

ARTICLE

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Science-based maize stover removal can be sustainable

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Abstract

Maize (*Zea mays* L.) stover can be harvested for multiple uses or left in the field to sustain soil organic carbon (SOC), cycle essential plant nutrients, and protect soil health. This 13-yr field study quantified effects of no (0 Mg ha⁻¹ yr⁻¹), low (1.0–1.4 Mg ha⁻¹ yr⁻¹), moderate (3.5–4.0 Mg ha⁻¹ yr⁻¹), or high rates (4.7–5.4 Mg ha⁻¹ yr⁻¹) of stover harvest from either continuous maize or maize–soybean [*Glycine max* (L.) Merr.] rotation on grain yield, plant nutrient concentrations, and multiple soil properties at two sites in Iowa. Stover harvest increased plant macro- and micro-nutrient removal, but did not affect average grain yields of either crops. Soil inorganic carbon (IC), SOC, bulk density, pH, and cation exchange capacity (CEC) showed no significant differences due to stover harvest. Plant tissue and soil-test nutrient concentration effects were also minor and site-specific. Stover harvest significantly ($p < .05$) decreased exchangeable K and Ca concentrations by 8.3–23.8% and 0.3–22.5% but overall soil health indicator effects were minimal. Overall, based on crop yields, plant nutrient and soil-test concentrations, soil health indicators, and carbon sequestration estimates, maize stover harvest can be sustainable provided: (a) grain yields consistently exceed 11 Mg ha⁻¹, (b) stover removal does not exceed 40% of the aboveground biomass (i.e., 3.5–4.0 Mg ha⁻¹ yr⁻¹), and (c) plant nutrients (especially K) are closely monitored.

1 | INTRODUCTION

Maize (*Zea mays* L.) stover, the aboveground plant material left in fields after grain harvest, was identified as a sustainable U.S. biofuel feedstock in the Billion Ton Report (Perlack et al., 2005). Reasons for harvesting stover as feedstock include: (a)

its relative abundance in high-yielding agriculture fields, (b) opportunities to manage crop residue with less tillage by harvesting a sustainable portion, (c) global applicability, and (d) unlike grain, stover does not directly compete with food production. Stover biomass, however, is not a waste because it also provides: (a) animal feed and bedding, (b) protection of soils from wind and water erosion, (c) conservation of soil water by reducing evaporation losses, (d) reduced soil surface temperatures and (e) C input needed to maintain soil organic carbon (SOC) levels. To meet those multiple demands, stover harvest should only occur in site-specific areas at

Abbreviations: BD, bulk density; BETO, Bioenergy Technology Office; CRW, western corn rootworm; DOE, Department of Energy; EC, electrical conductivity; IC, inorganic carbon; SOC, soil organic carbon; SOM, soil organic matter; TC, total carbon; TN, total nitrogen; TOC, total organic carbon.

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sustainable harvest rates (Ferguson et al., 2002; Lal, 2004a, 2004b; Robert, 2002; Wilhelm et al., 2007).

Concerns regarding long-term viability and sustainability of maize stover removal were previously highlighted by Karlen, Varvel, et al. (2011). Also, a global meta-analysis by Xu et al. (2019) showed that high rates of stover removal (>75%) reduced SOC stocks by 8.7% in the 0-to-30-cm soil depth, compared to no-removal, but negative effects on SOC stocks at moderate crop residue removal rates (<50%) were minimal (1.4%). Another meta-analysis by Qin et al. (2016) reported that removing <70% of the stover did not reduce SOC stocks and furthermore, Qin et al. (2018) projected that SOC stock could actually increase with 30% stover removal if appropriate crop and soil management practices were used (e.g., cover crops and no-tillage). Others have argued that in the absence of tillage, major soil health benefits associated with plant roots are retained, regardless of aboveground biomass management (Moebius-Clune et al., 2008; Nunes et al., 2020a). This suggests that with well-designed management guidelines, harvesting maize stover may not decrease overall soil health.

In contrast to those perspectives, several published articles show that residue removal can adversely impact top-soil physical, chemical, and biological properties. For example, an extensive literature review by Blanco-Canqui and Lal (2009) showed that unmulched soils are susceptible to particle detachment, surface sealing, crusting, and compaction that can reduce water infiltration, hydraulic conductivity, and air permeability and increase runoff and transport of non-point source pollutants. Residue removal can also accelerate evaporation, increase soil temperature fluctuations, and reduce soil nutrient availability to plants by removing nutrient-rich crop residues (Cherubin et al., 2018; Shaver et al., 2002; Wilhelm et al., 2007). In addition to increasing the potential for environmental damage, excessive stover removal may also reduce crop yield (Karlen et al., 2014). Meanwhile, depending on weather and soil characteristics, leaving all maize stover in the field can lead to other management problems (e.g., N immobilization, slow emergence, too wet or cold soils, and increased slug and pathogen problems) for subsequent crops (Sindelar et al., 2013). These contrasting results highlight the need for long-term studies to better understand maize stover removal effects on soil health and crop yield.

Given the uncertainties associated with long-term stover removal on agroecosystem sustainability, we designed a field study to evaluate the impact of three maize stover removal rates on three important sustainability metrics: (a) long-term crop yield, (b) plant nutrient response, and (c) soil test changes. Our goal was to quantify inputs and outputs associated with harvesting none, low, moderate, or high rates of maize stover from continuous maize and maize–soybean [*Glycine max* (L.) Merr.] rotations that represented common practices in the U.S. Corn Belt. We hypothesized that

Core Ideas

- Thirteen-year maize stover harvest effects on crop yield, nutrients, and soil health were quantified.
- Stover harvest increased plant nutrient removal, but crop grain yields were not affected.
- There was no effect on soil organic carbon, soil inorganic carbon, pH, bulk density, or cation exchange capacity.
- If maize stover is going to be harvested, it is essential to closely monitor soil-test K.
- With good soil management, crop residue harvest can be sustainable.

high stover removal would eventually decrease yield, plant-available nutrients, and SOC.

2 | MATERIAL AND METHODS

2.1 | Location and general background

Maize stover harvest studies were initiated at the Iowa State University (ISU) Boyd (42°0'25.2" N, −93°47'38.4" W) and Bruner (42°0'3.6" N, −93°44'9.6" W) research farms during the summer of 2005. The predominant soil types were Canisteo silty clay loam (fine-loamy, mixed, superactive, calcareous, mesic Typic Endoaquoll) on 0–2% slopes at the Bruner Farm and Clarion loam (fine-loamy, mixed, superactive, mesic Typic Hapludoll) on 2–5% slopes at the Boyd Farm. Average growing season temperature (April through September) is 17.7 °C, and typical annual precipitation is 990 mm (Iowa Environmental Mesonet, 2020). The research was initiated in response to a U.S. Department of Energy (DOE) Bioenergy Technology Office (BETO) request to provide field data for validating simulation models being used for the Billion Ton Report. The treatments included harvesting none, low, moderate, or high rates of maize stover from continuous maize and maize – soybean rotations. Each plot was 12-rows (0.76 m row spacing) wide and 500 or 900 m in length (i.e., 380 and 685 m²) for Bruner and Boyd sites, respectively. A pilot project summary (Hoskinson et al., 2007) and subsequent 5-yr evaluation (Karlen et al., 2011a) as well as other multilocation, sustainable maize stover harvest assessment publications (e.g., Karlen, Birrell, et al., 2011; Karlen, Varvel, et al., 2011; Karlen et al., 2013, 2014, 2015) include some data from these research sites, but this article provides a comprehensive summary of all yield, plant nutrient, and soil-test data.

Having been requested by the DOE-BETO to initiate a field study midway through the U.S. Corn/Soybean Belt growing season, two ISU research fields that had been scheduled for “bulk” crop production in 2005 were used for this study. Therefore, in contrast to normal agronomic research protocols, baseline soil fertility was not measured a priori. Instead, soil-test samples were collected after the first stover harvest in 2005 (Hoskinson et al., 2007). Laboratory overload then delayed analyses until after plots at the Boyd site, where the 2005 rate of stover harvest was high, exhibited slow soybean growth, and failed canopy closure in 2006. This 1-yr response to stover harvest was unexpected. Further investigation revealed that ISU bulk production fields generally received low rates of fertilizer and lime with minimal soil-testing to monitor fertility levels. Based on results from the initial soil-test, post-harvest surface (0–15-cm) samples were collected every year from 2005 to 2017, except for 2006, 2008, and 2014 (both sites) and 2010 (Boyd site), for routine soil-test analysis at both sites (Supplemental Table S1). Soil samples were also collected for the 0-to-15-, 15-to-30-, 30-to-60-, 60-to-90-, and 90-to-120-cm depth increments in 2007 and 2017 to quantify nutrient responses throughout the entire soil profile (Supplemental Table S1).

We planned to compare stover harvest effects for a maize–soybean (Boyd) rotation and continuous maize (Bruner), since those systems were being modeled for Iowa in the Billion Ton Report. However, our plan had to be changed in 2014 following a severe western corn rootworm (*Diabrotica virgifera virgifera*) (CRW) infestation at the Bruner site in 2013 (Supplemental Figure S1). After 10 consecutive years of maize production, the crop was essentially dead within 1 wk. In response, a 3-yr, soybean–maize–maize rotation was implemented at the Bruner site in 2014 (Supplemental Table S2).

2.2 | Grain and stover harvest

Plots were harvested with commercial-scale John Deere¹ combines that were modified for single-pass grain and stover harvest (Birrell et al., 2014). Grain was separated and transported to the seed tank where it passed through a paddle sensor calibrated to estimate yield as the combine moved through the field. Stover passed through the combine but rather than being discharged on the ground, it was dropped into a chopper/blower system that blew the residue into a trailing wagon equipped with load cells. At the end of each 380- or 685-m² plot stover weight was recorded and grain was transferred to a weigh-wagon to determine the exact weight for each plot. Grain and stover subsamples were collected to deter-

mine grain moisture using an electronic moisture meter and stover water content by drying in a forced-air oven at 70 °C until they reached a constant weight. Stover subsamples were ground to pass a 2-mm screen using a Wiley¹ Mill. Grain and 2-mm stover subsamples were ground to pass a 0.5-mm screen using a Udy¹ Mill. Carbon and N concentrations were determined by dry combustion using a Carlo-Erba¹ NA1500 NCS elemental analyzer (Haake Buchler Instruments). A second portion of the 0.5-mm grain and stover samples was sent to a commercial laboratory where P, K, Ca, Mg, S, Na, Al, B, Cu, Fe, Mn, and Zn concentrations were determined. Nutrient removal was calculated by multiplying stover and grain yields by the nutrient concentrations.

During the 13 yr, there were subtle changes in equipment and harvest protocols, but overall, removal rates were consistently classified as: (a) no removal (none – 0 Mg ha⁻¹ yr⁻¹), (b) low removal (~15% – 1.0–1.4 Mg ha⁻¹ yr⁻¹), (c) moderate removal (~40% – 3.5–4.0 Mg ha⁻¹ yr⁻¹), and (d) high removal (~60–70% – 4.7–5.4 Mg ha⁻¹ yr⁻¹) of aboveground biomass remaining following grain harvest. No crop residue was removed following soybean.

2.3 | Plant tissue nutrient concentrations

To monitor nutritional status of the crops and effects of the fertilization practices being used (Supplemental Tables S2 and S3), maize tissue samples were collected at Growth Stage V6 (Ritchie et al., 1996) and during early grain fill (Growth Stage R2) as frequently as possible. Soybean was also monitored by collecting petiole (leaves) samples during flowering. Ten plant tissue samples from each plot were dried in a forced-air oven at 70 °C, ground to pass a 0.5-mm screen, and submitted to a commercial laboratory for total C, N, P, K, Ca, Mg, S, Al, B, Cu, Fe, Mn, and Zn analyses.

2.4 | Surface soil sampling and analyses

For surface (0-to-15-cm) soil testing, six 3.2-cm diam. soil cores were collected randomly from each plot following grain and stover harvest operations (Supplemental Table S1). Cores were composited, weighed, and mixed by hand, before taking a 100-g subsample, drying it at 104 °C, and determining soil water content (Topp & Ferre, 2002). Field-moist weight of the composited cores was adjusted to a dry weight and divided by the volume represented to estimate bulk density (BD) of the surface layer. The remaining field-moist soil was passed through an 8-mm screen, air-dried, and then crushed to pass a 2-mm screen.

Samples in 2005 and 2007 were analyzed at the National Soil Tilth Laboratory (NSTL) now known as the National Laboratory for Agriculture and the Environment (NLAE).

¹ Mention of a trade mark or proprietary product is for information only and does not imply any endorsement of that product to the exclusion of another by the USDA-ARS, DOE, or Iowa State University (ISU).

Soil pH and electrical conductivity (EC) were measured on a subsample using a 1:1 soil/water ratio. Another subsample was extracted using Mehlich III solution and analyzed using an inductively coupled plasma-atomic emission spectroscopy (ICP-AES) to determine P, K, Ca, and Mg concentrations. A third subsample was extracted with diethylene-triamine-pentaacetic acid (DTPA) and analyzed for extractable Cu, Fe, Mn, and Zn. A fourth subsample was pulverized before analyzing for total carbon (TC) and total nitrogen (TN) using dry combustion. For samples with pH values >7.3 , inorganic carbon (IC) was also determined as outlined by Wagner et al. (1998). Total organic carbon (TOC) values were calculated by subtracting IC from TC values.

For 2009 and thereafter, composited soil cores were passed through an 8-mm screen, air dried, and crushed to pass a 2-mm screen before submitting to a commercial soil-test laboratory for analysis. Soil pH, EC, and micronutrients were measured using the same procedures, but P concentrations were measured using a Bray-1 extract, while cations (K, Ca, and Mg) were measured after extracting a subsample with 1 M ammonium-acetate (NH_4OAc) at pH 7.0. The mentioned soil attributes were determined following the methods described by Nathan and Gelderman (2012). Throughout the study, soil-test results were used to guide P and K fertilizer and lime rates (Supplemental Tables S2 and S3) based on ISU guidelines (Mallarino et al., 2013). All N fertilizer applications were made using anhydrous ammonia (NH_3) or urea-ammonium nitrate (UAN) solution as selected by the ISU farm managers.

2.5 | Profile soil sampling and analyses

In 2007 and 2017, four 5-cm diam. cores were collected randomly from each plot to a depth of 1.2 m using a Giddings¹ hydraulic probe. Cores were separated into five segments: 0–15, 15–30, 30–60, 60–90, and 90–120 cm. Each segment was weighed, and a subsample was taken to determine soil water content by drying for 48 h at 105 °C. The remainder of each segment was mixed, passed through an 8-mm screen, air-dried, and crushed to pass a 2-mm screen. Core samples were analyzed as described for the surface samples (Nathan & Gelderman, 2012).

2.6 | Statistical analyses

All data for grain and stover yield, soil-test parameters, and plant tissue nutrient concentrations were analyzed separately for the two sites. Using R (R Core Team, 2020), an ANOVA was constructed for each variable to evaluate year and harvest rate effects. Year, stover removal rate, and year vs. stover removal rate interaction were considered as factors within the ANOVA. A Shapiro–Wilk normality test (p values $> .05$

means that at 5% of significance, linear model residuals can be considered normal) was used to assess significance. Tabled means followed by the same letter within a specific treatment factor column (e.g., Year and Harvest Rate) are not significantly different ($\alpha = .05$) based on Tukey's test. Furthermore, to compare overall treatment effects (low, moderate, and high) across both sites, data were visualized using an effect size – calculated as percent change from the control or the “none” treatment (i.e., 100% stover remaining). Sigma Plot (v14.0) was used for visualizing the data.

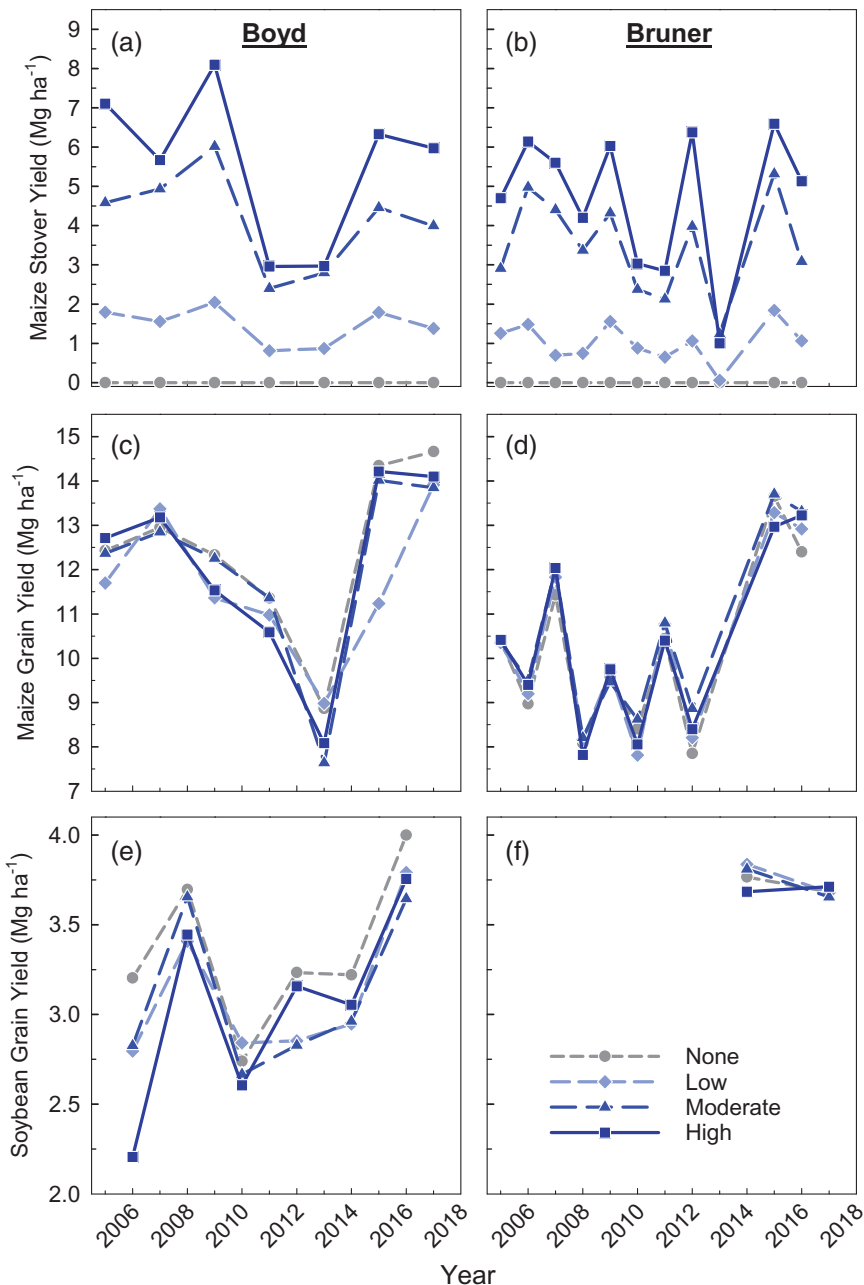
3 | RESULTS AND DISCUSSION

3.1 | Stover yield and nutrient removal

Stover yield showed significant differences among years (Figure 1, Supplemental Table S4) and as expected among harvest rates at both sites (Table 1, Supplemental Table S4). For the low, moderate, and high stover removal rates, the average stover yields over 13 yr were, respectively, 1.0, 3.5, and 4.7 $\text{Mg ha}^{-1} \text{yr}^{-1}$ at the Bruner site; and 1.4, 4.0, and 5.4 $\text{Mg ha}^{-1} \text{yr}^{-1}$ at the Boyd site (Table 1). Recognizing that stover has multiple functions (e.g., mitigating erosion, maintaining soil organic matter, and as a bioenergy/bio-product feedstock), an important question associated with its harvest is how much will plant nutrient export increase when compared to grain-only harvest? To answer that question, nutrient concentrations in stover and grain were measured each year (Figure 2, Supplemental Tables S5 and S6). There were significant differences among years, independent of site and element, but overall, mean concentrations were within expected ranges (Mengel & Kirkby, 2001) and similar to those reported by Karlen et al. (2015). Year-to-year differences were reviewed to guide annual fertilizer applications (Supplemental Tables S2 and S3), but our primary interest was in assessing main and/or interactive effects associated with stover removal. Our rationale was that although plant nutrient concentrations are influenced by fertilization and thus soil nutrient bioavailability, seasonal differences within well-managed production systems primarily reflect weather conditions (Mengel & Kirkby, 2001). Therefore, as expected, nutrient concentrations at these sites were similar to those reported by Rivas-Ubach et al. (2012) and Weih et al. (2016). Among stover harvest rates, plant nutrient concentrations in stover from high and moderate harvest treatments were slightly higher (Figure 2, Supplemental Table S5), presumably because more of the residue was from lower plant parts from which nutrients at the time of harvest had not been translocated or leached as previously discussed (Hoskinson et al., 2007; Karlen et al., 2015).

The three stover harvest rates at the Bruner site increased N, P, K, and S removal [6, 21, or 29 kg ha^{-1} ; 0.6, 2.1, or

FIGURE 1 Effect of maize stover removal rate on (a, b) total stover export, (c, d) maize grain yields, and (e, f) soybean grain yields from 2006 to 2017 at Boyd and Bruner sites



2.8 kg ha⁻¹; 8, 25, 34 kg ha⁻¹; and 0.4, 1.4, or 1.9 kg ha⁻¹] compared to grain-only harvest, which removed an average of 122, 23, 34, and 8 kg ha⁻¹, respectively. At the Boyd site, stover harvest also increased N, P, K, and S removal [8, 23, or 31 kg ha⁻¹; 0.5, 1.6, or 2.2 kg ha⁻¹; 9, 25, 34 kg ha⁻¹; and 0.4, 1.2, or 1.6 kg ha⁻¹] compared to grain-only harvest which averaged 144, 26, 40, and 10 kg ha⁻¹, respectively. For both sites, increased K removal (25–34 kg ha⁻¹) was the most notable plant nutrient management concern, especially since stover harvest doubled K removal compared to harvesting only the grains. These results emphasize the importance of managing K in areas where corn stover is removed.

3.2 | Grain yield

There was no significant interaction between stover harvest rate and year (Supplemental Table S4) and overall, long-term stover removal did not affect grain yield (Table 1, Supplemental Table S4). Yields did vary over time (Figure 1, Supplemental Table S4) due to weather, hybrid, and pest outbreaks. Across both sites maize yields ranged from 7.6 to 14.6 Mg ha⁻¹, while soybean yields ranged from 2.2 to 4.0 Mg ha⁻¹ (Supplemental Table S7). Studies at the Bruner site confirmed the importance of crop rotation. Maize was grown continuously at that site from the 1990s through 2002. It was planted to soybean in 2003 and returned to

TABLE 1 Overall average maize, soybean, and stover yield for the none, low, moderate, and high maize stover removal rates at the Bruner and Boyd research sites

		Yield		
Site	Removal rate	Maize	Soybean	Stover
Mg ha ⁻¹				
Bruner	None	10.11b ^a	3.73a	–
	Low	10.21ab	3.76a	1.03c
	Moderate	10.56a	3.74a	3.46b
	High	10.24ab	3.70a	4.71a
Boyd	None	12.40a	3.42a	–
	Low	11.62a	3.17a	1.37c
	Moderate	12.03a	3.16a	4.03b
	High	12.04a	3.11a	5.40a

^aMeans followed by the same letter within a column and for each site are not significant different ($\alpha = .05$) based on a Tukey's test.

maize in 2004 with the intention to monocrop for at least 10 yr. Annual fertilizer application was closely monitored and rates were increased from 2005 through 2012 (Supplemental Table S2), but average maize grain yield (9.53 Mg ha⁻¹) was only 87% of the National Agricultural Statistics Service (NASS) Boone County Iowa average (10.9 Mg ha⁻¹) for those years (<https://quickstats.nass.usda.gov>). In 2013, early-season maize growth was excellent (Supplemental Figure S1a) but 1 wk later, as the crop began to grow rapidly from V8 to VT (Richie et al., 1996) it nearly dies (Supplemental Figure S1b) due to a severe infestation of CRW. Extensive root pruning (Supplemental Figure S1c) prevented the crop from assimilating soil water and nutrients fast enough to meet physiological the exponential growth and development phase.

In response to the CRW infestation in 2013, soybean was grown at the Bruner site in 2014 to begin a 3-yr, soybean–maize–maize rotation. Soybean yields in 2014 and 2017 were high (Figure 1, Supplemental Table S4) with no significant difference in response to past stover harvest treatments (Supplemental Table S8). Maize yield following soybean then increased by almost 50% (8.8 vs. 13.1 Mg ha⁻¹) in 2015 and 2016 compared to yields for 2005–2012 (Figure 1). This suggests that although the evidence is circumstantial, CRW was likely limiting Bruner maize yields for several years prior to the 2013 crop failure.

At the Boyd site, there were also significant seasonal differences for both crops, but yields associated with the various stover harvest rates showed few significant seasonal differences (Supplemental Table S9) and no overall significant effect (Figure 1). Consistent with the grain yield increases at the Bruner site in 2015 and 2016, maize yield at the Boyd site (Figure 1, Supplemental Table S9) with the DeKalb DKC 54-38RIB hybrid (Supplemental Table S3) was also much greater when averaged for 2015 and 2017 (13.6 Mg ha⁻¹) than the average for hybrids grown at the site between 2005 and 2013 (11.3 Mg ha⁻¹).

Cumulative annual stover harvest had little effect on maize or soybean grain yields (Figure 1, Supplemental Table S4), although at the Bruner site, moderate removal did increase grain yield 4.5% compared to no removal (Table 1). Those results are consistent with Karlen et al. (2011a) who reported lower non-removal maize yield (11.4 Mg ha⁻¹) in 2007 compared to either moderate or high stover removal rates (12.0 Mg ha⁻¹). One reason that moderate stover removal rates can increase grain yield is due to slower soil warming in spring for mulched soils (no stover removed), which can impair germination and early root growth (Swan et al., 1994). Furthermore, the slight increase in average grain yield when stover was harvested suggests producers may want to consider moderate removal to help overcome stover management problems and costs associated with aggressive tillage practices to incorporate nongrain material.

Another recent Iowa study, with similar climate (same average mean annual temperature and precipitation) and soil (Mollisol) conditions, showed that grain yield response to maize stover removal was dependent on tillage system (O'Brien et al., 2020). Similar to our study, they found that for conventional tillage systems, stover removal increased yield compared to a no removal treatment from 2010 to 2012, while for no-till systems, removing maize stover increased yields only in the wettest year (O'Brien et al., 2020). Overall, those results suggest moderate stover harvest will likely have a neutral or even positive effect for this midwestern U.S. area, and is consistent with several prior studies conducted under similar climate soil conditions (Birrell et al., 2014; Karlen et al., 2014).

3.3 | Annual plant tissue nutrient monitoring

Stover harvest effects on plant nutrition were assessed by analyzing V6 (whole plant) and R2 (ear leaf) tissue

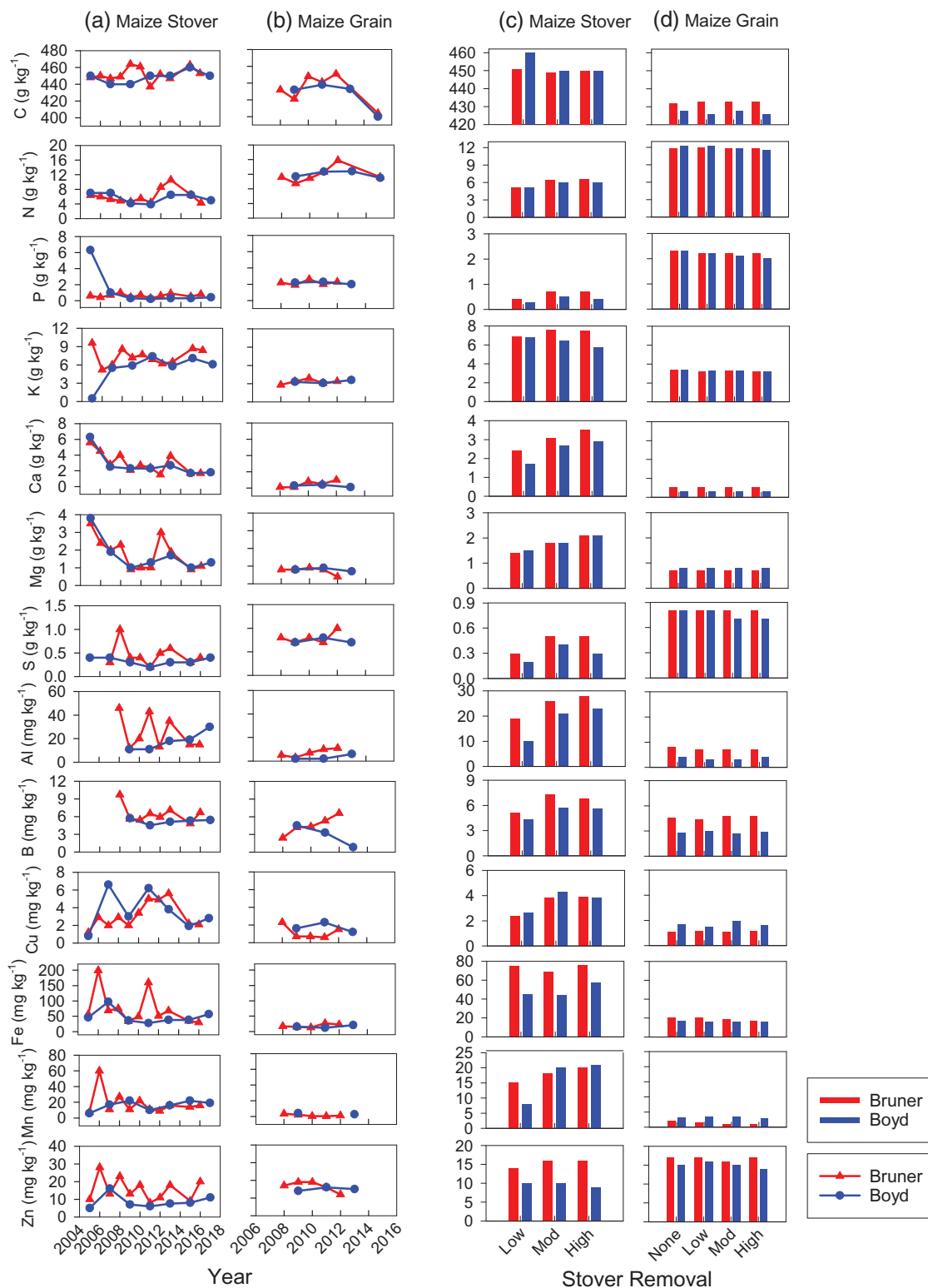


FIGURE 2 Element concentration within (a and c) maize stover and (b and d) maize grain as affected by year and stover removal rate at the Bruner and Boyd research sites. (Tukey comparison is presented in Supplemental Tables S5 and S6)

samples (Ritchie et al., 1996) throughout the 13-yr study. At both growth stages there were seasonal differences, presumably reflecting differences in hybrid, fertilization practices, and weather patterns (Supplemental Tables S2 and

S3). Overall, there were no significant effects on V6 nutrient concentrations at either site (Figure 3, Supplemental Table S7) due to stover harvest. At the Bruner site, ear leaf analysis showed significant K and Ca responses to

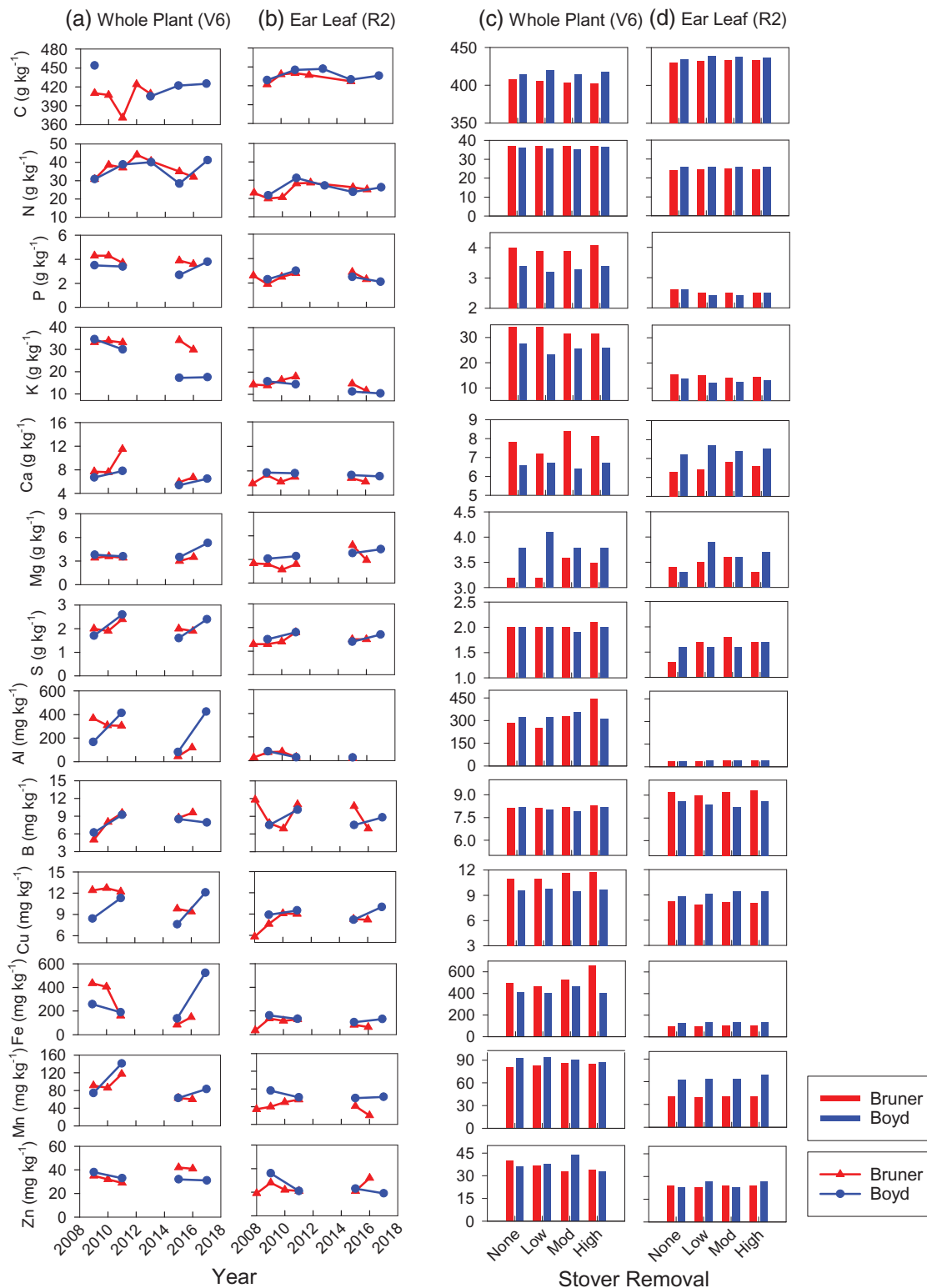


FIGURE 3 Element concentration within (a and c) maize whole plant and (b and d) ear leaf as affected by year and stover removal rate at the Bruner and Boyd research sites. (Tukey comparison is presented in Supplemental Tables S7 and S10)

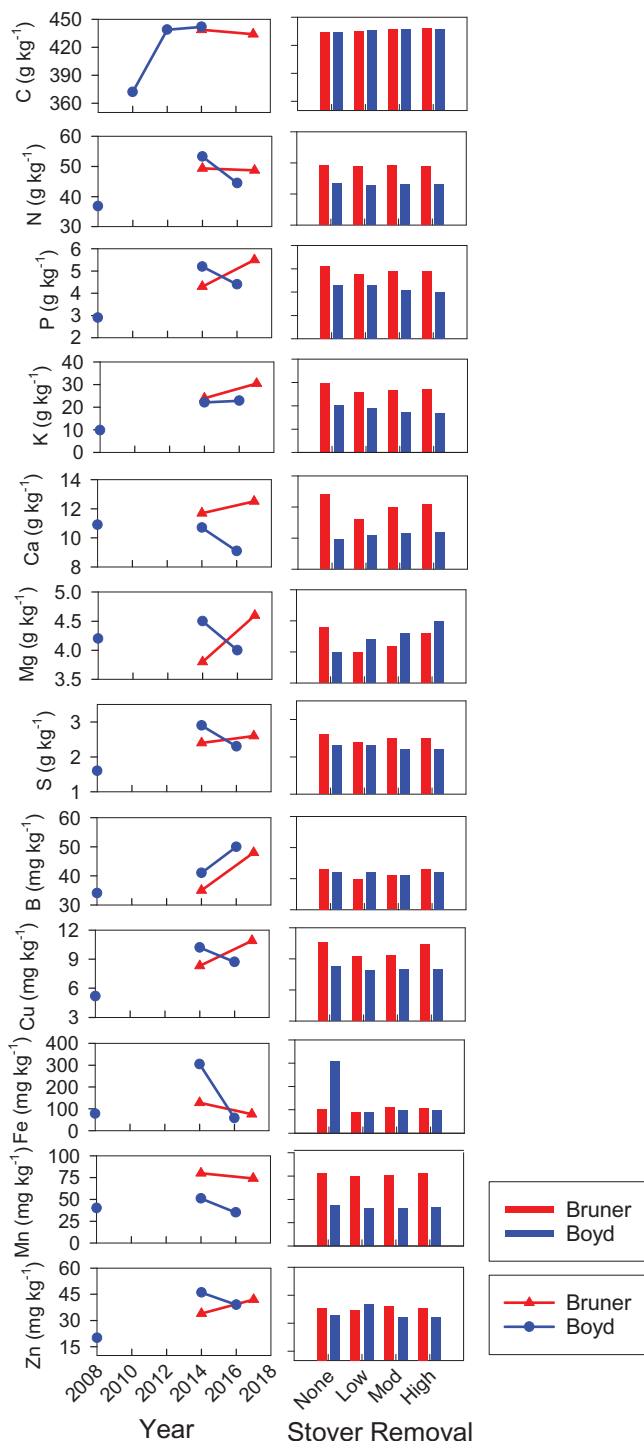


FIGURE 4 Element concentration within soybean petioles as affected by year and stover removal rate at the Bruner and Boyd research sites. (Tukey comparison is presented in Supplemental Table S11)

increasing rates of stover harvest, but not at the Boyd site (Figure 3, Supplemental Table S7) where stover was harvested every other year. Soybean petiole (leaf) samples at both sites showed 6.6–17% lower K concentrations with stover removal than without removal (Figure 4, Supple-

mental Table S11). The important conclusion from these plant tissue analyses is that if stover harvest is to be implemented for any use (i.e., animal feed, bedding, compost filler, bioenergy), K is the nutrient for which greater attention will likely be needed.

3.4 | Annual surface soil monitoring (0–15 cm)

Surface (0-to-15-cm) soil samples were collected and analyzed annually (Supplemental Table S1) to monitor fertilizer effectiveness throughout the 13-yr study (Supplemental Tables S2 and S3). The year vs. harvest rate interactions were not significant at either site (Supplemental Table S12). Independent of site and soil health indicator, there were significant year effects, but stover harvest rate effects were significant only for exchangeable Ca at the Boyd site and for K at both sites (Supplemental Table S12 and S13).

Significant seasonal differences (Figure 5) reflect several factors including fertilization rates (Supplemental Tables S2 and S3), weather patterns, and crop yield prior to sampling. Higher stover removal rates decreased topsoil exchangeable K and Ca concentrations compared to non-removal plots (Figure 5). This was consistent with reports by Karlen et al. (2011a) and the relatively low K soil-test values and ratings within ISU guidelines (Mallarino et al., 2013). The results are also consistent with those presented by Obrycki et al. (2018a) which showed 64% of the soil samples from 10 research sites had soil-test levels below 120 mg kg^{-1} , the threshold indicating a very low nutrient status for Iowa crop production. Coupled with plant tissue results, these soil-test findings emphasize that if maize stover is to be harvested for any use, producers should use routine soil-testing and plant analysis. Although often overlooked, attention to K should be given, even for these highly productive midwestern U.S. Mollisols (Typic Hapludolls and Typic Endoaquolls). Finally, the surface soil-test results, independent of stover harvest rate, show that Bray-1 P significantly decreased over time at the Boyd site (Figure 5a), perhaps reflecting slow but steady soil erosion at that site.

Potential negative effects of crop residue harvest on soil nutrient dynamics and availability are well documented (Khanal et al., 2014; Adler et al., 2015; Cherubin et al., 2018), but this study confirms the impact is dependent on harvest rate and overall soil nutrient supply (Khanal et al., 2014; Karlen et al., 2015). We suggest effects of maize stover harvest were not significant for most nutrients because the quantity removed in the grain (e.g., P, N, S) is much greater than within the residue (Figure 2). In contrast, crop residues generally have higher K content (Figure 2), so residue management has greater influence on soil K levels (Figure 5). For moderate to high maize stover harvest rates, K removal was twice

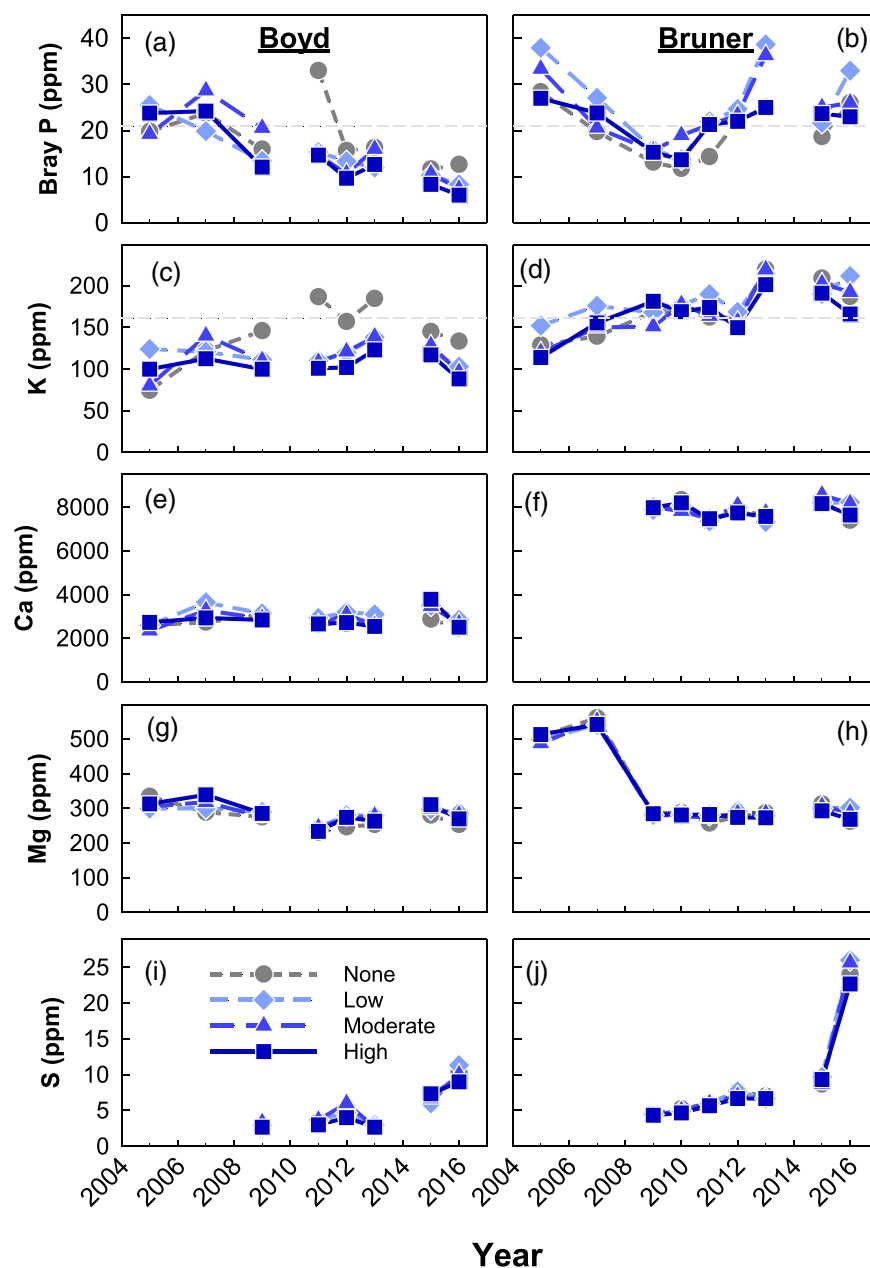


FIGURE 5 Plant-available nutrients at 0-to-15-cm soil depth from 2003 to 2016 as affected by maize stover removal rates at Boyd and Bruner sites. Horizontal lines represent (a, b) Bray-1 P and (c, d) K optimum concentration levels for plant growth

the amount removed by grain (Supplemental Tables S5 and S6). This type of response was also documented by Karlen et al. (2015), who showed maize residues contained 73% of the total K extracted and that residue harvest could export as much as 62 kg ha⁻¹ (Karlen et al., 2014).

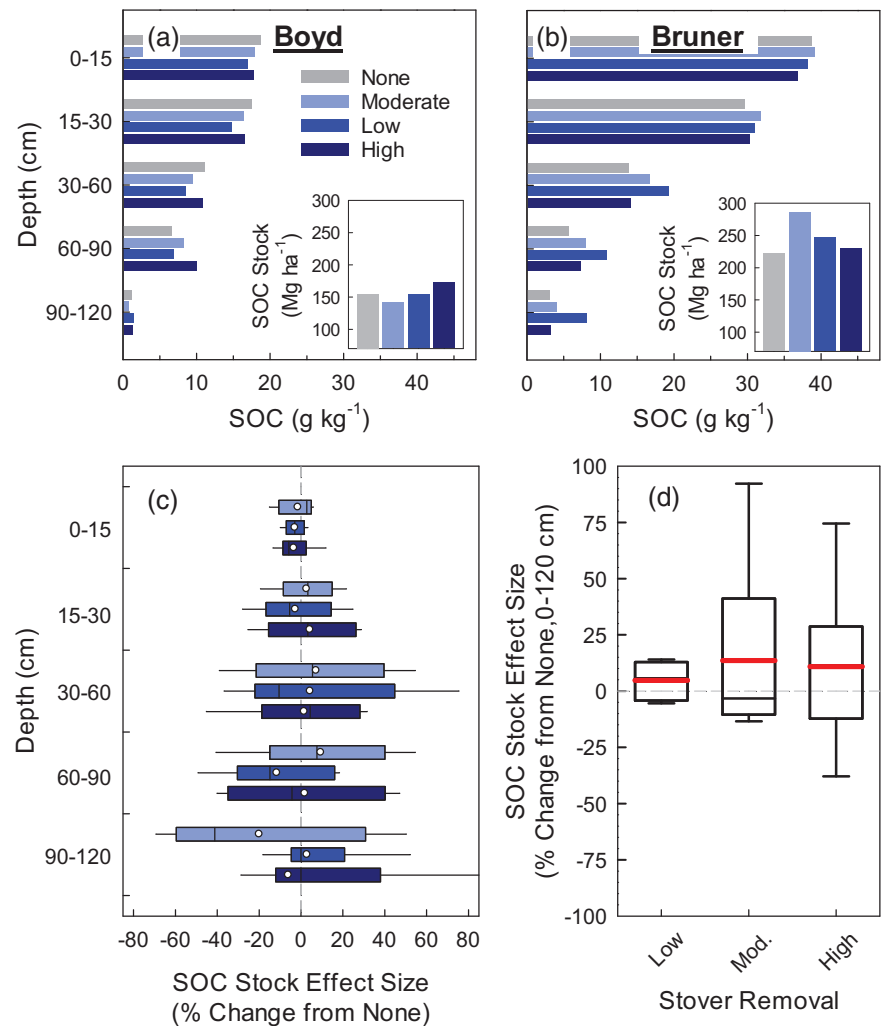
3.5 | Soil profile (0–120 cm) effects of stover harvest

Thirteen years of maize stover harvest did not significantly affect SOC concentration and/or stocks at either site (Figure 6a and 6b), across all removal rates and at each soil depth. The cross-site effect size (percentage change) of stover removal was highly variable, especially with depth (Figure 6).

Mean effect size (change) ranged from –20 to +9% differences across all depths. When calculated for the entire soil profile, SOC changes were also highly variable, ranging from –5 to +14%, –13 to +92%, and –38 to +75% for low, moderate, and high rates of stover removal, respectively. Those results are important because of the well-established relationship between total organic C and overall soil health (Johnson et al., 2014; Karlen et al., 2019; Nunes et al., 2020b; Sanderman et al., 2017; Xu et al., 2019).

According to several meta-analyses, effects of maize stover removal on SOC is site-specific and depends on removal rate. For example, Nunes et al. (2020a) found that compared to retaining 100% crop residues within an agroecosystem, removing moderate rates (35–65%) did not measurably affect SOC concentration within the top 15-cm soil depth. A global

FIGURE 6 Effect of maize stover removal rate on soil organic carbon (SOC) concentrations and stocks by 2017 – 13 yr after treatments were initiated. Individual C concentrations and SOC stock (0–120 cm) at (a) Boyd and (b) Bruner sites. Cross-site effect sizes (% change) shown for (c) C stocks by depth and (d) total soil profile stock changes (d)



meta-analysis by Xu et al. (2019) also showed negative effects of moderate crop residue removal on SOC stocks were minimal (1.4%). Similarly, Qin et al. (2016) reported another meta-analysis that showed stover removal did not reduce SOC stocks and even suggested that for some conditions SOC stocks could be increased (15–23%) if stover removal rate was <70%. Furthermore, Moebius-Clune et al. (2008) showed that major SOC benefits associated with roots remain, regardless of aboveground biomass management. Collectively, those results confirm that low-to-moderate stover removal rates can be sustainable with respect to SOC – at least at low-to-moderate removal rates.

Soil pH, CEC, macro-, and micro-nutrient concentrations throughout the soil profile were not significantly affected by up to 13 yr of maize stover removal (Figure 7, Supplemental Tables S14 and S15). High spatial variability and anticipated slow changes in these soil properties undoubtedly contributed to the lack of treatment differences, even though Hoskinson et al. (2007) confirmed stover harvest can decrease soil nutrient concentrations. For this long-term study, however, soil testing and plant analyses were used to ensure nutrient

removal by grain and/or stover was compensated for by applying fertilizers (Supplemental Tables S2 and S3).

Overall, stover removal tended to have a small effect on soil health due to relatively high SOM content at both sites (Figure 6) and annual periods of cold weather that decrease SOM mineralization compared to studies in more southern latitudes (Blanco-Canqui et al., 2009) or tropical weather and soil conditions (Cherubin et al., 2018). The one exception was for K (Supplemental Table S13), which after 13 yr of stover removal decreased within the 15-to-30-, 30-to-60-, and 60-to-90-cm depth increments at the Bruner site, and within the 0-to-15-cm increment at the Boyd site (Figure 7, Supplemental Tables S13 and S14). The significant effect of the maize stover harvesting rates for Ca at the Boyd site compared to Bruner site can also be related to the differences in SOC stocks between them (Figure 5).

The crop roots left in the soil together with a higher proportion of lower plant parts also contributed for the low impact of maize stover harvesting at low and/or moderate rates on overall soil health and plant nutrition indicators (Figures 2–7). Previous studies have also shown that major soil health

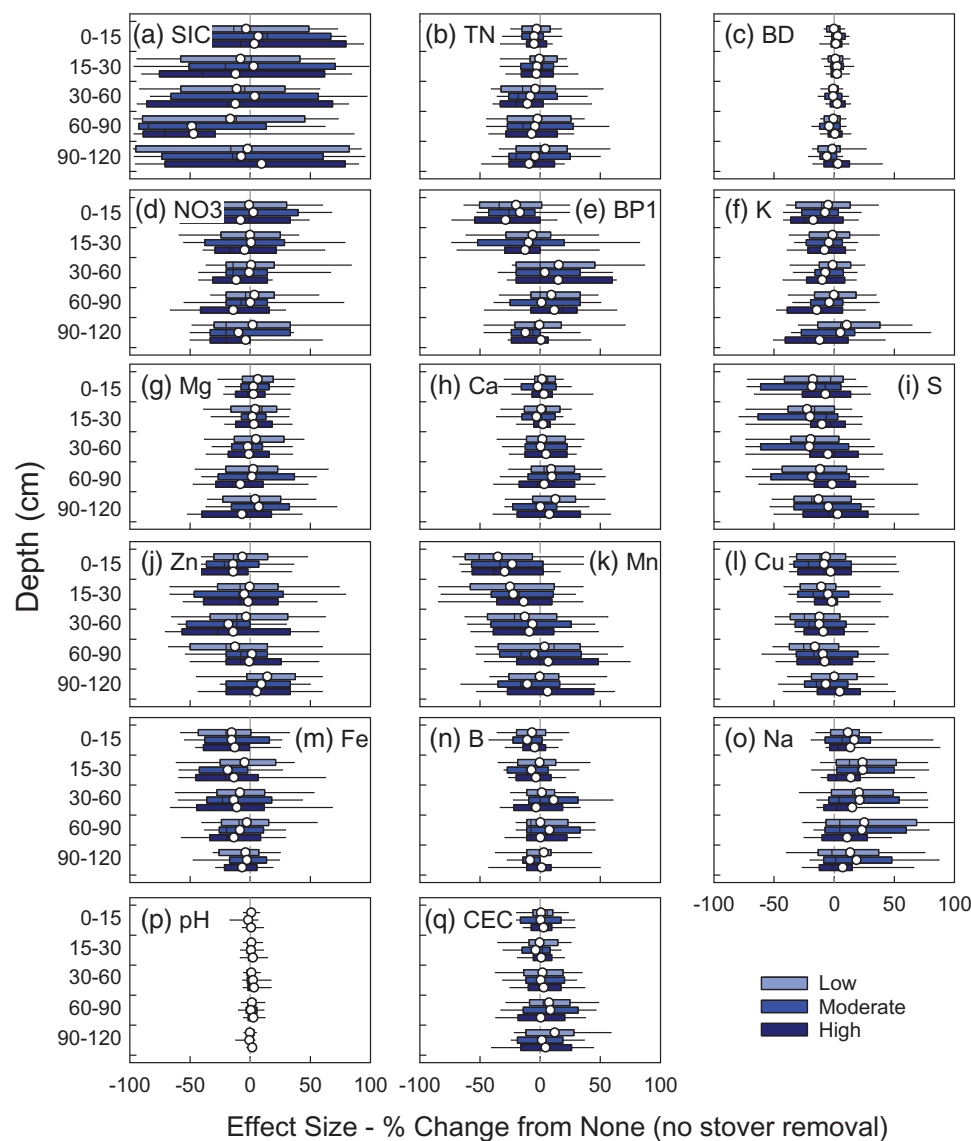


FIGURE 7 Cross-sties effect size of maize stover removal rate by 2017 (13 yr after treatments were initiated) on (a) soil inorganic-C, (b) total-N, (c) bulk density, (d) nitrate, (e) Bray-1 P, (f) exchangeable K, (g) Mg, (h) Ca, (i) sulfur, (j) Zn, (k) Mn, (l) Cu, (m) Fe, (n) B, (o) Na, (p) soil pH, and (q) cations exchange capacity within the 0 to 120 cm

benefits associated with roots remain, regardless of above-ground biomass management (e.g., Moebius-Clune et al., 2008). Root growth is well known for improving soil health due to its effect on soil structure (Stumpf et al., 2014; Lucas et al., 2019). During soil exploration, roots push through the soil and alter not only physical but several chemical and biological properties in their vicinity, rhizosphere (Hinsinger et al., 2009). Positive effect can persist after roots are degraded, leaving behind a dense system of connected pores system. This contributes to a healthier soil because of soil organic matter input by plant roots (e.g., tissue and exudates). The importance of roots for soil C sequestration is further emphasized by the fact that they have a high potential to be stabilized in soil. For example, Rasse et al (2005) showed that root C has 2.4 times longer residence time in soil

than shoot C. Therefore, our results confirm that with a diversified cropping system and reduced tillage practices (Nunes et al., 2018), root system can help mitigate potential detrimental effects of stover harvest on soil quality/health.

Finally, although cumulative effects of stover removal were not statistically significant on soil properties through time or with depth, we recognize long-term excessive stover removal can lead to soil erosion and nutrient losses. Those losses occur when levels of surface residue are insufficient to protect surface soils from raindrop impact and horizontal movement (Li et al., 2018). Such indirect soil erosion impacts can also lead to losses in soil function and greater nutrient applications to compensate for erosion losses (Fenton et al., 2005). Insidious soil erosion (Figure 8) coupled with multiple years of full-width tillage (Supplemental Table S3) and lack of winter



FIGURE 8 Excessive crop residue harvest negatively affects soil health by exposing the soil surface to wind and water forces contributing to insidious to severe soil erosion and reducing input of carbon needed to sustain soil organic matter and support biological activity

cover crops all contribute as confounding factors to the loss of SOM and nutrients.

4 | CONCLUSIONS

This 13-yr field study of stover harvest from continuous maize and maize–soybean rotations at two central Iowa locations provides evidence that crop residue removal for bioenergy feedstock, or any other use, can be sustainable if appropriate soil and crop management practices are used. Our recommendations for sustainable maize stover harvest are that (a) grain yields should consistently exceed 12 Mg ha^{-1} and (b) stover removal should not exceed 25–40% of the aboveground biomass. Those guidelines are for full-width chisel plow and field cultivator tillage in the absence of winter cover crops, and are consistent with our prior recommendations (e.g., Karlen et al., 2014). If no-tillage, extended crop rotations, and/or cover crops are used as part of the long-term farming practices and grain yields average at least 11 Mg ha^{-1} , 25–40% removal rates will likely be sustainable (Obrycki et al., 2018b). Finally, whenever maize stover is going to be harvested, it is essential that K be monitored more closely than for grain-only harvest.

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AUTHOR CONTRIBUTIONS

Marcio R. Nunes: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Resources; Writing-original draft. Mriganka De: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Resources; Writing-review & editing. Marshall McDaniel: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Resources; Writing-review & editing.

John Kovar: Conceptualization; Funding acquisition; Investigation; Methodology; Resources; Writing-review & editing. Stuart Birrell: Conceptualization; Funding acquisition; Investigation; Methodology; Resources; Writing-review & editing. Douglas L. Karlen: Conceptualization; Funding acquisition; Investigation; Methodology; Resources; Writing-review & editing.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

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SUPPORTING INFORMATION

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