricultural soils growing cereals is a practice that demands high capital inputs. Around 20–50% of N-based fertilizer can leave fields in the form of GHG (e.g., nitrous oxide and ammonia) and other reactive N species, such as nitrate, through leaching and runoff [20–23]. In addition, it has been reported that crop P deficiency can be found in as much as 67% of world agricultural lands used for crop production [24]. Phosphorus use efficiency by cereal crops worldwide is very low, and the efficiency of such crops to take up applied P fertilizer ranges between 15–30% [24].

Profitable and environmentally sensitive corn production requires that N and P be managed in an efficient manner [25]. Economic returns from the use of these nutrients can be maximized, while the potential for surface and groundwater enrichment with N and P can be minimized with the use of proper best fertilizer management practices. Therefore, identifying the optimal rates of these nutrients required for maximum grain yield when stover is removed for bioenergy production is needed [25]. Further research designed to understand the interactive effects of N and P application in different residue-management scenarios (removal or incorporation) is required. Such research should help to determine how to maximize N and P benefits on plant nutrition and improve overall corn biomass and grain yield productivity. The hypothesis of this study was that stover removal would decrease the amount of N and P fertilizer required for optimum crop productivity in the US Midwest. The objectives of this research were to evaluate the interactive effects of different N and P₂O₅ rates on corn productivity and nutrient accumulation with and without corn stover removal.

2. Materials and Methods

2.1. Site Description and Experimental Design

This study was conducted from 2013 to 2015 on University of Minnesota land and managed under conventional grain production by a local farmer. The maximum and minimum monthly temperatures and monthly rainfall observed during the field trial are presented in Figure 1. Weather data were collected from a local weather station located within 5 km of the study site. The rotation used prior to 2013 was soybean [*Glycine max* L. (Merril.)]/corn, with corn in 2012, and continuous corn was used from 2013 to 2015. The dominant soil is classified as Canisteo (fine-loamy, mixed, superactive, calcareous, mesic Typic Endoaquolls). In the fall of 2012, after the previous season's crop harvest, soil samples were collected (0.0–0.15m depth) from the entire experimental field on subplots of 205 m² and were used for a baseline determination of soil fertility. These subplots were set up using GPS and were only used for the initial soil sampling to allow us

to determine field variability, since the experimental area was very large. A total of 256 soil samples were collected from the sub plots in the 5.3 ha experimental site. Soil samples were air-dried for 48 h, sieved (2 mm), and stored at room temperature (22 °C) until analyses. Soil pH was measured in water (1:1 ratio w/v), and the average was 7.2. Soil test P was extracted with the Bray-1 reagent [26] and determined by the molybdate blue method of Murphy and Riley [27] using a Biotek Epoch microplate spectrophotometer (Biotek, Winooski, VT, USA) and showed an average of 11 ppm (considered medium in MN [28]). Ammonium (NH_4^+) and nitrate (NO_3^-) were analyzed after extraction in 2M potassium chloride (KCl) using the sodium salicylate method as described by Nelson [29] (average of $7.8 \text{ mg NH}_4^+ \text{ kg}^{-1}$) and the vanadium method [30] (average $5.2 \text{ mg NO}_3^- \text{ kg}^{-1}$).

Figure 1. Rainfall, maximum, and minimum temperatures obtained from the weather station located in Lamberton, MN in 2013–2015.

The treatments included six N rates, five P rates, and two residue management strategies. These treatments were selected because residue management is more likely to impact N and P than any other nutrient because those are the main limiting nutrients in most agricultural soils. Nitrogen rates ranged from 0 to 200 kg N ha^{-1} in 40 kg N ha^{-1} increments (0, 40, 80, 160, and 200 kg N ha^{-1}); P_2O_5 rates ranged from 0 to $100 \text{ kg P}_2\text{O}_5 \text{ ha}^{-1}$ in $25 \text{ kg P}_2\text{O}_5 \text{ ha}^{-1}$ increments (0, 25, 50, 75, and $100 \text{ kg P}_2\text{O}_5 \text{ ha}^{-1}$). Nitrogen was applied as urea ($\text{CO}(\text{NH}_2)_2$ –45% N) and P as triple superphosphate ($\text{Ca}(\text{H}_2\text{PO}_4)_2$ –45% P_2O_5). The residue management treatments included total surface residue removed (as much as possible being removed by baling in the fall of each year using standard baling equipment) and surface residue incorporated. Tillage operations consisted of disk ripping to a depth of 25 cm in the fall after corn and stover harvest and field cultivating to a depth of 9 cm in the spring prior to planting corn. Sulfur (10 kg ha^{-1}) and K_2O (70 kg ha^{-1}) were also applied in all subplots to assure no other nutrients were causing deficiency, in the form of potassium sulfate (K_2SO_4 –50% K_2O and 15% S) and potassium chloride (KCl –60% K_2O) following the University of Minnesota guidelines [28]. All fertilizer treatments were broadcast by hand to each plot in the spring and incorporated with tillage immediately after application and prior to planting corn. Corn seeds were planted at $86,487 \text{ seeds ha}^{-1}$; weeds were controlled using pre- and post-emergence herbicides, and insects were controlled using best-management practices.

The experimental design was a completely randomized factorial (6 N rates $\times$ 5 P₂O₅ rates $\times$ 2 residue management) with four replications set up in plots with dimensions of 3 $\times$ 12 m. Because of the large land area used, the experimental field was divided into two equal sections. In the north section, the residue was incorporated, and in the south section, the residue was removed in the spring of 2013 and 2014, respectively. Although not ideal, this period could be seen as allowing the land to adapt to the new management. Due to splitting the field into two sections, the residue factor was analyzed separately. Each section was composed of six main blocks, and each block consisted of 90 3 $\times$ 12 m plots. Each experimental plot consisted of four 0.76 m spaced rows, and yield data were collected from the center two rows, thereby avoiding edge effect. Fertilizer treatments were then randomly assigned to each plot in each of the sections. In 2015, a change in how the residue was managed took place; residue was removed from every other main block in both sections so that residue management could be implemented in both sections. The change in residue management in both sections caused a change in the experimental setup, and the study became an incomplete block design. Because there was residue management in each section in 2015, the data from both sections were combined and the effect of residue was compared in the statistical analysis.

2.2. Sample Collection and Analysis

Plant tissue samples were collected during each of the three growing seasons, at V6 (6 leaves completely unfolded) and R1 (female flowering) growth stages. At each sampling, four plants were randomly collected from rows one and four to avoid any impact on grain yield in the harvest rows (rows two and three). Tissue samples were then dried in a forced-air dryer at 35 °C until constant mass and dry weight was determined. Grain yield was determined at harvest (R6—physiological maturity) using a plot combine to harvest rows two and three, and a subsample of grain was retained for grain moisture and total nutrient accumulation. Corn grain yield was adjusted to 155 g kg^{−1} moisture. The dry tissue and grain samples were then ground to pass through a 1 mm sieve and analyzed for N and S concentration by combustion using a CNS analyzer (VarioMACRO, Elementar, Langenselbold, Germany). Phosphorus, K, Ca, and Mg concentrations were determined by sulfuric acid + hydrogen peroxide digestion and analyzed using inductively coupled plasma optical emission spectroscopy (ICP-OES, Optima 8x00 Perkin Elmer, Norwalk, CT, USA). Total nutrient accumulation in plant tissue (shoot and grain, separately) was calculated from biomass and grain yield and nutrient concentration.

2.3. Statistical Analysis

The variables collected for this study including in-season tissue (used for nutrient uptake) and grain (used for nutrient removal and yield) were subject to ANOVA. Data were analyzed at $p \leq 0.05$ using the mixed procedure of SAS 9.4 [31]. In 2013 and 2014, the main fixed effects included in the models were N and P₂O₅ application rate, growth stage (for plant tissue samples only), and year and their interactions. These main effects and interactions were analyzed for each residue management treatment separately in 2013 and 2014. Nitrogen and P₂O₅ application rates were considered continuous variables and therefore required the use of regression analysis. Growth stage and year were considered repeated variables. In 2015, the main effects of growth stage and N and P₂O₅ application, as well as residue management, were included in the model. In 2015, residue management was considered a fixed effect; growth stage (for plant tissue samples only) was considered a repeated variable, and N and P₂O₅ application rates were considered continuous variables and therefore required the use of regression analysis. Repeated measure analysis was used in combination with regression analysis to remove the covariance that existed from collecting data from the same plot over time. The covariance structure that best fit the model for each parameter was assessed by checking the Akaike Information Criteria (AIC) among all possible covariance structures. When appropriate, pairwise mean comparisons

were made at $p \leq 0.05$. The data from 2013 and 2014 were analyzed as a completely randomized design while the data from 2015 were analyzed as an incomplete block design.

3. Results

The summary of statistical analysis is presented in Appendix A (Tables A1–A3).

3.1. Grain Yield Response to N and P Fertilization under Removed and Incorporated Residue Management in 2013 and 2014

Grain yield response to increasing P_2O_5 and N rates was found to vary based on residue management. In 2013 and 2014, when residue was removed, the maximum grain yield ranged between 10,878 and 11,043 $kg\ ha^{-1}$ and required the application of 160–200 $kg\ N\ ha^{-1}$ combined with 75–100 $kg\ P_2O_5\ ha^{-1}$ (Figure 2A). Maximum grain yield in plots where residue was incorporated during the 2013 and 2014 years ranged between 9924 and 10,317 $kg\ ha^{-1}$ and required similar N application rates (160–200 $kg\ N\ ha^{-1}$) but lower P_2O_5 application rates, 50–75 $kg\ P_2O_5\ ha^{-1}$ (Figure 2B). This result shows that lower P_2O_5 rates were needed to maximize yield when residue was incorporated compared to where residue was removed; however, grain yield in plots where residue was incorporated was about 8% lower than where residue was removed. It is possible that soil and weather conditions led residue-removed plots to have higher nutrient and available water supply to the crop.

Figure 2. Grain yield under removed (A) and incorporated (B) residue management in 2013 and 2014 as a function of N and P_2O_5 rates.

3.2. Biomass and Nutrient Accumulation Affected by N and P Fertilization under Removed and Incorporated Residue Management in 2013 and 2014

Grain yield, in addition to grain K and S accumulation, was significantly greater in 2013 (9664 $kg\ ha^{-1}$, 104.5 $kg\ K\ ha^{-1}$ and 10 $kg\ S\ ha^{-1}$) than in 2014 (6913 $kg\ ha^{-1}$, 83.9 $kg\ K\ ha^{-1}$ and 7.6 $kg\ S\ ha^{-1}$) in plots with residue incorporated. Grain N accumulation was greater in plots where residue was removed in 2013 (107.9 $kg\ N\ ha^{-1}$) compared to plots where residue was removed in 2014 (99.2 $kg\ N\ ha^{-1}$). Table 1 presents grain N, P, K, and S, and biomass N and S accumulation response to N application rates where residue was removed, and Ca accumulation in grain and tissue where residue was incorporated, as well as N, K, Ca, and Mg grain accumulation.

Table 1. Grain N, P, K, Ca, Mg, and S accumulation and biomass N, Ca, S accumulation in 2013, 2014, and 2015 as a function of N application rates.

Source	Intercept (kg ha ⁻¹)	Slope Lin	Slope Quad
	Removed Residue 2013/14		
N-grain	58	0.58x	−0.002x ²
P-grain	83	0.37x	−0.002x ²
K-grain	69	0.35x	−0.001x ²
S-grain	5.9	0.04x	−0.0001x ²
N-shoot	43	0.42x	−0.0011x ²
S-shoot	4.0	0.02x	−0.0001x ²
Incorporated residue 2013/14			
Ca-grain	61	0.75x	−0.004x ²
Ca-shoot	35	0.27x	NS
2015			
N-grain	79	0.24x	NS
K-grain	68	0.65x	−0.003x ²
Ca-grain	43	0.62x	−0.003x ²
Mg-grain	46	0.67x	−0.003x ²

NS = not significant.

In plots where residue was removed in 2013, Ca and Mg grain accumulation showed no response to N application rate, and the average accumulation was 45 and 64 kg ha⁻¹, respectively (Table 2). In contrast, in 2014, Ca and Mg grain accumulation showed a non-linear response to increasing N application rate with maximum accumulation of 54 and 94 kg ha⁻¹, respectively (Table 2). When comparing nutrient accumulation between 2013 and 2014, maximum Ca and Mg accumulation was greater in 2014 than in 2013 (Table 2). For plots where residue was incorporated in 2013, P tissue accumulation response to N application rate was non-linear with maximum P accumulation of 84 kg ha⁻¹; while, in 2014, no response to N rates were observed, and maximum P accumulation was 30 kg ha⁻¹ (Table 2). In contrast to Ca and Mg, maximum P accumulation was observed in 2013 (Table 2). Sulfur tissue accumulation in plots where residue was removed showed a linear response to N application rate. Plants growing in 2013 had a higher rate of response to the N application rate (the unit of S taken up per unit of N applied) than plants growing in 2014, as indicated by the significantly greater linear slope (0.02 kg S kg⁻¹ of applied N in 2013 and 0.007 kg S kg⁻¹ of applied N in 2014) (Table 2). In addition, S accumulation in 2013 was greater than in 2014 even when no N was applied, as indicated by the significantly greater intercept (5.6 kg S kg⁻¹ of applied N in 2013 and 1.7 kg S kg⁻¹ of applied N in 2014) (Table 2). This result suggests that S availability in soils might be dependent on soil conditions, including nutrient availability and moisture level. 2014 received 100 mm more rainfall between June and August than 2013 (Figure 1). Soil moisture levels could have made a significant impact on S mineralization in the soil. Soil sulfatase enzyme activity was also higher (by 18.4%) in 2014 than in 2013 (to be published elsewhere). As expected, biomass accumulation and biomass N, P, K, Ca, Mg, and S accumulation tended to be greater in R1 growth stage than V6 (Appendix B, Table A4). In addition, in general, biomass and nutrient accumulation showed was greater in 2013 than 2014 (Appendix B, Table A4).

Table 2. Grain Ca and Mg accumulation and biomass P and S accumulation as a function of N rates and year (2013 and 2014).

Source	Intercept	Slope Lin	Slope Quad	Maximum Nutrient Accumulation
Removed Residue 2013/14				
		Grain Ca accumulation (kg ha ⁻¹)		
2013	45 ^{a,†}	NS	NS	45 ^b
2014	24 ^b	0.49x	−0.002x ²	54 ^a
		Grain Mg accumulation (kg ha ⁻¹)		
2013	64 ^a	NS	NS	64 ^b
2014	47 ^b	0.61x	−0.002x ²	94 ^a
Incorporated residue 2013/14				
		Biomass P accumulation (kg ha ⁻¹)		
2013	65 ^a	0.29x	−0.0012x ²	84 ^a
2014	30 ^b	NS	NS	30 ^b
		Biomass S accumulation (kg ha ⁻¹)		
2013	5.6 ^a	0.02 ^a x	NS	9.6 at 200 kg N ha ⁻¹
2014	1.7 ^b	0.007 ^b x	NS	3.1 at 200 kg N ha ⁻¹

NS = not significant. [†] Means within the column followed by different letters are significantly different (p -value ≤ 0.05).

Nitrogen application rate had a significant effect on biomass yield and also on Ca (2013 and 2014) and P biomass accumulation (2015) (Appendix B, Table A5). In general, biomass yield and biomass Ca accumulation increased as N application rate increased. The rate of increase in biomass yield and biomass Ca accumulation was greater in the second sampling (19.47 kg biomass kg⁻¹ of applied N and 0.31 kg Ca kg⁻¹ of applied N) than in the first sampling (3.69 kg biomass kg⁻¹ of applied N and 0.06 kg Ca kg⁻¹ of applied N) (Appendix B, Table A5). This result shows that plant nutrient removal rate varies drastically during the growing season. The lack of moisture during critical nutrient removal stages could have a significant impact on final grain yield. In contrast, in 2015 biomass P accumulation in the first sampling showed no response to N application rate and had an average P accumulation of 14 kg P ha⁻¹, which was lower than the P accumulation in the second sampling (Appendix B, Table A5). Phosphorus biomass accumulation was found to decrease as the N application rate increased in the second sampling, with a rate of decrease of −0.53 kg P kg⁻¹ N applied, in 2015 (Appendix B, Table A5). It is unclear why we have observed this negative trend in P accumulation.

Grain N accumulation and biomass N accumulation reached maximum removal (115.6–125.4 kg N-grain ha⁻¹ and 79.1–102.8 kg N-tissue ha⁻¹) when 160–200 kg N ha⁻¹ and 75–100 kg P₂O₅ ha⁻¹ were applied to plots where residue was incorporated in 2013 and 2014 (Figure 3A,B). Grain P accumulation reached maximum removal (108.0–117.6 kg P ha⁻¹) when 80–120 kg N ha⁻¹ and 75–100 kg P₂O₅ ha⁻¹ were applied to plots with residue incorporated in 2013 and 2014 (Figure 3C), and biomass P accumulation reached a maximum P removal (95–100 kg P-tissue ha⁻¹) at the highest N and P₂O₅ application rates to plots with residue removed in 2013 and 2014 (Figure 3D). Grain Mg accumulation was maximized (83.1–87.5 kg Mg ha⁻¹) with the application of 120–160 kg N ha⁻¹ associated with the application of 75–100 kg P₂O₅ ha⁻¹ to plots where residue was incorporated in 2013 and 2014 (Figure 3E).

Figure 3. N-grain (A), N-shoot (B), P-grain (C) under incorporated residue management, P-shoot (D) under removed residue management, and Mg-grain (E) under incorporated residue management in 2013 and 2014 as a function of N and P₂O₅ rates.

Grain Mg accumulation in plots where residue was incorporated in 2013 responded linearly to the P_2O_5 application rate, while in 2014, there was no response to P application (Table 3). Maximum Mg accumulation at 100 kg P_2O_5 ha⁻¹ in 2013 was 113 kg ha⁻¹, significantly greater than in 2014 (64 kg ha⁻¹) (Table 3). Contrasting results were observed for biomass N accumulation (averaged over both samplings), where no response to N application was observed in 2013, while a non-linear response was observed in 2014 (Table 3). However, the results of the study showed that, when adequate amounts of N are supplied, maximum tissue Mg accumulation (averaged over both samplings) was the same and averaged 12.7 kg ha⁻¹ in 2013 and 2014 (Table 3).

Table 3. Grain and biomass Mg accumulation under incorporated residue management as a function of P_2O_5 rates and years (2013 and 2014).

Source	Incorporated Residue 2013/14			
	Intercept	Slope Lin	Slope Quad	Maximum Nutrient Accumulation
Grain Mg accumulation (kg ha ⁻¹)				
2013	65 ^{a,†}	0.48x	NS	113 ^a at 100 kg P ha ⁻¹
2014	64 ^a	NS	NS	64 ^b at 100 kg P ha ⁻¹
Biomass Mg accumulation (kg ha ⁻¹)				
2013	13.2 ^a	NS	NS	13.2 ^a
2014	8.7 ^b	0.12x	−0.001x ²	12.3 ^a

NS = not significant. † Means within the column followed by different letters are significantly different (p -value ≤ 0.05).

Phosphorus biomass accumulation in plots where residue was incorporated showed different behavior in each sampling for the first two years of the study (Appendix B, Table A6). In most cases, biomass P accumulation did not respond to P_2O_5 application rate, with the exception for the second sampling in 2013, when a linear response to P_2O_5 application rate was observed (Appendix B, Table A6). This result suggests that P levels in the soil were not limiting P supply to the crop. However, the initial soil test level (11 ppm) in the research site should have led to a positive response to P application.

3.3. Grain Yield Response to N and P Fertilization under Removed and Incorporated Residue Management in 2015

In 2015, grain yield (averaged over both residue-management practices) was maximized (13,431–14,101 kg grain ha⁻¹) with the application of 160–200 kg N ha⁻¹ and 75–100 kg P_2O_5 ha⁻¹ (Figure 4A) in 2015. Under both removed and incorporated residue-management systems, grain P accumulation was at its highest (122.2–133.5 kg P ha⁻¹ for removed residue and 95.6–133.9 kg P ha⁻¹ for incorporated residue) with the application of 120–160 kg N ha⁻¹ and 75–100 kg P_2O_5 ha⁻¹ (Figure 4B,C).

3.4. Biomass and Nutrient Accumulation Affected by N and P Fertilization under Removed and Incorporated Residue Management in 2015

Grain K and Ca accumulation were greater in plots where residue was incorporated (100.4 kg K ha⁻¹ and 76.8 kg Ca ha⁻¹) compared to plots where residue was removed (85.4 kg K ha⁻¹ and 50.1 kg Ca ha⁻¹). In addition, grain K, Ca, and Mg accumulation showed a non-linear response to N rates (Table 1); however, grain N accumulation showed a linear response to N rates (Table 1).

Figure 4. Grain yield (A), P-grain with removed (B), and P-grain with incorporated residue management (C) in 2015 as a function of N and P₂O₅ rates.

Biomass accumulation and nutrient accumulation were greater where residue was incorporated compared with where residue was removed (Appendix B, Table A7). Biomass N and S accumulation in 2015 showed different behavior based on sampling and residue management (Table 4). Nitrogen accumulation when residue was removed showed a non-linear response to N application rate at the second sampling; for all other samplings and residue management, there was no response in N accumulation due to N application (Table 4). Nitrogen accumulation was greater in plots where residue was removed than where residue was incorporated in the second sampling, with no differences due to residue management in the first sampling (Table 4). Biomass S accumulation also behaved differently based on growth stage and residue management (Table 4). Sulfur accumulation was found to not be affected by N application rate, except for the second sampling in plots where residue was incorporated. When residue was incorporated, there was a decline in S accumulation as N application rate increased as indicated by the significant negative linear slope ($-0.04 \text{ kg S kg}^{-1}$ of applied N) (Table 4). It is difficult to speculate the reason for this result.

Table 4. Biomass N and S accumulation in 2015 as a function of N rates, residue management, and growth stages.

Source	2015			
	Intercept	Slope Lin	Slope Quad	Maximum Nutrient Accumulation
Biomass N accumulation (kg ha ^{−1})				
R0 GS1	7.2 ^{b,t}	NS	NS	7.2 ^c
R0 GS2	140 ^a	0.48x	−0.002x ²	169 ^a
R1 GS1	7.4 ^b	NS	NS	7.4 ^c
R1 GS2	145 ^a	NS	NS	145 ^b
Biomass S accumulation (kg ha ^{−1})				
R0 GS1	0.8 ^c	NS	NS	
R0 GS2	10.3 ^b	NS	NS	
R1 GS1	0.8 ^c	NS	NS	
R1 GS2	13.4 ^a	−0.04x	NS	

R0 and R1 refers to removed and incorporated residue management, respectively; GS1 and GS2 refers to the first and second growth stages, respectively. NS = not significant. [†] Means within the column followed by different letters are significantly different (p -value ≤ 0.05).

4. Discussion

The results of this study showed that plants grown in plots where residue was incorporated needed lower N and P₂O₅ application rates to achieve maximum nutrient accumulation and grain yield compared with plots where the residue was removed. We verified that residue-removed plots yielded more and therefore required more N and P application from fertilizers. The incorporation of large amounts of biomass into the soil may tie up resources that might not become available for plant use. Decreased nutrient availability could lead to the observed lower yield potential in plots with residue incorporated. Furthermore, under cold spring conditions and residue presence, soils may be more saturated with water, in addition to being cooler under residue-incorporated scenarios that can limit roots' efficiency to absorb nutrients early on. Similarly, Shah et al. [32] reported that, in highly productive systems, particularly under continuous corn wherein corn stover production is high, stover removal has the potential to increase crop yields in the short term. Moreover, according to Sawyer et al. [14], stover removal in a continuous corn system provided a soil environment conducive to increased overall productivity, plant N accumulation, and NUE. Stover removal exposes the soil surface, thereby increasing early-season soil temperature [14]. This can be beneficial for early plant growth, with subsequent improved yields, especially in areas such as the upper Midwest with short and cool spring temperatures, limited growing seasons, and no-till systems [33,34]. Grain yield in 2015 was found to not be affected by residue management, corroborating the results of Linden et al. [35], who reported that residue incorporation had the same yield compared with residue removal under normal weather conditions. Contrasting results were reported by Maskina et al. [36], who reported that grain yield was found to increase as the amount of crop residue incorporation increased. Thus, large-scale field studies under the above-mentioned climatic conditions deserve further investigation to more effectively determine the effects of corn stover removal on successor corn crop development and yield.

In 2015, biomass yield, P, Ca, and S accumulation were greater in plots where residue was incorporated than where residue was removed. In contrast, a different trend was observed in this experiment for grain yield and biomass N, K, and Mg accumulation, which were greater in plants grown in plots where residue was removed compared with those where residue was incorporated. Crop response to fertilizer and residue management has been reported to be dependent on several factors, such as soil moisture and temperature interactions, plant development, N availability, and tillage system [14,34,37]. Corn stover has a greater C/N ratio compared to legume crops, which means that corn residues decompose more slowly than residue from legume crops [32]. Due to high C amounts

when residues are retained in the field, decomposing stover immobilizes soil N and makes N inaccessible to crops early in the growing season when crop N demands are high [38]. One explanation for the lower available N is because microbial populations involved in plant residue decomposition increase exponentially in response to the extra C from the corn residue, leading to higher microbial consumption of available soil inorganic N [39]. Therefore, greater amounts of soil available N early in the season in plots where residue was removed compared with where residue was incorporated could explain the greater biomass N found under removed residue management due to more vigorous early-season biomass accumulation. The application of starter fertilizer using management practices that maximize N use, such as in-furrow application, could have a significant impact on interaction between soil microbes, plants, and nutrient mineralization throughout the growing season.

The removal of crops residue has been reported to also remove nutrients from the field [32]. The quantity of N, P and K removed from field when residue is harvested has been estimated to range between 5.2–8.8, 0.6–3.1, and 7.2–20 kg Mg⁻¹ of residue removed, respectively [32,40–44]. We verified that, under removed residue management, the maximum grain nutrient accumulation order (average of three years, in kg ha⁻¹) was P (115) > N (101) > K (88) > Mg (79) > Ca (50) > S (10), while the maximum biomass nutrient accumulation order (in kg ha⁻¹) followed: N (126) > K (124) > Ca (105) > P (98) > Mg (30) > S (10). Under incorporated residue management, the maximum grain nutrient accumulation order (in kg ha⁻¹) was P (114) > N (112) > Ca (97) > Mg (84) > K (75) > S (11), whereas the maximum biomass nutrient accumulation order followed: K (120) > N (118) > Ca (84) > P (73) > Mg (25) > S (9). Based on the biomass nutrient accumulation presented above, it seems evident that stover removal enhances the rate of nutrient depletion compared to systems where only grain is removed. Therefore, to maintain optimum crop productivity, nutrients must be replaced by fertilizer application, as suggested in the present study and also by Sawyer et al. [14]. Nonetheless, our results showed that, even under an exclusive grain-producing system, proper nutrient replacement should be performed; otherwise, the continued removal of nutrients could lead to future crop nutrient deficiencies.

Although grain yield response to N and P₂O₅ application rates under different residue management varied, most of the time the highest yield or nutrient accumulation was observed when the highest N rate was applied in combination with the highest P₂O₅ rate. During the 3-year field experiment, grain yield increased 7.5% when P was applied alone (7003 kg grain ha⁻¹) and 57.9% when N was applied alone (10,285 kg grain ha⁻¹). However, when N and P were applied together grain yield increases of up to 81.1% (11,798 kg grain ha⁻¹) compared to the unfertilized control (6515 kg grain ha⁻¹) were observed. Similarly, Schlegel and Havlin [25] reported a strong positive interaction between N and P on corn grain yield over a 50-year long-term agricultural field experiment. The authors reported that grain yield increased 20% when P was applied alone and 103% when N was applied alone compared to the unfertilized control. However, the authors reported that when N and P were applied together grain yield increased 225% compared to the unfertilized control. Therefore, the higher N and P availability as a function of the applied rates probably favored root system development, supported by the evidence of greater nutrient accumulation, biomass, and corn grain yield. There are several studies reporting that N and P fertilization leads to beneficial corn development and grain yield [2,18,25,45–48]. However, N and P application must follow best management practices because overapplication can have detrimental effects on the environment [49–51].

5. Conclusions

Corn stover management significantly impacted crop response to fertilizer application. In general, fields where residue was removed were found to have high grain productivity when high rates of P₂O₅ and N were applied; in contrast, fields where residue was incorporated showed higher grain productivity rates when intermediate rates of P₂O₅ and N were applied. In general, higher amounts of nutrients tended to be removed from plots

where residue was removed than from plots where residue was incorporated, showing the potential for nutrient deficiency if nutrients are not replaced accordingly. The results of this research show that residue removal could be a management practice for the harvesting of residue for biofuel use; however, close attention should be paid to nutrient levels, other than N and P, in fields where residue is removed. An economic risk analysis should also be done to help the farmer determine whether there is a positive economic return for using this type of practice. The cost of residue tonnage and the price for fertilizer should be considered when making a decision. Similar research should be conducted in other regions of the midwestern US to assess whether the results observed in this study can be generalized to other regions, or if site-specific recommendations are needed in fields where residue might be removed and used for biofuel production. We did not observe any significant insect or disease during the different growing seasons.

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Appendix A

Summary of Analysis of Variance

Residue-Removed Section, 2013 and 2014 Data

In 2013 and 2014, grain yield in plots where residue was removed was found to respond non-linearly to N and P_2O_5 application rates, as suggested by the significant interaction between N rate and P_2O_5 rate, as well as by the significant linear and quadratic response to the N application rates (Table A1). Grain N, P, K, and S accumulation was found to respond non-linearly to N application rates consistently in 2013 and 2014 (Table A1), while grain Ca and Mg accumulation showed different responses to N application rates between the two years (Table A1). Biomass accumulation, as well as N, P, K, Ca, Mg, and S tissue accumulation changed during the course of the study, as suggested by the significant growth stage $\times$ year interaction (Table A1). In addition, biomass Ca accumulation response to the N application rate changed by growth stage, as suggested by the significant interaction N rate $\times$ growth stage (Table A1). Biomass accumulation, as well as N and S accumulation in tissue, was found to respond non-linearly to the N application rate, while Ca accumulation responded linearly to the N application rate (Table A1). Phosphorus accumulation in tissue was the only variable to show an interactive response to both N and P_2O_5 application rates (Table A1).

The effects of N and P_2O_5 rates were more evident when residue was incorporated compared with where residue was removed in 2013 and 2014 (Table A2). Grain yield, and grain N, P, and Mg accumulation, as well as N tissue accumulation, were affected by both N and P application, as suggested by the significant interaction between the N application rate $\times$ P_2O_5 application rate (Table A2). Potassium and S grain accumulation were only affected by year, while Ca grain accumulation was only affected by the N application rate (Table A2). Biomass accumulation and nutrient accumulation in tissue, for all nutrients tested were found to behave differently at each growth stage in 2013 and 2014,

as suggested by the significant growth stage $\times$ year interaction (Table A2). Phosphorus tissue accumulation was found to respond non-linearly to the N application rate, with different rates of response in each year as indicated by the significant interactions between N application rate $\times$ year as well as the quadratic N term $\times$ year (Table A2). Phosphorus accumulation in tissue also changed as a function of P_2O_5 application rate, the P taken up varied for each growth stage and year, as suggested by the significant P_2O_5 rate $\times$ growth stage $\times$ year interaction (Table A2). Calcium accumulation in tissue was linearly affected by N application rate, while S accumulation showed a non-linear response to N application rate (Table A2). Magnesium accumulation was significantly affected by P application, but the rate of response in Mg accumulation changed in each year, as suggested by the significant P_2O_5 application rate $\times$ year interaction (Table A2).

Table A1. Summary of statistical analysis for grain yield; grain N, P, K, Ca, Mg, and S accumulation; biomass accumulation; biomass N, P, K, Ca, Mg, and S accumulation under removed residue management in 2013 and 2014 as a function of year, growth stage, and N and P_2O_5 application rates.

<i>p</i> -Value	Grain Yield	N-Grain	P-Grain	K-Grain	Ca-Grain	Mg-Grain	S-Grain
Effect	<i>p</i> -value						
Year (Y)	0.822	0.038	0.939	0.001	0.773	0.001	0.001
Nrate (N)	0.021	0.001	0.002	0.030	0.011	0.027	0.003
N $\times$ Y	0.444	0.289	0.090	0.078	0.032	0.031	0.210
Nquad (Nq)	0.043	0.002	0.001	0.014	0.007	0.014	0.019
Nq $\times$ Y	0.804	0.389	0.223	0.130	0.043	0.045	0.117
Prate (P)	0.153	0.381	0.118	0.300	0.267	0.442	0.343
P $\times$ Y	0.984	0.524	0.576	0.939	0.708	0.929	0.841
Pquad (Pq)	0.251	0.758	0.360	0.513	0.527	0.572	0.621
Pq $\times$ Y	0.793	0.550	0.424	0.808	0.972	0.724	0.861
N $\times$ P	0.002	0.933	0.853	0.956	0.709	0.782	0.760
N $\times$ P $\times$ Y	0.134	0.848	0.494	0.985	0.732	0.999	0.887

<i>p</i> -value	Biomass	N-shoot	P-shoot	K-shoot	Ca-shoot	Mg-shoot	S-shoot
Effect	<i>p</i> -value						
Growth stage (GS)	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Y	0.001	0.001	0.001	0.001	0.001	0.001	0.001
GS $\times$ Y	0.001	0.001	0.001	0.001	0.001	0.001	0.001
N	0.002	0.001	0.267	0.551	0.005	0.127	0.001
N $\times$ GS	0.026	0.249	0.243	0.110	0.034	0.819	0.318
N $\times$ Y	0.741	0.483	0.781	0.193	0.887	0.468	0.550
N $\times$ GS $\times$ Y	0.736	0.498	0.907	0.240	0.321	0.791	0.939
Nq	0.020	0.050	0.287	0.382	0.084	0.444	0.033
Nq $\times$ GS	0.102	0.868	0.368	0.225	0.186	0.931	0.752
Nq $\times$ Y	0.937	0.341	0.953	0.168	0.669	0.778	0.523
Nq $\times$ GS $\times$ Y	0.828	0.790	0.958	0.441	0.337	0.823	0.912
P	0.286	0.550	0.018	0.131	0.324	0.308	0.986
P $\times$ GS	0.315	0.479	0.212	0.109	0.316	0.423	0.622
P $\times$ Y	0.862	0.606	0.406	0.394	0.833	0.702	0.925
P $\times$ GS $\times$ Y	0.926	0.980	0.769	0.076	0.912	0.960	0.851
Pq	0.476	0.678	0.027	0.173	0.341	0.582	0.883
Pq $\times$ GS	0.445	0.512	0.128	0.270	0.262	0.446	0.773
Pq $\times$ Y	0.730	0.526	0.404	0.326	0.550	0.617	0.980
Pq $\times$ GS $\times$ Y	0.951	0.820	0.965	0.068	0.779	0.946	0.798
N $\times$ P	0.146	0.413	0.001	0.078	0.060	0.054	0.356
N $\times$ P $\times$ GS $\times$ Y	0.310	0.882	0.202	0.212	0.388	0.853	0.452

Nrate and Prate, and Nquad and Pquad refers to linear and non-linear models for N and P_2O_5 , respectively. Residue-incorporated section, 2013 and 2014 data.

Table A2. Summary of statistical analysis for grain yield; grain N, P, K, Ca, Mg, and S accumulation; biomass accumulation; biomass N, P, K, Ca, Mg, and S accumulation under incorporated residue management in 2013 and 2014 as a function of year, growth stage, and N and P₂O₅ application rates.

<i>p</i> -Value	Grain Yield	N-Grain	P-Grain	K-Grain	Ca-Grain	Mg-Grain	S-Grain
Effect	<i>p</i> -value						
Year (Y)	0.001	0.551	0.272	0.001	0.315	0.001	0.001
Nrate (N)	0.012	0.044	0.551	0.339	0.004	0.099	0.617
N × Y	0.054	0.437	0.990	0.524	0.110	0.115	0.533
Nquad (Nq)	0.429	0.519	0.083	0.425	0.001	0.087	0.807
Nq × Y	0.580	0.521	0.923	0.717	0.056	0.091	0.474
Prate (P)	0.367	0.097	0.040	0.404	0.856	0.629	0.182
P × Y	0.158	0.544	0.395	0.973	0.456	0.037	0.743
Pquad (Pq)	0.791	0.301	0.022	0.862	0.800	0.602	0.343
Pq × Y	0.185	0.306	0.283	0.984	0.520	0.068	0.966
N × P	0.014	0.001	0.019	0.783	0.923	0.034	0.053
N × P × Y	0.370	0.057	0.356	0.804	0.852	0.802	0.413
<i>p</i> -value	Biomass	N-shoot	P-shoot	K-shoot	Ca-shoot	Mg-shoot	S-shoot
Effect	<i>p</i> -value						
Growth stage (GS)	0.001	0.001	0.001	0.001	0.001	0.033	0.001
Y	0.001	0.028	0.001	0.001	0.080	0.004	0.001
GS × Y	0.001	0.010	0.001	0.001	0.001	0.012	0.010
N	0.082	0.250	0.081	0.264	0.007	0.230	0.001
N × GS	0.199	0.967	0.087	0.071	0.529	0.062	0.554
N × Y	0.721	0.426	0.026	0.590	0.654	0.920	0.042
N × GS × Y	0.702	0.865	0.463	0.677	0.634	0.132	0.457
Nq	0.137	0.889	0.083	0.168	0.217	0.136	0.049
Nq × GS	0.372	0.631	0.069	0.084	0.702	0.182	0.687
Nq × Y	0.814	0.667	0.035	0.670	0.535	0.808	0.139
Nq × GS × Y	0.776	0.944	0.625	0.725	0.870	0.104	0.562
P	0.305	0.711	0.768	0.787	0.464	0.265	0.534
P × GS	0.493	0.878	0.894	0.686	0.675	0.952	0.773
P × Y	0.941	0.625	0.588	0.100	0.944	0.019	0.409
P × GS × Y	0.804	0.886	0.041	0.678	0.513	0.477	0.604
Pq	0.085	0.494	0.735	0.829	0.386	0.106	0.212
Pq × GS	0.202	0.746	0.848	0.750	0.571	0.931	0.941
Pq × Y	0.978	0.460	0.645	0.067	0.946	0.020	0.459
Pq × GS × Y	0.726	0.841	0.124	0.950	0.391	0.640	0.523
N × P	0.302	0.043	0.658	0.958	0.481	0.619	0.606
N × P × GS × Y	0.946	0.702	0.177	0.987	0.903	0.743	0.991

Nrate and Prate, and Nquad and Pquad refers to linear and non-linear models for N and P₂O₅, respectively.

Effect of Both Residue-Management Sections, 2015 Data

In 2015, residue management only had a significant effect on K and Ca grain accumulation. Significant responses to N application rate were observed for grain yield and N, P, K, Ca, and Mg grain accumulation (Table A3). In most cases, a non-linear response to the N application rate was observed, with the exception of N accumulation (Table A3). Grain yield and grain P accumulation showed a significant interactive response to the N and P₂O₅ application rates, as suggested by the significant N application rate × P₂O₅ application rate interaction (Table A3). In contrast to grain accumulation and nutrient accumulation in the grain, biomass accumulation and nutrient tissue accumulation were affected by residue management, growth stage, and the interaction between residue management × growth stage (Table A3). Nitrogen, P and S tissue accumulation were the only variables to respond to the N application rate. For N and S tissue accumulation, there was a non-linear response to the N rate, with the rate of response changed based on residue management, while P accumulation responded linearly to the N application rate (Table A3).

Table A3. Summary of statistical analysis for grain yield; grain N, P, K, Ca, Mg, and S accumulation; biomass accumulation; biomass N, P, K, Ca, Mg, and S accumulation in 2015 as a function of residue management, growth stage, and N and P₂O₅ application rates.

<i>p</i> -Value	Grain Yield	N-Grain	P-Grain	K-Grain	Ca-Grain	Mg-Grain	S-Grain
Effect	<i>p</i> -value						
Residue management (R)	0.109	0.428	0.957	0.018	0.001	0.395	0.328
Nrate (N)	0.001	0.001	0.075	0.001	0.001	0.001	0.410
N × R	0.717	0.210	0.174	0.505	0.584	0.306	0.468
Nquad (Nq)	0.001	0.281	0.013	0.001	0.001	0.001	0.798
Nq × R	0.887	0.341	0.332	0.582	0.447	0.461	0.302
Prate (P)	0.813	0.509	0.646	0.252	0.418	0.871	0.745
P × R	0.104	0.069	0.384	0.687	0.630	0.681	0.773
Pquad (Pq)	0.615	0.501	0.503	0.704	0.602	0.609	0.886
Pq × R	0.225	0.251	0.655	0.679	0.583	0.421	0.951
N × P	0.001	0.490	0.019	0.194	0.723	0.634	0.540
N × P × R	0.279	0.086	0.047	0.694	0.768	0.678	0.552
<i>p</i> -value	Biomass	N-shoot	P-shoot	K-shoot	Ca-shoot	Mg-shoot	S-shoot
Effect	<i>p</i> -value						
R	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Growth stage (GS)	0.008	0.045	0.002	0.001	0.001	0.001	0.268
R × GS	0.005	0.023	0.002	0.011	0.001	0.048	0.043
N	0.887	0.314	0.015	0.978	0.096	0.273	0.912
N × GS	0.909	0.118	0.010	0.984	0.087	0.475	0.761
N × R	0.764	0.053	0.911	0.513	0.590	0.690	0.088
N × R × GS	0.438	0.013	0.837	0.548	0.678	0.690	0.050
Nq	0.633	0.550	0.071	0.655	0.157	0.120	0.771
Nq × S	0.794	0.260	0.105	0.746	0.199	0.609	0.723
Nq × R	0.361	0.014	0.953	0.293	0.393	0.768	0.036
Nq × R × GS	0.160	0.004	0.926	0.693	0.494	0.994	0.052
Pq	0.525	0.257	0.986	0.974	0.680	0.466	0.226
P × GS	0.468	0.106	0.970	0.699	0.602	0.696	0.123
P × R	0.544	0.923	0.550	0.820	0.565	0.713	0.802
P × R × GS	0.377	0.845	0.752	0.104	0.434	0.387	0.950
Pq	0.772	0.316	0.351	0.640	0.786	0.184	0.392
Pq × GS	0.687	0.152	0.352	0.727	0.827	0.534	0.307
Pq × R	0.485	0.883	0.467	0.850	0.434	0.920	0.809
Pq × R × GS	0.294	0.843	0.542	0.058	0.252	0.472	0.770
N × P	0.948	0.311	0.063	0.605	0.795	0.324	0.491
N × P × R × GS	0.985	0.154	0.776	0.797	0.900	0.612	0.644

Nrate and Prate, and Nquad and Pquad refers to linear and non-linear models for N and P₂O₅, respectively.

Appendix B

Table A4. Biomass accumulation and biomass N, P, K, Ca, Mg, and S accumulation in 2013 and 2014 as a function of growth stages and years.

Source	Removed Residue 2013/14						
	Biomass	N-Shoot	P-Shoot	K-Shoot	Ca-Shoot	Mg-Shoot	S-Shoot
2013 GS1	2189 ^{c,†}	83 ^b	80 ^b	76 ^c	29 ^c	13.4 ^c	6.4 ^b
2013 GS2	8151 ^a	112 ^a	92 ^a	166 ^a	114 ^a	40 ^a	10.1 ^a
2014 GS1	57 ^d	3.3 ^c	11.6 ^c	15.6 ^d	16.3 ^c	13.4 ^c	0.7 ^c
2014 GS2	5510 ^b	93 ^b	85 ^{ab}	123 ^b	71 ^b	21 ^b	6.7 ^b
	Incorporated residue 2013/14						S-shoot
	Biomass	N-shoot	K-shoot	Ca-shoot	Mg-shoot		
2013 GS1	1846 ^c	71 ^b	46 ^{ab}	29 ^{bc}	8.4 ^b		5.5 ^b
2013 GS2	8329 ^a	104 ^a	59 ^a	149 ^a	13.7 ^a		10.2 ^a
2014 GS1	209 ^d	7.2 ^c	28 ^c	19 ^c	5.9 ^c		0.6 ^d
2014 GS2	3732 ^b	54 ^b	38 ^{bc}	45 ^b	12.5 ^{ab}		4.2 ^c

GS1 and GS2 refers to first and second growth stages, respectively. [†] Means within the column followed by different letters are significantly different (*p*-value ≤ 0.05).

Table A5. Biomass accumulation, biomass Ca accumulation in 2013 and 2014, and biomass P accumulation in 2015 as a function of N rates and growth stages.

Source	Removed Residue 2013/14	
	Intercept	Slope Lin
	Biomass (kg ha ⁻¹)	
GS1	1112 ^{b,†}	3.69 ^b x
GS2	4981 ^a	19.47 ^a x
	Biomass Ca accumulation (kg ha ⁻¹)	
GS1	15.9 ^b	0.06 ^b x
GS2	58 ^a	0.31 ^a x
	2015	
	Biomass P accumulation (kg ha ⁻¹)	
GS1	14.0 ^b	NS
GS2	217 ^a	−0.53x

GS1 and GS2 refers to first and second growth stages, respectively. NS = not significant. † Means within the column followed by different letters are significantly different (p -value ≤ 0.05).

Table A6. Biomass P accumulation under incorporated-residue management as a function of P₂O₅ rates, growth stages, and years (2013 and 2014).

Source	Intercept	Slope Lin
	Biomass P accumulation (kg ha ⁻¹)	
2013 GS1	58 ^{b,†}	NS
2013 GS2	76 ^a	0.12x
2014 GS1	8.4 ^c	NS
2014 GS2	67 ^a	NS

GS1 and GS2 refers to first and second growth stages, respectively. NS = not significant. † Means within the column followed by different letters are significantly different (p -value ≤ 0.05).

Table A7. Biomass accumulation and biomass P, K, Ca, Mg, and S accumulation in 2015 as a function of residue management and growth stages.

Source	2015					
	Biomass	P-Shoot	K-Shoot	Ca-Shoot	Mg-Shoot	S-Shoot
R0 GS1	396 ^{c,†}	7.2 ^c	22 ^c	10.4 ^c	9.6 ^c	0.9 ^c
R0 GS2	9188 ^b	157 ^b	57 ^a	142 ^b	40 ^a	10.9 ^b
R1 GS1	429 ^c	9.9 ^c	20 ^c	11.6 ^c	8.4 ^c	0.7 ^c
R1 GS2	9983 ^a	189 ^a	51 ^b	172 ^a	37 ^b	11.8 ^a

R0 and R1 refers to removed and incorporated residue management, respectively; GS1 and GS2 refers to first and second growth stages, respectively. † Means within the column followed by different letters are significantly different (p -value ≤ 0.05).

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