Effect of crop residue harvest on long-term crop yield, soil erosion and nutrient balance: trade-offs for a sustainable bioenergy feedstock

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Background: Agricultural residues could potentially be converted to bioenergy, but the sustainable harvest rate is unclear. **Results:** Residue removal increases soil loss at rates that vary with topography, crop rotation and management; decreases yields (100-year mean yields changed -0.07% to -0.08% for every percent of residue mass removed); decreases soil carbon (roughly 40–90 kg C ha^{-1} year^{-1} per Mg of residue harvested); and decreases soil nitrogen (~ 3 kg N ha^{-1} year^{-1} per Mg residue harvested). **Conclusion:** Even where soil loss is within tolerable limits, harvesting residue is a question of trade-offs in terms of reduction of yield and loss of soil nutrients. The effects of increased residue harvest are highly variable, depending on local climate and soil erodibility and it is thus problematic to apply a single harvest rate globally. However, on flat land under conservation management, the majority of residue could be sustainably harvested for bioenergy.

As the role of renewable fuels increases in the US energy portfolio, bioenergy has garnered much attention as a low-carbon alternative to petroleum, particularly in the transportation sector. In recent years, there has been a dramatic expansion of biofuel production: in the USA, ethanol production increased by over a factor of six in the last decade (1998–2008) to 9 billion gallons per year (34 GL year^{-1}) [101]. The Energy Independence and Security Act (EISA), passed by the US Congress in 2007, mandates a further expansion to 36 billion gallons of biofuels per year (136 GL year^{-1}) by 2022. Of this, 21 billion gallons per year (79 GL year^{-1}) would be from so-called advanced biofuels – ethanol derived from sources other than corn starch, such as cellulosic ethanol. In addition to ethanol, biomass could also be combusted or cofired in power plants to produce electricity, displacing coal, or serve as chemical feedstock to replace natural gas. Alternatively, sequestered residue (e.g., in deep water) could present an option for reducing atmospheric concentrations of CO_2 [1].

Meeting the growing demand and legislated targets for increased production of bioenergy will require a dramatic increase in biomass feedstock supply and some have expressed concern over the potential negative impacts this would have. For example, the expansion of agriculture into natural areas could result in a loss of biodiversity [2,3] and may incur an insurmountable carbon debt from emissions from land conversion [4]. Intensive farming of land under the Conservation Reserve Program (CRP) or marginal lands could lead to deer [5] and bird [6] habitat destruction, increase water consumption [7], exacerbate soil loss [8] and increase nutrient run-off and eutrophication of riparian and aquatic systems [9]. Furthermore, economic analyses have suggested that competition for crops could increase food prices [10,11].

Some of these drawbacks can be mitigated by taking advantage of agricultural residues. Agricultural residues are already produced as a coproduct of food and fiber production and thus have a large potential as a bioenergy feedstock, requiring no new land or technology to produce. For these reasons, they are likely to be a much cheaper and a more immediately available source for biomass feedstocks than crops such as switchgrass (*Panicum virgatum*) or hybrid poplar (*Populus* spp.).

However, it is unclear what effect different rates of residue biomass removal will have on soil erosion and crop yields. If large-scale exploitation of crop residues

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Key terms

Bioenergy: Commercial or industrial energy derived from plant and other biological sources

Biomass: Mass of living matter within a given area

Agricultural residue: Stalks, leaves and other aboveground nonfood portions of agricultural crops

Soil erosion: Mechanical removal of soil by water or wind

Soil organic carbon: Carbon held within the soil from plant and animal sources

results in increased erosion and lower yields, then less residue would be available per unit area of land as time progresses, and aggregation and transportation costs would increase. Additionally, more land would need to be brought into production to feed a growing global population. The question of a sustainable residue harvest rate is a question concerning the conditions under which residue harvest is practical and environmentally sensible. It is also a question of trade-offs in terms of yield, erosion and nutrient balance.

Existing studies on sustainable residue harvest rates typically focus on a specific crop and often a single field site. Much of the current research on crop residue has focused on corn residue (stover) owing to the large of amount of biomass this crop produces and because annually, the USA produces more corn by mass than all other field crops combined [12]. Based on a series of field studies and limitations of current equipment available, the maximum logistical harvest rate for corn stover is approximately 75% by mass, although the sustainable harvest rate (in terms of erosion control and soil nutrients) is understood to be lower [13]. A review by Mann, Tolbert and Cushman stresses that research is needed, in order to understand the long-term relationship between corn residue removal, erosion, water quality, nutrient dynamics, crop productivity and management strategies [14]. Hoskinson *et al.* examined the economics of replenishing soil nutrients from different levels of stover removal and recommended a 40-cm cutting height, optimizing removal of the typically drier upper part of the corn stalk and leaving the wet portion to replenish soil nutrients [15]. Graham *et al.* concluded that only 28% of stover could be removed under current production practices if soil erosion were to remain below 0.5 Mg ha^{-1} [13]. Graham *et al.* also concluded that with improved conservation management practices, such as wide adoption of no-till practices, residue removal rates could approach 50% and up to 100 Tg of stover (dry basis) per year could be produced in the USA [13]. Adoption of no-till practices tend to reduce erosion, retain soil nutrients and reduce carbon loss over conventional tillage in the upper layers of the soil [16]. More stringent erosion control requirements, however, significantly reduce the estimated amount of corn stover available [13]. For example, even with no-till practices, removal of corn stover has been shown to increase soil bulk density and reduce soil water content in a 1 year field experiment [17,18]. Blanco-Canqui *et al.* offer a limit of corn stover harvest at 1.25 Mg ha^{-1} (~ a 25% removal rate) for sustaining soil quality, but point out that more research and monitoring is needed to better establish this threshold [18].

In a US Department of Agriculture (USDA) White Paper, Andrews reviews predicted impacts of residue removal on erosion, soil organic matter and nutrients, and future crop yields; a maximum 30% residue removal rate is given as a general recommendation, with the caveat that this number can only serve as a rough guide and site-specific research and guidelines need to be developed [19]. This value, 30% residue removal, is commonly used in larger modeling studies, such as in studies that consider the potential for ocean sequestration of carbon by sinking crop residues in the deep ocean [1].

However, these optimal residue harvest rates can only be understood as average values to be applied on a large geographic scale. In a literature review on corn stover, Wilhelm *et al.* recognized that removal rates would vary depending on local crop yield, climatic conditions and management practices, and stressed the need for the development of a procedural tool for recommending a maximum-possible amount of corn stover removal to sustain crop productivity [20]. Based on a modeling study of ten corn-producing counties, Wilhelm *et al.* suggested that, on average, approximately 30% of residue could be harvested above a base corn yield of 7–17 Mg ha^{-1} [21], depending on the tillage system used, but also noted a high degree of local variability. As cellulosic conversion technology progresses, Wilhelm *et al.* stressed the need for further study and validation of sustainable residue harvest for multiple locations and cropping systems [21].

Focusing on a specific crop, such as corn (*Zea Mays* L.), gives information regarding the logistics and dynamics of residue removal at the field level, but results are not necessarily applicable from one crop to another or to long timescales. While corn is the dominant crop in the USA, it is frequently grown in rotation with other crops and, moreover, many local areas specialize in other crops that can also provide a potential source for residue biomass. Residue biomass is substitutable between different feedstocks; for example, stringent erosion control on corn can raise the demand for residue from crops with less stringent erosion control requirements, such as wheat (*Triticum aestivum*). Therefore, an economic and environmental assessment must consider a variety of cropping systems over an extended period of time. The purpose of this study is to apply a biophysical simulation framework to examine multiple crop rotations at multiple locations over a 100-year timeframe in order to improve our understanding of the relationships among residue harvest, crop yields, soil loss, carbon and nitrogen balance, and management strategies of sustainable biomass feedstock systems from agricultural residues. The goal is to determine the sensitivity of crop yield, erosion and nutrient balance to residue removal through the simulation of hypothetical agricultural fields.

Materials & methods

We designed a factorial modeling study to determine the effect of different levels of residue harvest on soil erosion, crop yields and carbon and nitrogen balance. The Erosion Productivity Impact Calculator/Interactive Environment Policy Integrated Climate (EPIC) model [22] was selected to simulate all these interacting effects owing to its strength in management details (e.g., crop rotations, tillage and conservation management), erosion processes (i.e., water and wind erosion) and ecosystem nutrient balance [23].

▪ Study design

The simulations were designed to determine the cross effects of cropping system, location (soil and climate), topography (slope) and to predict under what conditions and management strategies residue harvest would be sustainable. In addition, this allows the prediction of trade-offs in terms of carbon and nitrogen loss. Four crop rotations were considered: winter wheat (*Triticum aestivum* [L.]) – sunflower (*Helianthus annuus*); spring wheat (*Triticum aestivum* [L.]) – canola (*Brassica napus*); corn (*Zea mays* L.) – soybean (*Glycine max* [L.] Merr.) and cotton (*Gossypium hirsutum*) – peanut (*Arachis hypogaea*). For each cropping system, four locations were selected **(Table 1)**. The first location selected for each cropping system was the highest-producing county (by mass of the lead crop) in the highest-producing state. The second selection for each

Table 1. List of location samples by crop rotation, including dominant watershed and soil type.

Sample	County	US state	Major HUC	Dominant soil
Winter wheat and sunflower				
First county in first state	Sumner	KS	11060005	Detroit
First county in second state	Whitman	WA	17060108	Palouse
Weighted random sample 1	Cassia	ID	17040210	Declo
Weighted random sample 2	Grant	OK	11060004	Dale
Spring wheat & canola				
First county in first state	Cavalier	ND	09020313	Barnes
First county in second state	Polk	MN	09020303	Minnetonka
Weighted random sample 1	Swift	MN	07020005	Buse
Weighted random sample 2	Grand Forks	ND	09020307	Arvilla
Corn & soybean				
First county in first state	Kossuth	IA	07100003	Kenyon
First county in second state	McLean	IL	07130009	Drummer
Weighted random sample 1	Dawson	NE	10200101	Blendon
Weighted random sample 2	Audubon	IA	10240003	Tama
Cotton & peanut				
First county in first state	Hale	TX	12050006	Acuff
First county in second state	Mississippi	AR	08020203	Askew
Weighted random sample 1	Bertie	NC	03010107	Craven
Weighted random sample 2	Darlington	SC	03040201	Eunola

First location selected for each cropping system was the highest producing county (by mass of the lead crop) in the highest producing state.
Second selection for each crop rotation was the highest producing county in the second highest producing state.

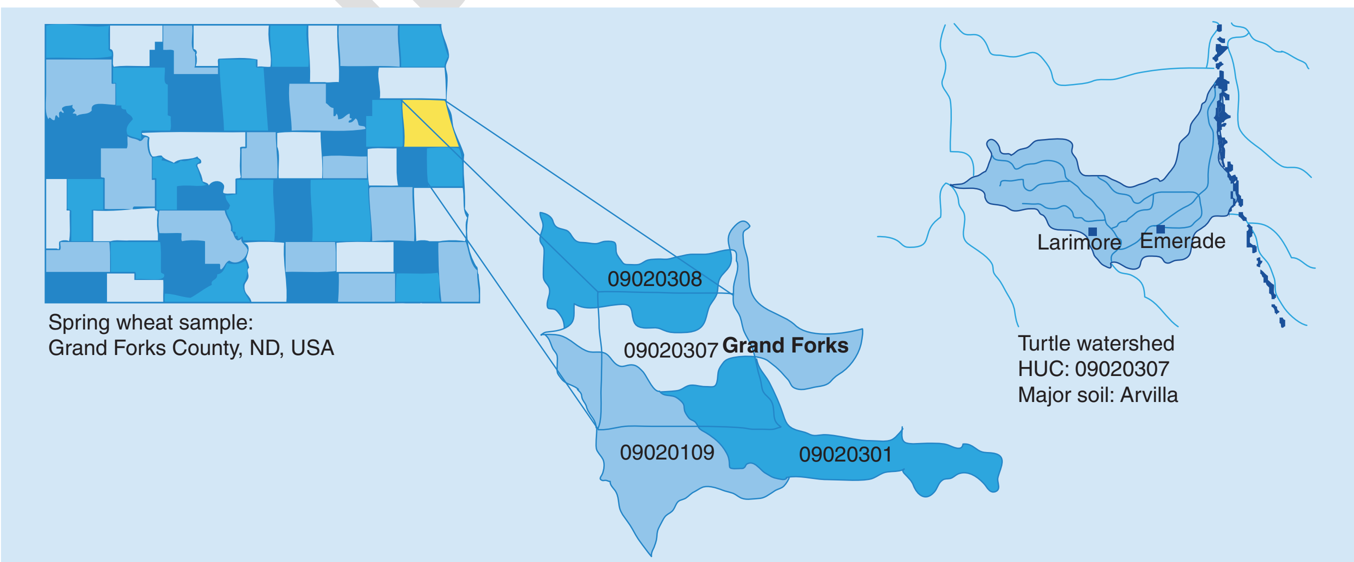


Figure 1. Method for selecting watersheds and soil type from county samples.
HUC: Hydrologic unit code.

crop rotation was the highest-producing county in the second highest producing state. Two additional counties were selected randomly for each crop rotation, by assigning probability weights based on the current annual production of the lead crop. This hybrid systematic-random selection process was designed to both ensure spatial variability and also choose characteristic regions where it would be most economic to produce, deliver and process residue biomass (Figure 1). Soil type, soil layer data and historical weather data were taken from the National Nutrient Loss Database [24]. For each location, the dominant eight-digit watershed (by area) was selected and within each watershed, the dominant soil type (by percentage) (Figure 2) was selected to represent a sample 1-ha plot (Table 2). This created a total of 16 sample locations (Table 1), dispersed across the USA. To account for differences in topography, four slopes (0.1, 1, 5 and 10%) were tested at each location, where slope length was assumed to be 100 m.

Crop systems were simulated for 100 years under two contrasting management strategies: the conventional management strategy, using conventional tillage and no conservation measures; and the conservation management strategy, which employed no-till management as well as strip cropping, contouring cropping and terracing. The conventional management system utilized a tandem disk set to a tillage depth of 75 cm, a field cultivator set to a tillage depth of 50 cm and a planter set to a depth of 40 cm.

The conservation management system used a no-till system, which retains organic matter and soil cover, as well as below-ground biomass, thereby reducing the amount of soil exposure and erosion. Contouring (planting in line with topographic contours) and strip cropping (planting crops in alternating swaths) reduce run-off by creating landscape breaks and slowing water flow. Terracing (building steps into a graded hillside) has the effect of reducing the slope length by the following relationship:

$$L_{terracing} = \frac{0.3\left(X \times S + Y\right)}{Sin\left(\arctan\left[S\right]\right)}$$

where $L_{terracing}$ is the slope length interval between terraces, S is the slope in percent, X is a location-specific constant that varies across the USA from 0.4 in the south to 0.8 in the north and Y is a soil erodibility constant, set to 2.5.

For each location, slope and management combination, six levels of residue harvested were modeled: 0, 15, 30, 45, 60 and 75%, the latter representing the theoretical maximum logistical harvest rate. Residue harvest was set up to occur annually, immediately after crop harvest, for all crops within a given rotation. Fertilizer and irrigation were automatically applied, based on plant nitrogen and water stress.

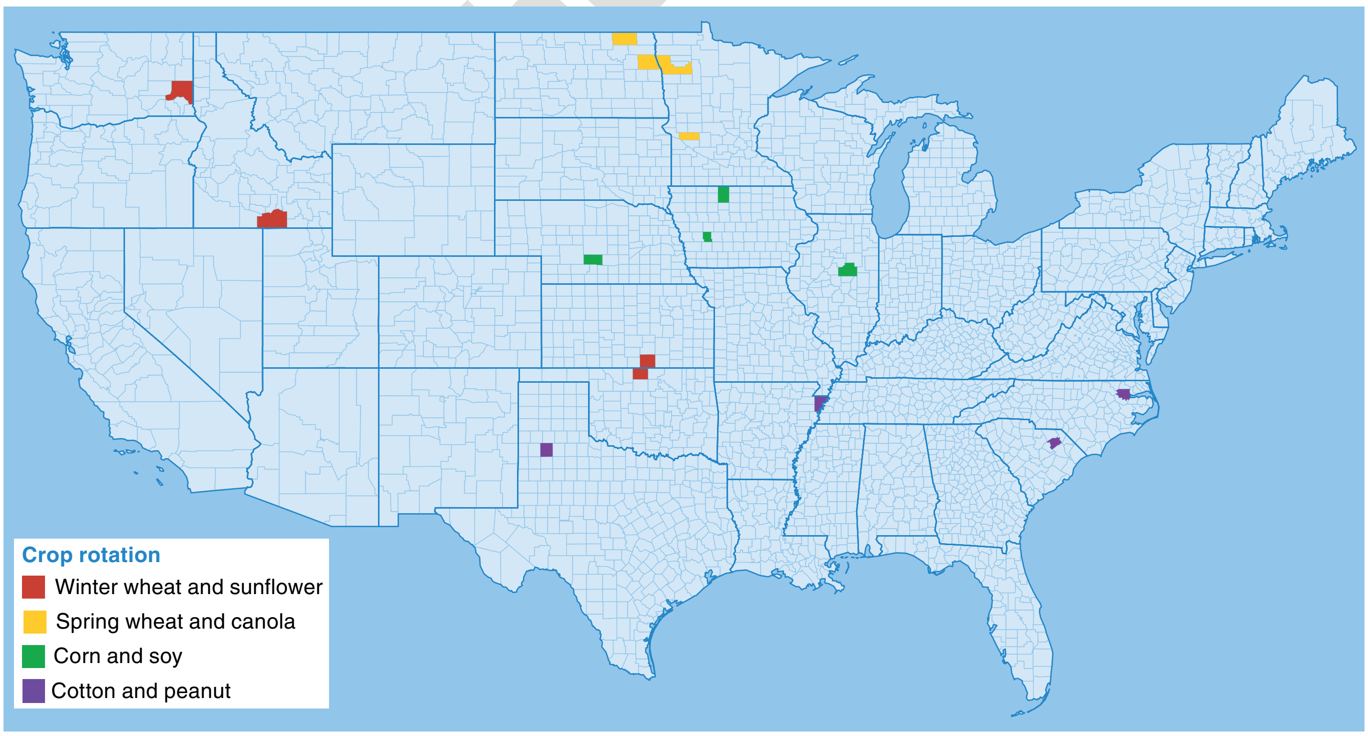


Figure 2. Map of sampled counties by crop rotation.

Table 2. Soil data used for simulated trials.

Soil	Horizons	Profile depth (m)	Bulk density 1st Horizon (Mg m^{-3})	AWC 1st horizon (m m^{-1})	AWC total profile (m m^{-1})	Sand content 1st horizon (%)	Silt content 1st horizon (%)	pH 1st horizon	SOC 1st horizon (%)	SOC total profile (%)
Winter wheat–sunflower										
Detroit	4	1.59	1.29	0.18	0.16	24.1	51.4	6.7	2.09	0.49
Palouse	3	1.44	1.22	0.20	0.20	11.3	67.7	7.0	1.52	0.88
Delco	4	1.52	1.37	0.14	0.12	43.0	39.5	7.9	1.08	0.25
Dale	3	1.61	1.30	0.20	0.19	11.4	68.1	7.0	2.02	0.94
Spring wheat–canola										
Barnes	5	1.51	1.34	0.16	0.12	43.0	39.5	6.7	3.38	0.54
Minnetonka	4	1.50	1.27	0.20	0.17	20.0	49.0	6.5	3.81	1.33
Buse	3	1.51	1.44	0.13	0.11	39.8	37.7	7.5	1.27	0.44
Arvilla	4	1.51	1.49	0.09	0.06	68.2	19.8	7.3	1.54	0.40
Corn–soy										
Kenyon	4	1.50	1.43	0.15	0.11	41.1	36.9	6.5	1.96	0.64
Drummer	4	1.50	1.27	0.21	0.18	9.4	67.1	6.7	2.80	0.66
Blendon	4	1.47	1.42	0.10	0.09	67.6	20.4	6.7	1.38	0.50
Tama	5	1.47	1.30	0.20	0.16	9.2	65.3	6.2	1.76	0.98
Cotton–peanut										
Acuff	4	1.97	1.44	0.09	0.09	52.9	18.7	7.2	0.74	0.30
Askew	4	1.83	1.43	0.19	0.16	8.7	66.2	6.2	1.12	0.39
Craven	4	2.01	1.40	0.15	0.14	29.3	53.7	5.1	0.61	0.18
Eunola	6	1.63	1.52	0.09	0.09	65.9	19.1	5.0	0.62	0.25

AWC: Available water content (field capacity – wilting point); SOC: Soil organic carbon.
Profile values represent weighted means based on soil horizon mass.

Characteristics of the EPIC model

The EPIC model simulates weather, hydrology, erosion, nutrients, soil temperature, plant growth, plant environment control, tillage and economic budgets on a field with homogenous soil, weather and management [22]. The model was developed in the early 1980s in order to estimate erosion and crop productivity. In 1985, it was used to estimate erosion for various land areas in the USA as part of the second Resources and Conservation Act (RCA). Since then, the EPIC model has been expanded to include aspects such as fertilizer application, crop rotation and tillage systems. Components of the model have been refined and validated with numerous empirical studies [25], for example, nutrient cycling [26,27], water erosion [28,29], wind erosion [30,31], soil carbon sequestration [32,33] and crop productivity [34,35].

Currently, EPIC is one of the only models able to simulate both water and wind erosion simultaneously on the same field. Water erosion is simulated in EPIC using the Modified Universal Soil-Loss Equation (MUSLE) [36]:

$$Soil\ loss = a(V \times Q_p)^b \times K \times L \times S \times C \times P$$

where a and b are constants, V is the volume of run-off, Q_p is the peak run-off rate, K is soil-erodibility factor, L and S define the slope length and gradient, C is the crop management factor and P is the conservation management factor. Simulation of conservation practices reduce soil loss in EPIC by changing the statistically derived run-off curve regression parameters (frequency and depth of tillage). EPIC also alters the runoff curve parameters based on the number of conservation measures in place, with different values between 0, 1 and 2 or more simultaneous conservation measures. EPIC does not distinguish between the specific conservation measures (strip cropping, contouring and terracing), with the exception that terracing also reduces the slope length, thereby further reducing soil loss.

Table 3. Relationship between residue removal rate and mean residue harvested (all locations, all years).

Residue harvest rate (%)	15	30	45	60	75
Mean residue harvested (Mg ha^{-1} year^{-1})	1.1	2.0	2.9	3.7	4.6
2σ residue harvested (Mg ha^{-1} year^{-1})	0.5	0.7	1.1	1.6	2.0

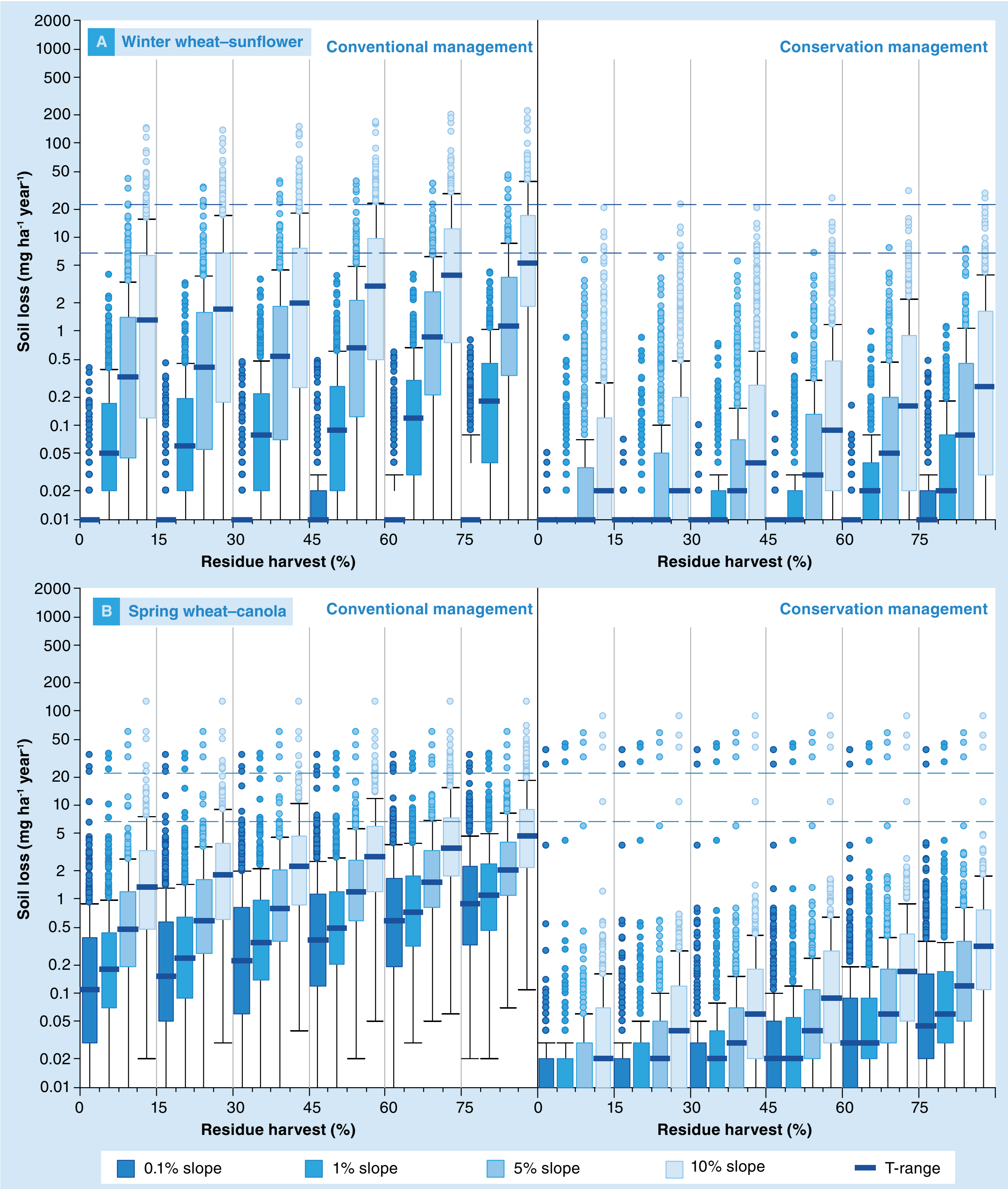
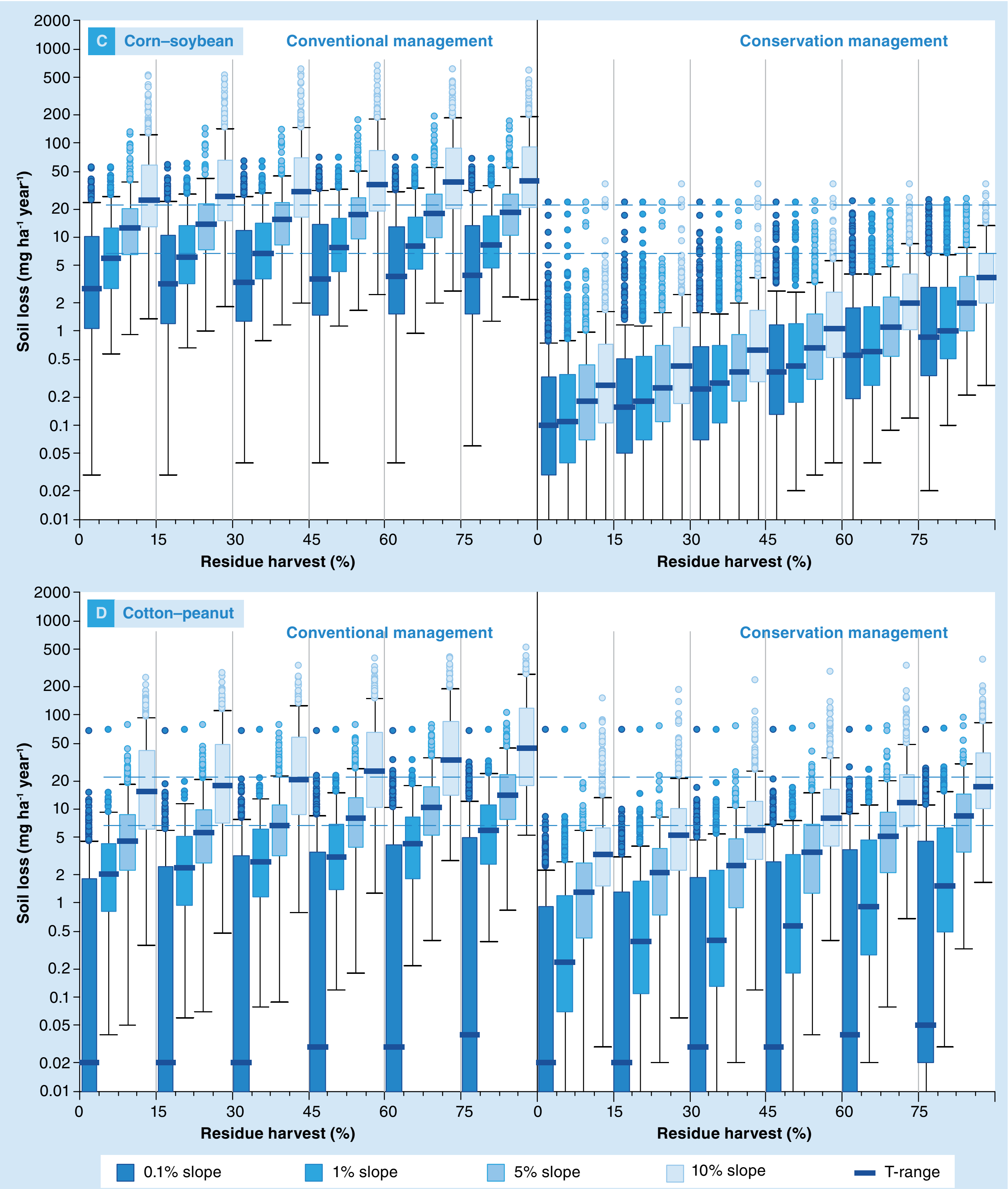


Figure 3. Total annual soil loss (sum of water and wind erosion) versus slope and residue harvest rate under both conservation and conventional management. Each point represents total soil loss for a given year at a given location, there are 100 years at four locations for a total of 400 points at each level. The bars represent the median values; the box encloses the 25th and 75th percentiles (1st and 3rd



quartiles). Error bars extend to 1.5 times the interquartile range for each level. The 'T' value represents a range of typical tolerable soil losses, from 3–10 tons acre^{-1} year-1 (6.7–24.5 Mg ha^{-1} year^{-1}). Note the logarithmic scale on the y-axis.
(A) Winter wheat–sunflower rotation, **(B)** spring wheat–canola rotation, **(C)** corn–soybean rotation and **(D)** cotton–peanut rotation.

Wind erosion is calculated with the Wind Erosion Stochastic Simulator (WESS) [31]. The EPIC model generates weather data stochastically with a fixed random number seed, based on historical records. Operations were scheduled using climate data specific to each location and each modeled year.

▪ Simulation runs & analysis

The model runs were implemented and executed with i_EPIC, an interactive Windows®-based program developed at the Center for Agricultural and Rural Development at Iowa State University to facilitate the management and execution of large simulations with the EPIC model [37]. Though EPIC makes calculations at daily time step, output data were aggregated both at an annual time step for all runs and at the total simulation length of 100 years. Analysis of the output data (e.g., regressions and box plots) was done with the R environment (GNU S).

Results & discussion

The relationship between residue harvest rate and residue collected is summarized in Table 3. On average, as the residue harvest rate increases by 15%, residue harvested increases by approximately 0.9 Mg ha^{-1} year^{-1}.

In general, crop erosion increases with increased residue harvest, particularly in the simulations using conventional management (Figure 3). Slope was also a confounding factor; row crops, such as corn, under conventional tillage were generally more susceptible to erosion with increasing slope. However, implementation of conservation management practices allows for more residue to be sustainably removed at greater slopes.

In terms of mitigating soil loss, the results suggest that most of the available residue can be sustainably harvested from the winter wheat–sunflower rotations, although with 10% greater slopes under conventional management, the limit is around 45%, depending on local values for tolerable soil loss (Figure 3A). Most residue can also be sustainably harvested from spring wheat–canola rotations (Figure 3B) and remain under tolerable soil loss for most locations. The spring wheat–canola fields located in the upper Midwest were highly susceptible to extreme weather events, particularly wind erosion. Reducing residue harvest had little impact in preventing erosion from extreme weather events on these fields, rather, implementation of conservation management reduced soil loss from these events at all levels of residue harvest. For the corn–soybean rotation, conservation management is critical if residue is harvested. Under conventional management, residue harvest is practical only on fields with slopes of less than 1% (Figure 3C). Conservation management, on the other hand, allows for most of the residue to be removed, up to slopes of 10%, although erosion does increase with increasing residue removal (Figure 3C). Conservation management had less effect on cotton–peanut rotations, where 45–60% residue harvest is sustainable only on slopes of 1% or less under conventional management and approximately 5% or less under conservation management (Figure 3D). In this study, cotton–peanut fields with slopes of 10% could only have 15% sustainable residue harvest under conservation management and, even then, erosion would be within the range of tolerable soil loss. This is likely due to the soil disturbance involved with harvesting ground nuts. Thus, residue harvest would likely be impractical from cotton–peanut rotations on steep slopes. Thresholds for sustainable residue removal rates, based

Table 4. Residue harvest thresholds with respect to tolerable soil loss.

Management system		Residue harvest rate (%)											
Crop rotation	Slope (%)	Conventional						Conservation					
		0	15	30	45	60	75	0	15	30	45	60	75
Winter wheat–sunflower	0.1	A	A	A	A	A	A	A	A	A	A	A	A
Spring wheat–canola	0.1	A	A	A	A	A	A	A	A	A	A	A	A
Corn–soy	0.1	B	B	B	B	B	B	A	A	A	A	A	A
Cotton–peanut	0.1	A	A	A	A	A	A	A	A	A	A	A	A
Winter wheat–sunflower	1	A	A	A	A	A	A	A	A	A	A	A	A
Spring wheat–canola	1	A	A	A	A	A	A	A	A	A	A	A	A
Corn–soy	1	B	B	B	B	B	B	A	A	A	A	A	A
Cotton–peanut	1	A	A	A	B	B	B	A	A	A	A	A	A
Winter wheat–sunflower	5	A	A	A	A	A	A	A	A	A	A	A	A
Spring wheat–canola	5	A	A	A	A	A	A	A	A	A	A	A	A
Corn–soy	5	B	C	C	C	C	C	A	A	A	A	A	A
Cotton–peanut	5	B	B	B	B	B	C	A	A	A	B	B	B
Winter wheat–sunflower	10	A	A	B	B	B	B	A	A	A	A	A	A
Spring wheat–canola	10	A	A	A	A	B	B	A	A	A	A	A	A
Corn–soy	10	C	C	C	C	C	C	A	A	A	A	A	B
Cotton–peanut	10	C	C	C	C	C	C	A	B	B	B	C	C

A: Erosion less than tolerable soil loss; B: Erosion within tolerable soil loss range; C: Erosion exceeds tolerable soil loss.
Erosion values represent the 75th percentile of annual soil loss in Mg ha^{-1}.

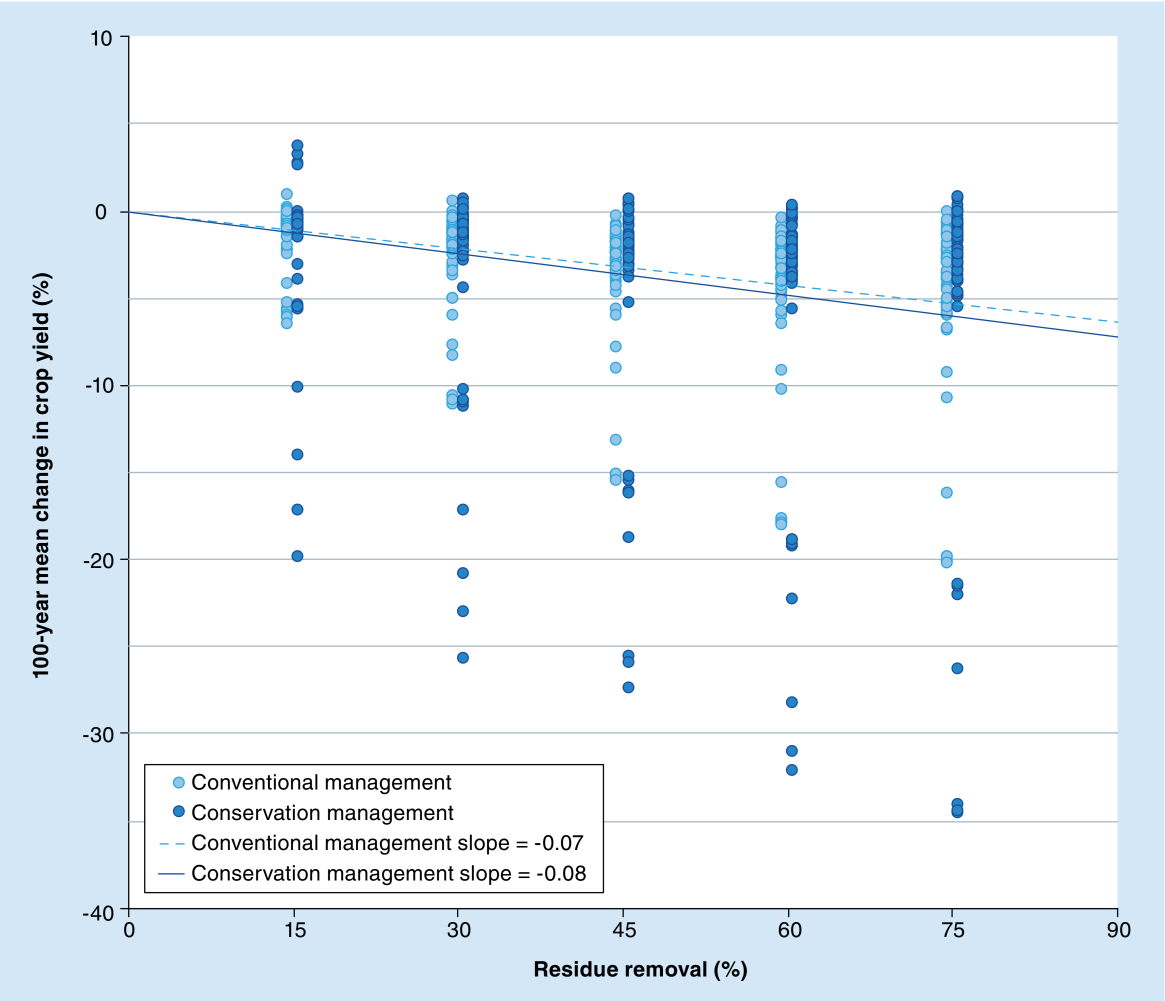


Figure 4. Mean percentage change in yield versus residue harvest rate by management over the base rate. The base rates are the corresponding trials (location, slope and management) with no residue removal.

on the 75th percentile of annual soil loss in (Mg ha^{-1}), are given in Table 4. Conservation management is able to allow a greater amount of residue to be harvested on land with higher slopes, particularly for corn–soy rotations. It is less effective at mitigating erosion on cotton–peanut rotations. Moreover, while corn stover has been the focus for much current research crop residues, Table 4 suggests that other crop residues, such as wheat straw, may be harvested more sustainably at greater rates. The 30% removal rate suggested by the USDA [19] and frequently employed as a parameter in large-scale national studies (see, for example, Strand, *et al.* [1]) is a rather conservative estimate in terms of soil loss. Additionally, given the variability with location, topography and management, it would be problematic to apply any single rate broadly across the entire country.

Although in general residue removal had only a modest effect on crop yields (Figure 4), in many fields erosion increased dramatically with increased residue removal. In some locations with steep slopes, too much residue removal caused a collapse of the system through excessive soil loss. In particular, the Declo soil in Cassia, ID, USA consistently saw large declines in yield with increasing residue removal, up to a 22% reduction at 75% residue harvest rate. Of the four winter wheat–sunflower locations, Cassia was under the most water stress and required more irrigation than any other location with this crop rotation. Increased residue removal exacerbated water stress in Cassia reducing crop yield. Grand Forks, ND, USA also experienced large percentage reduction in yields, but less consistently. Overall crop yields in Grand Forks were lower than in other locations for spring wheat–canola, owing to the high susceptibility to wind and water erosion.

Residue harvest did not reduce long-term yields as much in other locations; overall, for every additional percent of residue removed, the 100-year mean yield drop for all crops was approximately 0.07–0.08% (Figure 4). Even at a 75% residue harvest rate, the

100-year average annual yield dropped by approximately 6%, although for most locations the long-term yield reduction was less than 5% at this level of residue harvest. Interestingly, no significant difference was found between the yield drop in conservation versus conventional management strategies. The relationship between mean crop yields and residue removal is heteroscedastic (the variance in yields increases with increasing residue removal). The less residue left on the field, the more susceptible the field is to extreme weather events, increased erosion and reduced crop yield; but the relationship is probabilistic, depending on the local climate.

For many locations, management strategy, crop rotation and topography have a greater impact on erosion and crop yield than the rate of residue removal. Our simulations suggest that residue processing can be tailored to the crops of specific locations; in addition to corn, crops such as wheat, sunflower and canola may be a substantial source for residue biomass in areas where these crops are grown.

In most systems, the total carbon pool of the entire soil profile was reduced by increasing the residue harvest rate. However, since only a small part of the carbon in the residue left on the field is converted to soil carbon, these reductions were small, especially under conservation (no-till) practices. Mean reductions in total annual carbon per tonne of residue harvested were 90 kg ha^{-1} $year^{-1}$ under conventional practices and 40 kg ha^{-1} $year^{-1}$ under conservation practices (Figure 5). Even at 75% residue removal under conventional management, where 2 Mg C ha^{-1} $year^{-1}$ would be removed from the field, the total system would lose on average less than 0.5 Mg C ha^{-1} $year^{-1}$. This corroborates the finding that most of the carbon in agricultural residue decays into the atmosphere and only a small amount accrues in the soil (see, for example, Huggins

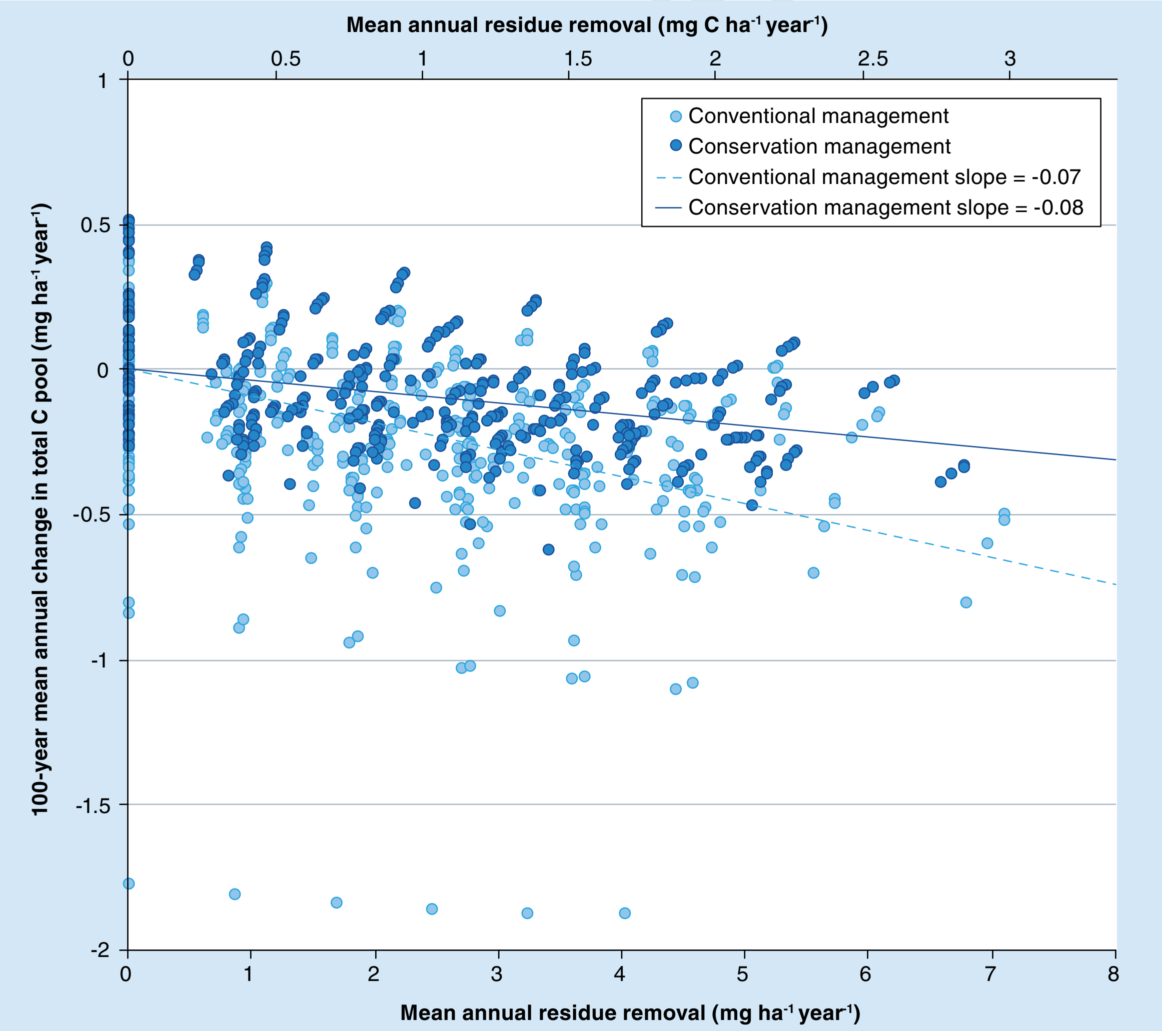


Figure 5. The 100-year mean annual carbon loss versus 100-year mean residue harvested (in absolute mass and mass carbon), by management. It is assumed that residue is 42% C.

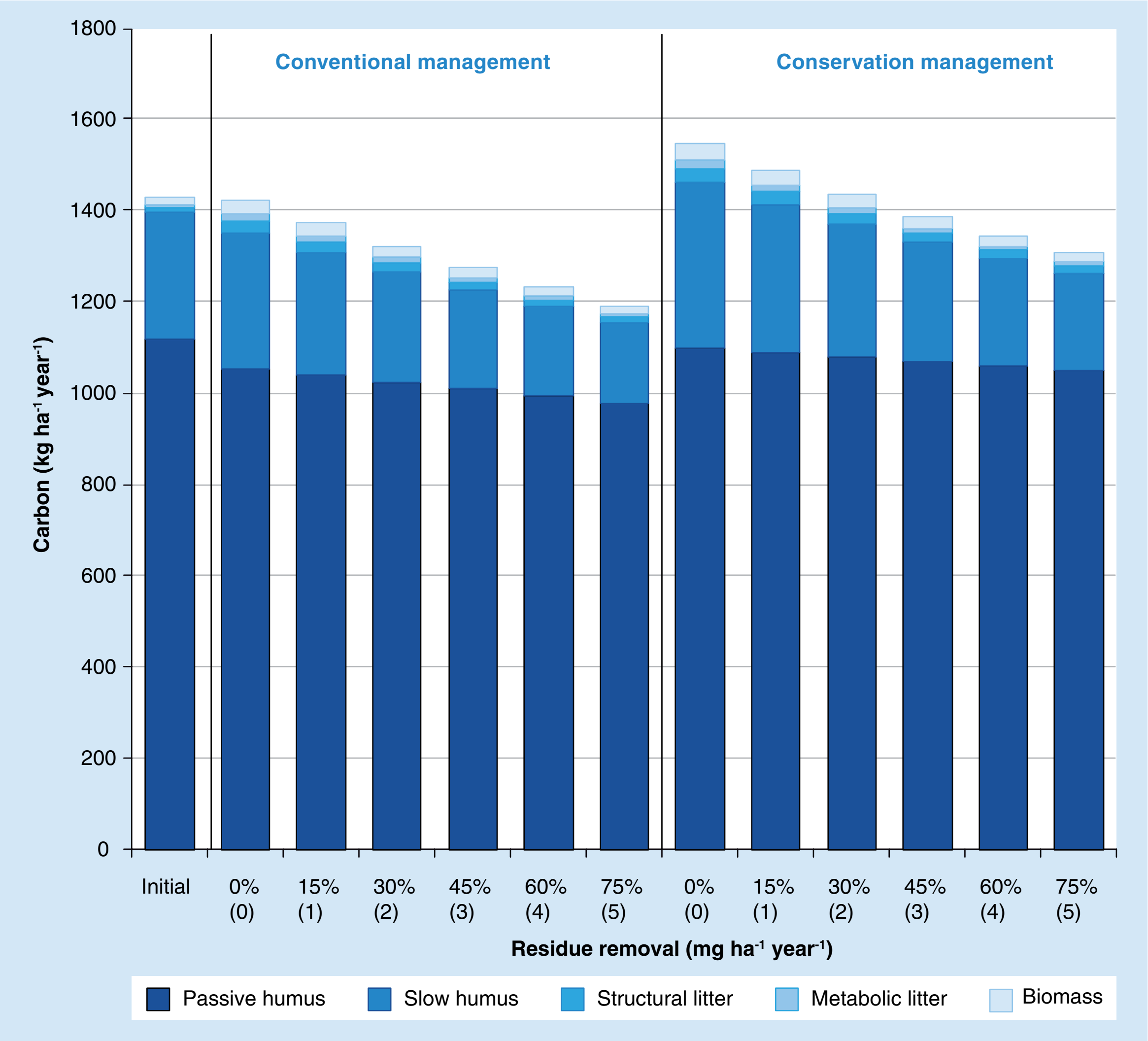


Figure 6. Mean soil carbon balance with different rates of residue harvest and management systems. Columns represent the mean from all slopes and all years.

et al. [38]). In general, all soil carbon pools are reduced with increasing residue harvest, although most of this loss occurs in the humus pools (Figure 6). Under conventional tillage, any amount of residue harvest, on average, results in a decrease in the total soil pool, but under conservation tillage, residue removal rates 30% and under, on average, will increase the total soil carbon pool (Figure 6). Therefore, using aboveground crop residue for bioenergy would emit carbon that would have mostly decayed into the atmosphere anyway. Assuming a typical residue harvest collection cost of approximately US\$150–175 ha^{-1}, the price of carbon under a hypothetical carbon policy would only slightly increase the cost of residue harvest and would not be a significant economic consideration.

Residue removal increases the loss of soil nitrogen in all pools. Nitrogen loss is particularly dramatic in the slow humus under conventional management, where, on average, up to 15 kg ha^{-1} year^{-1} is lost when high rates of residue are harvested (Figure 7). Again, less nitrogen is lost under conservation management; however, conservation management is less effective at retaining nitrogen as it is at retaining carbon. The mean rate of soil nitrogen loss is approximately 3 kg ha^{-1} year^{-1} per Mg of residue harvested and would not be a large economic consideration: approximately US\$1 per tonne of residue harvested.

Thus, harvesting agricultural residue for bioenergy is a question of trade-offs. Removal of residue results in increased soil loss, a general reduction of crop yield and loss of soil nutrients. However, much of these detriments can be mitigated through best-management practices. It is possible that sustaining yields while harvesting residue would increase demand for crop inputs such as irrigated water and fertilizer, although in this study, no significant

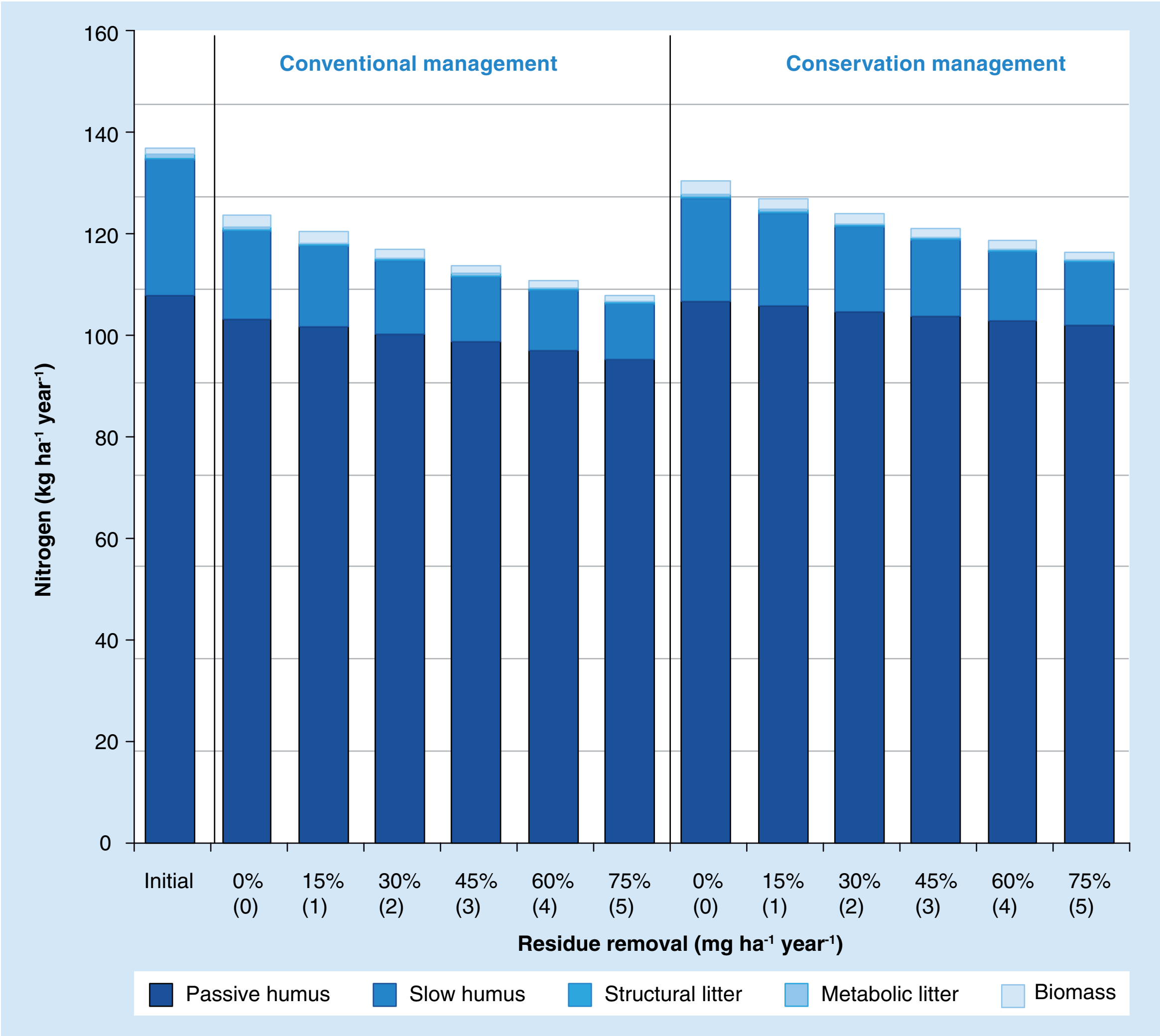


Figure 7. Mean soil nitrogen balance with different rates of residue harvest and management systems. Columns represent the mean from all slopes and all years.

difference was found in water use or fertilizer between the different levels of residue harvest. However, the base-level fertilizer and irrigation rates were set high, in order to produce maximum yields, and large treatment increments and application rates were used. In addition, a cap was induced so that the field would not be unrealistically fertilized or watered. All fields simulated in this study were irrigated and fertilized automatically based on plant stress, at large increments and a maximum-allowable application rate per year (irrigation: 100–200 mm ha^{-1} per application, maximum 1500 mm ha^{-1} year^{-1}; nitrogen fertilizer: 50 kg ha^{-1} application, maximum 200 kg ha^{-1} year^{-1}). These application rates were designed to approximate practical economic decisions a grower would likely make (e.g., it would not be economical to conduct multiple field passes in a season, applying only a small amount of fertilizer each time the crops became slightly stressed). In all trials the base level of irrigation and fertilization was set high enough to ensure maximum potential crop yield and the frequency of subsequent applications of fertilizer and water (as determined by plant stress) was highly variable across location and time.

These results are based on simulations and therefore are subject to errors and assumptions in the input data and model structure. In this study, there is no direct validation, since the fields, topography, management and crop choices were hypothetical and were designed to isolate the effect of specific parameters. Though EPIC has been validated with field results in numerous studies (discussed in previous sections), we cannot expect any model to perfectly predict the future. The principle uncertainties in these results would fall under two broad categories: future technology and future climatic conditions.

First, EPIC assumes no changes in agronomic properties of crops (e.g., increases in yield and changes in harvest index) and no developments in management strategies as technology and conservation management practices improve. Historically, crop yields have increased in the USA with improved technology, precision agriculture, best-management practices and chemical and genetic engineering. Yet it is unclear how these trends will continue into the future.

Second, weather data are based on historical climate data and therefore do not include regional climatic changes, particularly the expected increase in extreme weather events. No attempt was made in this study to project the behavior of plant growth under different global climate change scenarios, particularly increased atmospheric CO_2 concentrations; the atmospheric concentration of CO_2 was set at 390 ppm for the duration of all model runs. Holding atmospheric CO_2 concentrations stable for the next century is likely to be unrealistic, but this was done to isolate long-term trends and to allow for a basic discernment of the sensitivity of erosion, crop yield, carbon and nitrogen to different levels of crop residue harvest without the confounding variable of climate change. These two sources of uncertainty could dramatically affect the sustainability of residue harvest, both positively in the case of improved technology or negatively in the case of more extreme weather events.

Conclusion

In the search for a single number that represents a sustainable harvest rate, we find that sustainability is highly dependent not only on what crops are grown but also where and what conservation management practices are in place. In terms of remaining within tolerable soil loss, the currently accepted 30% of residue sustainable removal rate is likely a conservative estimate for large-scale national calculations. If conservation practices are in place on relatively flat land, a higher rate of sustainable residue harvest is likely possible. However, all farming is ultimately local and there is high variability in the sensitivity of erosion and yield to residue removal based on location (soil, climate and topography). In addition, crop rotation has an effect on the sustainable residue harvest rates. For example, more crop residue could be harvested from wheat rotations than corn–soy rotations, thus, applying a single residue harvest rate across a broad area (e.g., the entire USA) is likely to be impractical.

The question of residue harvest is one of trade-offs: removing residue will, in most cases, reduce soil carbon, reduce soil nitrogen, reduce yields and increase erosion. Nevertheless, with prudent use of conservation management practices and targeted collection on areas where the slope is modest, it may be possible to harvest a large percentage of crop residue for bioenergy while experiencing only little adverse effect on yield, soil loss, soil carbon and soil nitrogen loss.

Future perspsective

The US government has set aggressive targets for production of cellulosic ethanol by 2022. The feedstock for this will likely be made in large part by agricultural residue, as it is currently much cheaper to produce than dedicated bioenergy crops. It is likely that biorefineries will be optimized to take advantage of this local feedstock and perhaps seasonally adjust the enzymes to most efficiently convert residue biomass into ethanol. Growers will likely employ simulation models such as EPIC to determine the most sustainable management practices and residue removal rates for their particular fields. A market for agricultural residues may encourage greater adoption of no-till and conservation practices, as farmers attempt to not only maximize crop yields, but maximize a sustainable residue harvest as well.

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Executive summary

- Harvesting residue increases soil loss, particularly on fields with steep slopes. On flat areas, a large proportion of residue may be harvested and still remain with tolerable soil loss.
- Harvesting residue decreases crop yields, under both conventional and conservation management, although less so under conservation management.
- Conservation management practices (e.g., contour cropping, strip cropping, terracing and no-till) can reduce soil loss and allow for a higher rate of sustainable residue harvest. This is particularly the case for corn–soy rotations and less so for cotton–peanut rotations.
- Harvesting residue slightly reduces soil carbon in most cases, particularly when no conservation measures are in place. In some instances (e.g., under conservation management and 30% or less residue harvest) the soil carbon pool may increase.
- A carbon price for lost soil carbon would not significantly affect the cost of residue harvest.
- Harvesting residue reduces soil nitrogen, particularly in the humus pool. This would likely have to be made up with additional fertilizer.
- Sustainable residue harvest rates are highly local, depending on climate, topography, soil type and crop type.
- While corn stover has received much attention as a potential residue resource, other crops residues, such as wheat straw, could be harvested sustainably at higher rates.

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