Corn residue harvest:

An analysis of productivity and environmental performance at the field-scale

A report to Verbio

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The authors are Professors of Agronomy at Iowa State University and have more than two decades of experience measuring and modeling soil, water, and plant dynamics in Iowa cropping systems including grain production and environmental performance.

Major findings

- In Iowa corn systems, crop residue production is increasing at the same rate as grain yield (approximately 100 pounds dry matter/acre/year and 2 bushels/acre/year).

- Crop residue inputs have now reached more than 5.4 tons/acre/year (12 metric tons/hectare/year), creating significant agronomic and environmental challenges for corn production.

- Partial residue harvest can increase crop productivity, on-farm profitability, and environmental performance.

- Experiments in the north central US Corn Belt demonstrate that residue harvest in continuous corn cropping systems consistently increases grain yield of the following corn crop while reducing the optimum nitrogen fertilizer input and environmental nitrogen losses to nitrous oxide.

    - These experimental results include tens to hundreds of site-years and were generated by independent research teams from Iowa State University, University of Illinois, University of Minnesota, University of Wisconsin-Madison, and the USDA Agricultural Research Service.

- Outside of unusually dry years and the dry western Corn Belt, we found no research that indicates residue harvest in continuous corn systems will increase agronomically optimum nitrogen fertilizer inputs or decrease grain yield.

- Process model simulations confirm these results and demonstrate that the increases in grain yield despite reductions in optimum nitrogen fertilizer input are the result of more efficient soil nitrogen cycling and fewer nitrogen losses to the environment.

- Review of the scientific literature and our process model simulations indicate that 50-66% residue harvest in continuous corn systems can reduce field-scale greenhouse gas emissions by 10-50% depending on the year and system.
    - Using a case study from an Iowa State University Extension publication, we estimate a 38% reduction for central Iowa.
    - Using a process model simulation, we estimate a 35% reduction for central Iowa.

Crop residue inputs in the US Corn Belt have reached unprecedented levels. Since 1960, Iowa corn yields have increased at a rate of 2 bushels per acre per year (130 kg ha^{-1} y^{-1})[1]. Crop residue production in corn has increased at a nearly identical rate because grain yield and total biomass have increased in tandem; the harvest index of corn, which is the ratio of grain to total aboveground biomass, has not changed much during this time (Lorenz et al. 2010; Hutsch & Schubert 2017).

A grain yield of 225 bushels per acre (14 Mg ha^{-1} at 15.5% moisture), which is now common in north central Iowa, generates approximately 5.4 tons per acre (12 Mg ha^{-1}) of residue inputs to the soil (dry matter basis). At the current trend in yield gain of 2 bushels per acre per year, residue inputs increase at ~100 lbs dry matter per acre per year. This increase in residue production has created opportunities for residue management that can improve productivity, profitability, and environmental performance.

Historically, residue retention was important to maintain soil carbon and reduce erosion. However, at current levels of residue production, residue harvest is generally beneficial because large amounts of residue decrease soil temperature, increase soil moisture, and increase environmental nitrogen losses in the forms of nitrate to waterways and nitrous oxide to the atmosphere (Fig. 1). Together, these factors increase net greenhouse gas emissions, reduce nitrogen fertilizer use efficiency (NUE), and reduce yield of subsequent crops (Sawyer et al. 2017). Rational residue harvest can mitigate these challenges.

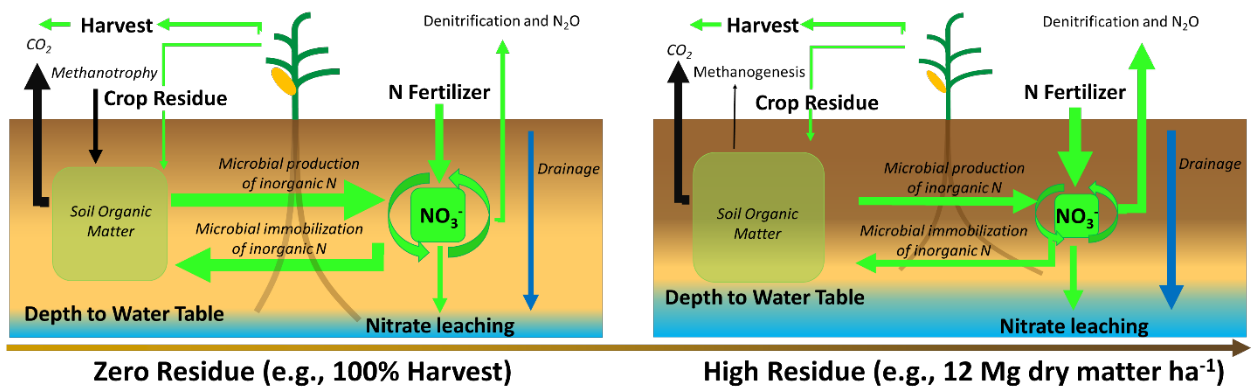

Figure 1: A systems view of the processes directly affected by residue inputs. The two panels represent scenarios along a gradient of residue input. There is strong evidence that well-planned crop residue harvest can increase grain yield while decreasing nitrogen fertilizer inputs because residue harvest decreases environmental N losses and improves soil N cycling. Note: residue harvest results in higher grain yields despite lower nitrogen fertilizer inputs. Residue harvest also reduces nitrous oxide emissions and nitrate leaching.

Across six site-years in southwest and north central Iowa, Pantoja et al. (2015) found that residue harvest increased grain yield in continuous corn systems by 10% (15 bu ac^{-1} or 960 kg ha^{-1}). At the same time, the residue harvest decreased the optimum nitrogen fertilizer rate that was required to produce that grain by 22% (42 lbs N ac^{-1} or 47 kg N ha^{-1}). These results are not unusual: across 239 site-years spanning the US Corn Belt, Karlen and Johnson (2014) found that corn residue harvest led to a 3% average yield increase in the subsequent corn crop; however, at the 45 site-years from central Iowa included in this study, the average yield increase was 8%. The benefits of residue harvest tend to be greater in wetter environments such as central Iowa.

[1] Linear equation fitted ($r^2 = 0.86$) to USDA NASS Iowa state-wide average corn grain yield data from 1960-2021. y = 2.02 bu/ac * (year) + 67.34

As residue harvest consistently increases grain yield, it also consistently reduces the optimum nitrogen fertilizer rate required to achieve that yield. In some cases, residue harvest can reduce the optimum nitrogen input by more than 100 lbs ac^{-1} (112 kg ha^{-1}) (Schoessow et al., 2010, Sindelar et al., 2013, Pantoja et al., 2015). **Reductions in nitrogen fertilizer inputs, especially when coupled with increases in grain yield, consistently decrease environmental nitrogen losses to nitrate and nitrous oxide** (Lawlor et al. 2008; Shcherbak et al. 2014). Moreover, because residue harvest reduces soil moisture, residue harvest can further reduce nitrate and nitrous oxide losses beyond what is expected from the reduction in nitrogen fertilizer input alone because soil moisture is the primary control on nitrogen losses and positively associated with nitrogen losses.

Hence, three **in-field** processes lead to greater grain yield per nitrogen fertilizer input and lower nitrogen emissions when residue is harvested from corn systems in the north central Corn Belt: **1)** lower optimum nitrogen fertilizer input; **2)** reduced soil moisture (see references below), and **3)** greater nitrogen uptake (i.e., higher yield). In addition, **outside the field**, reductions in nitrogen fertilizer input avoid greenhouse gas emissions associated with ammonia production. These emissions reductions are significant: on average, across the US corn crop, nitrous oxide emissions and nitrogen fertilizer synthesis account for 36 and 24% of total greenhouse gas emissions from corn production (CO_2e ha^{-1}) (Northrup et al. 2021). The proportions are undoubtedly higher in the highly productive northern Corn Belt. In the following sections we describe the experimental and modeling evidence to support these conclusions.

The Impact of Residue Harvest on Global Warming Potential in Iowa

Here, using data from an Iowa State University Extension publication that advises farmers about residue management with local production practices (Sawyer & Mallarino 2012), we make a simple estimate of the reduction in global warming potential associated with a change from continuous corn to continuous corn with 50% residue harvest. Our estimate indicates that **residue harvest results in a 38% reduction in global warming potential of corn production**. The reduction is due to lower nitrogen fertilizer input and a switch to no-tillage. In central Iowa, all continuous corn systems require tillage – corn cannot be grown continuously without tillage owing to the detrimental effects of residue on planting and germination. However, residue harvest allows continuous corn to be grown without tillage, creating a carbon sink in the soil. In central Iowa, there is strong experimental evidence showing that no-tillage increases soil carbon stocks (Al-Kaisi & Kwah-Mensah 2019) while there is no evidence that partial residue harvest reduces soil carbon stocks (see section 'Soil Organic Carbon Stocks', below).

Table 1. Comparison of continuous corn and continuous corn production with no-tillage and residue harvest on the global warming potential of each system.

System	Economic Optimum Nitrogen Rate (lb N/acre)[1]	Grain Yield (bu/acre)[1]	CO_2e from NH_3 Synthesis (lbs CO_2e/acre)[2]	N_2O Emissions (lb N/acre)[3]	CO_2e from N_2O Emissions (lbs CO_2e/acre)	Soil Carbon Sequestration[4,5] (lb C/acre)	Soil Carbon Sequestration (lb CO_2e/acre)	Global Warming Potential (metric tons CO_2e per acre)
Continuous corn with no residue harvest and tillage	228	179	720	3.65	1708	-71	-260	0.98
Continuous corn with 50% residue harvest and no-till	212	173	669	3.39	1588	-250	-917	0.61

[1]Data from Sawyer & Mallarino; [2]Assuming 2.6 Mg CO_2e/Mg NH_3; [3]Assuming 1.6% of nitrogen fertilizer emitted as N_2O; [4]Data for continuous corn with full tillage and no residue harvest assume a small soil carbon sink based on data from Poffenbarger et al. (2015); [5]Negative numbers indicate net soil C storage. Data on soil carbon sink for continuous corn with no tillage from Al-Kaisi & Kwaw-Mensah (2019). There is no experimental evidence to suggest partial residue harvest leads to soil carbon loss although theory and models indicate a small loss. Note: residue harvest did not increase yield in this comparison because of the switch to no tillage; in the same study, residue harvest did increase yield when tillage was maintained. Finally, we do not include reduced N_2O emissions due to nitrogen harvested in residue because, in cereals, there is no experimental evidence to support this assumption. See sections below.

Nitrogen Fertilizer

There is a misconception that residue harvest, because it removes nitrogen from the field, results in greater nitrogen fertilizer requirements to produce the next crop. On the contrary, empirical data from several nitrogen fertilizer rate x residue removal experiments demonstrate this to be false (e.g., Coulter & Nafziger 2008; Sindelar et al. 2013; Pantoja et al. 2015). In the rainfed Corn Belt, there is no evidence to suggest that residue harvest increases the economically or agronomically optimum nitrogen fertilizer input. Even the harvest of nitrogen-rich soybean residue has been shown to increase the following corn grain yield while reducing the optimum nitrogen fertilizer rate required to achieve that yield (Schoessow *et al*., 2010). Coulter & Nafziger (2008) found that, in average rainfall years in Illinois, partial or full residue harvest reduced the economic optimum nitrogen rate (EONR) by 23 kg N ha^{-1} (11%) while increasing grain yield from 12.9 to 13.5 Mg ha^{-1} (5%). In Minnesota, Sindelar et al. (2013) found that residue harvest reduced the EONR by 15 kg N ha^{-1} (7%) while increasing grain yield at the EONR by 7%. Pantoja et al. (2015) found that stover harvest in central Iowa reduced the EONR by 46 kg N ha^{-1} (18%) while increasing the grain yield at the EONR from 10.7 to 11.0 Mg ha^{-1} (3%).

Several biophysical processes can explain these results. First, residue harvest reduces soil moisture and increases soil temperature. In central Iowa, where crop production suffers from excess water and most fields benefit from artificial subsurface drainage, reduced soil moisture increases the microbial production of nitrate from the soil (an obligate aerobic process). As a biological process, higher temperatures also benefit this process. This is why, in dry ecosystems such as Nebraska or in drought years in the wet Corn Belt, residue harvest does not increase yields (e.g., Coulter & Nafziger 2008; Wortmann et al. 2016). Second, crop residues have a high ratio of carbon to nitrogen. Hence, microbes must scavenge and immobilize ammonium and nitrate in the soil environment to meet their metabolic requirements for residue decomposition. The more residue, the more scavenging. This immobilization and transformation of ammonium and nitrate into microbial biomass (organic nitrogen) reduces plant-available ammonium and nitrate concentrations in the soil (whether it is produced by microbes from soil organic matter or added in fertilizers). Third, residue removal can improve seed germination and decrease the risk of pathogens. The first two processes are reproduced in ecosystem process models.

Environmental Nitrogen Losses: Nitrate and Nitrous Oxide

There is widespread scientific agreement that reductions in nitrogen fertilizer inputs reduce environmental nitrogen losses to nitrate and nitrous oxide (Lawlor et al. 2008; Shcherbak et al. 2014). Using a statistical model that relates nitrogen fertilizer rate to nitrate loss (Lawlor et al. 2008) – a model that has been adopted by the Iowa Nutrient Reduction Strategy to track progress – the reduction in economic optimum nitrogen fertilizer inputs from residue harvest reported by Pantoja et al. (2015) for central Iowa would reduce nitrate loss by 30%. There is no similar model for nitrous oxide emissions in central Iowa, but using the Tier 1 Emissions Factor for nitrogen fertilizer of 1.6% from the United Nations International Panel on Climate Change (i.e., assuming 1.6% of nitrogen fertilizer is emitted as N_2O[2]), the reduction in EONR reported by Pantoja et al. (2015) would reduce nitrous oxide emissions by 0.75 kg N ha^{-1}, which is equivalent to 350 kg CO_2e ha^{-1} y^{-1}. This reduction in emissions is addition to the avoided

[2] Tier 1 emissions factors also include an emission of N_2O that is proportional to crop residue nitrogen inputs. Although crop residue harvest should and does reduce N_2O emissions beyond the reduction in N fertilizer, the reduction, from a biophysical perspective, is not due to the nitrogen harvest but instead because of residue harvest on soil temperature and moisture.

emissions that would have occurred with the synthesis of the nitrogen fertilizer that was not needed, which is equivalent to approximately 148 kg CO_2e ha^{-1} y^{-1} or 0.22 metric tons $acre^{-1}$ y^{-1} (assuming 2.6 Mg CO_2e per Mg NH_3; Wang et al. 2018).

Moreover, the UN IPCC Tier 1 Emission Factor (EF) of 1.6% is well known to underestimate N_2O emissions in the north central US Corn Belt. Working in Ames, IA, Parkin & Kaspar (2006) estimated that the region-specific EF is three-fold higher. Lawrence et al. (2021) determined that the UN IPCC EF is relatively accurate for well drained soils in central Iowa, but a significant underestimate for poorly drained soils, and poorly drained soils account for more than 50% of soils in north central Iowa. Notably, Griffis et al. (2013 & 2017), using both top-down and bottom-up measurements of N_2O emissions, estimated that the EF is >5% for this region.

In addition, crop residue harvest may further reduce nitrogen losses beyond what is expected from the reduction in fertilizer input alone because crop residue harvest reduces soil moisture due to greater evaporation. In central Iowa, Flerchinger et al. (2003) found bare soil has 30% greater evaporation than soil with corn residue. Reduced soil moisture generally reduces nitrogen losses to nitrous oxide because most nitrous oxide emissions derive from microbial nitrate respiration (i.e., denitrification), which is an obligate anaerobic process. There are many experimental data to support this conclusion; they are summarized in several meta-analyses of experimental results (Xia et al. 2018; Abalos et al. 2022). More specifically, **an analysis of nine locations including 26 site-years spanning the US Corn Belt from central Nebraska to western Indiana found that residue harvest – without any change in nitrogen fertilizer input – reduced average N_2O emissions by 7% (Jin et al. 2014)**. Consistent with the positive effect of soil moisture on N_2O emissions, the reduction in emissions associated with residue harvest increased with the amount of growing season precipitation. Central Iowa had the third highest growing season precipitation of the nine locations in the study and, at this location, residue harvest reduced N_2O emissions by approximately 15%. If residue harvest was coupled with the reduction in nitrogen fertilizer inputs that it enables, the reductions in N_2O emissions would be even larger.

Reduced soil moisture is also likely to reduce nitrate leaching losses because reduced soil moisture reduces the volume of drainage (e.g., Daigh et al. 2014) and drainage volume is the primary control on nitrate loss (fertilizer input is a secondary control; Zhao et al. 2016). Unfortunately, we know of no drainage monitoring experiments that examine the effect of residue harvest on nitrate leaching. However, several experiments report reduced soil moisture with residue harvest and several model simulations indicate residue harvest reduced nitrate leaching losses (Malone et al. 2019). For example, in model simulations, Cibin et al. (2016) found residue harvest led to 20% less nitrate leaching and Gassman et al (2017), working in central Iowa, found residue harvest led to 6% less nitrate leaching (though likely due to an incorrect mechanistic pathway).

Soil Organic Carbon Stocks

We have high confidence that rational crop residue harvest in central Iowa will not reduce soil carbon stocks. Data demonstrate that soil carbon stocks in Iowa are increasing at least partly because crop residue inputs are increasing in tandem with grain yield. Research clearly demonstrates – and there is widespread scientific consensus – that soil carbon stocks are a linear function of soil carbon inputs (Paustian et al. 1997). Across four Iowa locations including 60 site-years, Poffenbarger et al. (2015) measured changes in soil organic carbon as a function of crop residue input. The authors developed the following equation to explain change in soil organic carbon (y; Mg carbon ha^{-1} y^{-1}) as a function of residue carbon input (x; Mg C ha^{-1} y^{-1}): y = x*0.075-0.24. This equation indicates that carbon inputs of approximately 3.2 Mg C ha^{-1} y^{-1} are sufficient to maintain soil carbon stocks. Since crop residues are approximately 45% carbon, on average, 7.1 Mg ha^{-1} y^{-1} of crop residues (dry matter) should remain in the field to maintain soil carbon stocks. At typical crop residue production in central Iowa, this allows for harvest of ~4.9 Mg dry matter ha^{-1} y^{-1} (2.2 ton per acre per year) without risk of losing soil carbon. The results from Poffenbarger et al. (2015) are consistent with several other experiments. At two sites in central Iowa, 13 years of moderate residue harvest (4-5 Mg dry matter ha^{-1} y^{-1}) had no effect on soil organic carbon stocks from 0-120 cm (Nunes et al. 2021). And meta-analyses find that moderate residue harvest (33-66%) does not lead to soil carbon loss in the Midwest US (Qin et al. 2016; Xu et al. 2019; Nunes et al. 2020).

The production of a humus product from the residue during renewable natural gas production and return of the humus product to the field where the residue was harvested would likely account for at least a 1:1 substitution or replacement of harvested crop residue. For example, 1 Mg C ha^{-1} y^{-1} of humus return would replace at least 1 Mg residue C ha^{-1} y^{-1}. However, similar to biochar and in contrast to plant carbon, humus carbon likely contains a greater fraction of carbon compounds that resist microbial decomposition (i.e., are 'recalcitrant' or 'stable'). Hence, the replacement value of humus may be greater than 1:1 (e.g., 0.75 Mg humus C replaces 1 Mg crop residue C). Moreover, there are many other practices that may enable greater residue harvest without soil carbon loss by increasing carbon inputs (e.g., humus or manuring) or reducing carbon outputs to CO_2 (e.g., reduced tillage).

The risk of soil carbon loss from excessive residue harvest is low because there is a first order relationship between microbial decomposition (i.e., CO_2 output) and organic carbon inputs. In other words, outputs of CO_2 from the soil are proportional to organic C inputs to the soil. Hence, a very large annual residue harvest of, for example, 9 Mg dry matter ha^{-1} y^{-1} (4 tons per acre) might result in some initial loss of soil carbon, but the loss would be finite rather than continuous as microbial decomposition adjusts to the new residue C input level and the soil carbon stock re-equilibrates at a slightly lower level.

Cropping Systems Modeling

We used a cropping systems process model to supplement the literature described above. Cropping systems process models use numerical representations of biophysical processes to simulate how genetic, management, and environmental variables interact to affect outcomes of interest such as grain yield and environmental nitrogen losses. Weather forecasts, for example, are outcomes of process model simulations. In cropping systems research, process models are particularly important because outcomes of interest are the result of many interacting variables including weather. The number of potential interactions limits the potential for controlled experiments across all possible conditions.

The scientific literature indicates that residue harvest leads to higher yields, lower optimum nitrogen fertilizer rate, and less environmental nitrogen losses as nitrous oxide and nitrate. However, no study has simultaneously examined all outcomes. To gain further insight into residue harvest impacts on both productivity and environmental performance – specifically for central Iowa – we used the Agricultural Production Systems Simulator (APSIM version 7.9). Iowa State University is one of seven institutions developing and maintaining this model, which finds large acceptance in the global scientific community. The APSIM model can simulate crop growth (yields, biomass, grain N, etc.), water balance including drainage, evaporation, and nitrogen-carbon cycling including mineralization, denitrification, and other processes. The model has been extensively calibrated and applied to answer cropping systems questions in Iowa environments (Archontoulis et al., 2014, 2016, 2020; Puntel et al., 2016, 2018; Martinez-Ferial et al., 2016, 2018, Dietzel et al., 2016; Castellano et al., 2019; Baum et al., 2020; Pasley et al., 2021) and the model has been further improved to account for excess moisture stress on root growth and yields as well for the continuous corn yield penalty (i.e., lower yields despite higher nitrogen requirements in corn following corn than corn following soybean; Ebrahimi-Mollabashi et al., 2019; Pasley et al., 2020; Archontoulis et al., 2020).

Here we used a well-calibrated and validated version (the model sufficiently reproduces observations, see Martinez Feria et al., 2016; Dietzel et al., 2016) for a central Iowa field (Kelley). The Kelley field is part of the Iowa State University experimental network and is located 10 miles from Ames. The soil is from the Nicollet soil series, with subsurface drainage at 1.1 m and tile-to-tile distance of 13 m. For additional information on the location and model performance, we refer to Dietzel et al. (2016) and Martinez-Feria et al. (2016).

We performed a 31-year simulation using historical weather-years (1990-2020) in which we explored a continuous corn crop with 4 levels of residue harvest every year (at crop harvest): 0, 33, 66 and 99% (Fig. 2). Every year the crop was planted on May 5 (111-day hybrid using 2020 genetics) and received 200 kg N ha^{-1} fertilizer on April 15. Over the 30-year period, the model results for the baseline scenario (0% residue removal) indicated a grain yield of 228 ± 42 bu^{-1} ac^{-1} y^{-1}, nitrate leaching of 18.5 ± 15.2 lb N ac^{-1} y^{-1} (20.7 ± 17 kg ha^{-1} y^{-1}) and N_2O emissions of 6.1 ± 0.9 lb N ac^{-1} y^{-1} (6.9 ± 1.0 kg ha^{-1} y^{-1}).

Residue harvest increased yields and decreased N losses (Fig. 2) in line with literature reports (see above). The simulated results can be used to estimate the percent residue removal to maximize ecosystem services. For example, as shown in Figure 2, 66% residue harvest increased grain yield by 6% (~15 bu ac^{-1}) compared to the 0% residue removal scenario while there was an 81% reduction in nitrate leaching (17 kg NO_3^--N ha^{-1}), and 20% reduction in nitrous oxide emissions (1.4 kg N_2O-N ha^{-1}). Although residue harvest resulted in 5% lower equilibrium soil carbon stocks, humus return would mitigate this effect. **Note: the reduction in soil carbon is finite while the reductions in nitrogen losses and the increase in yield are perpetual so long as the management remains the same.**

The reductions in nitrogen losses were caused by lower levels of soil moisture; the residue removal treatments increased soil water evaporation. The depth to the water table increased by 9.8" or 25 cm (31-yr average). This large increase in depth to water table benefits root growth and therefore crop resilience to unfavorable weather. The increase in yield is attributed to the increased plant-available nitrogen as the microbes had to immobilize less ammonium and nitrate in the soil to break down the high carbon-to-nitrogen ratio corn residue. The lower equilibrium soil organic carbon stock is due to less carbon return to the system. This result is inconsistent with experiments described above and is likely due to the fact that the soil carbon loss is real but small and much less than the within-field variability in soil carbon stocks, which creates significant measurement challenges. Another observation from the 31-year simulation is that residue harvest increased grain yield stability (i.e., the year-to-year variability in grain yield). The coefficient of variation of grain yield was 18% with 0% residue harvest and decreased to 11% with 66% residue removal harvest.

In the simulations described above, we used 200 kg N fertilizer ha^{-1} (180 lbs N ac^{-1}). To explore the impact of residue harvest on the economic optimum nitrogen fertilizer rate, we performed additional simulations with varying levels of nitrogen fertilizer to reconstruct the yield response to nitrogen fertilizer. Results indicated that 66% residue harvest decreased the optimum N rate by 40-50 lbs N ac^{-1}

and decreased environmental nitrogen losses across all nitrogen fertilizer rates (Fig 3). However, inconsistent with literature reports, the yield penalty due to residue retention was eliminated with sufficient N fertilizer input (i.e., yields converge at the highest N fertilizer input; Fig 3). One possible reason for this discrepancy is that field experiments often do not include sufficiently high N fertilizer inputs in continuous corn systems to estimate the economic optimum N rate (Poffenbarger et al. 2017).

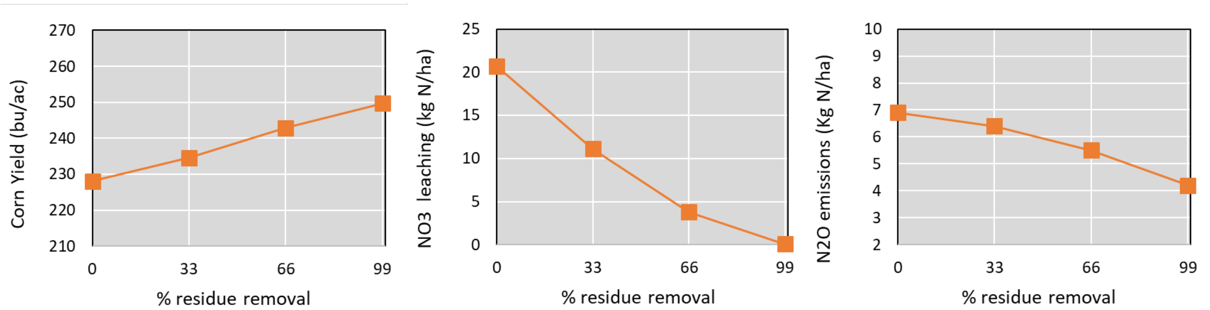

Figure 2. Simulated 31-year residue removal (0, 33, 66 and 99%) impacts on mean annual crop yields, NO_3^--N leaching, and N_2O emissions in Kelley, Iowa. In this scenario, we simulated a continuous corn system with no-tillage and 200 kg N ha^{-1} y^{-1}.

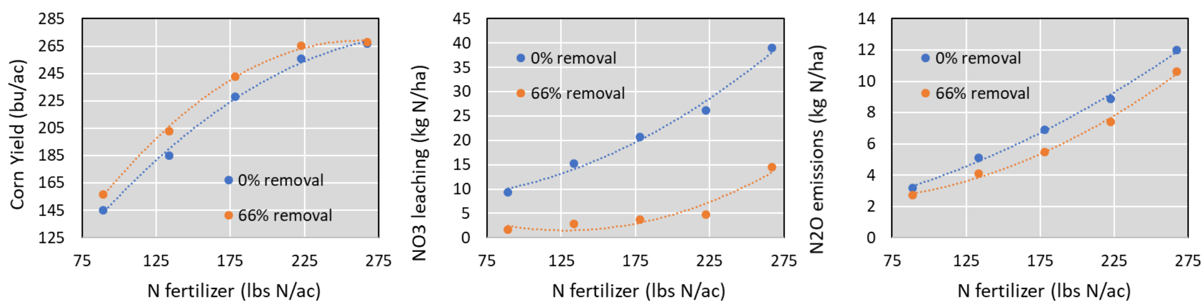

Figure 3. Simulated 31-yr average residue removal practice effects on the yield response to N fertilizer (left panel), NO_3^--N leaching (middle panel) and N_2O emissions (right panel).

Cropping Systems Modeling: The Net Effect on Global Warming Potential

Using the model simulation outputs above, we estimated the effect of 66% residue harvest on the global warming potential (GWP) of corn production as the sum of CO_2 equivalents (CO_2e) from the following processes: N_2O emissions from the soil surface, downstream N_2O emissions from leached NO_3^-, and greenhouse gas emissions associated with the synthesis, delivery and application of N fertilizer. Because N_2O has a long lifespan in the atmosphere, we used the 100-year warming potential where one kg of N_2O traps 298 times the heat of one kg of CO_2 (1 kg N_2O emission from the soil surface = 298 kg CO_2e). To account for N_2O emissions that are produced from NO_3^- after it is leached from the field, we used the Intergovernmental Panel on Climate Change (IPCC) EF5 emission factor of 0.011 kg N_2O-N kg^{-1} NO_3^-–N leached. The synthesis, delivery and application of nitrogen fertilizers emits large amounts of greenhouse gases and we used a factor of 2.6 kg CO_2e kg^{-1} NH_3. We excluded GHG emissions associated with potential effects of residue harvest on CH_4 emissions/consumption from the soil and fuel use for farm operations. Nevertheless, residue harvest would almost certainly decrease CH_4 emissions and perhaps generate soil CH_4 consumption (net CO_2e sink).

Residue harvest of 66% led to a net reduction of 0.75 metric tons CO_2e per acre per year (35%). The reduction was largely due to reductions in N_2O emissions and nitrogen fertilizer inputs (Table 2).

Table 2. Comparison of continuous corn and continuous corn production with 66% residue harvest on the global warming potential of each system.

System	Economic Optimum Nitrogen Rate (lb N/acre)	Grain Yield (bu/acre)	CO_2e from NH_3 Synthesis (lbs CO_2e/acre)	N_2O Emissions (lb N/acre)	CO_2e from N_2O Emissions (lbs CO_2e/acre)	NO_3 leaching (lb N/acre)	CO_2e from N_2O Emissions from NO_3 leaching (lbs CO_2e/acre)	Global Warming Potential (metric tons CO_2e per acre)
Continuous corn with no residue harvest and tillage	267	267	843	7.9	3,699	23	120	2.11
Continuous corn with 66% residue harvest and tillage	222	268	701	4.9	2,295	3.4	17.5	1.37

We did not include potential differences in equilibrium soil organic carbon stocks although the model simulation indicated 5% lower equilibrium soil organic carbon stocks with 66% residue harvest. It is important to recognize that the global warming potential associated with soil organic carbon loss – if it occurs – is finite whereas the global warming potential associated with N fertilizer use and losses accrue every year of crop growth. If 66% residue harvest did cause a 5% reduction in soil organic carbon stocks, in most central Iowa soils, this difference would be approximately 4,000 kg C ha^{-1} or 5.9 metric tons CO_2e per acre. In this case, the annual reduction in global warming potential due to residue harvest (Table 2) would take approximately 8 years to account for the lower equilibrium soil carbon stock (i.e., 5.9 / (2.11 – 1.37)). However, addition of the humus product is likely to equalize soil carbon stocks. Our model analyses did not accommodate addition of the humus product.

The magnitude of model outputs in this analysis is conditional to user input such as soil, weather, hybrid, and management. However, the direction of model results is robust (i.e., increase yield, decrease in optimum nitrogen fertilizer rate, decrease N_2O, decrease in NO_3^-). This analysis (Figs. 2–3, Table 2) represents a case study for an experimental location with a large amount of measured data including crop N uptake and nitrate leaching. Nonetheless, readers should focus on the direction of results.

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