

The broad impacts of corn stover and wheat straw removal for biofuel production on crop productivity, soil health and greenhouse gas emissions: A review

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Abstract

Biofuel production from crop residues is widely recognized as an essential component of developing a bioeconomy, but the removal of crop residues still raises many questions about the sustainability of the cropping system. Therefore, this study reviews the sustainability effects of crop residues removal for biofuel production in terms of crop production, soil health and greenhouse gas emissions. Most studies found little evidence that residue management had long-term impacts on grain yield unless the available water is limited. In years when water was not limiting, corn and wheat removal rates $\geq 90\%$ produced similar or greater grain yield than no removal in most studies. Conversely, when water was limiting, corn grain yield decreased up to 21% with stover removal $\geq 90\%$ in some studies. Changes in soil organic fractions and nutrients depended largely on the amount of residue returned, soil depth and texture, slope and tillage. Reductions in organic fractions occurred primarily with complete stover removal, in the top 15–30 cm in fine-textured soils. Soil erosion, water runoff and leaching of nutrients such as total nitrogen (N) and extractable soil potassium decreased when no more than 30% of crop residues were removed. Stover management effects on soil bulk density varied considerably depending on soil layer, and residue and tillage management, with removal rates of less than 50% helping to maintain the soil aggregate stability. Reductions in CO₂ and N₂O fluxes typically occurred following complete residue removal. The use of wheat straw typically increased CH₄ emissions, and above or equal to 8 Mg/ha wheat straw led to the largest CO₂ and N₂O emissions, regardless of N rates. Before using crop residues for biofuel production, it should therefore always be checked whether neutral to positive sustainability effects can be maintained under the site-specific conditions.

KEYWORDS

bioeconomy, bioenergy, climate change adaptation, crop productivity, crop residues, ecosystem service, environmental sustainability, greenhouse gas mitigation, nutrient cycling, soil health

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1 | INTRODUCTION

Over the last decade, economic and environmental concerns have spurred increased interest in the use of crop residues as a renewable source of energy (Barros et al., 2020; Sharma et al., 2020). Although many crops are good candidates for biofuels (Battaglia, Fike, et al., 2019; Kumar, Lai, Battaglia, et al., 2019; Kumar, Lai, Kumar, et al., 2019; Von Cossel et al., 2019), residues from corn and wheat have received the greatest attention because of low cost and high availability (Battaglia et al., 2017; Battaglia, Groo, et al., 2018; U.S. Department of Energy, 2011). Corn stover is expected to play a central role in the goal to decrease dependency on fossil fuels (Sindelar, 2012). In the United States, corn stover produced could supply between 90 and 196 million Mg biomass/year (Gallagher et al., 2003; Graham et al., 2007; Walsh et al., 2000) and straw produced from wheat and barley around 71 million Mg/year (Tarkalson et al., 2009). The 2011 US Billion-Ton Update (U.S. Department of Energy, 2011) estimated a total corn stover supply between 117 and 127 million Mg/year in 2030 with corn stover prices between \$55 and 65 Mg⁻¹ of dry matter. With the same prices, but in a high-yield scenario that assumes a 1% annual growth in crop yields, corn stover supplies are estimated to be between 207 and 246 million Mg/year for the period 2022–2030.

Biofuels from cellulosic feedstocks may help to address concerns about the use of grain crops for biofuel production (Tenenbaum, 2008; Thompson, 2012). Using residues from annual cropping systems may both increase and diversify farm income, and, depending on the end products could reduce fossil fuel use and greenhouse gas (GHG) emissions (Wilhelm et al., 2004). Because the grain enterprise to some extent “subsidizes” stover and straw, crop residue production costs are limited. Moreover, harvesting the residues and grains together reduces need for land conversion that might be associated with dedicated energy crop production.

Although residue harvest may provide several benefits, for example, the reduction of pest and disease pressure (Wilhelm et al., 2004), concerns have arisen about potential negative impacts because they act both as sinks and sources of soil carbon that provide important ecosystem services (Su et al., 2020). Crop residues contribute to agricultural productivity by reducing soil erosion and enhancing soil physical properties (Raffa et al., 2014; Wilhelm et al., 2007) through their positive effects on soil organic carbon (SOC), nutrient availability, bulk density, water holding capacity and water infiltration (Barber, 1979; Blanco-Canqui & Lal, 2009; Franzluebbers, 2002; Kenney, 2011; Zhang et al., 2020). However, there are still many tradeoffs and insecurities about the dependence on agronomic (e.g., residual management, tillage intensity and fertilization rate) and abiotic (e.g., soil characteristics, climate conditions) parameters. Therefore, the objective of this review is to summarize the current

knowledge about the sustainability effects of corn stover and wheat straw removal for biofuel production with special focus on evaluation in terms of (a) agronomic performance, (b) soil quality parameters and (c) GHG emissions.

2 | EFFECTS OF CROP RESIDUE MANAGEMENT ON AGRONOMIC PERFORMANCE

Crop residue management strategies can have significant long-term effects on agronomic performance in either direction (Table 1). One of the first field studies seeking to understand the impact of crop residue management on agronomic performance was conducted by Morachan et al. (1972) in Iowa. In this study, five stover return rates (i.e., 0, 2, 4, 8 and 16 Mg ha⁻¹ year⁻¹) were applied over 13 years in continuous corn on a silty clay loam soil. During the first 9 years, there was no grain yield differences among treatments. However, grain yield reductions occurred for most comparisons over the latter year of the experiment, as more stover was returned to the soils.

Morachan et al. (1972) proposed two explanations for these observations: first, high stover return rates were associated with lower soil pH, which may have caused an Al-induced Ca deficiency in plants; second, increments in leaf K/Ca and K/Ca+Mg balances with residue addition may have caused severe cation imbalances in plants and, thus, poor plant growth and subsequently low grain yield. Four years after termination of field treatments, maximum grain yields were observed in plots that formerly received 8 and 16 Mg/ha of stover (Morachan et al., 1972), which may have reflected the higher nutrient status with high residue returns since the area was not fertilized following study completion (Larson et al., 1972).

In a 3-year study in no-till clay-loam soils in Nebraska with corn stover return rates of 0%, 50%, 100% and 150%, Doran et al. (1984) observed a yield decrease of 21% when no stover was returned, compared with maximum yields achieved with 100% and 150% return rates. Variations in grain yields were partially explained by 52% and 59% reductions in available water in June and July in plots without stover in the third year. At this time, corn stands were at tasseling and silking (Abendroth et al., 2011), critical stages for grain yield determination when the presence of abiotic or biotic limitations or both can severely decrease grain yields (Battaglia, Lee, et al., 2018; Battaglia, Lee, Thomason, Fike, et al., 2019; Battaglia, Lee, Thomason, & Van Mullekom, 2019; Claassen & Shaw, 1970; Hall et al., 1981; NeSmith & Ritchie, 1992).

Wilhelm et al. (1986) continued with the work started by Doran et al. (1984) in the subsequent 4 years (1980–1983), replacing the corn–sorghum [*Sorghum bicolor* (L.) Moench]–soybean [*Glycine max* (L.) Merr.] rotation with

TABLE 1 Overview of the effects of removing corn stover and wheat straw within the categories of agronomic performance, soil quality parameters and greenhouse gas (GHG) emissions

Category	Positive sustainability effects	References	Negative sustainability effects	References
Agronomic performance	Corn grain yield rather remained stable under favorable weather conditions	Karlen et al. (1984), Morachan et al. (1972)	Corn grain yield rather decreased under water limiting conditions	Doran et al. (1984), Karlen et al. (1984), Linden et al. (2000), Power et al. (1998), Wilhelm et al. (1986)
	Corn grain yield rather increased, regardless of precipitation levels	Bordovsky et al. (1998)		
	Corn grain yield increased depending on the amount of residues removed, the soil type, the topography and the management	Blanco-Canqui, Lal, Post, and Owens (2006), Power et al. (1986)		
	Faster emergence of corn	Dam et al. (2005), Schneider and Gupta (1985), Swan et al. (1987), Wilhelm et al. (1986)		
Soil quality parameters	Reduced pest and disease pressure	Wilhelm et al. (2004)	SOM decreased in the long term	Barber (1979)
	Nitrogen fertilizer replacement increases in fine-textured soil	Fontaine et al. (2020), Power and Doran (1988)	SOC reduced under no-till conditions	Dendooven et al. (2012), Sindelar (2012)
	SOC does not reduce under conventional tillage	Dendooven et al. (2012)	SOC reduced under coarse-textured soils	Blanco-Canqui, Lal, Post, Izaurrealde, et al. (2006)
	No short-term effects on SOC in fine-textured soils	Blanco-Canqui, Lal, Post, Izaurrealde, et al. (2006), Johnson et al. (2013)	POM reduced, for example, in fine-textured soils	Baker et al. (2014), Dolan et al. (2006), Kenney (2011), Kim et al. (2009), Moebius-Clune et al. (2008), Sindelar (2012)
	SOC rather not affected in the long term	Bahrani et al. (2002), Curtin and Fraser (2003), Undersander and Reiger (1985)	Total N, P and K rather decreased, for N however, it strongly depends on soil texture	Blanco-Canqui and Lal (2009), Karlen et al. (1984), Morachan et al. (1972), Susser et al. (2020)
	POM rather not affected, regardless of tillage management	Johnson et al. (2013), Johnson and Chamber (1996), Nicholson et al. (1997)	Increased water runoff and soil loss depending on both the amount of residuals removed and the rainfall energy	Lindstrom et al. (1984), Lindstrom (1986)
	Soil bulk density remained stable or increased in upper soil layers (0–15 cm depth)	Dolan et al. (2006), Karlen et al. (1994) Sindelar (2012)	Soil available water decreased	Blanco-Canqui, Lal, Post, and Owens (2006), Power et al. (1986), Wilhelm et al. (1986)
	Soil aggregate stability (here: water aggregate stability) not affected	Hammerbeck et al. (2012), Karlen et al. (1994)	Soil bulk density rather decreased, not yet fully understood	Clapp et al. (2000), Dolan et al. (2006)
			Soil aggregate stability (here: water aggregate stability) decreased depending on the amount of removed crop residues	Blanco-Canqui and Lal (2009), Bordovsky et al. (1999)

(Continues)

TABLE 1 (Continued)

Category	Positive sustainability effects	References	Negative sustainability effects	References
GHG emissions	Did not affect both soil N ₂ O and CH ₄ fluxes in corn cultivation. Rather decreased soil CO ₂ fluxes	Baker et al. (2014), Dendooven et al. (2012), Jin et al. (2014)		
	CO ₂ and N ₂ O fluxes reduced moderately, CH ₄ fluxes significantly reduced (uptake instead of emission)	Lenka and Lal (2013)		

Abbreviations: GHG, greenhouse gas; POM, particulate organic matter; SOC, soil organic carbon; SOM, soil organic matter.

no-till continuous corn. Grain yields during the first and the fourth years were irresponsive to treatments, likely due to the mixed effects of above-average air temperatures and below-average precipitation during the growth cycle. However, for each Mg/ha of residue applied in the range from 0 to 8 Mg/ha, grain yields increased by 0.32 Mg/ha in the second year and 0.26 Mg/ha in the third (Wilhelm et al., 1986).

Karlen et al. (1984) researched the effects of three stover removal rates under conservation tillage (i.e., 0%, 66% or 90%) on a sandy loam soil in South Carolina over a 3-year period. In non-irrigated plots, removing up to 90% of the stover did not reduce grain yields in the first, decreased grain yields the second and increased grain yields the final year compared to 0% removal. Under irrigation, removing 66% or 90% of the stover supported greater yields than 0% removal during the first year, but had no effect in the following 2 years. Karlen et al. (1984) suggested that lower soil coverage with the high removal rate treatment may have exacerbated water deficits in the second (dry) year, which, in turn, could explain the grain yield reductions with 90% removal during that year. When moisture was not limiting, harvesting crop residues had no impact on grain yields under non-irrigated conditions. Similar results were reported by Linden et al. (2000) working with corn in a silt loam in Minnesota. When all the stover was removed compared with 100% return, corn grain yields decreased by 18% in a dry over a 12-year period. Corn grain yields did not vary by residue management in all 24 tillage-year comparisons when available water was not a limiting factor. Similar results were found with different wheat straw treatments under irrigation. Working in a fine sandy loam soil in the Texas Rolling Plains, Bordovsky et al. (1998) observed a 6% grain yield increase in irrigated wheat after complete straw removal compared with no removal across 8 years, likely the result of more uniform plant stands with less surface residue. Regardless of the water status during crop cycle, complete residue removal in dryland conditions did not affect wheat yield during any year compared with no removal (Bordovsky et al., 1998).

Blanco-Canqui, Lal, Post, and Owens (2006) evaluated the impacts of six corn stover return rates on continuous no-till corn yields on two silt loam and one clay-loam soil over 2 years in Ohio. Regardless of soil texture, there were no yield differences among treatments during the first year. In the second year, grain yields among treatments did not differ for silt loam and clay-loam soils with less than 2% slope. Grain yields from a silt loam with ~10% slopes and more years under no-till were 21% lower with 0% and 25% compared to treatments with 50%, 75%, 100% and 200% return rates. The authors attributed these effects to lower soil moisture content and increased soil temperatures when little or no stover was returned to soils with pronounced slopes. This suggests that up to 50% of the stover could be potentially removed without affecting grain yields in the short term (≤ 2 years), although responses depend on type of soil, topography and management history. Similar results were reported by Power et al. (1986) who found soil temperatures up to 7°C lower with full corn stover retention compared with complete removal due to the reduction of intercepted radiation in bare soils.

Removing residues from the field may result in faster corn emergence (Swan et al., 1987; Vetsch & Randall, 2002; Wilhelm et al., 1986), especially in regions with a short and cool spring season. Dam et al. (2005) observed slower spring corn emergence in central Canada, ranging from 14% to 63%, in no-till + no stover removal compared with no-till + complete stover removal and conventional tillage with or without stover removal as a result of the high surface residue cover and lower soil temperatures with no residue removal in no-till (Dam et al., 2005). Similar findings were reported by Swan et al. (1987) working in Wisconsin and Minnesota with different tillage systems and surface residue coverage. In three sites-years, the number of growing degree days (GDD) from planting to V6 stage linearly decreased as soil cover increased. In two sites-years, for each unit increase in the percent of residue cover, the soil GDD decreased by 0.82 units, and by 0.53 units in the third location. Increases in the

percent residue cover also increased the air GDD required to achieve both 80% emergence and V6 stage. Each unit increase in percent cover increased the air GDD requirement to complete the planting emergence and the planting-V6 stage between 0.18 and 0.51, and 0.51 and 0.81 units, respectively (Swan et al., 1987). Similarly, Schneider and Gupta (1985) found that corn emergence occurred more rapidly in the treatments with least surface residue coverage. In another experiment, Swan et al. (1994) found that 200% corn stover retained rates decreased plant density at harvest by 5% and increased grain moisture by 4% in two silt loam soils in Wisconsin over a 7-year period, compared with 100% retained rates.

Power et al. (1998) found that returning 150% of the total stover had the greatest impact over a 10-year period, increasing final grain yields by 16% compared with complete removal. However, long-term differences between 0% and 100% return were not significant. Moreover, these results were not affected by time and other management practices such as tillage, N fertilization or cover crops. More likely, they reflect long-term changes in soil properties, microbial activity and soil N mineralization rates. Conversely, Dam et al. (2005) found no long-term residue effect on either corn grain or dry matter yields working with a factorial arrangement of crop residue (two levels: without and with residue) and tillage (three levels: no-till, reduced tillage and conservation tillage) in Canada. In his experiment, significant tillage \times residue interaction for both grain and corn dry matter yields was only found in 2 out of 12 years. When differences occurred, treatments with no residue retained were among the maximum yields in all comparisons.

3 | CROP RESIDUE MANAGEMENT EFFECTS ON SOIL QUALITY PARAMETERS

Among environmental considerations for biomass harvest systems, one of the most important is the effect on soil quality parameters such as soil organic matter (SOM) and SOC, nutrient balances, soil pH, aggregate stability and water holding capacity (Chen et al., 2020; Guan et al., 2020; Kan et al., 2020; Li et al., 2019; Su et al., 2020; Susser et al., 2020).

3.1 | Crop residue management effects on SOM, SOC and POM

Soil organic matter and SOC are the indicators most widely studied to determine the effects of crop residue removal (Zhang et al., 2020) and are highly influenced by crop residue management (Benjamin et al., 2008; Huggins et al., 1998; Kendall et al., 2015; Zhang et al., 2020). Barber (1979) studied the effect of returning 0, 100 and 200% corn stover, and

fallow for 6 years followed by 5 years of 100% corn stover return in continuous corn for 11 years on a silt loam soil in Indiana. In the 0–15 cm depth, SOM was greatest (~3.4%) with the 200% stover return after the 6th and 11th years. Returning 0% and 100% corn stover decreased SOM in the 0–15 cm soil depth by 18% and 11% compared to 200% return. Differences between the 0% and 100% return rate were only apparent at the end of the 11th year, when no stover return decreased SOM by 10%. These results likely reflect the contribution of the crop root system in SOC maintenance in the previous years.

Response to stover removal often varies by depth and tillage system. Removing all corn stover reduced SOC between 21% and 34% through a soil profile (measured in 20 cm increments to 60 cm depth) in a silty clay loam under long-term no-till. Removal did not reduce SOC under conventional tillage at any depth, but SOC values for complete stover removal under conventional tillage were 15%–35% lower than similar treatments under no-till. Highest SOC across all comparisons were observed for complete stover retention under no-till (Dendooven et al., 2012).

Regardless of tillage system, SOC decreased in surface layers when no stover was returned (14% and 4% in the 0–5 and 5–15 cm depths, respectively), but did not differ in deeper layers (15–30 and 30–60 cm) of a clay loam soil in Minnesota (Sindelar, 2012). In a silt loam soil with 10% slope in Ohio, SOC decreased up to 27% in the 10–20 cm depth when removal rates were $\geq 75\%$. In silt loam and clay loam soils with limited ($< 2\%$) slopes, different removal rates did not affect SOC in the 10–20 cm depth. In all three soils, removal rates $\geq 75\%$ decreased SOC between 20% and 30% in the top 10 cm soil (Blanco-Canqui & Lal, 2009).

Blanco-Canqui, Lal, Post, Izaurralde, et al. (2006) studied continuous no-till on silt loam and clay loam soils in Ohio. They observed that removal rates as low as 1.25 Mg/ha reduced SOC and degraded soil structure after just 1 year in coarse-textured but had little to no impact in fine-textured soil. Liang et al. (1998) found that retention of residue C was 81%–175% higher and its turnover slower, in clay than in coarse-textured soils in a 12-year experiment with continuous corn in Canada. Although this may partially explain the lack of short-term changes in the SOC levels in clay loam soils observed by Blanco-Canqui, Lal, Post, Izaurralde, et al. (2006) and Johnson et al. (2013), it conflicts with the changes reported by Sindelar (2012) for similar soils. According to Blanco-Canqui, Lal, Post, Izaurralde, et al. (2006), soils where short-term changes in the SOC levels are less prone to occur may have reached an equilibrium state that buffers them against changes when stover is added or removed. Baseline SOC levels for the 0–5 cm depth were much smaller (i.e., 2.5 g/kg soil) in the experiment conducted by Sindelar (2012) compared with values measured by the other two authors (i.e., 20–30 g/kg soil).

The particulate organic matter (POM) fraction, composed of fine plant and microbial residues in early stages of humification (Bernard et al., 1996; Carter, 2002), is highly responsive to changes in C inputs (Gregorich & Janzen, 1996) and management (Cambardella & Elliot, 1992; Sequeira & Alley, 2011). The POM fraction has an estimated turnover time between 1 and 8 years (Carter, 2000) and can represent up to 45% of the active SOM pool (Carter et al., 1998).

Johnson et al. (2013) investigated the response of POM and SOC to corn stover return rates (full, ~7.8 Mg/ha; moderate, ~3.8 Mg/ha; low ~1.5 Mg/ha) and tillage (chisel-tilled; well-established [10 year old]; newly established [0 year old] no-till) at two depths (0–5 and 5–10 cm) in a clay loam soil in Minnesota. For most comparisons, POM did not differ with stover return rate, regardless of tillage system and only decreased at the 0–5 cm in long-term no-till with low stover returns (i.e., 1 comparison out of 18). Johnson et al. (2013) concluded that changes in SOC and POM levels in response to stover management may take longer than 3 years to be detected in clay loam soils and that POM levels in long-term no-till plots can be reduced in three or fewer cycles of stover treatments if only low levels of stover are returned. In contrast, Sindelar (2012) measured short-term changes in SOM and POM in response to residue removal in a clay loam soil in Minnesota. Here, POM was more responsive than SOC to stover management, and changes were observed to depths of 30 cm. Sindelar (2012) concluded that stover removal in a continuous corn rotation can negatively affect SOM and POM within 3 years in fine-textured soils.

Others also reported decreased SOM and SOC with corn residue removal (Baker et al., 2014; Dolan et al., 2006; Kenney, 2011; Kim et al., 2009; Moebius-Clune et al., 2008). Retention of crop residues, on the other hand, has resulted in positive (Clapp et al., 2000) to little or no effect (Johnson & Chamber, 1996; Nicholson et al., 1997). Perhaps, the smaller carbon contribution of surface (compared with root) residue to POM and SOC pools renders less evident the occurrence of changes with varying stover retention rates. In a simulated no-till experiment, Gale and Cambardella (1998) demonstrated that 66% of the ^{14}C in surface residue had been respired as carbon dioxide (CO_2) after 360 days of decomposition, while 11% remained as surface residue and 16% in the soil. In contrast, 56% of the root-derived ^{14}C in the soil evolved as CO_2 , and 42% remained in the soil. Large (500–2,000 μm) and small (53–500 μm) POM fractions contained 11%–16% of the initial root-derived ^{14}C , but less than 3% of the initial surface residue-derived ^{14}C . These trends agree with findings from Larson et al. (1972) and Barber (1979), who reported greater root (23% and 18%) than aboveground C (18% and 8%–11%) entering the SOM pool.

Negative impacts of wheat straw removal on SOC and SOM have been less evident. Working in a 14-year study

in a silty clay loam soil and furrow irrigation in Texas, Undersander and Reiger (1985) did not find differences in SOM in the 0–15 and 15–30 cm depths when comparing 0 and 100% wheat straw removal rates. Regardless of straw management, Bordovsky et al. (1999) reported SOC increases in the 0–7.5 cm depth over an 11-year study with irrigation in a fine sandy loam soil in Texas. However, these increases occurred more rapidly when the straw was not removed. In Iran, Bahrani et al. (2002) did not observe a reduction in SOC in the top 30 cm of soil after removing all straw from the soil surface. Curtin and Fraser (2003) reported no differences in SOC in the 0–15 cm soil depth in a silt loam soil in New Zealand for treatments including incorporation, burning or removal of aboveground wheat straw.

Although no field studies on the impact of residue removal on soil quality have been conducted in Virginia, some authors studied the impact of other practices on these parameters. Working in the Coastal Plain region of Virginia with sandy loam soils under no-till, Spargo et al. (2012) found that total SOC and N increased linearly with time under no-till in the 0–2.5 and 2.5–7.5 cm depths. No changes in C and N pools were found for the 7.5–15 cm depth. Similarly, linear increases in POM-C and POM-N fractions were reported with time under no-till for the 0–2.5, but not for the 2.5–7.5 and 7.5–15 cm depths. Sequeira and Alley (2011), working in the Valley/Ridge province of Virginia studied, the short-term effects of crop rotation, tillage and cover crop management on different soil C POM-and N pools in the top 15 cm soil. Soil organic N, both in the bulk soil and POM fraction, was not affected by any combination of factors, whereas SOC in both pools were only affected by cover crop management. Overall, both soil organic pools had significantly more C when the rye cover crop was left on the field compared to harvest after chemical killing.

3.2 | Crop residue management effects on nutrient balances, pH and cation exchange capacity

The balance between stover removed to carbon returned to the system has to be considered to address economic concerns regarding short-term increases in nutrient removal rates and replacement costs (Battaglia, Groover, et al., 2018) for crop yield limiting nutrients such as N and P (Adeyemi et al., 2020; Adnan et al., 2020; Diatta et al., 2020; Ketterings & Czymmek, 2007).

Blanco-Canqui and Lal (2009) found that only complete stover removal decreased N content in the soil, but this response was largely affected by soil texture. With complete residue removal, total N decreased in the silt loam but not the clay loam soil, and trends were more noticeable in the 0–10 cm than in the 10–20 cm depth. Similarly, Karlen et al. (1994)

found lowest NO_3^- content in the 0–2.5 and 2.5–7.5 cm depths in a silt loam soil in Wisconsin following 0% compared with 100% and 200% corn stover retention. However, increasing the amount of returned residue may increase N immobilization, which may require additional N fertilizer application (Fontaine et al., 2020; Power & Doran, 1988).

Available soil P appears much less affected by crop residue management, irrespective of soil texture. Blanco-Canqui and Lal (2009) reported large reductions (40%) in soil P only with 100% stover removal in the surface 10 cm of a silt loam soil (Blanco-Canqui & Lal, 2009). Available P at different depths was not affected by residue management in sandy loam soils in South Carolina (Karlen et al., 1984) and silt loam soils in Wisconsin (Karlen et al., 1994).

Soil K, on the other hand, responded with greater variability than available P to stover management, regardless of soil texture. At 0–10 cm depth, stover removal rates of 75% and 100% reduced extractable K in silt loams with 2% or 10% slopes and a clay loam with <1% slope (Blanco-Canqui & Lal, 2009). Similarly, Morachan et al. (1972) observed 16% and a 53% reduction in soil extractable K when no stover was returned, when compared with return rates of 4 and 16 Mg^{-1} across 11 years in a silty clay loam soil, respectively. Karlen et al. (1984) found that harvesting 66% and 90% of the corn residues for 2 years reduced soil extractable K in the 5–20 cm depth of an Ap horizon of a sandy loam soil in South Carolina, but had no effect on K in the 0–5 cm depth of an Ap, as well as the E (20–40 cm) or Bt (40–90 cm) horizons. In this study, soil extractable Ca, Mg and Mn levels were unresponsive to stover management in most comparisons (Karlen et al., 1984). In another study, Ca, Mg and cation exchange capacity (CEC) only decreased with 100% stover removal in the surface (0–10 cm) of sloping soils (10%; Blanco-Canqui & Lal, 2009). Soil pH only increased in two comparisons for complete stover removal. In most comparisons, soil pH was not affected by different removal rates at any depth, similar to reports from Karlen et al. (1984). Similarly, Morachan et al. (1972) reported a significantly lower pH of 4.8 for the 16 Mg/ha stover return rate versus pH 5.3 when no stover was returned.

In summary, parameters such as soil Ca, Mg, available P, NO_3^- and CEC seem less prone to change than extractable K and total soil N with stover management. The greatest differences typically occur with stover removal rates close to 100% and at the 0–10 cm depth. However, these responses can be highly dependent upon slope, soil texture and depth.

3.3 | Crop residue management effects on soil erosion and water quality

Protection against potential soil erosion, with its concomitant effects on soil and water quality, is one of the major concerns related with crop residue harvest for alternative uses

(Andrews, 2006; Mann et al., 2002; McAloon et al., 2000), but few experiments have studied these parameters together under different residue management schemes. Lindstrom (1986) conducted experiments in a loam soil in Minnesota and a silty clay loam soil in South Dakota to determine the relationship between water runoff and soil loss as a result of changes in the amount of corn residue remaining on surface. Lindstrom (1986) found decreasing water runoff and soil erosion with increasing amounts of residue left on the soil surface up to approximately 70% retention rates. Retention rates above 70% had no further reductions in runoff or soil loss. Moreover, the rainfall energy needed to start the runoff process was higher when residue was left on surface (Lindstrom et al., 1984). Residue management can also impact the amount of P in water runoff and efforts to reduce this risk have been on the rise over the last 20 years (Czymmek et al., 2020). Grande et al. (2005) found that total P and dissolved reactive P in the runoff were inversely related to the amount of residue remaining on surface. However, the amount of crop residues can increase long-term soil microbial activity and thus increase plant available P (Susser et al., 2020), a further indication that crop residues management should be carefully considered.

3.4 | Crop residue management effects on available water, aggregate stability and bulk density

In a 4-year study in a silty clay loam soil in Nebraska with continuous corn and 0%, 50%, 100% or 150% stover return, Wilhelm et al. (1986) found that 100% return increased soil available water at planting (i.e., water stored between -0.03 and -1.50 MPa in the 0–1.8 m depth) by 25% and 13% compared to 0% and 50% return rates. Moreover, an increase of 6 mm in soil available water around planting was calculated for each extra Mg/ha of residue returned. Increased corn stover return rates reduced soil temperatures at 5 cm depth, with positive effects on water conservation, similar to reports from Power et al. (1986) in Nebraska and Blanco-Canqui, Lal, Post, and Owens (2006) in Ohio. When added to the model, soil temperature and available water accounted for 80% and 90% of the total variation in corn grain and residue yields, respectively. Corn stover retention can also have positive impacts on soil available water in late crop growth. Doran et al. (1984) measured increases in soil available water greater than 100% around the critical period in corn when 100% of the stover was retained relative to 0% retention in a 3-year study in Nebraska.

The interrelationship between SOM formation, stabilization and turnover with biological activity and aggregate dynamics has been studied since the early 1900s (Six et al., 2004). Soil aggregate stability is an indicator of the

cohesive forces maintaining the soil particles together against the disruptive effect of water, wind and management (Amézqueta, 1999; Six et al., 2004). Stover removal rates $\geq 50\%$ reduced water aggregate stability in some studies (Blanco-Canqui & Lal, 2009; Bordovsky et al., 1999), but had little impact in others (Hammerbeck et al., 2012; Karlen et al., 1994). In the long-term study conducted by Bordovsky et al. (1999) in Texas, microaggregation values were 15% and 19% higher when residue was retained, both in non-irrigated (27.1 g/kg vs. 23.5 g/kg) and irrigated conditions (32.3 g/kg vs. 27.1 g/kg). Karlen et al. (1994) found no difference in percentage of water stable aggregates between 0% and 100% corn stover retained in a 10-year period in Wisconsin. Conversely, treatments that retained 200% stover rates increased the amount of water stable aggregates by 38% compared with 0% and 100% retention. Working in a corn–soybean rotation in a silty clay loam soil in South Dakota, Hammerbeck et al. (2012) reported a 40% increase in the water aggregate stability for aggregate sizes between 0.84 and 2.0 mm with no removal compared with stover removal rates >4.0 Mg/ha. However, stover management in this study did not affect water aggregate stability for other aggregate sizes.

Evidence about the impact of corn stover management on soil bulk density (BD) is conflicting. Working in a silt loam soil in Minnesota, Clapp et al. (2000) found decreases in BD at the end of the 13th year in the 0–5 cm depth with 100% stover retention in no-till, but not in moldboard or chisel-plow tillage systems. However, 100% stover retention increased BD for the 20–40 cm depth for all tillage system. Similar results were found at the end of the 22nd year, when BD decreased by 6% at the 0–5 and 5–10 cm depths but increased by 5% in the 30–45 cm depth when 100% of the stover was retained (Dolan et al., 2006). These results agree with the findings from Sindelar (2012), where 100% stover retention reduced BD by 0.26 and 0.14 g/cm³ in the 0–5 and 5–15 cm depths. Conversely, 0% and 100% stover retention did not change the BD in the first 20 cm in Québec (Dam et al., 2005) or 50 cm of soil in Iowa (Karlen et al., 1994).

4 | CROP RESIDUE MANAGEMENT EFFECTS ON GHG EMISSIONS

One of the main goals of bioenergy production systems is the mitigation of the projected climate change at the global scale (Baker et al., 2014). However, crop residue removal can have detrimental consequences through its effects on soil processes that may increase the production of GHG, especially nitrous oxide (N₂O; Baker et al., 2014). Furthermore, some authors have stated that the release of N₂O resulting from biofuel production may counterbalance the reduction

in global warming resulting from fossil fuel displacement (Crutzen et al., 2008).

4.1 | CO₂, CH₄ and N₂O fluxes under different corn residue management

CO₂ is the largest contributor to global warming and is expected to continue so in the future (Houghton, 2007). Produced in considerably less amount than CO₂, N₂O is a long-lived GHG and a major contributor to climate change (Gentile et al., 2008), with a global warming power (GWP) 265–310 times greater than CO₂. Methane (CH₄) has a shorter lifetime than CO₂ but an estimated GWP 28–36 greater than CO₂ (EPA, 2017).

As part of a USDA multi-location research project, the impact of 0% and 100% corn stover removal rates on N₂O and CO₂ fluxes were measured in a 2-year study in Minnesota (Baker et al., 2014). Baker et al. (2014) concluded that full stover removal may have little impact on N₂O soil fluxes. Full stover removal reduced the soil CO₂ flux by up to 10%, but this reduction did not offset the C removed from the system compared with zero or intermediate removal rates, thus implying a net loss of C from the system. Working on the same project, Jin et al. (2014) summarized soil GHG data from nine corn systems under different stover management. Overall, stover removal reduced CO₂ emissions by 4%, similar to reports from Baker et al. (2014). Additionally, Jin et al. (2014) reported decreases in N₂O of 7% relative to no removal. Jin et al. (2014) concluded that lower GHG emissions in response to stover removal might imply a confounded effect of lower C and N inputs, and microclimatic differences related to spatial changes in soil cover. In another study, complete stover removal reduced CO₂ and N₂O fluxes by 11% and 36%, regardless of tillage system, in a silty clay loam soil in Mexico. In this study, neither tillage system nor residue management affected the CH₄ fluxes from soil (Dendooven et al., 2012). Similarly, Abalos et al. (2013) reported a 51% decrease in the N₂O fluxes with no stover application, compared with stover applied at ~ 10.5 Mg/ha in a clay loam soil in Spain. Different than Dendooven et al. (2012), Baker et al. (2014) and Jin et al. (2014), however, corn stover removal did not affect the CO₂ fluxes from the soil in the Abalos et al. (2013) study.

Incorporation of crop residues resulted in mixed effects on N₂O emissions, and responses are mostly strongly influenced by soil texture, feedstock quality and climate variability (Yuan et al., 2018). Gentile et al. (2008) measured a reduction of fertilizer-derived N₂O emissions when urea (120 kg N/ha) was applied with a low-quality corn feedstock (42% C, 1.3% N, C:N ratio of 31, 3.1% lignin, 1.1% polyphenols) at ~ 9.5 Mg/ha in two coarse textured soils in

Zimbabwe, likely explained by an increased in the N immobilization from the fertilizer. Conversely, the interactive effects following application of urea and corn stover increased the N₂O losses in two fine-textured soils from Ghana and Kenya, compared with fertilizer alone. In this case, increases in N₂O fluxes in the urea + stover treatment were explained by increases in both the N₂O fluxes from the fertilizer and the soil N pool. According to authors, this response may imply that denitrification was the main factor controlling N₂O fluxes in fine-textured soils where addition of residue rapidly depletes O₂ levels through increased microbial activity (Tiedje et al., 1984). The addition of high-quality residues with low C:N ratio increased N₂O emissions for all soil textures (Gentile et al., 2008). Similarly, Huang et al. (2004) reported increases in both N₂O and C₂O after incorporation of crop residues in a 21-day incubation study with a fine-textured silty clay soil, independent of the type of residue utilized. The degree of this response was quantitatively dependent on the C:N ratio of the residues applied (C:N range: 8–118; 57 and 63 for corn stover and wheat straw, respectively), with fluxes of both gases negatively correlated ($r > .78$) with C:N ratio (Huang et al., 2004), similar to recent reports from Lin et al. (2013) and Shan and Yan (2013).

4.2 | CO₂, CH₄ and N₂O fluxes under different wheat residue management

Removal of wheat straw residues also has the potential to reduce the flux of GHGs from soils. Lenka and Lal (2013) studied the effects of three wheat straw retention quantity (0, 8 and 16 Mg ha⁻¹ year⁻¹) and two fertilization rates (0 and 244 kg N ha⁻¹ year⁻¹) on CO₂, N₂O and CH₄ fluxes during a 15-year no-till residue management study in Ohio. No crop was grown during the 15 years where treatments were imposed, and residues were applied as baled air-dried wheat straw from external sources. A significant interaction of wheat straw × fertilizer was found for all three gas fluxes. Diurnal CO₂ and N₂O fluxes were lowest for 0 and 8 Mg ha⁻¹ year⁻¹ for both fertilization rates, averaging 1.587 g CO₂ m⁻² day⁻¹ and 0.510 mg N₂O m⁻² day⁻¹, respectively. Retaining 16 Mg ha⁻¹ year⁻¹ of wheat straw increased CO₂ and N₂O fluxes both in unfertilized (+30% and 52%) and fertilized plots (+45% and 100%), respectively. Soils that received no wheat straw under both fertilization rates had a net CH₄ uptake between -2.390 and -2.790 mg CH₄ m⁻² day⁻¹. Incorporation of 8 and 16 Mg ha⁻¹ year⁻¹ of wheat straw, with and without fertilizer, resulted in net CH₄ emission (range: 0.108–3.153 mg CH₄ m⁻² day⁻¹) with greatest values (not significantly different among them) when fertilizer was applied (Lenka & Lal, 2013).

5 | CONCLUSIONS

In this review, we highlighted the variety of positive and negative sustainability concerns associated with removing crop residues for expanded uses. The targeted development of future threshold values could ensure that not too much residue is removed as is necessary to maintain the overall sustainability of the agroecosystem, especially that related to overall soil quality because of its concomitant impact on crop productivity and GHG fluxes. In the future, however, it remains to be clarified whether simply returning the crop residues at a later stage is sufficient to ensure the maintenance of overall sustainability or whether it would be necessary to separate used and unused crop residues during the harvest. The latter would involve particular technical challenges that would need to be further explored before implementation of more sustainable crop residue removal at regional level. Furthermore, there is still little empirical evidence on the interactions of relevant residue removal-affected parameters such as productivity, GHG emissions, nutrient balances, aggregate stability, bulk density and available water. Notwithstanding these identified technical and agronomic challenges and depending on site-specific conditions such as soil type, SOM and topography, it is expected that 30% of the available crop residues could be used for expanded uses in a bio-based economy without decreasing the overall sustainability of the agroecosystem. Consequently, there is every indication that crop residues of wheat and corn can play a key role to achieve a thriving future bio-based economy through diversification of feedstock resources, but the removal rate must be carefully considered.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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