Balancing limiting factors and economic drivers for sustainable midwestern US agricultural residue feedstock supplies

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ACRONYMS: CQESTR, carbon sequestration (model); EISA, Energy Independence and Security Act of 2007; HI, harvest index; MSC, minimum source carbon; MT, mulch/reduced tillage; NT, no-till; OM, organic matter; RUSLE2, Revised Universal Soil Loss Equation 2.0; SOC, soil organic carbon; SOM, soil organic matter; T, tolerable soil loss; WEPS, Wind Erosion Prediction System; WEQ, Wind Erosion Equation

Abstract

*Advanced biofuels will be developed using cellulosic feedstock rather than grain or oilseed crops that can also be used for food and feed. To be sustainable, these new agronomic production systems must be economically viable without degrading the soil and other natural resources. This review examines six agronomic factors that collectively define many of the limits and opportunities for harvesting crop residue for biofuel feedstock in the midwestern United States. The limiting factors include soil organic carbon, wind and water erosion, plant nutrient balance, soil water and temperature dynamics, soil compaction, and off-site environmental impacts. These are discussed in relationship to economic drivers associated with harvesting corn (*Zea mays *L.) stover as a potential cellulosic feedstock. Initial evaluations using the Revised Universal Soil Loss Equation 2.0 (RUSLE2)* *show that a single factor analysis based on simply meeting tolerable soil loss (T) might indicate that stover could be harvested sustainably, but the same analysis, based on maintaining soil organic carbon (SOC), shows the practice to be non-sustainable. Modifying agricultural management to include either annual or perennial cover crops is shown to meet both soil erosion and soil carbon requirements. The importance of achieving high yields and planning in a holistic manner at the landscape scale are also shown to be crucial for balancing limitations and drivers associated with renewable bioenergy production.*

Introduction

Globally, humankind is in the midst of one of the greatest technological, environmental, and social transitions since the industrial revolution, as we strive to supplement fossil energy with renewable sources. Almost daily, we are confronted through the media and other venues with concerns about energy supply, security, and the need to develop renewable and sustainable sources of energy without negatively affecting food, feed, and fiber supplies for a rapidly increasing global population. In 2009, the United States transportation sector consumed about 14 million barrels of oil per day, 9 million of which are used in light-duty vehicles,[1] and this consumption is expected to increase the demand for biofuel.

Currently, US biofuel production is dominated by ethanol made from corn grain and by biodiesel made from soybean [*Glycine max* (L.) Merr.]. The social, economic, and environmental effects of domestic biofuel production have been mixed. Diverting corn, soybean oil, or other food crops to biofuel production has been implicated for inducing competition between food and feed, and fuel,[2,3] but increases in crop price have also helped revive rural economies. These competing forces mean that achieving the goals associated with the US Energy Independence and Security Act of 2007 (EISA)[4] will require changes in the agricultural practices and decision processes that became "the norm" during the latter half of the 20th century.

Agriculture has a great ability to adapt to the challenges of meeting food, feed, fiber, and fuel demands in a sustainable manner. With photosynthesis as its fundamental process, agriculture provides a renewable source of light-energy capture that fixes carbon dioxide in building-block compounds for many other complex molecules, including materials needed to sustain humankind. Determining the adaptive capacity of the world's agricultural sector to sustainably meet these challenges requires addressing a complex and dynamic set of issues. Very simply, the first and most basic concern is an assessment of the aggregate productive capacity of agricultural lands under existing agronomic management scenarios. Of the world's 13.5 billion ha of land surface area, roughly 61% is currently in grassland or forest, and 12% is in cropland.[5] An additional 14% is considered potentially suitable for rain-fed crop production, although this projection should be treated with considerable caution because much of the land is in forests, wetlands, and other uses that provide valuable environmental services, including carbon sequestration, water filtration, and biodiversity preservation. Expansion of crop production in these areas could have detrimental effects.

Although the data suggests that, overall, there may be enough agricultural land to support a growing biofuels industry,[6] actual availability of that land is very regionally dependent. There may be a substantial discrepancy between available agricultural land and the demand for biomass for biofuel development. Biomass availability also depends on supply systems and economic viability of accessing the biomass resource. Another important component of economic viability is the purchase cost, which, as it increases, tends to encourage more resource availability.

Many plant species are being evaluated as potential feedstock materials that will have a major role in helping make the transition from fossil to renewable fuels. Examples include dedicated herbaceous crops such as switchgrass (*Panicum virgatum* L.) and *Miscanthus*; woody species such as poplar (*Populus* spp.) and willow (*Salix* spp.); and agricultural co-products such as sugarcane (*Saccharum* spp.) bagasse and a portion of the crop residues and woody litter that can be gleaned from fields and forests. Harvesting these plant residues, dedicated energy crops, or woody species as feedstock for renewable energy must be balanced with efforts to protect the soil, water, and air resources needed (1) to meet growing global food, feed, and fiber demands, and (2) for environmental services that keep our environment clean and habitable.

This review examines six agronomic factors that collectively define many of the limits and opportunities for harvesting corn stover for biofuel feedstock in the US Corn/Soybean Belt. Corn stover is estimated to be the source for ~75% of the total annual crop residue supply currently available for biofuel production.[7] The limiting factors include soil organic carbon, wind and water erosion, plant nutrient balance, soil water and temperature dynamics, soil compaction, and off-site environmental impacts.

Determining sustainable corn-stover removal rates for a biofuels industry

Corn stover is the aboveground plant material left in fields after the grain is harvested. Stover was identified in the *Billion-Ton Study* as an important potential feedstock[6] because of (1) its abundance (~35 million ha of corn were planted in the United States in 2008 and 2009) and (2) perceptions that excessive amounts of corn stover can be a nuisance to producers.[8–10]

Current corn stover collection technology is capable of recovering ~40% of the crop residue,[11–13] and foreseeable single-pass harvest technologies will be capable of collecting more than 70% of the aboveground crop residue.[14] Unfortunately, these equipment collection efficiencies often greatly exceed the amount of stover that can be sustainably removed. Several studies have shown that sustainable residue removal rates are extremely site-sensitive and often allow even less than 40% residue removal to maintain SOC and essential plant nutrients, as well as to prevent wind and water erosion, soil compaction, and other forms of environmental degradation.[7,10,15,16]

Excessive harvest of corn stover as a biofuel feedstock or for any other purpose will decrease annual carbon input and may slowly diminish SOC levels and threaten the soil's production capacity.[15,17]

Among many agricultural scientists, concerns that excessive harvest of corn stover could reduce crop yield[10,18] are greatest for areas where inherent SOC levels have already been reduced (30%–50% compared to pre-cultivation levels) due to artificial drainage, intensive annual tillage, and less diverse plant communities (i.e., increased monoculture or simple corn/soybean rotations).[19] Research over the past century has conclusively shown that improper crop production practices can result in SOC loss[20] and, in almost all circumstances, results in decreased soil productivity[20,21] and soil quality.[22,23]

There are soil and crop management practices that can minimize or stop the loss of SOC, or even begin to restore SOC. Eliminating or decreasing tillage and increasing the number of crops included in a rotation are examples of such practices.[24,25] This has led to the perception that when no-tillage management practices are used in combination with improved plant genetics, fertilizers, and crop protection compounds, crop residues are not important for modern grain production systems. This may not be true. Conversion from intensive tillage to no tillage does not always result in SOC accrual.[26,27] Furthermore, even on lands managed using no-tillage methods, it is having the soil covered with crop residues that protects land from the ravages of wind and water erosion.[28] Crop residue also provides other critical functions associated with nutrient cycling, soil structure, and biological activity and diversity.[29]

The importance of crop residues for soil erosion control was recognized by Perlack et al[6] who estimated the amount of crop residue available for use by the biofuels industry based on the difference between the amount produced and the amount required for soil erosion control.[6,7,30] RUSLE2 and Wind Erosion Prediction System (WEPS),[31,32] which were designed to determine the on-site quantity of crop residue needed to limit soil erosion to at least the T level, were the primary tools used to estimate the amount of residue needed to remain in the field. The T level refers to the tolerable soil loss, where *T* is defined as the maximum rate of soil erosion that will not lead to prolonged deterioration or loss of productivity.

More recently, however, concerns have been raised about the role of crop residue in maintaining soil quality for future productivity.[6,10,17] Soil quality studies have found SOC concentrations, which are directly related to soil organic matter, to be the most useful indicator currently available for determining soil quality and future productivity.[33] Using methodologies and databases compiled by Johnson et al[15,34] to estimate crop residue requirements to maintain SOC, Wilhelm et al[35] found that, in many cases, the amount of crop residue needed to maintain SOC (and thus soil productivity) is often far greater than the amount needed to control wind or water soil erosion as predicted by WEPS and RUSLE2.

Limitations of current removal-rate estimation methodologies

The emerging cellulosic biofuel industry and its accompanying demand for increased production of cellulosic feedstocks are creating a paradigm shift for agronomic systems by establishing a commodity-scale market that competes for the same biomass resources currently used to maintain soil productivity. Current soil resource assessment methodologies have limited capacity for estimating how much agricultural residue can sustainably be harvested for a commodity-scale biofuels market. The consideration of only erosion control factors can overestimate the amount of residue that can be sustainably harvested and, over time, increase the risk for reduced soil quality and reduced yields of both primary crops (grain) and residues. Including the more complex soil quality indicators of SOC in the assessment is not an easy task and requires the consideration of many interdependent regional, environmental, and management variables. There is a growing urgency for new methods and tools that will more accurately estimate the impact of residue removal on all aspects of soil productivity.

In addition to erosion and SOC, soil productivity is impacted by the net gain or loss of plant nutrients, soil water and temperature dynamics, compaction, and other environmental degradation processes (e.g., acidity, salinity, compaction, etc). While there is an agronomic knowledge base for independently assessing the impact of crop residues on each of these variables, development of a tool that integrates these and other variables into a single assessment will provide farmers and others better guidelines for producing and harvesting crop residues. The principles for optimizing production and collection of crops residues can also be applied to dedicated herbaceous and woody species.

Historically, a linear, single-factor analysis approach has been used to evaluate residue harvest sustainability. We hypothesize that by considering multiple factors and approaches simultaneously, different combinations of factors will create step changes that will enable a reallocation of resources and achieve multiple goals in a positive, sustainable manner. To test this hypothesis, strategies for minimizing the negative agronomic impacts of harvesting crop residues are contrasted with the positive benefits of sustainable feedstock production. Finally, some potential approaches are outlined and demonstrated for providing sufficient crop residue to maintain soil productivity and an economically viable quantity of crop residue for harvest as an advanced biofuel feedstock.

Agronomic factors impacting soil productivity

The six limiting factors discussed in this review are shown in *Table 1*. The first four depend upon the balance of crop residue inputs and outputs, while the last two are general consequences of crop residue management practices. To better understand the interdependence of these factors, this review examines the individual dynamics of each and their combined impact on SOC, soil quality, and, ultimately, the sustainable amount of corn stover that could be harvested to support biofuel or other bioproduct industries.

SOIL ORGANIC CARBON

At any point in time, the current level of SOC (or the SOC change over a period of time) can be reduced to the following relationship, provided the rate of humification and mineralization remains constant[29]:

$$\Delta SOC = OC_{input} - OC_{output}$$

where OC_{input} is the amount of organic carbon (C) added to the system and OC_{output} is the amount of organic C removed.

This elementary equality, however, belies the complex biological, chemical, physical, and human factors and processes interacting to produce the current SOC level. Few factors or production practices change only inputs or outputs; most affect both, often simultaneously. The estimates by Johnson et al[34] of the amount of crop residues needed to sustain SOC illustrate that, in many ways, the entire sustainability question is a matter of balance: balancing C inputs and C outputs. Correctly assessing the quantities and composition of crop residue needed to maintain soil sustainability for future production is the interactive result of all six limiting factors (*Table 1*), each dependent upon site-specific soil and environmental characteristics.

Simply stated, SOC is any organic form of carbon found in the soil. Soil organic carbon and soil organic matter (SOM) are related terms, with SOC being the carbon fraction of SOM. The SOC content of the SOM is variable, however, from soil to soil and with depth throughout the soil profile. In the absence of an experimentally determined relationship between SOM and SOC for a particular soil, it is acceptable to estimate SOM to comprise about 50% C and can be expressed as SOM = SOC/0.50.[36] Though SOM represents only a small portion of the soil matrix (usually less than 10% by mass), it is crucial to the fundamental function of soil as a plant growth medium (*Figure 1*). Allison[37] and Sikora and Stott[38] summarized these plant

Table 1. Agronomic factors limiting the quantity of corn stover available for sustainable harvest as an alternative fuel feedstock

Limiting factor	Affected soil properties and processes	Characterization methods
Soil organic carbon	Soil structure, nutrient cycling, water entry and retention, and biological activity	Measurement or simulation models such as CQESTR, DayCent, and EPIC
Wind and water erosion	Soil, nutrient, and agrichemical loss, and water- and air-quality degradation	Simulation models such as RUSLE2 and WEPS
Plant nutrient balance	Productivity and fertilizer requirements	Measurement or simulation models such as IFARM
Soil water and temperature dynamics	Seedbed condition, plant emergence, crop growth and development, leaching, drought resistance, workable days, load-bearing capacity, water-use efficiency, and other factors	Measurement and simulation models such as those based on the concept of least limiting water range
Soil compaction	Seedbed quality, plant emergence, tillage energy requirements, soil structure, runoff, plant rooting volume, fertilizer-use efficiency, and other factors	Measurement and possible use of simulation models based on the concept of least limiting water range
Off-site environmental impacts	Nutrient leaching, runoff, stream-bank erosion, sedimentation, water- and air-quality contamination, impaired wildlife habitat, and other factors	Measurement and use of simulation models such as EPIC, SWAT, IFARM, ALMANAC, and others

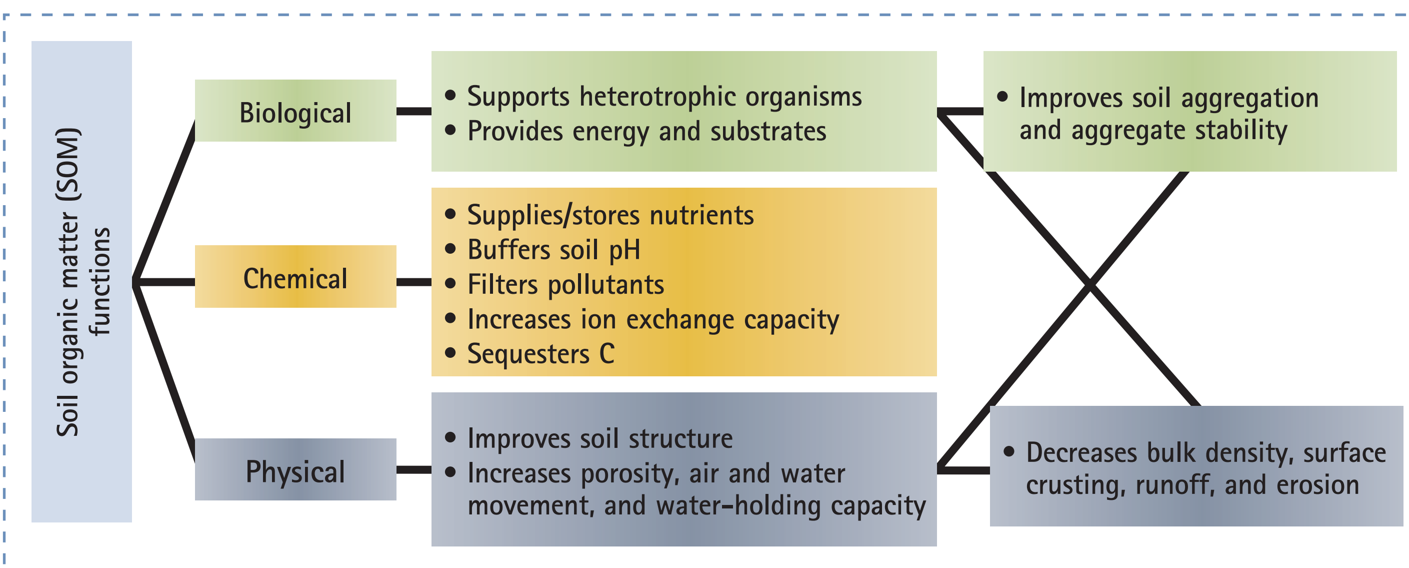

Figure 1. Biological, chemical, and physical functions of soil organic matter

production functions. Organic matter imparts many positive physical and chemical properties to soil, all revolving around the dynamics of organic matter input and decomposition by soil organisms.[39,40] Soil organic matter influences soil aggregation and aggregate stability,[41–43] which, in turn, impact water infiltration, soil water-holding capacity, aeration, bulk density, [21] and soil erodibility,[44] as well as penetration resistance, resistance to compaction, and soil tilth.[45] Chemical properties that are at least partly dependent on SOM include pH, nutrient availability and cycling, ion exchange capacity, filtering harmful chemical compounds, and buffering capacity.[46] The organic fraction of soil also affects biotic activity, persistence, and diversity and biodegradability of organic compounds.

Regardless of the mechanism, loss of SOM negatively affects the soil functions or processes cited above and shown in *Figure 1*, especially soil quality and productivity. Shukla et al[33] identified SOC as the most dominant indicator of soil quality from among the 21 chemical and physical parameters they evaluated. After removing all stover for the intended purpose of energy production from an Arquidoll silt loam soil for 10 years, as compared to returning stover to the soil,[47] they showed that about 8%–11% of the surface residue returned to the soil was converted to SOC annually. Maskina et al[48] reported that on a silty clay loam in Nebraska where all stover had been removed for 5 years, SOM was 24.7 g kg^{-1}, compared to 27.4 g kg^{-1} in the top 30 cm where all stover had been returned. Furthermore, they reported that grain yield decreased from 5.4 Mg ha^{-1} to 4.6 Mg^{-1}, and stover yield decreased from 3.4 to 3.0 Mg ha^{-1}, as a consequence of previous corn stover removal. Bauer and Black[49] reported that the impact of SOM on yield in a loam soil in North Dakota, where every 1-Mg ha^{-1} of SOM in the top 30.5 cm increased total wheat (*Tritium aestivum* L.) aboveground biomass by 35.2 kg ha^{-1} and wheat straw by 15.6 kg ha^{-1}. These studies emphasize the importance of SOM in maintaining crop production capacity.

Since the 1850s, cultivation of extensive areas of virgin land has led to a net transfer of C from the soil to the atmosphere. The loss of SOC (20%–50%) during the first 50 years after converting native prairie or forest to production agriculture is well documented.[22,50–56] An estimated 5 Pg (5×10^{15} g) of carbon have been lost from US soils as a result of cultivation.[57] These losses are greatest during the first few years after land conversion and slow after about 20 years of cultivation, when the soil approaches a steady state (*Figure 2*). Greater source C inputs are then required to maintain production levels and offset the effects of lost SOC.[49]

To increase SOC, the amount of organic inputs must exceed outputs. Photosynthesis rates have slightly exceeded decomposition on the geological time scale, which accounts for accumulated SOM reserves in native prairie and forest lands. Concentration of recalcitrant organic C structures in the stable organic matter (OM) pool is the result of decomposition and humification of easily decomposable plant, microbial, and faunal materials. Stabilized OM is not immune to decomposition, but it decomposes at a much slower rate than the other carbon pools. Further decomposition of SOM releases smaller organic compounds that are ultimately converted into inorganic CO_2.

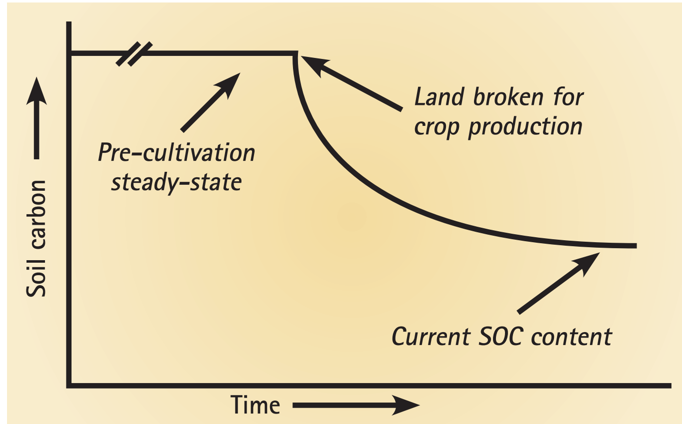

Figure 2. During the first 50 years after converting native prairie or forest to production agriculture, 20–50% of the original steady-state SOC was lost.[22,50–56]

Decomposition of crop residue is controlled by temperature and moisture conditions (which are discussed in greater detail later in this review), placement within the soil matrix, size of residue pieces, sorption of solid phases, and incorporation into aggregates.[58] Decomposition of SOM also depends on plant residue quality factors (including the C:N ratio and specific protein, carbohydrate, lignin, and polyphenol composition). These differences in plant composition also influence the value they have as potential feedstock materials for bioenergy conversion, which has led to various studies examining differential harvest strategies to determine which plant fractions should be harvested and which should be left in the field to protect the soil and help retain SOM levels.[59] Several studies using ^{14}C or ^{13}C to quantify SOM decomposition have shown that root material originating from exudates and dead root matter contribute substantially to the retention of C in the SOM pools.[60–62] Crop residue amount, orientation, and placement all have significant and complex effects on soil, water, and thermal regimes, which, in turn, have important consequences for soil C dynamics.[63]

Avoiding SOC loss

There are two basic methods to avoid SOC loss: (1) decrease output via erosion or mineralization, or (2) increase input (increase the amount of organic substrates available to the system by producing more or removing less). Controlling erosion prevents the loss of topsoil, which is typically richer in SOC than is deeper soil. Reducing or eliminating tillage can reduce erosion[64] and slow or mitigate the loss of SOC in some soils.[25,65] Determining how much crop residue must be left on the land and how much can be removed requires greater understanding regarding how much input C is required to maintain SOC for different soils, rainfall and temperature conditions, and production practices. This is not a new effort for agronomists and soil scientists,[9] but a focused, well-coordinated effort is needed to confirm initial estimates published by Johnson et al[15,29,34] and to extend the analysis to a broader array of soil and environmental conditions.

Limiting removal of crop residues may be effective for maintaining soil quality, but it does not address the reality of the effects of emerging biofuels markets that will directly compete for these resources. Until viable alternatives are developed, limiting removal of crop residue as a biofuels feedstock will be the primary mechanism to maintain SOC. This emphasizes the importance of determining removal limits based on soil quality requirements so that, in some areas, producers will be able to redirect a portion of their crop residue to these new markets without negatively impacting their long-term productivity and economic viability.

Increasing carbon inputs is another method mentioned to avoid SOC loss. This is key to finding a solution that balances both soil productivity maintenance *and* sufficient biomass production yield to support a biofuel industry.[66,67] The long-term goals must be to (1) maximize the capture and use of light and CO_2 available on every unit of current arable land, and (2) strive to use the resulting crop dry matter in the most appropriate manner.

Crabtree and Lewis[68] estimate that the sun delivers to the earth in one hour the amount of energy used by humans annually. Obviously, not all of this energy can be captured in the form of plant biomass, but opportunities exist for improving our efficiency in capturing and using solar energy. To achieve the goal of vastly increased capture of solar radiation and production of reduced C, a series of technologies must be applied. Some of these technologies already exist, but others have yet to be developed.

Existing management techniques, such as adding cover crops to the crop sequence, using planting times and patterns that maximize solar radiation interception, and double cropping, can be deployed in the near term to reap immediate gains in C input to the system. Other techniques must be refined before deployment, such as sensor-driven application of inputs (nutrients and pesticides) based on crop need. Changes in crop genetics and production practices that seem visionary or pioneering today will be developed and honed for future application in out years; examples include developing canopies with structures that result in greater penetration of light to lower leaves, increasing the efficiency of the carbon fixation enzymes, and reduction of photorespiration.[69] The goal of these efforts is not to increase the demand for existing resources, but to optimize the use of existing resources and increase the sustainable productivity of all resources so that there are sufficient quantities to meet increasing demands for food, feed, fiber, *and* biofuels.

To achieve these multiple goals, Johnson et al[34] used empirical data and linear regression to correlate C inputs to SOC and proposed *minimum source C* (MSC) as a term to describe the annual C input needed to ensure no net change in SOC content. Since the initial review,[34] several other studies allowing MSC estimates have resulted in similar aboveground MSC estimates.[29] Using aboveground non-grain C inputs, MSC was 2.5 ± 1.7 Mg C ha^{-1} yr^{-1} (n = 28) for different crops and tillage practices at several experimental sites. This was slightly higher than the mean MSC of 2.2 ± 1.1 Mg C ha^{-1} yr^{-1} (*n* = 21) presented by Johnson et al.[34] The studies also suggest that moldboard plow systems had higher MSC requirements than those with no tillage. Similar results were also reported by Bayer et al.[70] Assuming a C concentration of 400 g kg^{-1} (40%) in corn stover, 6.25 Mg ha^{-1} yr^{-1} must be left in the field to supply 2.5 Mg C ha^{-1} yr^{-1} of source C. This agrees with the value of 6 Mg ha^{-1} of corn stover reported by Larson et al[71] as the amount of crop residue required to sustain SOC.

Midwestern corn yield and harvest index data further illustrates the impact of both corn grain yield and the harvest index (ratio of dry grain to dry grain + dry aboveground stover) on the potential amount of stover available for bioenergy production after the average[29] amount of stover needed to sustain SOC has been supplied (*Table 2*). The two harvest index values are provided because, in recent years, partitioning of plant photosynthate between grain and vegetative plant parts has been altered due to the emphasis on achieving high grain yields.[34] The critical point is that by increasing plant productivity, more dry matter will be available to address the competing demands. Furthermore, the loss of leaves and upper portions of the

Table 2. Corn yield and harvest index effects on available feedstock after supplying the average amount of carbon projected by Johnson et al[29] to sustain SOM

Grain yield @ 15.5 moisture		Harvest index†	Available dry feedstock‡		Harvest index†	Available dry feedstock‡	
bu ac⁻¹	*Mg ha⁻¹*		*t ac⁻¹*	*Mg ha⁻¹*		*t ac⁻¹*	*Mg ha⁻¹*
150	9.4	0.50	0.76	1.70	0.55	0.1	0.3
170	10.7	0.50	1.23	2.76	0.55	0.5	1.1
190	11.9	0.50	1.71	3.82	0.55	0.9	2.0
210	13.2	0.50	2.18	4.88	0.55	1.3	2.9
230	14.4	0.50	2.65	5.94	0.55	1.7	3.7
250	15.7	0.50	3.12	7.00	0.55	2.1	4.6
270	16.9	0.50	3.60	8.06	0.55	2.4	5.5
290	18.2	0.50	4.07	9.12	0.55	2.8	6.4

†Defined as dry grain weight / (dry grain weight + dry aboveground biomass weight) at physiologic maturity.
‡After providing the average 6.25 Mg ha^{-1} of crop residue required to sustain SOM at current levels (Johnson et al[29])

stalk that typically occurs between physiological maturity and grain harvest can be as high as 39%.[72] Therefore, using the harvest index (HI) at physiological maturity to calculate the amount of stover that can be sustainably collected could result in an overestimate of stover actually available for harvest. Conversely, using only the HI at the time of grain harvest could underestimate the amount of stover that could be sustainably harvested, since it does not account for crop residues that have already dropped onto the soil. Thus, it is important to understand both physiological maturity and harvest time HIs.

WIND & WATER EROSION OF SOIL

The importance of soil erosion in restricting the amount of crop residue available as feedstock is widely acknowledged[7,30] and has been considered in oft-quoted estimates of feedstock availability.[6] Efforts by the USDA's Agricultural Research Service (ARS) and Natural Resource Conservation Service (NRCS) to develop and implement technologies and practices that limit soil loss (including loss of SOC) are broadly recognized. The ARS and NRCS, in conjunction with the Forest Service, land grant universities, and other research groups, have developed computer models RUSLE2[31] and WEPS[32] to assist land managers, producers, and support agencies in creating conservation plans. These plans include engineering (e.g., building terraces) and crop and soil management practices (e.g., no tillage, contour farming, or crop rotations) and are designed to reduce soil loss to within tolerable limits defined by the T value. One of the major components of many conservation plans is providing adequate crop residue on the soil surface to resist the erosive effects of raindrop splash, flowing water, and wind.

Two previous analyses by Nelson[7] and Nelson et al[73] help illustrate how precursors to RUSLE2 and WEPS (the Revised Universal Soil Loss Equation [RUSLE] and the Wind Erosion Equation [WEQ]) have been used to estimate the quantities of crop residue (corn stover and wheat straw) potentially available throughout the United States. Those models were applied by first determining the amount of crop residue that needs to remain on an individual field (residue retention rate) to maintain soil loss at or below USDA-defined T values. The amount of residue required (i.e., residue retention rate) is a function of field physical characteristics (i.e., slope, soil type), geoclimatic variables (i.e., precipitation, wind), and field management practices (i.e., crop rotation, tillage). *Table 3* demonstrates how dramatically residue retention rates can change for selected soils with respect to rainfall and wind erosion forces in Sumner County, Kansas, when managed for continuous corn using mulch/reduced tillage (MT) or no-till (NT) scenarios. While not all soils within a county would be used to grow any one crop, these analyses illustrate the amount of residue needed to protect against erosion if they were.

Lal[50] extensively reviewed the issues of soil erosion, soil quality, and use of predictive models to develop conservation plans. Although

Table 3. Effect of soil type, erodibility, and slope on the amount of crop residue required to protect soils in Sumner County, Kansas, USA, from erosive rainfall and wind forces when managed for continuous corn using two different tillage practices

						Residue required to control rainfall erosion		Residue required to control wind erosion	
Soil series	Soil classification	LCC†	Soil erodibility	Avg field slope	Tolerable soil loss	Reduced tillage	No tillage	Reduced tillage	No tillage
			(K‡)	(%)	Mg ha^{-1} yr^{-1}				
Crisfield (fine sandy loam)	Udic Haplustepts	1	0.20	1.0	12.2	0.13	0.00	6.20	4.48
Farnum (loam)	Pachic Argiustolls	1	0.28	0.5	12.2	0.02	0.00	4.88	3.61
Shellabarger (fine sandy loam)	Udic Argiustolls	2	0.20	2.0	12.2	1.63	0.25	6.20	4.48
Pratt (fine sand)	Lamellic Haplustalfs	4	0.17	5.5	12.2	5.08	1.75	7.50	5.73
Owens	Typic Haplustepts	4	0.32	2.0	12.2	8.22	3.92	8.15	5.73
Rosehill (silty clay)	Udertic Haplustolls	4	0.32	4.5	12.2	9.59	5.06	7.50	5.33
Kirkland (silt loam)	Udertic Paleustolls	4	0.43	2.0	12.2	5.17	1.79	4.23	3.18
Renfrow (silt loam)	Udertic Paleustolls	4	0.43	3.5	12.2	7.68	3.49	4.23	3.18
Elandco (silty clay loam)	Cumulic Haplustolls	5	0.43	0.5	12.2	0.25	0.02	4.23	3.18
Drummond (loam)	Mollic Natrustalfs	6	0.43	0.5	4.5	2.80	0.63	5.55	4.03

†LCC = Land Capability Classification, the greater the value the greater the limitations or risk for damage if used for crop production
‡The soil erodibility factor (K) is a dimensionless value, representing both susceptibility of soil to erosion and rate of runoff. A lower value indicates less susceptibility to these erosive forces.

RUSLE2 and WEPS are among the best tools currently available, the credibility of using T (an important factor upon which they are based) to determine residue retention rate has been called into question.[28] Factors such as compaction, loss of biological activity, acidification, salinization, and others are increasingly recognized as threats to soil resources that can be as or more important than erosion. Continued use and development of RUSLE2 and WEPS will need to be augmented with other tools to ensure practices associated with harvest of crop residue or other feedstock materials for bioenergy production will result in a sustainable industry.

PLANT NUTRIENT BALANCE

Development of sustainable feedstock supply chains for bioenergy production will require a different nutrient management plan than that for grain crop production. Several factors contribute to this, including increased nutrient removal when plant material in addition to the grain is harvested. Recent studies by Karlen et al[74], using a single-pass harvest strategy of cutting plants just below the ear and collecting cobs plus plant material from the ear shank upward, showed that average N-P-K removal was increased by 23, 2, and 29 kg ha^{-1} for continuous corn, and 36, 4, and 27 kg ha^{-1} for rotated corn, respectively, when compared to harvesting only the grain. Using varied but functionally similar harvest strategies for collecting cob and upper portions of the corn stalk, data from the first year of a multi-location regional partnership project funded in part by the US Department of Energy (DOE) through the Sun Grant Association showed that, compared to harvesting only corn grain, overall, N, P, K, Ca, Mg, and S removal were increased by 42, 5, 45, 10, 3, and 3 kg ha^{-1}, respectively. Based on October 2009 fertilizer prices (US\$1.229, \$6.936, \$1.108, \$0.067, \$0.1867, and \$1.12 kg^{-1} for N, P, K, Ca, Mg, and S, respectively), replacement cost for those nutrients was calculated to be \$140.75 per hectare, or \$28.72 Mg^{-1} of residue (dry basis).

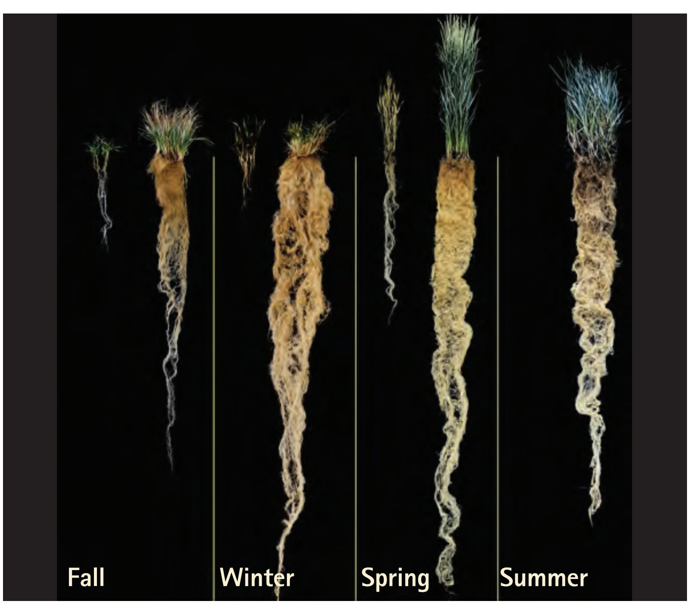

Figure 3. A comparison of plant root systems excavated from silt loam soil in the Palouse region of the United States (Photo: The Land Institute, Salina, Kansas)

These reports agree with findings by Hoskinson et al,[59] who measured macro- (N, P, K), secondary (Ca and Mg), and micronutrient (Cu, Fe, Mn, and Zn) concentrations in samples from various corn stover harvest scenarios. They also found that by cutting plants just below the ear, N, P, and K removal were increased by 34, 4, and 34 kg ha^{-1}, respectively, compared to harvesting only the grain.[59] These findings were consistent with earlier reports by Holt[75] and Lindstrom,[76] who suggested that increased fertilization rates would be needed to maintain soil fertility and crop yield if crop residues were harvested. In a multistate study using average 2005 to 2009 fertilizer prices for N as anhydrous ammonia, P as superphosphate, and K as mutriate of potash, the replacement value was \$17.59 Mg^{-1} stover (dry basis) removed above the ear (excluding cobs).[77]

In addition to accounting for increased nutrient removal, it is also important to know how various feedstock materials may be affecting profile nutrient distribution. Illustrated in *Figure 3* is the different rooting systems for annual winter wheat (*Triticum aestivum*) compared to established perennial winter wheat grass (*Thinopyrum intermedium*). One effect of such differences in plant rooting systems is that deep-rooted perennials can often transport nutrients located deep in the profile to upper levels. This is a positive attribute if past management has resulted in substantial nutrient leaching, but it can also result in nutrient-poor subsoils if not properly accounted for in a full-profile nutrient balance.

The complexity of nutrient management issues related to harvesting crop residues is further illustrated by considering the research of Power and Doran,[63] who found that N immobilization (use of soil N by soil microorganisms, making it unavailable to support crop growth) increased as the rates of residue return increased. This suggests that, when residues are left in the field, additional N fertilizer may be needed to avoid mining soil N for residue decomposition. More simply stated, removing crop residues will reduce the need for N additions because less N will be needed to support decomposition of high C:N residue. Similarly, in an experiment in India (in a warm and humid climate and with soils very low in organic matter), Beri et al[78] compared residue removal, burning, and incorporation for rice (*Oryza sativa* L.) and wheat straw on tilled soils. The incorporated residue treatment resulted in the highest soil mineral N and P but the lowest yields for both crops. The authors attributed this result to immobilization of N and P during decomposition of the incorporated residues, making the nutrients unavailable to support plant growth. Clapp et al[79] had similar results in NT corn, noting that added fertilizer N increased residue-derived carbon sequestration.

In addition to nutrients being immobilized (tied up) in the process of residue decomposition, nutrients are subsequently released, as biomass decomposes and the SOC moves through the various levels in the carbon cycle. In these later stages of the decomposition process, mineral elements are cycled into forms available for plant uptake and offset the need for fertilizer in crop production systems. These contrasting research outcomes and intricate interactions highlight the difficulties faced in developing optimum crop management guidelines and the need for synchronization between supply of nutrients from soil or fertilizer applications and the demand for that nutrient by the crop.

SOIL WATER & TEMPERATURE DYNAMICS

Water and temperature are unique among the limiting factors because of the impact these factors have on crop growth and development. All plant physiological processes take place in an aqueous environment, and water is the transport medium within a plant, so crop growth and development are dependent on water that is extracted from the soil by crop roots.[80] Seed germination and plant growth are also highly sensitive to temperature.[80,81] This dependency is so important to crop growth and development that corn hybrid maturity is rated on the basis of "growing degree days" ("heat units" accumulated for each day of the growing season) rather than calendar days.[82] The complexity and intimate interactions in these processes cannot be overstated, and texts by Eastin et al,[83] Gardner et al,[84] and Salisbury and Ross[80] are recommended to provide further information on the dependency of fundamental plant physiological processes on water and temperature.

The dynamics of water and temperature are intrinsically coupled to the soil system, and changes in crop residue management strategies have a direct impact on these dynamics. Soil water and temperature are unique among the limiting factors. Not only does the crop residue directly impact the water and temperature status of the underlying soil, the soil water and temperature conditions created by the crop residue (on the surface or partially incorporated into the soil) directly affect crop residue decomposition rates. Additionally, since water and temperature are the two major environmental variables influencing crop production (the main source of C input to the soil system), these factors influence this interactive dependency between crop production and the soil system dynamics to a greater extent than do other limiting factors.

The complexity and intimate interactions in these processes cannot be overstated.

One way to illustrate the importance of water with regard to corn production is to contrast the amount of water required for a biorefinery with that required to produce the crop that would be processed. A modern 378 million L biorefinery requires ~1 134 L of water to process 2.4 billion kg of corn grain (0.4 L kg^{-1}). To produce the 2.4 billion kg of corn grain, an area of 64 263 ha would be required if yields averaged 14.1 Mg ha^{-1}. Producing 14.1 Mg ha^{-1} of corn grain will require 1.75–2.22 m ha^{-1} of water, depending upon potential evaporation in the area. The total water use thus ranges from 454 to 467 billion L for producing the crop compared to 1 134 L for processing it. Furthermore, in addition to producing the grain crop and fixing carbon, the entire process is an integral part of the overall hydrologic cycle and thus provides many other benefits, including temperature moderation.

While soil water and temperature effects under midwestern US rain-fed conditions are the emphasis of this paper, in other regions these factors are also affected by decisions on when, where, and how to use irrigation to support bioenergy feedstock production in those regions. The limitation of irrigation also depends on the source of irrigation water. The impact of draining down geological water (a very slowly renewed or nonrenewable resource) is more severe than using irrigation water from annually recharged resources. Nonetheless, there could be competition for annually recharged resources. Irrigation can dramatically alter crop production. For example, without irrigation, a typical wheat yield in many areas could be 2.7 Mg ha^{-1}. With irrigation, yields of 8.1 Mg ha^{-1} or more have been achieved in the Pacific Northwest and elsewhere throughout the United States. Assuming a harvest index of 0.40 and a wheat straw requirement of 2.24 Mg ha^{-1}, the amount of harvestable straw would be 0.39 Mg ha^{-1} without irrigation compared to 8.3 Mg ha^{-1} with irrigation.[85] This shows that for wheat produced under irrigation, sustainable crop residue harvesting could be possible, whereas without irrigation it may not be possible unless other strategies were implemented to mitigate the detrimental effects of crop residue removal.

Soil water & temperature effects on SOC

Temperature and seasonal weather conditions play a major role in biomass production and SOM accumulation or decomposition (*Figure 4*). Generally, an increase in soil temperature will increase biomass production and SOM decomposition, while an increase in water content may slow the decomposition rate, but these dynamics are quite complex and can change from day to day and vary with soil texture.[86,87] Although annual fluctuations in biomass production are less with irrigation, variation in precipitation from year to year under dryland production systems can cause large differences

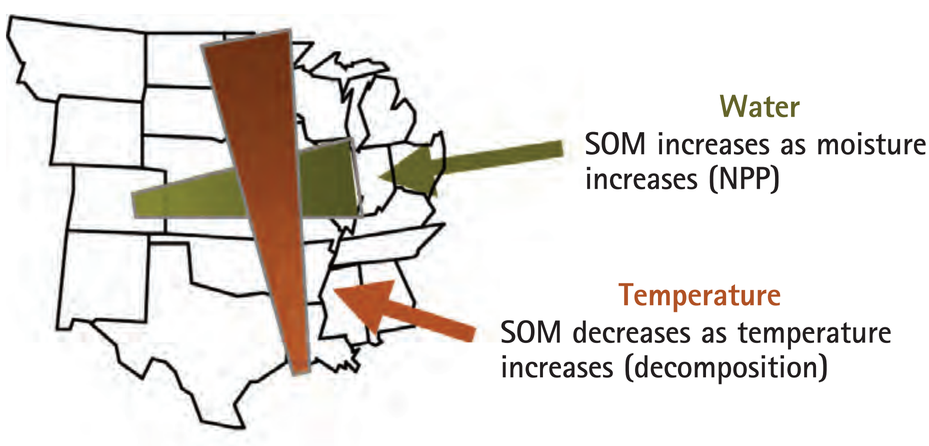

Figure 4. Water and temperature impact of SOM accretion and retention (after Brady[90])

in crop residue production[88] and change the rate of decomposition.[10] Both temperature and moisture changes impact microbial populations and alter their composition. This variation, in turn, impacts SOC accumulation or losses most in the soils. For example, VandenBygaart et al[89] reported a loss of 24 ± 6% of the SOC after native land was converted to agricultural land. No-till increased the storage of SOC in Western Canada by 2.9 ± 19.3 Mg ha^{-1}, but in Eastern Canada, conversion to NT did not increase SOC. In general, the potential to store SOC when no-till was adopted decreased with increasing background levels of SOC.

Effects of crop residues on soil water & temperature dynamics

Rain-fed corn yield is dictated largely by water availability.[88,91] In an eastern Nebraska no-tillage cropping study with variable amounts of crop residue, Power et al[92] and Barber[47] found increased crop yields for corn and soybean when crop residues were left on the soil surface rather than removed. This yield effect was most pronounced in drier years, leading researchers to attribute yield increases to residue-induced water conservation, although they also cited benefits from reduced erosion and increased SOM. Using data from the same study, Wilhelm et al[18] calculated that grain and stover yields increased 0.13 and 0.29 Mg ha^{-1} for each Mg ha^{-1} of residue that was added, but grain and stover yields decreased 0.13 and 0.29 Mg ha^{-1} for each Mg ha^{-1} of residue that was removed.

Similar effects were documented for soybean. In studies by Clapp et al[79] and Linden et al.,[93] where residue was returned, corn yields exceeded those where it was not returned by ~22% in drier-than-average years. Differences were not significant in years with near-average precipitation. This effect, however, was tillage-dependent, with residue-induced yield differences being apparent each year in reduced tillage (chisel plow) treatments but not significant in no-till treatments. Yield declines in no-till treatments did begin to appear after four years regardless of the residue management practice, suggesting another factor may have become limiting.

The negative effects of corn residue removal on crop grain yield vary depending on climate. Kaspar et al[94] reported increases in several measures of corn growth and grain yield with removal of various natural (previous crop residues) and artificial (fiberglass insulation) crop cover materials in central Iowa. Vetsch and Randall[95] found that conventional tillage (minimal surface residue) resulted in greater grain and silage yields compared to no-tillage and spring disk tillage systems. These findings are consistent with the earlier summary of multiple reports by Benoit and Lindstrom.[96] Areas where rainfall frequently limits crop production, any area experiencing extended drought, and areas with warm, dry soils at seeding will have greater negative yield impacts from residue removal than areas with adequate, uniformly distributed rainfall or cool, wet soils at seeding.

Residue mass and placement affect soil water content and temperature.[97] Sauer et al[98] found that fresh residue, being thicker, provided more insulation and, therefore, reduced evaporation and temperature, compared with weathered residue or bare soil. Soil temperatures are lower under residues due to surface reflectance. The extent of this effect varies with color, water content,[68] and thickness of the residue layer, all of which change with age, weathering, and residue type.[98] Collectively, these factors account for slower residue decomposition under no-till than conventional management.[23]

Sharratt et al[99] found that stubble mulch under no-till had higher winter soil temperatures and earlier spring thawing compared with residue removal or residue chopped treatments. Therefore, in colder climates, retained corn stover residue should be left upright in the field to (1) minimize problems with spring seed germination due to low soil temperatures and (2) enhance the residue's soil protective properties where needed.

Considering the effects of crop residue on soil water and temperature, if spring weather conditions provide adequate soil moisture, corn emergence and development will likely proceed faster for no-till with stover removal than without. However, if spring weather conditions result in low soil-moisture content, this leaves the no-till system with stover removed at a greater risk for plant water stress and possible yield depression than would be experienced in reduced-tillage and conventional-tillage systems.

The limiting factors discussed thus far directly influence soil productivity, depending on the balance of crop residue inputs and outputs. The limiting factors that follow are consequences of crop residue management practices associated with stover removal that result in environmental degradation either on or off site: soil compaction and off-site environmental impacts.

SOIL COMPACTION

Soil compaction is a physical process that reduces soil quality by decreasing the volume of pore space within the soil. This, in turn, reduces aeration and atmospheric gas exchange, water retention, and transport, and it can also reduce the soil volume that roots explore for water and nutrients. These resulting, or secondary, effects are the cause of crop yield reduction rates usually associated with compacted soils.

The importance of crop residue and SOM in maintaining soil density and the implications of removing residues on soil compaction were discussed in detail by Wilhelm et al.[10] The authors identified two factors that result in increased soil compaction when corn stover is harvested and, thus, potentially limit or constrain the amount of residue available for biofuel production. One is the removal of organic matter at or near the soil surface and the resultant reduction in SOM. The tendency of a soil to compact is strongly influenced by the amount of SOM that is present, but the magnitude of the effect is difficult to quantify. The relationship was reviewed competently by Soane,[100] who reported that SOM improves soil aggregate stability and structure, which increases the ability of soil to support a load or to rebound after a load is released. This increases the soil's resilience against compactive forces.

A second factor connecting soil compaction to stover harvest is the increase in equipment traffic that occurs with the residue collection process. Typically, there will be three additional equipment operations to concentrate, consolidate, and transport corn stover from fields.[10] Each trip through the field results in a soil compaction event that will gradually increase soil bulk density, decrease water infiltration, and thus increase runoff.[101] The extent of compaction depends upon axle load borne by each wheel, soil water content at the time of the event, soil type, and whether or not the land is managed with controlled traffic practices.[10] The negative impact of soil compaction may not be recognized, but for all practical purposes, a field that has experienced severe compaction from heavy axle loads (i.e., large combines and grain carts) may have reduced productivity, depending on soil type, water content, and the operating and tire width of equipment used.

Practical management alternatives or remedial actions for compact soils are limited. The most effective could be termed "avoidance practices." Avoidance is especially important, as numerous studies in the Midwest US report no significant improvement in crop yield after deep tillage.[102–106] Producers can attempt to control wheel traffic to within the same paths for all operations, which will minimize the total affected surface area. Without controlled traffic, a large percentage of the field's surface area may become compacted, rendering the entire field less productive. The degree and persistence of compaction is strongly influenced by (1) equipment size (weight) and tire load, and (2) soil water content at time of the operation. Smaller equipment with tires or tracks with greater surface area result in less consolidation of soil particles compared to equipment of greater size and less tire surface area. Regardless of machine and tire size, operations conducted on wet soil have greater impact than the same operations with the same loads conducted on dry soil.

Recommendations to reduce compaction include using small machines with relatively large tires (or tracks) to perform harvest operations, operating with small loads, and conducting field operations on dry soil. Controlling wheel traffic so that only a portion of the land is exposed to equipment tires (compacting events) is another alternative. Also, in areas where soils are frozen for part of the year, conducting potentially compacting activities at times when soils are completely frozen could reduce the negative impact. In addition, limiting removal of organic matter (residue) from the land or adding additional sources of organic matter to the system may reduce the impact as well. Cropping sequences that include species with large taproots or deep-rooted perennials may serve to remediate compacted cropland or set-aside land soils.

OFF-SITE ENVIRONMENTAL IMPACTS

This limiting factor refers to the direct or indirect effects that residue harvest has on habitat or quality of habitat for wildlife. Beyond the direct impact on production at the site, erosion, sediment, and dissolved materials that drain off-site have serious negative impacts on water quality and aquatic life. These factors are intimately linked to habitats for aquatic plants and animals.

As discussed previously, and especially with regard to environmental degradation, many authors have questioned the use of T values as an acceptable upper limit for soil erosion losses.[17,49,107,108] For many locations across the Midwest, the established T values are far above the estimated average rate of soil formation. The first soil fraction eroded in most instances includes surface particles that contain the highest amount of SOC and nutrients that represent the major portion of any soil's fertility and, therefore, its capacity to support crop growth. It is not surprising, then, that if soil erosion proceeds at T-value rates throughout the Midwest, there will be dramatic losses in this region's crop production capacity.[50] Other deleterious effects will also occur beyond the eroded fields. Water quality will be impaired within the area where the erosion occurs, the areas through which the sediment travels, and the water body ultimately receiving the sediment and dissolved or suspended materials.

Drivers encouraging crop residue harvest

Our review and discussion to this point have focused on agronomic factors that impact the amount of agricultural residues that can be harvested sustainably as a bioenergy feedstock. These factors are presented as cautionary relative to the national goals of maximizing cellulosic biofuel feedstock for offsetting the current use of fossil fuels. Economics at the farm-management level also drive decisions toward higher removal rates. Benefits are realized for feedstock supply and logistics when greater tonnages are available per acre. As demonstrated in *Figure 5*, residue collection decisions are based on opposing forces seeking to balance the conflicting interests of economics and sustainability. While the economic impacts of residue removal decisions are reasonably straightforward, understanding the interconnected relationship with sustainability is complicated because of the multi-variant nature of the agronomic systems presented in this review. Holistic, systems-based, limiting factor analyses are needed not only to (1) establish methods for accurately estimating sustainable removal rates, but also to (2) guide development of innovative agronomic strategies that can help satisfy sustainability and economic constraints simultaneously (*Figure 5*).

An important first step in understanding the holistic nature of agricultural systems is to recognize that they are not directly analogous to the industrial models of efficiency that have been applied to them during recent decades.[109] Although this has occurred most notably from the separation and consolidation of animal and crop production operations, it is also a factor contributing to many unintended, off-site consequences associated with soil, water, and air quality. To prevent unintended consequences from becoming associated with cellulosic bioenergy feedstock supply system logistics, the development of new agronomic strategies must take multi-factored approaches and more holistically consider the technological, environmental, and social transitions occurring within agriculture.

As outlined in a National Academy of Sciences publication,[1] one approach for addressing the multiple competing forces (*Figure 5*) is to use a landscape-scale management approach that simultaneously examines not only the global need for renewable biofuels and the many strong economic and social drivers associated with it, but also the issues of carbon sequestration, water and air quality, wildlife food and habitat, erosion, sedimentation, hypoxia, community develop-

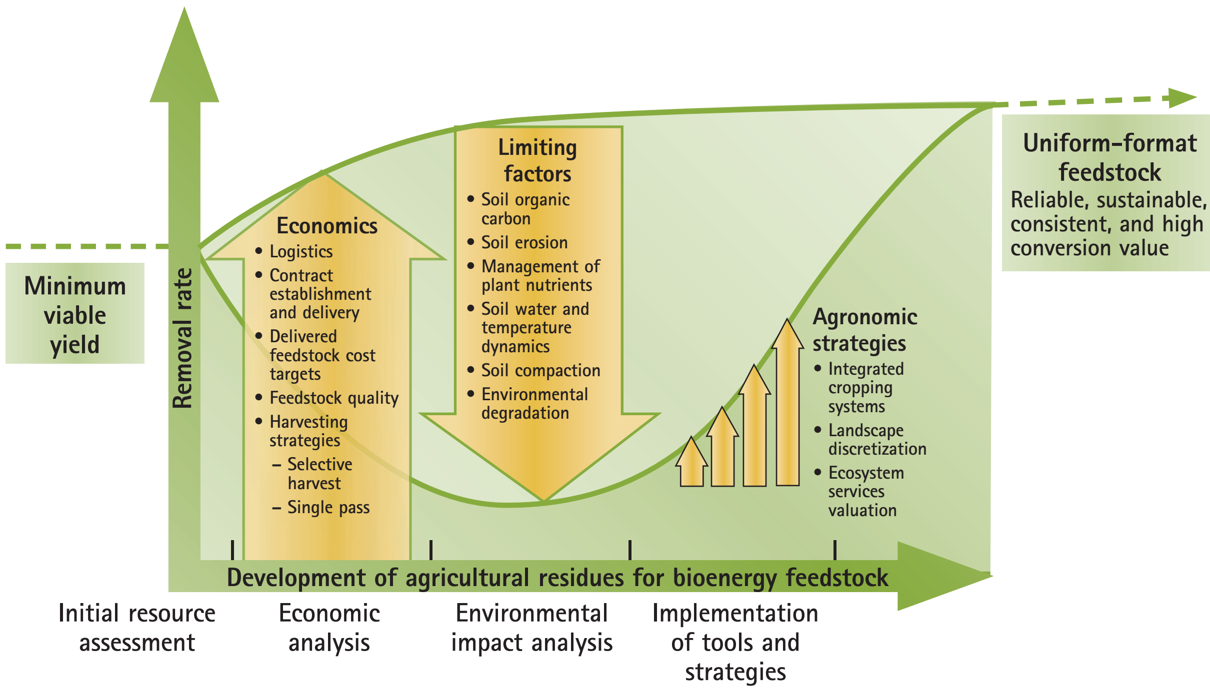

Figure 5. An illustration of competing economic and environmental sustainability forces that must be balanced to achieve sustainable cellulosic feedstock supplies that will support the transition from fossil to renewable fuels

ment, transportation infrastructure, and many other equally important issues using rigorous, science-based, and structured assessment techniques, as illustrated in *Figure 6*.

By incorporating annual, perennial, and intercropping mixtures into future farming operations, a diversified landscape could help address a number of the previously discussed interrelated land management concerns. Implementing this type of landscape-scale vision includes the harvest of crop residues but not exclusively, and it will also address many concerns regarding productive capacity to support a biofuels industry.[110–113]

To understand the sustainable landscape vision, it is important to recognize that agriculture is more than farms, farmers, and commodity crops (e.g., corn, soybean, wheat, cotton [*Gossypium spp* L.], rice, and sugarcane). Developing lignocellulosic feedstock and biofuel enterprises within definable watersheds could provide several unique opportunities to more fully integrate economic, environmental, and social aspects of agriculture into integrated systems. By planning to harvest only in areas where the amount of crop residue exceeds that required to maintain soil resources[114] and by striving to develop dedicated bioenergy crops, agriculture as a system could help mitigate increased nitrate (NO_3-N) concentrations in streams and groundwater, the need for dredging of sediments, and potential hypoxia problems.

By using biofuel feedstock production as the economic driver, many ecosystem services could be captured through implementation of a landscape management plan that includes establishment of woody species as buffers near streams and long-term perennial biomass crops at slightly higher landscape positions.[1] During their dormant period before harvest, these vegetative buffers could provide several months of environmental services by reducing leaching of NO_3-N and runoff of soluble phosphorus (P) while capturing carbon dioxide. Slightly higher on the landscape, diverse perennial

Figure 6. Landscape management vision to more fully integrate economic, environmental, and social aspects of agriculture into agronomic systems to produce food, feed, fiber, and fuel sustainably (Photo: USDA-NLAE)

mixtures of warm-season grasses and cool-season legumes could produce biomass and store organic carbon in soils. In autumn, these perennials would provide a source of biomass in addition to at least three landscape management benefits (biomass production, C sequestration, and water quality). Further up the landscape, a diversified rotation of annual and perennial crops could be used to meet food, feed, and fiber needs. Erosion could be partially mitigated by using cover crops or living mulches. Intensive row-crop production areas could be established using best management practices (BMPs), and if fertilizer recovery were less than desired, there would be substantial buffer areas at lower landscape positions to capture residual nutrients and sediment.

Currently, this landscape vision is conceptual, but calculations based on a recent US study in Iowa suggest that converting just 10% of a watershed from no-till corn and soybean to strips of herbaceous perennial plants could decrease water runoff by 49% and soil erosion by 96%, while simultaneously increasing native plant, bird, and beneficial insect populations (*Figure 7*). This confirms that understanding complex interactions among economics, soil and crop management decisions, productivity, and environmental consequences can result in agricultural systems that would meet global food, feed, fiber, and fuel demands in a truly sustainable manner.

A FIRST-STEP CASE STUDY

The transition to a full landscape-scale management approach for feedstock production will require time and tools to develop strategies for implementation. Due to the inherent variability associated with soils and their landscapes, many field studies need to be performed and new agronomic approaches developed that are customizable to various conditions. To demonstrate how combined field studies and integrated tools can identify agronomic transitions that may provide landscape-scale benefits, this review discusses a case study with three management scenarios: Current Analysis Approach, Analysis with SOC, and Implementing Innovative Management Strategies.

The analytical focus of this case study is the use of cover crops as a method to protect the soil surface during the autumn and spring months and thus allow for increased stover removal as a bioenergy feedstock. Our analysis is based on an ongoing, multi-year study funded by USDA and DOE. The study is being conducted on the Clarion-Nicollet-Webster Soil Association Area at the Iowa State University Agronomy and Agricultural Engineering Farm near Ames, Iowa. For detailed descriptions of the experimental design, refer to Karlen et al.[74,115,116,59]

Building upon the design and data from the Ames study the RUSLE2 and CQESTR (carbon sequestration) simulation models were used to estimate how the rye cover crop could impact several of the factors discussed in this review that could limit the amount of corn stover that could be collected in a sustainable manner. The results are summarized in *Table 4*, which shows an analysis for three rates of stover removal with and without annual or perennial cover crops and using either conventional or no-till management practices.

The first example (Current Analysis) illustrates an evaluation based solely on soil erosion loss and how stover harvest and tillage affects that factor in relation to current tolerable soil loss (T) values. This analysis shows that, based on potential soil loss alone, harvesting stover at a stubble height of 10 cm would be sustainable (i.e., soil loss is <T).

The second analysis (Analysis with SOC) uses the CQESTR SOC model in addition to the current RUSLE2 model and projects the impact of stover harvest and tillage on SOC changes for a corn crop in the absence of either an annual or perennial cover crop. Unlike the results based solely on soil erosion, if potential changes in SOC are included, the only sustainable combination that would allow stover harvest would be to use no-till practices and to collect only the stover from the ear shank upward or at a cutting height of ~60 cm.

Figure 7. Examples of conventional residue removal management strategies (left) and innovative cover-cropping management strategies (right). Cover cropping can potentially add value through other ecosystem services, including carbon sequestration, reduced nutrient runoff, and reduced erosion. (Photos: Idaho National Laboratory and USDA-NLAE)

Table 4. Various soil- and crop-management scenarios evaluated using the RUSLE2 and CQESTR simulation models to predict effects of stover harvest on soil erosion and soil organic carbon changes on the Clarion-Nicollet-Webster Soil Association Area in Ames, Iowa

Case Study: Ames, Iowa – 10.12-ha Experiment

Scenario		Conventional management strategies		Conventional management strategies		Innovative management strategies (cover cropping)	
Analysis approach		Water erosion (T = 11.2 Mg ha^{-1}) (Mg ha^{-1})		Water erosion and SOC (kg ha^{-1})		Water erosion and SOC (kg ha^{-1})	
Tillage		Conv till[a]	No till[b]	Conv till[a]	No till[b]	No till[b]	No till[b]
Cover crop		–	–	–	–	rye	legume/clover
Removal rate	0%	2.91	0.25	-75.89	58.86	130.84	229.59
	50%	9.63	0.94	-114.18	24.29	87.64	191.79
	100%	10.53	5.15	-135.81	-16.82	43.81	145.88
Results		Overestimated sustainable residue removal at a removal rate of up to 100% in both conventional tillage and no-tillage scenarios		No sustainable residue removal in conventional tillage scenario and limited sustainable residue removal at a removal rate of 50% or less in no-tillage scenarios		Consistent sustainable resource is available in no-tillage scenarios implementing cover cropping strategies	

[a]Conventional tillage (chisel plow)
[b]No tillage

The third scenario (Innovative Management Strategies) shows the effects of combining no-till with either an annual cover crop (i.e., here, cereal rye) or a perennial cover crop, which, in the Ames, Iowa, study, is white clover (*Trifolium repens* L.). In this scenario, the cover crop is either killed (annual) or suppressed (perennial) with Roundup prior to planting corn. This analysis shows that, from an SOC perspective, stover could be removed at the high rate. Obviously, this combination would also meet the erosion (T) requirement because no-till in the absence of a cover crop would meet that standard.

Some other factors that are not illustrated in these case studies (*Figure 7*) but that need to be considered include: increased nutrient removal; any real or perceived effects on soil compaction, water, and temperature regimes; and other off-site environmental impacts. Again the important concept is that sustainability of any agricultural management practice, including harvest of feedstock for bioenergy production, must be evaluated with regard to multiple factors and their potential trade-offs and interactions with all ecosystem services.

Conclusions

This paper has reviewed the economic and energy security drivers motivating development of alternative renewable energy sources worldwide and discussed six crucial factors that can potentially limit the amount of feedstock available for bioenergy production. Simply stated, there are two approaches to meet an increasing demand for cellulosic feedstock while simultaneously satisfying the agronomic limiting factors:

(1) Produce more residue per unit area each year so that sufficient biomass is available for both soil system maintenance and biofuel production.

(2) Develop agronomic systems that retain and use crop residues and residue fractions more efficiently, thus providing more feedstock for biofuel.

In reality, both approaches will be needed. Developing and implementing these approaches will require parallel consideration of the drivers and limiting factors discussed in this review. It is clear that understanding individual factors, even with the best tools and data available, is not sufficient for determining system viability. It is also clear that developing and implementing the innovative strategies that can push agronomic systems toward effectively providing for biofuels markets will require the holistic, multi-variant understanding outlined in this review.

To help achieve these multiple goals, user-friendly packages of simulation models are being developed to simultaneously evaluate management strategies from several different perspectives. Three analyses from the "Residue Management Tool" were used to illustrate how these tools can be used. The importance of approaching agriculture as a holistic system rather than as a series of single-factor problems is also discussed. Overall, we conclude that corn stover can contribute to a sustainable supply of bioenergy feedstock, but it will not be the only source. For the best success, corn stover harvest as a bioenergy feedstock should be incorporated into an overall landscape management plan that simultaneously addresses economic, environmental, and social challenges.

Dedication

This paper is dedicated to the memory of Wally Willhelm, who challenged the research community to "establish shared goals and develop enthusiastic, committed teams dedicated to creating the best technology and finding the best solutions to energy problems"

[Willhelm WW. My biomass, your biomass, our solution. *BioFPR* 2, 8–11 (February 2008)]. One of Wally's last career priorities was to help the cellulosic ethanol industry understand that residues play a vital role in maintaining soil functions and preserving the capacity of agricultural lands to produce food, feed, and fiber. He did not propose that residues had no role in a biomass-for-fuel market but that harvest of residues would need to be balanced with other management strategies that ensured that the complex, interdependent processes within soil systems are protected for future production. Though he was unable to see this manuscript through to completion and publication, the discussion has remained true to his vision.

ACKNOWLEDGMENTS

Development of a residue removal tool, which was initiated to address the need identified in this manuscript, has become a reality through the significant contributions of the authors and Rob Anex, Brian Gelder, and Ed Van Ouwerkerk at Iowa State University; Tom Richard at the Pennsylvania State University; David Lightle and Paul Finnell at USDA-Natural Resources Conservation Service; and Daniel Yoder and Jim Lyon at the University of Tennessee. The authors also acknowledge Leslie Ovard at Idaho National Laboratory for coordinating the author's input and technical editing of the manuscript.

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