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Crop Residues

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8.1 Overview

Crop residues (e.g., corn stover and small grain straw) are sometimes excluded when discussing cellulosic energy crops *per se*, but because of the vast area upon which they are grown and their current role in the development of cellulosic energy systems, this chapter will review several important attributes of this "herbaceous" feedstock. Crop residues are potential feedstock sources for second-generation biofuel production. These materials, along with dedicated energy crops (e.g., switchgrass [*Panicum virgatum* L.], Miscanthus [*Miscanthus* × *giganteus*]), are considered to have greater potential for biofuel production than current first-generation feedstock (i.e., corn grain) [1–3]. Production of ethanol and other fuel sources from these lignocellulosic materials is receiving increased financial support for research and development [4–6]. Furthermore, biofuel production from crop residues provides a multipurpose land use opportunity where grain can be harvested to meet food and feed demands, while a sustainable portion of the residues provide a potentially available biofuel feedstock.

Corn stover, the aboveground plant material left in fields after grain harvest, was identified as an important biomass source in the Billion-Ton Study (2005 BTS) [7]. The vast area from which this feedstock could potentially be harvested was confirmed by USDA National Agricultural Statistics Service (NASS) data showing that between 2005 and 2011, corn was harvested in the U.S.A. from an average of 32 460 000 ha each year [8]. Wheat straw was the other dominant residue identified in the 2005 BTS, and from 2005 through 2011, wheat was harvested in the U.S.A. from an average of 20 037 000 ha each year. Based on these

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vast harvest areas, the 2005 BTS projected total annual corn and wheat residue production to be approximately 250 and 90 million Mg, respectively, with a sustainable removal of 82 and 12 million Mg after accounting for that needed to mitigate wind and water erosion.

The 2005 BTS projections of available crop residue immediately raised concern among many soil scientists because harvesting residues as a biofuel feedstock or for any other purpose (e.g. animal feed) will decrease annual carbon input and may gradually diminish soil organic carbon (SOC) to a level that threatens the soil's production capacity [9]. Concerns within the U.S. Corn/Soybean Belt were accentuated knowing that for many soils artificial drainage, intensive annual tillage, and less diverse plant communities have already reduced SOC by 30–50% when compared to pre-cultivation levels [10]. Returning a portion of crop residues to replenish SOC was deemed essential for sustainability [11–16] because crop residues influence many vital soil, water, and air functions. Many scientists stated that caution must be used to ensure that harvesting residue for any use does not compromise ecosystem services or decrease overall soil productivity. Furthermore, others argued that for several current cropping systems, soil erosion and organic matter depletion indicate that crop residue returns to the soil are already insufficient [17, 18].

As a result of soil resource sustainability concerns raised by the 2005 BTS, a follow-up report (2011 BT2) was developed by the U.S. Department of Energy (DOE) to include (1) a spatial, county-by-county inventory of potentially available primary feedstocks, (2) price and available quantities (i.e. supply curves) for individual feedstocks, and (3) a more rigorous treatment and modeling of resource sustainability [19]. The 2011 BT2 recognizes the importance of crop yield variation and the need to balance the economic drivers with ecologically limiting factors [20]. Table 8.1 presents some of the estimated feedstock supplies for various crop residues at selected price levels. These values are also consistent with several other estimates including those used for the U.S. National Academy of Science (NAS) study on Liquid Transportation Fuels from Coal and Biomass [21]. The 2011 BT2 also provides a more realistic overview of total crop residue availability and sets some achievable research and development goals for available feedstock supplies by creating various production scenarios that strive for higher crop yields and integrate multiple cellulosic energy crops into potential production systems.

Several assessments examining the multiple roles that crop residues have for maintaining multiple ecological functions have been published since the 2005 BTS [22–30]. Therefore, this chapter focuses on current corn stover and wheat straw research designed to address

Table 8.1 *Estimated 2012 crop residue supplies (Mg) at selected prices using the 2011 BT2 baseline management scenario data.*

	Price ($/Mg)		
Crop residue	40	50	60
Barley straw	356 088	1 289 300	1 536 821
Corn stover	17 064 661	66 172 906	77 444 014
Oat straw	17 052	17 505	17 505
Sorghum stover	565 515	880 516	996 884
Wheat straw	6 062 751	16 759 637	20 481 511
Total	**24 066 067**	**85 119 864**	**100 476 735**

concerns raised by those previous reviews and to help ensure that commercial bioenergy develops in an economically, environmentally, and socially acceptable manner.

8.2 Corn Stover

Following the release of the 2005 BTS, a collaborative research team[1] (Table 8.2) with members from the USDA-Agricultural Research Service (ARS) Renewable Energy Assessment Project (REAP) and several universities was established as part of the Sun Grant Regional Partnership (RP) to determine the amount of corn stover that could be harvested in a sustainable manner [31]. The core treatments included no tillage or the least amount possible for economic crop production [e.g. Coastal Plain soils near Florence, SC, have a naturally occurring hardpan (E horizon)], so in-row subsoiling is needed each year prior to planting], three residue removal rates (none, approximately half, and the maximum mechanically collectable amount), and four replications. Leveraging the Sun Grant Partnership funds with long-term ARS research expanded both the number of treatments being evaluated as well as the number of years of study. For example, at Mead, NE, the rainfed and irrigated studies were initiated in 1999 and 2001, respectively. At Morris, MN, the study was initiated in 2005, taking advantage of a tillage experiment established in 1995. At Ames, IA, two studies were initiated in 2005 and one in 2008. Additional management practices being evaluated at one or more of the locations include alternate tillage practices (e.g. chisel plow or strip-tillage), use of cover crops, rotation with soybean, harvesting of cover crops as well as the corn stover, and application of biochar.

For each experimental site, soil samples were collected to a depth of 1.0–1.5 m, divided into increments of 0–5, 5–15, 15–30, 30–60, 60–90 and 90–150 cm, and analyzed for several soil quality indicators [e.g. total organic carbon (TOC), total nitrogen, pH, bulk density, and soil-test phosphorus (P) and potassium (K)]. The Soil Management Assessment Framework (SMAF) was used to evaluate and combine the different indicators, and thus establish a baseline soil quality index that could be used to determine long-term effects of the various stover harvest rates [15]. To date, TOC and soil-test potassium have had the lowest indicator scores at several RP and other REAP sites [16]. Longer-term data leveraged from the REAP plots at Brookings showed that through the first eight years TOC decreased as residue removal rates increased (Figure 8.1). A more detailed examination of samples collected in 2008 showed higher organic carbon content in all aggregate size classes from the low removal treatment than in the high removal treatment (Figure 8.2). Higher total protein was also measured in soil samples from the low removal treatment than from the high removal treatment.

Whole plant samples were collected and fractionated into bottom, top, cob, and grain fractions. Plant parts lying on the ground within the sampling area (1.5 m^2) were also collected. Harvest index values and total nutrient uptake were collected using those samples. Stover was collected using a variety of mechanical harvesting techniques, all resulting in post-harvest soil surface cover differences, such as those shown for the Lamberton, MN,

[1] Funded in part by the North Central Regional Sun Grant Center at South Dakota State University through a grant provided by the US Department of Energy Office of Biomass Programs under award number DE-FC36-05GO85041.

Table 8.2 *The Regional Partnership Stover team's principle investigators, institutions, location, and site coordinates established to determine sustainable corn stover harvest strategies.*

Principle Investigators	Institution	Location	Site Coordinates	Dominant Soil or Soil Association
Doug Karlen[a]	USDA-ARS	Ames, IA	42 01′ 75.667 N	Clarion-Nicolet-Webster
Stuart Birrell	Iowa State Univ.		93 76′ 44.830″ W	
Shannon Osborne	USDA-ARS	Brookings, SD	44 20′ 20.30″ N	Kranzburg-Brookings
Tom Schumacher	South Dakota State Univ.		96 47′ 31.82″ W	
Jeff Novak	USDA-ARS	Florence, SC	34 17′ 00.32″ N	Goldsboro-Lynchburg-Coxville
Jim Frederick	Clemson Univ.		79 44′ 30.37″ W	
Jane Johnson	USDA-ARS	Morris, MN	45 68′ 26.44″ N	Barnes-Aastad
Lowell Rasmussen	Univ. of Minnesota – Morris		95 80′ 22.03″ W	
John Baker	USDA-ARS	St. Paul, MN	44 42′ 57″ N	Waukegan
John Lamb	Univ. of Minnesota – St. Paul		93 05′ 59″ W	Normania-Ves-Webster
			43 43′ 40″ N	Garwin
			95 24′ 21″ W	
			44 21′ 35″ N	
			93 12′ 10″ W	
Gary Varvel	USDA-ARS	Mead, NE	41 16′ N (irrigated)	Tomek
Richard Ferguson	Univ. of Nebraska		96 41′ W	Aksarben
			41 15′ N (rain fed)	
			96 40′ W	
Paul Adler	USDA-ARS	Univ. Park, PA	40 86′ N	Opequon-Hagerstown complex
Greg Roth	Pennsylvania State Univ.		77 85′ W	

[a]Team Leader

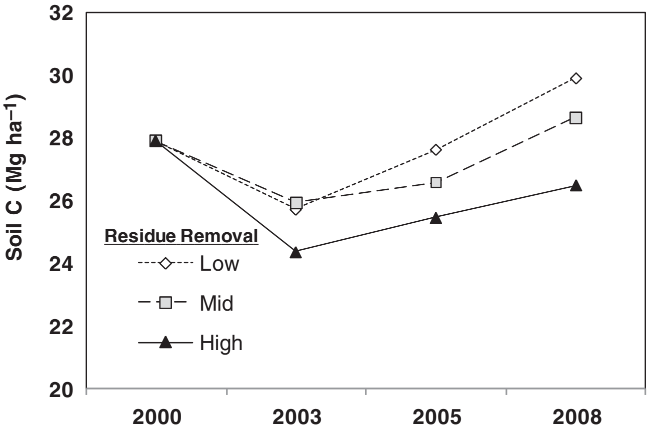

Figure 8.1 *Eight-year residue removal effect on SOC in the top 15 cm (6 inches) near Brookings, SD. (Figure provided by Shannon Osborne, USDA-ARS).*

site in the autumn (Figure 8.3) or the subsequent spring (Figure 8.4) following either conventional (chisel plow) or strip-tillage.

Additional data being collected at some but not all RP locations include greenhouse gas (GHG) emissions (CO_2 and nitrous oxide, N_2O), nitrate nitrogen (NO_3-N) and phosphorus concentrations in water leaching through the soil profile, microbial biomass carbon, particulate organic matter, glomalin-related soil proteins, the humic acid fraction of soil organic matter, aggregate stability, lignin, cellulose and other structural carbohydrates, and energy values for the various stover fractions. Collectively, these measurements are providing the data needed to develop the sustainable stover harvest strategies outlined through modeling in the 2011 BT2 report.

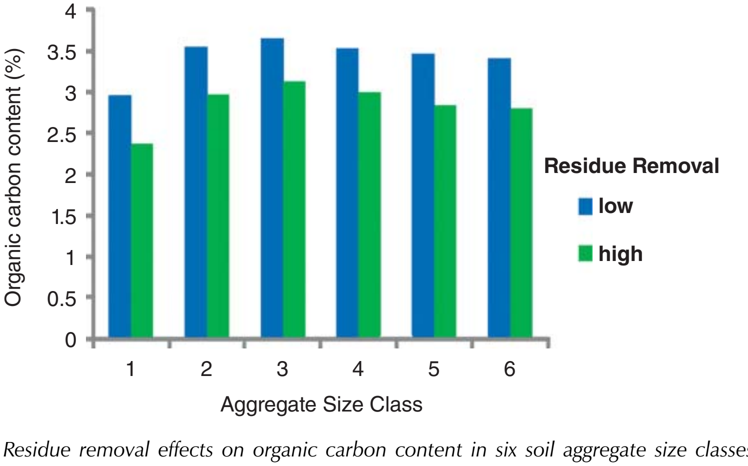

Figure 8.2 *Residue removal effects on organic carbon content in six soil aggregate size classes from the surface 5 cm near Brookings, SD. (Figure provided by Shannon Osborne, USDA-ARS).*

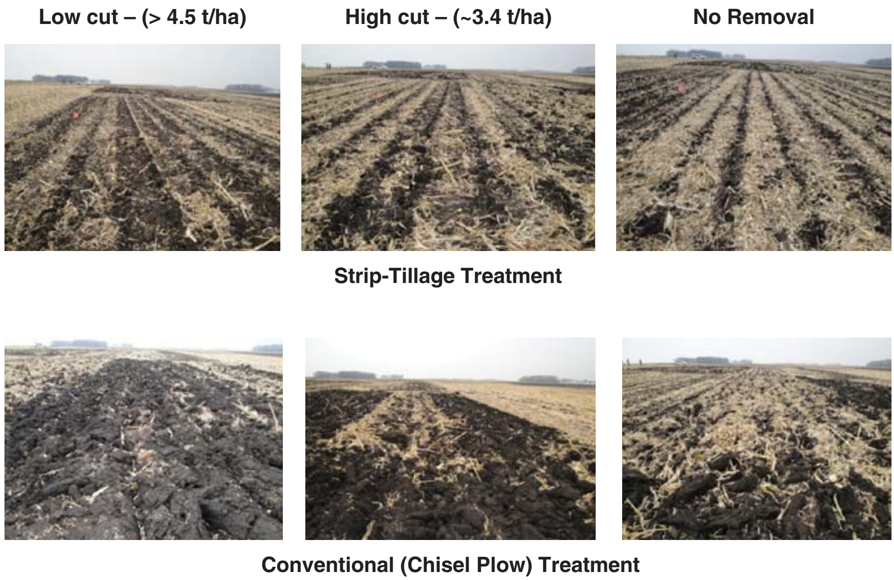

Figure 8.3 *Autumn (November 2010) soil cover following various corn stover harvest treatments and either conventional (chisel plow) or strip-tillage at the Lamberton, MN, research site. (Photos provided by John Baker, USDA-ARS).*

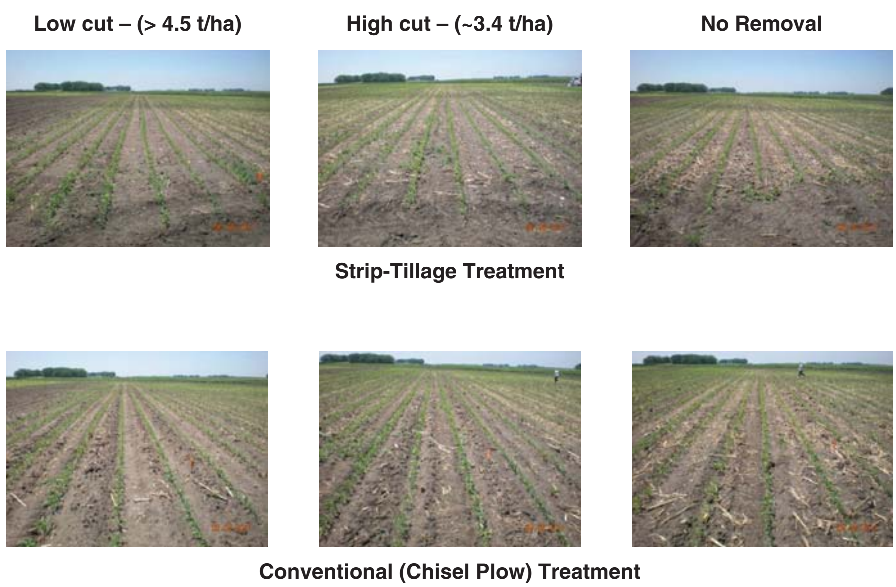

Figure 8.4 *Spring 2011 soil cover following various corn stover harvest treatments and either conventional (chisel plow) or strip-tillage in autumn 2010 at the Lamberton, MN, research site. (Photos provided by John Baker, USDA-ARS).*

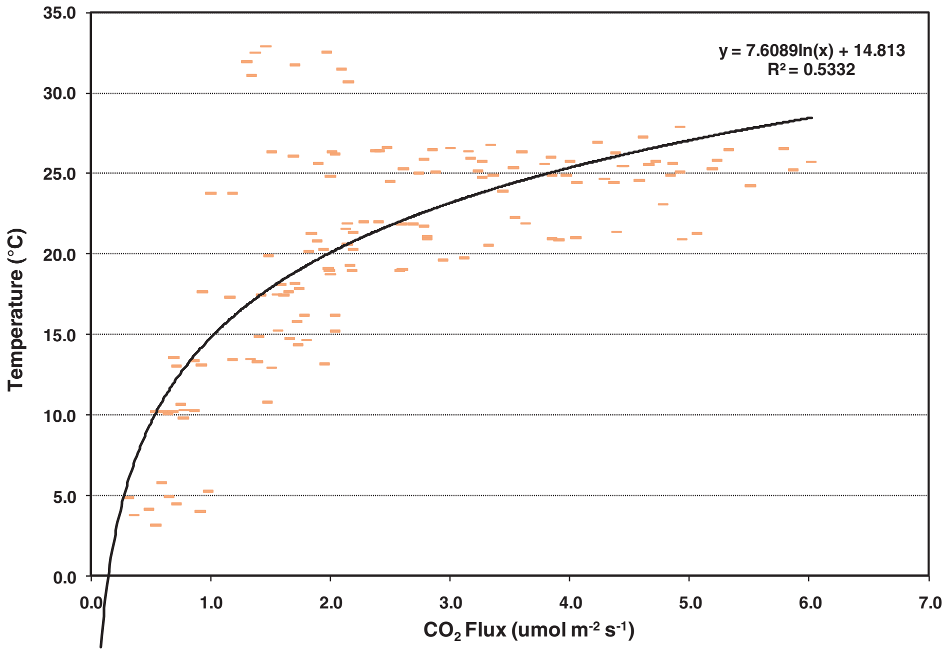

Figure 8.5 *Soil CO_2 flux versus soil temperature for all 2010 treatments at the Ames, IA, site. Each point represents the average of eight measurements (4 mid-row, 4 in-row). (Figure provided by Tom Sauer, USDA-ARS).*

One example (Figure 8.5) of the information being gathered shows the dependence of CO_2 flux on soil temperature. The relatively strong logarithmic relationship suggests that a temperature-based interpolation method (Q_{10}) will be most effective for estimating annual CO_2 fluxes. These results also suggest that management practices which result in warmer soil temperatures, for example, through residue removal, may lead to higher CO_2 fluxes. However, this effect will likely be offset by lower amount of available carbon substrate, that is, residue, so that the overall effect of stover harvest on annual CO_2 flux will likely be a reduction in treatment differences.

With regard to N_2O, Figure 8.6 shows that precipitation strongly influences the flux by reducing oxygen availability and stimulating denitrification. The lag between precipitation and maximum emission is evident, and is consistent with reports in the literature suggesting that the nitrous oxide flux is not maximized when the soil is saturated, but rather when water-filled pores space (WFPS) is about 65%. Annual sums of net N_2O emission at this site were highest for the non-removal treatment and lowest for the maximum collectable treatment. They were also positively correlated with cumulative soil respiration, indicating that carbon availability was a controlling factor with respect to denitrification.

As recognized in the 2011 BT2 report, crop yield is a major driver associated with the availability of stover as a potential cellulosic bioenergy feedstock. Corn produces the highest volume of residue of all the major crops grown in the U.S.A. and because of the approximate 1:1 relationship between grain yield and aboveground biomass, the volume of

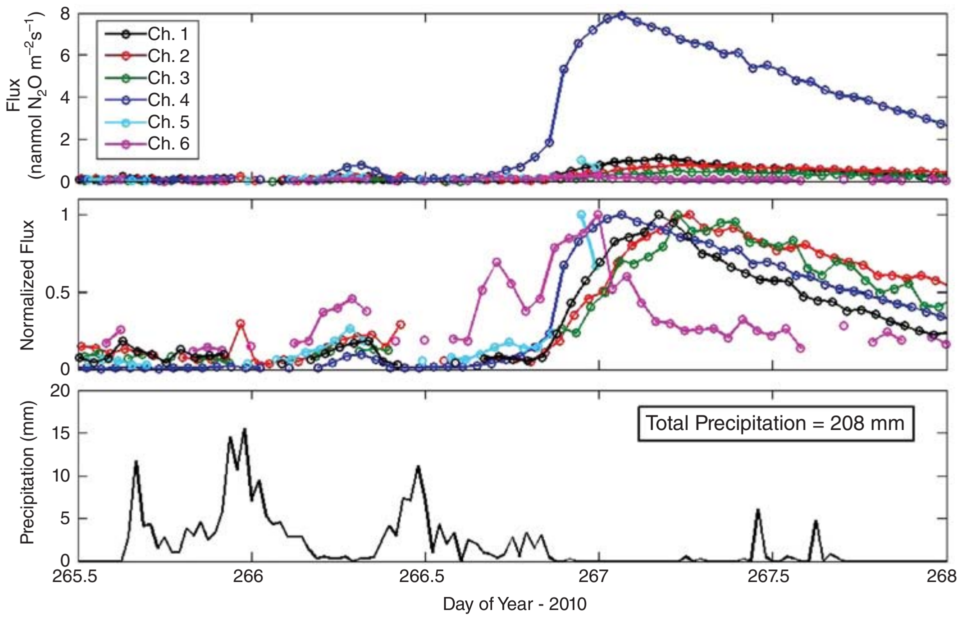

Figure 8.6 *Nitrous oxide and rainfall relationships at the Rice County, MN, site in 2010. The "Ch. 1 to Ch. 6" designations simply refer to the six chambers used for the measurements. (Figure provided by John Baker, USDA-ARS).*

available residue is directly proportional to grain yield (Table 8.3). To date, the RP studies have shown variable crop yield responses associated with stover harvest. This includes (1) no detectable short-term (3-year) effects at the Brookings, Florence, Morris, or University Park sites; (2) trends for increased yield when stover is harvested from no-till treatments at Ames and Mead; and (3) inconsistent site-differences at the Lamberton, Bauer Farm, and Rosemount sites in Minnesota. Another five-year assessment of stover removal effects near Ames, IA [16], showed that the most consistent grain yield response was a 21% lower average for continuous corn than for rotated corn. That study also showed that harvesting corn stover increased the average NPK removal by 29, 3 and 34 kg ha^{-1} for continuous corn and 42, 3, and 34 kg ha^{-1} for rotated corn, respectively, when compared to harvesting only the grain. Furthermore, it showed that the lower half of the corn plant contributed very little to the total available feedstock biomass because of its high water content and that it was not a desirable feedstock because of its high potassium, chloride, and ligin content, as well as an increased amount of soil contamination that interferes with both biochemical and thermochemical conversion processes.

So, what is the bottom line with regard to harvesting corn stover as a cellulosic feedstock? Firstly, producers must know their land. Prior to initiating any harvest strategy they should have good soil-test and nutrient management records for any areas from which crop residues may be harvested. Obviously, any land with erosion problems must be excluded and efforts should be made to use available stover in those areas to restore and rebuild the soil. Harvesting stubble will remove additional nutrients and could affect long-term soil organic matter levels, erosion rates, and water conservation. Producers should have and be using

Table 8.3 *Projected available stover as a function of corn grain yield, after accounting for the amount of crop residue needed to protect soil resources against erosion and to sustain soil organic matter levels as suggested by Wilhelm et al. (2007) [13]. (Based on [13]. With permission Copyright © 2007, American Society of Agronomy).*

Grain yield at 15.5% moisture		Dry stover	Total Stover[a]	Available[b] CC Stover	Available[c] CS Stover	Total Available
Bushels per acre	kg ha^{-1}	Mg ha^{-1}	Million Mg	Million Mg	Million Mg	Million Mg
150	9416	7.96	155	36.9	0.3	37
160	10 044	8.49	165	44.1	3.4	48
170	10 672	9.02	176	51.4	6.5	58
180	11 300	9.55	186	58.6	9.6	68
190	11 927	10.08	196	65.8	12.7	79
200	12 555	10.61	207	73.1	15.8	89
210	13 183	11.14	217	80.3	18.9	99
220	13 811	11.67	227	87.5	22.0	110
230	14 438	12.20	238	94.8	25.1	120
240	15 066	12.73	248	102.0	28.2	130
250	15 694	13.26	258	109.2	31.3	141
260	16 322	13.79	269	116.5	34.4	151
270	16 950	14.32	279	123.7	37.5	161
280	17 577	14.85	289	130.9	40.6	172
290	18 205	15.38	300	138.1	43.7	182
300	18 833	15.91	310	145.4	46.8	192

[a]Assuming stover collection from 60% of the 2005–2011 U.S.A. harvested corn area (32 460 000 ha) (i.e. 19 476 000 ha). This is approximately the area of corn production in Illinois, Iowa, Indiana, Nebraska, and Minnesota.
[b]Available after subtracting 5.25 Mg ha^{-1} for maintaining soil organic matter in continuous corn (CC) on 70% of the harvested area.
[c]Available after subtracting 7.90 Mg ha^{-1} for maintaining soil organic matter in a corn-soybean rotation on 30% of the harvested area.

long-term nutrient management and soil conservation plans. They should also be using the least amount of tillage possible. Again, avoid stover harvest from highly erosive areas and use routine soil-test and plant analyses to monitor the response on a routine basis. Finally, consider adopting other conservation practices, such as the inclusion of annual or perennial cover crops, buffer strips, and crop rotation, in order to enhance the sustainability of stover harvest.

8.3 Wheat Straw

Cereal grains (wheat, barley, oats, sorghum and rice) are widely grown in the United States and wheat straw constituted 20–25% of potential 2012 U.S. biofuel feedstocks (Table 8.1). Agronomic considerations for determining supplies of wheat straw that can be harvested sustainably include: (1) annual wheat straw yield and its stability; (2) straw harvesting efficiencies; (3) crop rotation and tillage practices for assessing soil conservation and sustainability factors; (4) nutrient removal and fertilizer replacement values; (5) site-specific field evaluations including economic factors that inform decision support systems; and (6) competing economic uses for harvested cereal straw. Addressing these issues has been the focus of several recent research efforts including the Sun Grant partnership

[32, 33], the U.S. Pacific Northwest, the Climate Friendly Farming™ project [34], and the USDA Solutions To Economic and Environmental Problems (STEEP) grant program [35].

In the United States, the amount of wheat straw potentially available for use as a biofuel feedstock was assessed through the Sun Grant partnership where the team used USDA-NASS county level grain yield data from 1999 through 2008 [32]. Grain yield data were combined with the harvest index (HI), the ratio of grain yield to total aboveground biomass (grain plus straw) at harvest, to estimate straw yields. The HI of wheat, however, is not a constant value [32], with reported values ranging from 0.20 to 0.70 with an average across locations and years of 0.44. This average is greater than the historic HI value of 0.375 commonly used for winter wheat [19], presumably because newer grain varieties are more efficient and produce less straw per unit of grain than older varieties. The HI data have important implications for estimating the amount of straw produced based on grain yield because an increase in HI from 0.375 to 0.44 results in a 24% reduction in estimated wheat straw yield. Consequently, generating straw yield maps for the United States based on grain yield can only be considered as a first step toward evaluating straw feedstocks for the purpose of siting biofuel plants. In addition to overall production, understanding the year-to-year stability of straw yield is also an important consideration for assessing feedstock supplies. Karow [32] noted that significant annual fluctuations in wheat straw stocks could occur where some areas with high average straw yields also had years with no or limited wheat straw yield.

Overall straw yield serves as a starting point for quantifying available biofuel feedstock that can be sustainably harvested. Factors such as straw harvesting efficiencies, residues (straw) required for controlling wind and water erosion, and for maintaining soil productivity then reduce the amount of straw that can be harvested without impairing the soil resource base. Current straw harvesting efficiencies (e.g. straw baling) are near 50% [7]; however, technological advances could increase residue harvesting efficiencies to around 75% [36]. It is more difficult to assess the multitude of crop rotation and soil tillage factors that influence how harvesting crop residues will affect soil conservation and other agroecosystem services. In many cases, conservation needs that depend on leaving adequate cereal residues in the field will be more limiting than current harvesting efficiencies.

In developing estimates for straw feedstocks that could be sustainably harvested, Kerstetter and Lyons [37] estimated that dry straw inputs of 3.4–5.6 Mg ha^{-1} yr^{-1} are required for conservation purposes in the western United States, whereas others [38] reported 4.5 Mg residue ha^{-1} yr^{-1} were needed. These numbers are similar to the 4–5 Mg residue ha^{-1} yr^{-1} reported [39] to be required for maintaining soil organic matter in dryland cropping systems near Pendleton, OR. Assuming a harvest index of 0.4, wheat grain yields of 2.0–3.3 Mg ha^{-1} yr^{-1} (3.0–5.0 Mg ha^{-1} yr^{-1} of wheat straw) would be needed to supply straw for conservation needs and harvestable straw estimates would need to be based on grain yields that exceed this threshold. An important point to realize in these calculations is that the quantities of residue required for conservation needs are on an annual basis. In many dryland scenarios, however, continuous wheat is seldom grown and crop rotations often include a fallow year when no crop or crop residues are produced [4]), or where other crops such as peas (*Pisum sativum*) or lentils (*Lens culinaris*) that produce far less residue than wheat are grown [14]. Thus, crop residue production must be quantified for an entire rotation in order to assess the average annual residue returns on a rotational basis. Therefore, in a two-year, wheat-fallow rotation, wheat will need to produce grain yields of 4.0–6.6

Mg ha^{-1}, twice that reported [37, 38] to meet conservation needs. Unfortunately, many estimates of wheat straw availability have assumed continuous wheat [37, 38]) production when assessing conservation needs. This has resulted in "sustainable harvest estimates" for wheat straw that are greatly inflated when compared to the actual amount available with other rotations. Accurate estimates of the wheat residue quantities returned to soil are in themselves insufficient to assess sustainable residue harvest, due to the important influence of other key factors such as crop rotation and tillage practice.

Evaluating the impact of straw harvest on important soil quality indicators such as SOC, aggregation, or erosion requires long-term research, since annual changes are generally very small and can be temporally dynamic. In recognition of this need, the Sun Grant partnership organized a symposium at the 2009 International American Society of Agronomy (ASA) meetings entitled "Residue Removal and Soil Quality – Findings from Long-Term Research Plots." Presentations at this symposium examined residue removal impacts in the context of various management practices including crop rotation, tillage, applied fertilizer and irrigation. The articles developed from this symposium were subsequently published in the *Agronomy Journal* (Huggins *et al.* [33]). The series includes results from long-term studies in Europe, Canada, Australia, and the United States. Key points included an assessment [40] that reviewed long-term studies from Europe, Australia, and Canada and cautioned against annual removal of straw because of the potential decrease in SOC. Due to the site-specific nature of residue harvest, they recommended that straw removal studies be coupled to areas where residue harvest is actually being considered and to not extrapolate using data from other areas.

Near Pendleton, OR [41], it was concluded from long-term dryland cropping system studies that residue removal in this predominantly wheat-fallow area will increase SOC depletion and that residue harvest will only be sustainable if wheat-fallow was replaced with continuous cropping and no-tillage. Nafziger and Dunker [42] reported on the long-term SOC trends under different crop rotation and fertilizer treatments at the University of Illinois Morrow Plots and emphasized the importance of adequate nutrient levels for maintaining SOC. Long-term plots at the University of Missouri Sanborn Field showed that the amount of field residues returned was positively related to SOC (Miles and Brown, 2011 [43]). Gollany *et al.* (2011) [44] evaluated five long-term field experiments in North America with the CQESTR model and concluded that increasing soil carbon inputs through manure additions and/or crop intensification as well as reducing tillage were important strategies for mitigating residue harvest impacts on SOC. Finally, in irrigated systems, Tarkalson *et al.* (2011) [30] reported that SOC either increased or remained constant when wheat residues were removed and hypothesized that belowground biomass production was important for maintaining or increasing SOC under irrigation. They also pointed out that irrigated cropping systems in the Pacific Northwest and elsewhere tend to be diversified with crops such as alfalfa (*Medicago sativa*), potato (*Solan* spp.), and sugarbeet (*Beta vulgaris*) in addition to wheat and corn, and that very little data on residue removal effects on SOC is available for those situations.

In combination, these papers conclude that under dryland or rainfed conditions, residue harvest will negatively impact soil organic matter and associated soil properties; however, harvest effects will be situation-dependent. Consequently, assessing residue harvest must be placed in a farming systems context that includes an evaluation of economic and environmental trade-offs specific for a given farm and location. Future challenges include the development of science-based, site-specific decision aids that enable growers to make economically sound and environmentally sustainable choices regarding residue harvest.

In 2009, USDA-ARS and land grant scientists in the Pacific Northwest established long-term field studies from a combination of current and new field locations to assess economic impacts of residue removal as well as effects on soil properties, soil-borne disease and crop performance [35]. Specific objectives of the project funded through the USDA Solutions To Economic and Environmental Problems (STEEP) grant program are to: (1) establish or use existing long-term field sites and assess impacts of wheat residue removal by mechanical harvest and burning on economic returns and subsequent crop performance; (2) assess environmental impacts (soil carbon sequestration, nutrient cycling, soil erosion) of residue removal by mechanical harvest and burning on established sites; and (3) develop field-scale and regional assessments of economic and environmental trade-offs associated with harvesting or burning crop residues.

Preliminary STEEP research from the Washington State University (WSU) Cook Agronomy Farm (CAF) estimated that the potential site-specific (37-ha field) lignocellulosic ethanol production from winter wheat residues would range from 813 to 1767 l ha^{-1} and average 1356 l ha^{-1}; thus, indicating that targeted harvesting of crop residues would be an important consideration. Harvesting only winter wheat residues, in a three-year rotation with spring wheat and spring peas (*Pisum sativum*), reduced residual carbon inputs to levels below that required to maintain SOC under conventional tillage practices. This occurred as a function of both residue removal and inclusion of the low residue producing spring pea crop in rotation with wheat. Harvesting winter wheat residues under conventional tillage resulted in negative Soil Conditioning Indices (SCI) throughout the field. In contrast, SCIs under no-till were positive despite residue harvesting. Increased nutrient removal is also a consideration associated with harvesting crop residues for any use. In the STEEP study, the estimated value of N, P, K, and sulfur (S) removed in harvested wheat residue was \$13.71 Mg^{-1}. In high residue producing areas of the field, the estimated value of harvested residue in fertilizer replacement dollars exceeded \$25 ha^{-1}. Based on the potential SOC impact and increased nutrient cost, we concluded that substantial trade-offs exist in harvesting wheat straw for biofuel and that trade-offs should be evaluated on a site-specific basis. Furthermore, support practices such as crop rotation, reduced tillage and site-specific nutrient management need to be considered if residue harvest is to be a sustainable option (Huggins and Kruger, 2010 [14]).

Potential impacts of crop residue removal on SOC were also simulated for different tillage and rotation scenarios in the Pacific Northwest using the CropSyst model [45]. Preliminary outcomes show that harvesting winter wheat residue at the lowest simulated removal rate (50%) resulted in SOC losses over a 30-year simulation (Figure 8.7). Harvesting less than 50% of the residue was not considered to be practical or a cost-effective use of producer time and equipment. Use of continuous no-till practices, however, partially compensated for the effects of winter wheat residue removal on SOC.

From an economic perspective dryland wheat growers typically receive from \$3 to \$5 Mg^{-1} in the Pacific Northwest, from custom operators who harvest the majority of the straw that is exported from this region. Traditionally, the primary motive for growers to sell residue is to reduce post-harvest tillage operations, thus reducing their total operating costs in high-yielding areas by \$35–60 ha^{-1} depending on tillage practices. However, growers have expressed concerns over long-term impacts of continual straw removal. Once the field

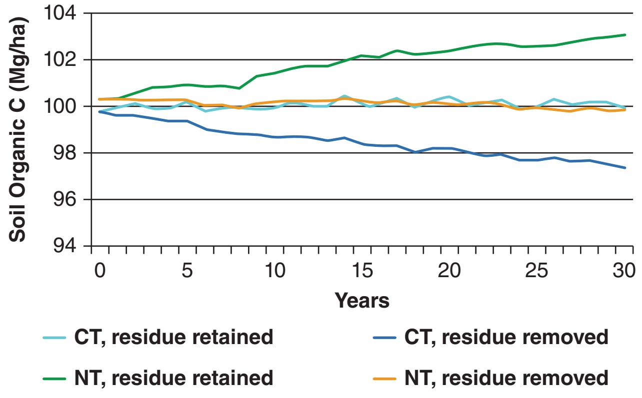

Figure 8.7 *Thirty-year simulated changes in soil organic carbon under a three-year crop rotation of winter wheat, spring wheat, spring pea using the CropSyst model. Simulations consist of conventional tillage (CT) and no-tillage (NT) and residue retained (no harvesting) and residue removed where 50% of the winter wheat residue is harvested (removed) and all other residue (spring wheat and pea) retained.*

studies and model simulations are more complete, we will estimate long-term economic impacts using partial enterprise budgets including nutrient replacement costs over time.

Sun Grant researchers are also evaluating existing straw markets to identify areas of potential residue harvest [32]. Existing markets for straw can be useful for identifying where straw is readily and reliably available. Identifying these potential markets is also important because they may significantly influence straw prices in a future biofuel market. With this background, the next steps in the DOE Sun Grant project are to identify those areas in the United States where sustained residue harvest seems feasible and to characterize those areas by determining: (1) What makes residue harvest possible in these areas? (2) Are these conditions likely to continue in the future? (3) If the area is irrigated, is the water source stable and will electricity costs affect production? (4) Are alternative markets already in place for harvested residues and, if so, at what cost would residues need to be purchased for biofuel use to be competitive? These and other questions need to be addressed as we think about residue harvest for biofuel use and the design of needed research and decision support systems for a residue-based biofuel system [33]).

8.4 Future Opportunities

Harvesting residues from corn and wheat will undoubtedly provide the most plentiful agricultural source of cellulosic biomass for the foreseeable future because of the extensive area upon which these crops are grown in the U.S.A. However, to achieve a sustainable harvest strategy only a portion of the total residue produced can be harvested and a sufficient amount must be left behind to meet all other critical ecosystem services and soil protection requirements. The ultimate challenge of balancing economic drivers favoring increased harvest to meet conversion demand with minimal transportation cost against the ecologically limiting factors (Figure 8.8) was well illustrated by Wilhelm *et al.* [20]. In fields where excess residue interferes with subsequent planting, stand establishment,

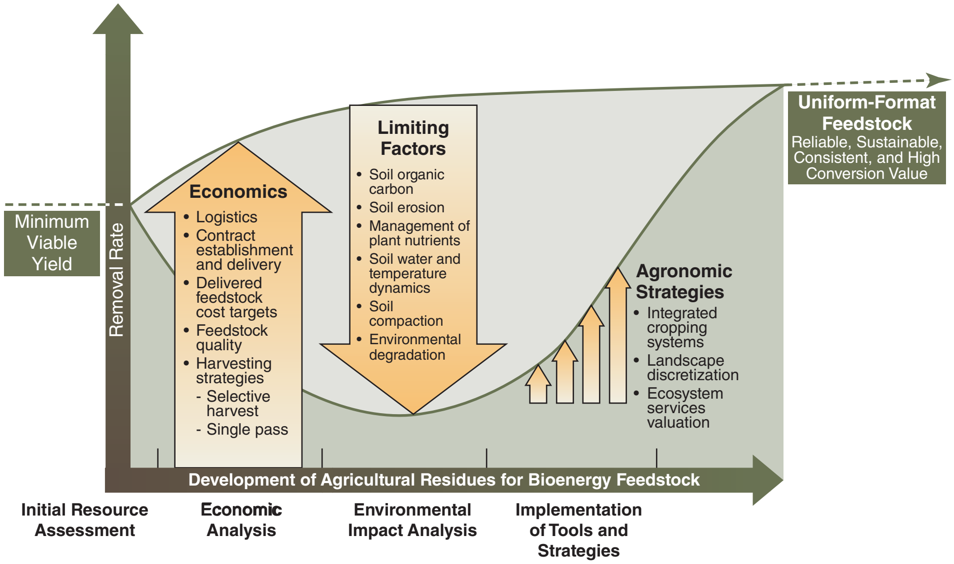

Figure 8.8 *A conceptual illustration of how economic drivers must be balanced against limiting factors based on soil protection and provision of ecosystem services. The bars to the right illustrate various soil and crop management practices that can be implemented to help ensure sustainable feedstock supplies are developed and available. (Reprinted with permission from [20], Copyright © 2010, Mary Ann Liebert Inc.).*

and nitrogen immobilization, partial residue harvest will likely increase subsequent yields. However, in more rolling and erosive landscapes most of the residue produced will likely be needed for soil protection. So, how can producers know whether or not they should consider harvesting their residues?

One strategy being developed with much of the REAP and RP data described above is the Residue Management Tool. This tool uses various databases and input information such as (1) the location and spatial extent of the potential harvest area, (2) crop rotations, (3) tillage management, (4) residue harvest methods, and (5) other land management practices to establish the potential for a safe and sustainable harvest. Every scenario involving these factors can be examined with the tool using an integrated systems model for which the input information can be defined. Using the location and spatial extent (which can be obtained directly from a combine using output files from the yield monitor), the site-specific crop yields, soils data, and climate data are assembled from the coupled databases. As the integrated residue removal tool executes its set of scenario runs, the data management modules are dynamically accessed to acquire and format the data needed for each of the models being coupled together. The integrated residue removal tool loops across the complete set of scenarios pushing each model output to the results database. The tool then aggregates the results calculated for each of the scenario runs.

Currently, the tool uses models such as RUSLE2 and WEPS to determine the amount of residue needed to mitigate water and wind erosion, and CQESTR or DAYCENT to monitor changes in the soil organic matter pool. Nutrient balance models (e.g. IFARM) and soil-test information help ensure those needs are being met and work is ongoing to develop least-limiting water relationships between soil aeration, compaction, and plant response. By connecting all of these models and supporting input information, various soil and crop management scenarios can be created and used to develop and guide sustainable crop residue harvest programs.

The initial version of the Residue Management Tool has been developed and is currently being evaluated for use with corn stover feedstock systems. However, since the tool is simply a computer framework that connects user supplied information about the location and spatial extent to be investigated, crop rotations, tillage management practices, residue removal methods, and land management practices, it can be easily adapted for other cellulosic energy crops by changing or adding additional simulation models to those it currently connects. Also, by expanding the spatial scale, the tool could be used to design landscape management scenarios [21] that could utilize multiple cellulosic energy crops to achieve economically viable feedstock production goals while simultaneously providing other ecosystem services, such as erosion control, nutrient cycling, buffering and filtering, wildlife habitat, carbon sequestration, and opportunities for rural development. The need for such an integrated framework was recently recognized by the Chicago Council on Global Affairs in a report that examined not only agronomic crops but also various waste streams as potential cellulosic feedstock for sustainable bioenergy production.

We conclude that although crop residues may often be excluded from cellulosic energy crop discussions, they will undoubtedly be part of cellulosic bioenergy systems for many years. The best option from our perspective is to integrate them into an overall feedstock production and delivery system that will be economically, environmentally, and socially acceptable for many years to come.

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