Chapter 5

Crop Residues of the Contiguous United States: Balancing Feedstock and Soil Needs With Conservation Tillage, Cover Crops, and Biochar

Jane M.F. Johnson USDA-Agricultural Research Service, North Central Soil Conservation Research Laboratory, 803 Iowa Ave., Morris, MN 56267, U.S.A. (jane.johnson@ars.usda.gov)

Francisco J. Arriaga, USDA-Agricultural Research Service, National Soil Dynamics Research Laboratory, 411 S. Donahue Dr., Auburn, AL 36832, U.S.A.

Gary M. Banowetz, USDA-Agricultural Research Service, National Forage Seed Production Research Center, 3450 S.W. Campus Way, Corvallis, OR 97331, U.S.A.

David R. Huggins, USDA-Agricultural Research Service, Land Management and Water Conservation Research Unit, Pullman, WA 99164, U.S.A.

David Laird, Department of Agronomy, Iowa State University, Ames, IA 50011, U.S.A.

Michael J. Ottman, Plant Sciences Department, University of Arizona, Tucson, AZ 85721, U.S.A.

Brian J. Wienhold, Agricultural Research Service, Agroecosystems Management Research Unit, 279 Plant Science, UNL, Lincoln, NE 68583, U.S.A.

Abstract

Crop residues are among the cellulosic feedstocks expected to provide renewable energy. The availability of crop species and residue availability varies across the United States. Estimates of harvestable residues must consider all the residues produced during the entire rotation. Inclusion of fallow or low residue producing crops requires that less feedstock be harvested. A re-occurring theme among the regions is that soils need to be safeguarded against erosion and against loss of soil organic matter (SOM). First, highly erodible lands are categorically excluded from harvesting residues in all regions. The minimum of residue needed to meet soil needs is highly variable. Where sufficient residues are produced to meet soil conservation and SOM considerations, harvesting of a portion may be considered. Soil conservation practices include eliminating or at least reducing tillage to keep the soil covered, avoiding fallow and adding perennials, applying amendments (manure, biochar) and planting cover crops in areas with sufficient moisture. Calculating regional or national availability of residue feedstock is valuable for evaluating the feasibility of bioenergy production; however, on a field basis, site-specific decision aids will be needed.

The United States is seeking to replace/supplement fossil fuel with renewable energy including cellulosic feedstocks. Cellulosic feedstocks can be used for production of liquid fuels (e.g., ethanol), syngas, or as feedstock to produce combined heat and power. The U.S. Department of Energy (DOE) and U.S. Department of Agriculture (USDA) "Billion Ton Report" estimated annual feedstock supplies at 175 million dry Mg (193 million tons) or about 16 percent of the biomass produced (Perlack et al. 2005). This value included crop residue, grain for ethanol and animal wastes. Estimates for available biomass (excluding dedicated perennials) ranged from about 360 to 500 million dry Mg (400 to 550 million dry ton) and excluded harvesting residues from lands classified as highly erodible (Perlack et al. 2005). Corn (*Zea maize* L.) stover on a national level is the largest untapped agronomic feedstock, although other feedstocks could be primary at a local or regional scale such as sugarcane (*Saccharum officinarum* L.) bagasse in the southeast, or wheat (*Triticum aestivum* L.) and grass straw from seed grasses production in the northwest (Perlack et al. 2005). An integrated or landscape approach to safeguard soil and environmental resources is vital for a sustainable bioeconomy which balances energy and conservation needs (Dale et al. 2010; Johnson et al. 2010a; Mitchell et al. 2010).

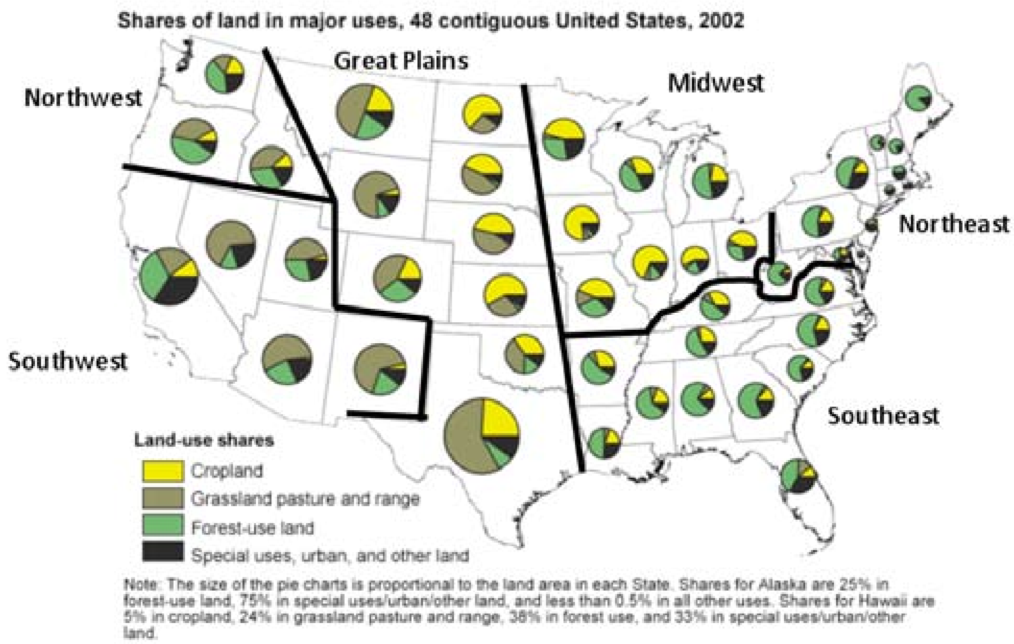

Figure 1. The major land use area of the United States. The six geographical regions are arbitrary and intended to provide the reader with a visual representation of the regions Source: USDA-Economic Research Service http://www.ers.usda.gov/Data/MajorLandUses/map.htm verified September 7, 2010.

In the United States about 373 million hectares (922 million acres) were classified as farm land in 2007 (USDA-NASS 2007). About 44 percent of this land is designated cropland with another 48 percent designated as pasture land; however this varies dramatically among states and regions (Figure 1). The United States has a wide range of climatic zones allowing production of a vast array of crops. The major row crops are corn, soybean (*Glycine max* L. [Merr.]), wheat, cotton (*Gossypium hirsutum* L.), sorghum (*Sorghum bicolor* L.), and rice (*Oryza sativa* L.). Corn and soybean are grown in most regions of the country; the majority of wheat is produced in the Great Plain and Pacific Northwest, sorghum is more common in the south Central Plains, while rice and cotton are restricted to Southeast. The Midwest and Central Plains have the largest percent of land designated to crop land, whereas the southeast and northeast proportionally consist of more forest land (Figure 1).

Concerns that harvesting crop residue can promote excessive erosion, reduce soil quality, undermine soil productivity and disrupt ecosystem services is a reoccurring theme among residues and regions. The specifics of those risks, agronomic consequences and mitigation strategies will interact among crops and climatic conditions. Harvesting crop residues needs to be managed to avoid accelerating erosion or reducing soil organic matter (SOM), and safe-guarding soil productivity (Lal 2004; Nelson et al. 2004; Wilhelm et al. 2004; Lemus and Lal 2005; Steiner et al. 2006a; Steiner et al. 2006b; Graham et al. 2007; Johnson et al. 2007b; Wilhelm et al. 2007; Lal 2008; Blanco-Canqui and Lal 2009). Other considerations on the amount of residue to harvest include potential nutrient removal (Hoskinson et al. 2007; Banowetz et al. 2009b; Johnson et al. 2010b), negative impacts on soil biota (Johnson et al., 2009) or loss of wildlife habitat (McLaughlin and Walsh 1998). Studies reviewed by Johnson et al., (2009) suggested that removing residue can negatively impacts soil biota, but most of these studies were outside of the U.S. There are situations where environmental and/or agronomic risks should out-weigh any potential benefits associated with harvesting crop residue and, thus, is not recommended (Lal 2004; Wilhelm et al. 2007; Lal 2008; Huggins and Kruger 2010; Johnson et al. 2010a). Indeed even when all crop residues are returned to the land, biomass input can be insufficient as soil erosion and SOM depletion are symptomatic of many production systems (Mann et al. 2002; Montgomery 2007). However, there may be mitigating options that can be adopted that facilitate harvesting some crop residues. The mitigation or compensating strategies will vary among crops, climate, topography and landscape.

Southeast and Northeast

Most states within the Northeast and Southeast regions have considerably more land area in forest or urban land use compared to cropland (Figure 1). Soils in both regions are largely Ultisols (http://www.cei.psu.edu/soiltool/), which are well weathered with low SOM. Annual precipitation in the Southeast and Northeast regions ranges from 1,000 to 1,500 mm, with more precipitation in the Southeast (Owenby et al. 2001). Although climate and parent material are partially responsible for the low SOM contents, decades of cultivation with conventional tillage practices, as well as low biomass production and high erosion levels, have led to large portions of these regions having degraded soils, especially in the Southeast.

Crops in the Southeast vary corn, cotton and soybean are commonly grown throughout the region (Table 1). Other crops are more geographically restricted due to specific soil and/or climatic requirements (Table 2). For instance, peanut (*Arachis hypogaea* L.) is grown mainly in the Coastal Plain, sugarcane in Louisiana and Florida, and rice in Arkansas, Louisiana and Mississippi. Livestock production is an economically vital component of the agricultural sector (Kemper et al. 2006) that also has potential as a bioenergy feedstock (Ro et al. 2009).

The Northeast is characterized by a cooler climate compared to the Southeast. Major crops in this region include corn, soybean, and wheat (Table 3) but barley (*Hordeum vulgare* L.), oat (*Avena sativa* L.), and potato (*Solanum tuberosum* L.) are also commonly grown.

Crop	Regional Yield Average	Regional Yield Std. dev.	Land area
	----------------Mg ha^{-1}	-----------------	Million ha
Corn	8.13	1.24	2.25
Cotton†	0.93	0.14	1.28
Soybean	2.55	0.40	5.26
Total area			8.79

Table 1. Average 2009 crop yield and acreages for the three most common crops in the Southeast states of Alabama, Arkansas, Florida, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, South Carolina, Tennessee, and Virginia*. * www.nass.usda.gov/quickstats/verified August 25, 2010 †Cotton not reported for Kentucky in 2009.

Crop	States	Regional Yield Average	Regional Yield Std. dev.	Land area
		------------Mg ha^{-1}	------------	Million ha
Peanut	Alabama, Florida, Georgia, Mississippi, N. Carolina, S. Carolina, Virginia,	3.74	0.34	0.37
Rice	Arkansas, Mississippi, Louisiana	7.40	0.30	0.88
Sugarcane	Florida, Louisiana	15.21	1.20	0.33
Total area crops				1.59

Table 2. Average 2009 crop yield and acreages for important specialty crops with potential as a local cellulosic feedstock in the Southeast region*. * www.nass.usda.gov/quickstats/verified August 25, 2010.

Crop	Regional Yield Average	Regional Yield Std. dev.	Land area
	------------Mg ha^{-1}------------		Million ha
Corn	8.74	0.52	0.89
Soybean	2.87	0.12	0.59
Wheat	3.85	0.41	0.23
Total area in row crops			1.72

Table 3. Average 2009 crop yield and acreages for the three most common crops in the Northeast states Delaware, Maryland, New Jersey, New York, Pennsylvania and West Virginia* * www.nass.usda.gov/quickstats/verified August 25, 2010.

A key component to crop production in these regions is the use of conservation agriculture, which incorporates the use of no-till and/or reduced tillage. Additionally, winter cover crops are often integrated with these production systems. The additional residues on the soil surface create a mulch layer that restricts weed growth and improves available plant water during the summer growing season. Legumes are sometimes used to provide additional nitrogen for the cash crop, but their residue decomposes faster compared to other cover crops, such as rye (*Secale cereale* L.), oats, and wheat.

Soils are most susceptible to erosion when they have limited residue cover or few actively growing crops. Campbell et al. (1979) estimated that 60 percent to 90 percent of crop residues grown in the summer were needed to control erosion, thus leaving 40 percent or less that may be available for harvest. This work assumed conventional tillage and considered erosion control, but it did not take into consideration protecting SOM content nor did it consider mitigating strategies such as conservation tillage or cover crops. Dabney et al. (2004) measured more water runoff on a silt loam in Mississippi managed without tillage but lower sediment loss was observed compared to conventional tillage. They estimated that soil disturbance increased sediment loss by 26 to 47 percent, and concluded that the reduced erosion in no-till (NT) was caused by improved soil properties and greater crop residue amounts on the soil surface. Similarly, Truman et al. (2009) found lower runoff and sediment losses with strip-till than conventional tillage for three soils in the Southeast. Nevertheless, chemical compounds that are highly soluble in water might have a greater potential to be lost by runoff with NT and strip-till (Potter et al. 2006; Franklin et al. 2007), but chemicals that tend to bind to soil particles have a greater risk to be lost from erosion with conventional tillage (Potter et al. 2004).

Research on crop residue harvest in the southeast and northeast is limited. However, current available information is in agreement that conservation systems can help offset any negative impact of crop harvest. A four-year study on a South Carolina sandy loam, found that although harvesting corn stover increased N, P and K removal rate, there was no corresponding difference in soil N, P and K due to stover harvest (Karlen et al. 1984). Removal of secondary and micro-nutrients was increased but only slightly. They estimated that between 3 and 7 Mg ha^{-1} of corn stover could be harvested as long as conservation tillage practices were used to help control erosion. The authors concluded that current fertilization practices were adequate to cope with nutrient losses. Moebius-Clune et al. (2008) studied the effect of harvesting corn stover for 32 years on 25 soil quality indicators of a silt loam in New York. Stover harvest was more sustainable without tillage than with plow tillage but the authors did not directly evaluate the impact of soil erosion in this study. Retaining mulch residue reduced sediment and P losses by 95 and 50 percent, respectively, compared to burying the residue, a common practice in potato production systems (Griffin and Honeycutt 2009). Studies mentioned above reported that no tillage was effective in reducing erosion, but water runoff might be increased under certain circumstances (Potter et al. 2006; Franklin et al. 2007). However, Truman et al. (2009) reported significant reductions in runoff and sediment loss for three different soils in the Southeast with the use of conservation tillage practices and winter cover crops.

Crops respond differently to cover crop use and residue management. For example, yields of a two-year potato-barley rotation were not significantly affected by the use of cover crops. The exception was red clover (*Trifolium pratense* L.) that reduced some disease pressure (Griffin et al. 2009). Delaying tillage increased ground cover and did not adversely affect yields. Griffin et al. (2009) concluded that cover crops and delaying tillage could be used as conservation practices for potato production in Maine without adversely affecting yields. Commonly sugarcane crop residue is burned since yield is reduced by leaving residue over the top of the row (Judice et al. 2007; Viator et al. 2008). However, burning crop residues reduces the amount of organic matter in the soil and creates air quality issues. An alternative management option is to mechanically remove the residue from the top of the sugarcane rows, which leaves large amounts of residue on the row middles that can interfere with other field operations (Judice et al. 2007). Therefore, it may be feasible to remove some sugarcane residue to avoid yield reductions and disruptions to field operations.

The Southeast and Northeast regions have adequate precipitation for biomass production. Further, winter temperatures in the Southeast are mild enough that certain winter crops, including cover crops such as cereal rye and wheat, can be grown during this time of the year and be harvested in the spring for their biomass. This approach protects the soil from erosion during the winter and increases organic matter inputs. A five-year study found that planting a rye cover and harvesting its biomass in the spring is better for a Coastal Plain soil in terms of soil quality and cotton production compared to having no cover (F.J. Arriaga, unpublished data). Both regions present significant opportunities for biomass harvest, but care must be taken to balance long-term productivity, environmental impacts and biomass production.

Midwest/Corn Belt

The Midwest region has a large amount of land area dedicated to row crops (Figure 1). The region is dominated by Mollisols and Alfisols, many of which have an inherently high SOM content (http://www.cei.psu.edu/soiltool/). Precipitation ranges from 500 to 1000 mm, and mean annual temperature ranges from 1.7 to 12.8°C. Both parameters increase as you move east and south across the region (Owenby et al. 2001). In general, the use of no tillage production systems increases as you move east and south across the region, with the least in Minnesota and the most in Indiana and Ohio (Johnson et al. 2005).

Crop	Regional Yield Average	Regional Yield Std. dev.	Land area
	------------Mg ha^{-1}	------------	Million ha
Corn	10.42	0.80	19.80
Soybean	3.01	0.31	18.18
Wheat	4.00	0.72	2.22
Total area in row crops			47.03

Table 4. Average 2009 crop yield and acreages for the three most common crops in the Midwest states Indiana, Illinois, Iowa, Michigan, Minnesota, Missouri, Ohio and Wisconsin*. * www.nass.usda.gov/quickstats/verified August 25, 2010.

There are many crops grown in the Midwest region but corn and soybeans represent the overwhelming majority, followed by wheat (Table 4). Over 90 percent of the acreage is rainfed (USDA 2009). Corn grown in rotation with soybean is common, but continuous corn or a three-year corn, soybean, and wheat sequence is also practiced. This region has been targeted for both production of grain-based ethanol and second-generation bioenergy production because of the extensive production acreage and high yields (Table 4), especially for corn (Nelson 2002; Perlack et al. 2005; Graham et al. 2007; Johnson et al. 2007b).

Numerous classical and recent articles have been published about potential environmental risks of harvest or over harvesting of crop residues for the Midwest and other locales (Larson 1978; Larson 1979;

Lal 2004; Wilhelm et al. 2004; Johnson et al. 2006; Johnson et al. 2007b; Wilhelm et al. 2007; Lal 2008; Johnson et al. 2010a). Crop residues are the first line of defense against erosive forces in annual row crops systems (Larson 1978; Merrill et al. 2006; Cruse et al. 2009), thus feedstock estimates limit residue harvest to avoid increasing wind or water erosion (Nelson et al. 2004; Perlack et al. 2005; Graham et al. 2007). The rate of wind and water erosion decreased in the Midwest between 1982 and 2007 (USDA 2009); for this trend to continue adequate residue needs to remain on the landscape. Furthermore, there are cases where the amount of residue needed to avoid loss of SOM exceeds that needed to control erosion (Wilhelm et al. 2007).

Empirical estimates of the average annual above ground biomass inputs necessary to maintain SOM ranged from 4.0 to >20 Mg dry residue ha^{-1} yr^{-1} in the Midwest region (Johnson et al. 2009). The very high estimate was from a study in Minnesota which examined a larger portion of the soil profile than many of the other studies (Huggins et al. 2007). Excluding this high estimate, the regional average annual above ground biomass inputs necessary to maintain SOM averaged 6.7 Mg dry residue ha^{-1} yr^{-1} (Johnson et al. 2009). Assuming a harvest index of 0.5, this corresponds to a grain yield of 7.8 Mg ha^{-1} (124 bu $acre^{-1}$ at 15.5 percent moisture) or if a harvest index of 0.53 is used the grain yield increases to 8.7 Mg ha^{-1} (140 bu $acre^{-1}$ at 15.5 percent moisture). This is a very crude estimate; site specific estimates considering local erosion risk and management factors (e.g., tillage, crop rotation) are required for local or field-scale recommendations.

Harvesting crop residue has direct impacts on soil properties but also has indirect impacts through modifications of microclimate effects (Johnson et al. 2009). Changes in microclimate interact with climatic condition for negative or positive agronomic consequences (Hillel 1998). A dark soil surface is desirable especially in cool, wet climates as it hastens soil warming and drying; thereby, creating a more favorable early-season growing conditions. However, the same processes can increase evapotranspiration and may exacerbate water deficits. The complex microclimate interactions may explain the variability in yield response to residue harvest. Yield responses to residue harvest in the Midwest ranged from decreases in Minnesota (Linden et al. 2000), Ohio (Blanco-Canqui and Lal 2007), Wisconsin (Swan et al. 1994), to no response in Indiana (Barber 1979), Minnesota (Linden et al. 2000; Wilts et al. 2004; Johnson and Barbour 2010), Ohio (Blanco-Canqui and Lal 2007), and Wisconsin (Swan et al. 1994), to an increase in Iowa when stover was selectively removed form over the row (Kaspar et al. 1990).

Corn and soybean production is the largest contributor to nitrogen (N) deposition in the Mississippi River Basin (Alexander et al. 2008). Nutrients, pathogens, pesticide and turbidity from agricultural sources contribute to the impairment of surface and ground water (US-EPA 2009). However, use of cellulosic biofuels (i.e., corn stover and switchgrass) is predicted to decrease nitrate loading in the Mississippi Basin. Therefore, combined with aggressive nutrient management strategies, biofuel production could reduce the hypoxia zone in the Gulf of Mexico (Costello et al. 2009).

The amount of nutrient removed by crop residue harvest is a function of concentration and rate. Nutrient concentration varies by crop (Johnson et al. 2009) and plant fraction harvested (e.g., cob, stover cutting height), and for some nutrients, plant maturity at harvest (Johnson et al. 2010b). It is easy to measure the rate of nutrient removal, but predicting the impacts on soil fertility is more challenging. The impact of nutrients removed with crop residues varies by soil type, specific nutrient, crop rotation, climatic conditions and other management variables (Johnson et al. 2010b). Replacement cost for nitrogen (N), phosphorus (P) and potassium (K) ranged from about \$12 to \$18 Mg^{-1} for cobs and total stover, based on five-year average fertilizer costs (Johnson et al. 2010b), which is slightly more than was replacement cost estimated by Hoskinson et al. (2007). Micronutrient status may also be impacted, and at the very least crops need to be monitored for micronutrient deficiencies that were not an issue when residues were returned.

The general principles for avoiding or mitigating environmental consequences of harvesting residues apply in the Midwest (Johnson et al. 2010a). First, all residues need to be returned on highly erodible land. Those areas with relatively low erosion risk may be considered for crop residue harvest provided sufficient residue covers the soil for erosion control and for maintaining SOM. Reducing or eliminating tillage, adding cover crops, and applying soil amendments such as biochar or manure will also be useful for maintaining soil productivity. Mitigation by no tillage and use of cover crops becomes more challenging in the north and west portions of the Midwest regions, due to shorter growing season and potential competition for soil water. Assuming manure application is managed following environmentally sound practices, it may substitute for some of the removed residue. However, those farms that have manure may also have a demand for the crop residue for bedding and/or feed. Transportation costs restrict use of manures to a relatively small geographical region near their production site.

Great Plains

The Great Plains region as defined in this paper includes North and South Dakota, Nebraska, Kansas, Oklahoma, Texas, Colorado, Wyoming and Montana (Figure 1). The continental climate of this region is characterized by highly variable seasonal precipitation and temperatures (Varvel et al. 2006). Annual precipitation averages <250 mm in the northwestern to >1500 mm in the southeastern part of the region. Average annual temperatures increase from 3.5°C in the north to 21°C in the southern part of the region. Prairie was the dominant pre-settlement vegetation with short grass prairie in the west and tall grass prairie in the east. Soils are primarily Mollisols with areas of Alfisols, Vertisols, and Ultisols (http://www.cei.psu.edu/soiltool/).

The climatic patterns of the Great Plains were a strong determinant of the vegetation and soils present and influenced cropping practices. When the prairie was plowed, farmers planted a combination of small grains and row crops; however, the limited and variable growing season precipitation resulted in low yields and crop failures. Crop-fallow was established to manage soil water. The practice resulted in higher yields and lower incidence of crop failure during the year a crop was planted. Unfortunately, crop-fallow systems also resulted in extensive wind erosion (Merrill et al. 1999), loss of SOM (Bauer and Black 1981), loss of soil structure (Skidmore et al. 1975), and the development of saline seeps (Halvorson and Black 1974).

Improved reduced tillage practices and the availability of effective herbicides led to the development of more intensive cropping systems, with reduced use of fallow and improved precipitation use efficiency (Peterson et al. 1996). Cropping intensification resulted in increased annual yields, increased annual returns and reduced risk (Dhuyvetter et al. 1996; Helmers et al. 2001), reduced wind erosion, and improved soil quality (Campbell et al. 1998; Wienhold and Halvorson 1998; Varvel 2006). The success of these more intensive cropping systems is largely dependent on producing and maintaining sufficient crop residue to protect the soil from erosion, reduce evaporation, and sustain the soil biota. On a regional basis cropping systems that use reduced tillage and more diverse rotations have improved physical (Pikul et al. 2006), chemical (Mikha et al. 2006), and biological (Liebig et al. 2006) soil properties.

The Great Plains is underlain with extensive groundwater resources and numerous rivers traverse the region. These water resources are used extensively for irrigation and agriculture is the dominant water user in the region. Irrigation stabilizes crop yields and allows growing of higher water demanding crops. Within the region, excessive irrigation with surface water can result in reduced water flows for downstream users and excessive use of groundwater can result in aquifer depletion requiring pumping from greater depths and eventually exhaustion of the resource (McGuire 2007). Irrigation in excess of crop demand results in leaching of nutrients and agricultural chemicals through the root zone resulting in contamination of groundwater resources.

Crops differ in their production potential and water availability is most commonly the factor limiting yield in this region, hence yield can be very different between irrigated and rainfed systems (Table 5). Residue remaining after harvest also varies greatly across the region. Residue amounts are dependent on crop production levels but also vary among species. Crops such as wheat, corn, and sorghum produce nearly as much straw and stover as grain. Other crops such as cotton or soybean produce much less residue.

Crop	States	Irrigated Yield	Dryland Yield
		-----------------Mg ha^{-1}	--------------
Wheat	North Dakota, South Dakota, Nebraska, Kansas, Oklahoma, Colorado, Wyoming, Montana, and Texas.	3.0 – 4.6	1.5 – 3.0
Corn	Nebraska, Kansas, Texas.	8.8 – 12.9	2.4 – 9.4
Soybean	Nebraska, Kansas, Texas.	2.1 – 3.3	1.1 - 2.6
Sorghum	Nebraska, Kansas, Oklahoma, Colorado, and Texas	4.7 – 6.5	2.4 – 5.6
Cotton	Oklahoma and Texas.	1.1 – 1.4	0.3 - 0.4

Table 5. Range of state average yields in 2008 for crops commonly grown in the Great Plains*.

* www.nass.usda.gov/quickstats/verified August 31, 2010.

Residue produced in rainfed systems in the western part of the region is essential to protecting the soil from wind and water erosion, improving soil water storage, and sustaining soil biota. Blanco-Canqui et al. (2009) measured runoff, sediment, and nutrient loss from no-tillage wheat and tilled sorghum and concluded that residue removal could not exceed 25 percent without significantly increasing the potential for erosion losses. In the low rainfall area of the Texas Rolling Plains, residue removal in wheat and grain sorghum decreased the saturated hydraulic conductivity (Ks) and micro-aggregation of the soil (Bordovsky et al. 1999). Crop residue also reduces evaporative losses from the soil, increases snow capture, and use of reduced tillage maintains infiltration capacity (Smika and Wicks 1968). The increase in cropping intensity resulting from improved precipitation capture and storage positively effects soil microbial communities and has resulted in soil C sequestration in the region (Halvorson et al. 2002; Acosta-Martinez et al. 2010). In these systems there is limited potential for using crop residue as a feedstock without negatively affecting the soil resource.

In the eastern part of the region where greater precipitation occurs and in irrigated systems yields are greater and significantly more straw and stover may be produced. In these systems residue production may reach levels that interfere with planting and slow warming of the seedbed in the spring. Under high production conditions a portion of the residue may be available for use as a feedstock (Graham et al. 2007). Wilhelm et al. (2004) identified soil compaction, nutrient removal, increased susceptibility to wind and water erosion, and negative effect on SOM as concerns associated with corn stover removal. A subsequent study estimated the amount of stover that needed to be retained to provide conservation functions and sustain the SOM (Wilhelm et al. 2007). This study also provided a model for estimating harvestable stover from continuous corn or corn-soybean rotations under plow or conservation tillage.

The cob fraction of corn stover has recently been proposed as a residue component that could be utilized as a feedstock without raising the concerns raised by Wilhelm et al. (2004). The cob fraction represents a consistent fraction of stover (20 percent) and the cob:grain ratio (17 to 20 percent) is similar across years and management (Varvel and Wilhelm 2008; Halvorson and Johnson 2009). Cob removal from plots where residue was removed or retained did not increase runoff, sediment, or nutrient loss from a silt loam soil on a 7 percent slope (Wienhold and Gilley 2010). Using the cob:grain ratio reported above and 2008 grain production data from York County Nebraska Wienhold and Gilley (2010) estimated that cob production was twice that needed to meet the feedstock needs of a cellulosic plant similar to that being built near Emmetsburg, IA. As cellulosic biofuel plants come on line the cob fraction may be a viable feedstock.

Residue removal effects on the soil resource may be ameliorated using cover crops or manure. Cover crops serve as a source of additional C, utilize residual soil nutrients reducing the potential for leaching losses, and provide protection from wind and water erosion. The main limitation to the use of cover crops in the Great Plains is competition between the cover crop and the cash crop for available water. In irrigated systems of the Great Plains, cover crops have been used successfully to reduce wind erosion and utilize residual fertilizer (Delgado et al. 2007). The Great Plains is a major beef, swine, and poultry production region. Livestock manure is readily available for use as a nutrient and C input that may offset residue removal effects. Ginting et al. (2003) applied beef feedlot manure or compost at rates to replace 150 kg N ha^{-1} removed in corn grain harvest. At this application rate microbial biomass increased 20 to 40 percent, mineralizable N increased 40 to 70 percent, and pH increased 0.5 units compared to soil without manure. Additional research is needed to assess the role of manure application as a mitigating strategy to compensate for the additional nutrient removal due to biomass harvest.

Southwest

The southwestern United States, for the purposes of this paper, includes the states of Arizona, California, New Mexico, Nevada, and Utah (Figure 1). This region encompasses a large geographical area with natural vegetation types ranging from desert to forest (Figure 1). However, crop production in this region occurs primarily in arid to semi-arid areas with low SOM. Literally hundreds of crops are grown in this region using a myriad of crop rotations. The most widely planted crops in this region that may contribute residue feedstocks are corn, sorghum, wheat, and barley, which require irrigation (Table 6). A common crop rotation would be cotton for a few years rotated to wheat or barley, then to corn or sorghum before being planted back to cotton or a forage crop. On a local scale vegetable residue could be harvested. However, this region is not likely to have extensive crop residues available compared to other regions.

Crop	Dry land Yield	Irrigated Yield	Dry land	Irrigated
	------------Mg ha^{-1}------------		Million ha	
Wheat	1.5	5.9	0.10	0.30
Barley	1.9	5.1	0.02	0.04
Corn	3.4	10.7	0.02	0.22
Total			6.2	4.4

Table 6. Harvested crop land area and average grain yield for irrigated and dryland wheat, barley and corn in the Southwestern states of Arizona, California, New Mexico, Nevada and Utah*. * www.nass.usda.gov/quickstats/survey (2008) and census (2007) data verified September 7, 2010.

Conservation tillage is not widely adopted in the southwest for various reasons. In California, for example, conservation tillage adoption was estimated at 2 percent of the farmland in 2004 (Horwath et al. 2008). The farmland is level or not as steep as farmland in areas where conservation tillage is more widely practiced. Furthermore, conservation tillage does not lend itself to flood or furrow irrigation systems, which is widely used in this region, where residue may impede irrigation water movement. Also, conservation tillage may result in poor stand establishment of small seeded crops or interfere with conventional cropping practices of certain crops.

There is scant literature on the impact of harvesting crop residue in this region. However, residue removal often has had negative impacts on soil properties and crop performance in arid and semi-arid areas around the world with a climate similar to the southwestern region (Dalal 1989; Radford et al. 1992; Thompson 1992; Yamoah et al. 2002; Shafi et al. 2007). Thus, potential negative consequences should be anticipated if crop residues are harvested in this region without mitigation strategies.

Potential mitigation strategies for residue removal include conservation tillage, cover crops, and the addition of carbon-rich soil amendments. Conservation tillage may mitigate some but not all negative aspects of crop residue removal. In a cotton-tomato (*Lycopersicon esculentum*) rotational system in California's Central Valley, conservation tillage alone did not increase soil organic carbon (SOC) (Veenstra et al. 2007), similar to results obtained in other arid and semi-arid regions (Buschiazzo et al. 1999; Chan et al. 2001). Conservation tillage has been shown to reduce wind erosion and dust particles in the air in California's Central Valley (Baker et al. 2005). In Arizona, reduced tillage of a previous barley crop increased water infiltration in cotton (Martin et al. 2003). However, no-till systems in Arizona may reduce cotton yields (Adu-Tutu et al. 2005). One of the problems with widespread adoption of conservation tillage is management of the residue in flood and furrow irrigation systems. Irrigation is necessary for high productivity (Table 6). In flood systems, the residue can float in the irrigation water and form an impenetrable barrier to emerging seedlings. In furrow systems, the residue can accumulate in the furrow and block water movement. So, in these cases, removal of the residue may encourage the implementation of conservation tillage.

The use of cover crops appears to have more potential to increase SOM in the southwestern region than conservation tillage. The use of cover crops in a cotton-tomato rotation in the Central Valley of California increased SOC (Veenstra et al. 2007). In the Coachella Valley of California, the use of cover crops increased SOM, but also increased horticultural crop yields (Wang et al. 2008). In California, a combination of cover crops and organic amendments increased SOM by 36 percent (Horwath et al. 2002). Despite their advantages, cover crops are not widely used due to their cost of establishment and maintenance, and since the economic returns are not realized directly on the crop itself.

Northwestern Region

The Northwest region is defined for this paper as Washington, Oregon, Idaho and far western Montana (Figure 1). This region has a wide range of climatic conditions. East of the mountains annual precipitation ranges from 200 to 500 mm and winter temperatures frequently drop below 0°C and snow cover is common. In contrast, western Oregon annual precipitation in the range of 850 to 1700 mm and winter temperatures seldom fall below 0°C with average daily high temperatures frequently exceeding 8°C in December and January. Soils in the region include Mollisols, Inceptisols, Entisols and Aridisols (http://www.cei.psu.edu/soiltool/).

Both dryland and irrigated small grains including wheat and barley are major components of the region's agronomic cropping systems. A typical system (90 percent of cropland) is a two-year, tillage-based, winter wheat-summer fallow rotation (Schillinger et al. 2003). This region also produces forage and turf grass seed. Kentucky bluegrass (*Poa pratensis* L.) seed production occurs in the relatively dry, semi-arid regions of eastern Washington, northern Idaho, and central and eastern Oregon. Perennial (*Lolium perenne* L.) and annual ryegrass (*Lolium multiflorum* L.), bentgrass (*Agrostis* sp.), tall (*Schedonorus phoenix* (Scop.) Holub) and fine (*Festuca* sp.) fescues, and orchardgrass (*Dactylis glomerata* L.) seed production occurs in the high rainfall areas of western Oregon.

Crop	Dry land Yield	Irrigated Yield	Dry land	Irrigated
	------------Mg ha^{-1}------------		Million ha	
Wheat	3.1	6.5	1.40	0.44
Barley	2.3	5.1	0.16	0.17
Corn	n†	12.0	n	0.08
Total			4.77	2.73

Table 7. Harvested crop land area and average grain yield for irrigated and dryland wheat, barley and corn in the Pacific Northwest states of Idaho, Oregon and Washington *. * www.nass.usda.gov/quickstats/survey (2008) and census (2007) data verified September 7, 2010. † n = no data, little to none grown.

Crops that produce high amounts of residue that could be used as bioenergy feedstocks are wheat, barley, corn and perennial grasses raised for seed. Regionally, dryland and irrigated wheat produce the greatest quantities of straw (Table 7). Dryland wheat (1.4 million ha yr^{-1} harvested) and irrigated wheat (0.44 million ha yr^{-1} harvested) produce about 6.44 and 4.22 Mt yr^{-1}, respectively, of dry wheat straw assuming a grain to straw ratio of 0.59 and a harvested grain water content of 12.5 percent. Grass-straw production across the region average 2.4 Mg ha^{-1}, with an average annual production of about 2.24 Mt yr^{-1} (Banowetz et al. 2008). The grass straw yield ranged from 3.5 to 7.5 Mg ha^{-1} in the drier eastern portion and 9 to 13 Mg ha^{-1} in the wetter western portion of the region; as most grass seed crops are produced under dryland condition (Banowetz et al. 2008). Irrigated barley (0.17 million ha yr^{-1}) produces 1.12 Mt yr^{-1} of dry barley straw and dryland barley (0.16 million ha yr^{-1} harvested) produces 0.49 Mt yr^{-1} of dry straw assuming a barley grain to straw ratio of 0.67 and a harvested grain water content of 12.5 percent. The region's corn is grown almost exclusively under irrigation (0.082 million ha yr^{-1} harvested) and assuming a corn grain to stover ratio of 1:1, and a grain water content of 15.5 percent, about 0.83 Mt yr^{-1} of dry corn stover are produced.

Irrigation increases the concentration of residue stocks (Table 7), which has important economic and environmental implications. From an economic standpoint, concentrated feedstocks reduce harvest and transportation costs and bioenergy facilities could be strategically located in areas where feedstock supplies would be greater and more stable (less yield variability due to weather) (Kerstetter and Lyons 2001). Environmentally, a smaller proportion of total crop residues would need to be returned to the land to provide agro-ecosystem services and maintain soil productivity (Huggins and Kruger 2010). In locations with sufficient rainfall or irrigation, a portion of the grass straw may be harvested and still provide enough residue to meet USDA-NRCS conservation guidelines (Banowetz et al. 2008; Mueller-Warrant et al. 2010).

Removal of grass straw and other agricultural residues from production systems is accompanied by the removal of macro– and micronutrients that accumulate in the biomass during the growing season. Straw harvested from dryland Kentucky bluegrass in eastern Washington removed 48 to 96 kg of K, 2 to 10 kg of P, and 662 to 1029 kg C ha^{-1} (Banowetz et al. 2009a). In the high rainfall area of western Oregon, harvest of 2.4 Mg ha^{-1} of perennial ryegrass removed 40 to 47 kg K, 3.4 to 3.8 kg P, and 922 to 986 kg C ha^{-1} (Banowetz et al. 2009b). Similar quantities of P and K were removed during harvest of a selection of native grasses that are used in roadside and buffer areas of the west (El-Nashaar et al. 2009). These nutrients have value for soil productivity and their replacement increases production costs.

Research to quantify the impact of straw removal from perennial grass seed production systems has focused on full removal of the straw by baling or returning all chopped straw to the field. A ten year study at three locations of western Oregon found that seed yield of perennial ryegrass, tall fescue, and creeping red fescue was unaffected by residue management but returning straw combined with direct seeding, reduced soil erosion from 40 to 77 percent (Steiner et al. 2006a; Steiner et al. 2006b). Residue management did not alter meadowfoam (*Limnanthes alba* Hartw. ex Benth.) biomass or oil yield when it was produced as a rotation crop with these three grasses. A subset of this long-term study found that SOC, microbial biomass C, dissolved organic C, soil K and the activity of soil enzymes ß-glucosidase and arylsulfatase activity in the 0-10 cm were greater when straw was returned to compared to when straw was harvested (Richard Dick and Steve Griffith, unpublished data). In contrast, a four-year study of the impact of high versus low residue management on soil C in the low rainfall areas of eastern Washington showed no significant differences in soil C associated with straw residue or tillage methods (Griffith, unpublished data).

Amounts of crop residue required for conservation needs and other agroecosystem services are still under debate (Huggins et al. 2011). Kerstetter and Lyons (2001) estimated that leaving 3.4 to 5.6 Mg ha^{-1} yr^{-1} of dry straw is required to soil for conservation purposes in western states, whereas Banowetz et al., (2008) 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 by Rasmussen and Collins (1991) to be required in dryland cropping systems near Pendleton, OR. Yields of cereal crops under irrigation often produce large amounts of residue. For example, a wheat yield of 6.5 Mg ha^{-1} may produce 9.7 Mg ha^{-1} of straw (Tarkalson et al. 2009; Tarkalson et al. 2011). Harvesting straw in irrigated situations does not appear to adversely affect SOM (Tarkalson et al. 2009; Tarkalson et al. 2011).

Kerstetter and Lyons, (2001), Western Governors' Association (2006), and Banowetz et al., (2008), assumed similar quantities of straw are produced in the region year-to-year. However, due to crop rotation and wheat-fallow systems, straw production does not occur in the same field every year. Typically dryland cereal crops are grown in rotation or combined with fallow periods (Schillinger et al. 2003). While a typical wheat yield of 3 Mg ha^{-1} will produce about 4.5 Mg ha^{-1} of residue, this is only sufficient if a crop is grown annually on the same fields. Thus, residue production must be considered over the entire rotation when calculating available feedstocks (Johnson et al. 2006; Huggins and Kruger 2010). Johnson et al. (2006) estimated that straw yield may be adequate for sustaining SOC provided wheat is grown continuously without fallow, assuming a biomass return rate of 4.5 ± 2.5 Mg straw ha^{-1} yr^{-1} (n=9). They further suggested that critical source C for wheat-fallow maybe twice that in continuous wheat. Neglecting the impact of fallow or rotation in considering the amount of biomass needed to be returned will over estimate the amount of residue that can be sustainably harvested.

Estimating available residue as a percentage (e.g., 10 to 50 percent) of the total residue and assuming the remaining unharvested residue is sufficient for meeting conservation and soil maintenance needs (Berndes et al. 2003; Frear et al. 2005; Fischer et al. 2007), underestimates available feedstocks when residue production is high (e.g. irrigation) and overestimating available feedstocks when residue levels are low (e.g. dryland with fallow). It neglects that the percentage of crop remaining is not the same as percent soil coverage. Calculating the regional availability of residue feedstocks is important for evaluating the feasibility of bioenergy production. However, on a field basis considerable variability can exist in both feedstock production and availability, thereby requiring residue harvest decision aids that are site-specific (Huggins and Kruger 2010; Johnson et al. 2010a).

Other issues that need consideration include economic savings that result from residue removal in terms of subsequent field operations; time and cost for field operations (Western Governors' Association 2006); disease and weed factors that can be ameliorated by removing crop residues; the value of nutrients removed in harvested residues (Patterson et al. 1995; Banowetz et al. 2009a; Banowetz et al. 2009b; Huggins and Kruger 2010); soil water conservation that results from maintaining surface residues; and mitigating practices such as the use of conservation tillage, site-specific nutrient management (Huggins and Kruger 2010) and cover crops.

Biochar: a Potential Mitigation Strategy

Co-products of lignocellulosic feedstock conversion to bioenergy vary by platform. The high lignin by-product of fermentation, although could be applied to soil (Johnson et al. 2007c) is more likely to be used for feedstock on-site for its energy value (Sheehan et al. 2004). Gasification processes that strive for high energy conversion result in a low carbon ash that has potential as a source of inorganic minerals (P and K) (Johnson et al. 2007b). In contrast, pyrolysis, which is the thermo-chemical decomposition of organic compounds in the absence of oxygen at temperatures typically above 400ºC, produces biochar (a.k.a., charcoal, char, agri-char, green coal, and black carbon), bio-oil and syngas. Slow pyrolysis produces approximately equal masses of all three co-products, whereas fast pyrolysis is optimized for the production of bio-oil, gasification is optimized for syngas production, and flash carbonization is optimized for biochar production (Laird et al. 2009).

Quality of the biochar, bio-oil and syngas co-products depends on properties of both the feedstock and the thermo-chemical reaction conditions during pyrolysis. Biochars made from low-ash woody feedstocks can be used to replace pulverized coal. Generally biochars, produced from crop residues and most herbaceous biomass, are not suitable for use as green-coal because they contain too much silica, which scales the walls of combustion chambers. However, they do have potential to be used as a soil amendment.

Soil biochar application recycles most of the nutrients that are removed by the harvesting of biomass. During pyrolysis over 90 percent of the K, P, Ca, Mg, and most micronutrients, and about half of the N in the biomass feedstock are partitioned into the biochar fraction (Mullen et al. 2010). When biochar is applied to soils, most of these nutrients are bioavailable. The N, however, is bound in recalcitrant biochar fractions and is not biologically availably to plants on agronomically significant time scales. Many biochars are alkaline and as such they also function as a liming agent when added to soils.

Soil biochar applications are a highly effective means of increasing the level of SOC. The C content of biochar ranged from 40 to 80 percent by mass depending feedstock and pyrolysis conditions (Spokas and Reicosky 2009). Most of the C in biochar is present as complex compounds that are either not biologically available or are mineralized slowly in soil environments. A portion of the C in the biochar is readily degraded by soil microorganisms. As a general rule, the fraction of this easily degraded C in biochar decreases as the pyrolysis temperature increases. Literature estimates of the half-life of biochar C in soils range from decades to millennia (Swift 2001; Hamer et al. 2004; Kuzyakov et al. 2009; Steinbeiss et al. 2009) due to differences in biochar quality. By contrast the half-life of C in fresh crop residues is typically measured in months to years (Johnson et al. 2007a). Thus, pyrolysis of biomass transforms easily degraded C into highly stable C and this change in stability accounts for most of the ability of soil biochar applications to increase SOC levels. Complex interactions exist between biochars and biogenic soil organic C, and between biochars and net primary productivity. Therefore, it is difficult to predict the impact of amending soils with a specific biochar on C input and subsequent SOC levels.

Soil biochar applications may increase the nutrient and water holding capacities of soils and reduce soil bulk density. Low particle density and high internal porosity allow biochar to function as a soil conditioning agent (similar to exfoliated vermiculite). The reduction in soil bulk density resulting from biochar applications is more than can be explained by simple dilution (Laird et al. 2010). Fresh biochar contains little oxygen and has a low cation exchange capacity (CEC), however surfaces of biochar are oxidized as it ages in soil environments creating carboxylate and phenolate groups that add CEC to soils (Cheng et al. 2006; Liang et al. 2006). Therefore, the impact of biochar amendments on soil CEC's is influenced by both biochar quality and the length of time the biochar are in a soil environment. The application of pecan shell-biochar to a Norfolk sandy loam improved soil fertility but did not increase the CEC after incubating for 67 days (Novak et al. 2009). By contrast, a 500-day incubation of a Clarion soil with a hardwood biochar increased the soil's CEC by almost 20 percent, and the effective CEC of the hardwood biochar was estimated to be 187 cmol kg^{-1} (Laird et al. 2010). As surfaces of biochar particles oxidize, they are transformed from hydrophobic to hydrophilic, which along with a reduction in soil bulk density and the high internal porosity of biochar particles, facilitates the retention of plant available water by when amended to soils.

Biochar quality varies substantially depending on the nature of the feedstock and the condition during pyrolysis. Concerns have been raised that some biochars may have detrimental impacts. Biochars that contain significant levels of polyaromatic hydrocarbons, for example, are potentially hazardous (Dellomo and Lauwerys, 1993). The production of polyaromatic hydrocarbon can be controlled by maintaining pyrolysis temperatures below 700°C (Garcia-Perez et al., 2008). Furthermore, toxicity studies conducted with two biochars, one from poultry litter and the other from pine chips, increased mortality and weight loss of earthworms (*Eisenia fetida*) (Liesch et al. 2010). In contrast, there are reports that biochar can promote colonization by beneficial mycorrhizal fungi (Warnock et al. 2007) and increase microbial activity (Focht 1999). Clearly, there is a need for continued research on the biochar properties from a range of feedstocks and thermochemical conditions, and the responses of soils to biochar applications.

The fundamental hypothesis underlying "The Charcoal Vision" is that applying biochar to soil will recycle nutrients and sustain or even enhance soil quality even when surface residues are harvested for bioenergy production (Laird 2008). Biochar research published to date strongly supports this hypothesis with two important caveats; 1) biochar quality is very important, there are good biochars and bad biochars, and 2) biochar will not protect soils from erosion. Soil biochar applications may allow a greater fraction of total crop residues to be sustainably harvested for bioenergy production relative to systems in which biochar is not applied to soil. However, even with biochar applications, a fall cover crop must be grown or enough residues must be left on the surface, to protect the soil from erosion.

Summary

Regardless of the region controlling erosion, safeguarding SOM and related soil productivity issues are reoccurring themes. There is a need for controlled studies that compare the impact of residue removal or retention on SOC, soil biota, and other physical parameters. Additional quantification of macro- and micro-nutrient removal associated with residue harvest is needed. As well as studies to assess how nutrient management may need to be altered.

A key mitigation strategy is to follow standard conservation practices established by the USDA-NRCS. Eliminating or at least reducing tillage keeps crop residue on the soil surface. Cover crops are another strategy to keep the soil covered; thereby, reducing erosion risk and sequestering more carbon. Although, not discussed at length as the discourse focused on crop residues, adding perennials within a rotation and/or on the landscape can improve soil and water quality. The mitigation strategies proposed for supporting crop residue harvesting are applications of standard soil conservation practices and the use C-rich soil amendments such as manure or biochar to build soil C levels. Calculating regional or national availability of residue feedstock is valuable for evaluating the feasibility of bioenergy production. Nevertheless, on a field basis site, specific decision aids will be needed. Harvesting crop biomass requires aggressive conservation practices to avoid unintended environmental degradation in all regions.

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