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# Abstract

Crop residue, a byproduct of harvested food and fiber, makes up a substantial amount of crop production biomass. Although traditionally considered an agricultural waste, residue is now recognized for its value in reducing soil susceptibility to wind and water erosion and contributing to soil health and soil fertility. This chapter reviews the benefits of residue retention and the methods for estimating residue coverage and biomass. Additionally, recent and emerging residue management tools are described, including a stripper header that leaves nearly all standing residue, improved information about managing decomposition rates through utilization of different crops and varieties, and new budgeting tools for balancing the tradeoffs related to harvesting or burning residues. This chapter provides growers with general principles about sustainable residue management practices for inland Pacific Northwest (PNW) cropping systems.

Research results are coded by agroecological class, defined in the glossary, as follows:

Annual Crop Annual Crop-Fallow Transition Grain-Fallow

# **Key Points**

- Soil erosion is a major contributor to soil degradation and air pollution in the inland PNW. Erosion can be mitigated by strategic management of crop residue.
- The challenges of residue management vary across the inland PNW. Heavy residue produced in high-yield areas can make planting difficult and contribute to unfavorable growing conditions in the early spring. In areas with low or intermediate yields, additional residue is desired for enhancing soil and water conservation benefits.
- Appropriate residue management strategies depend on agroecological class, tillage, cropping system, and varieties.
- Different residue management strategies have tradeoffs between production, economics, environment, and soil health. The estimate of immediate economic tradeoff of harvest residue and burning can help support decisions about residue management practices.

# Introduction

Crop residue, a byproduct of harvested food and fiber, makes up a substantial amount of crop production biomass. Residues are traditionally considered an agricultural waste. However, they are increasingly recognized for their value in reducing soil's susceptibility to wind and water erosion, improving soil water conservation, and contributing to **soil health**. When harvested, crop residues are also valuable as livestock feed and bedding, and as feedstock for mushroom, fiberboard, and paper production. More recently, the prospect of using crop residue for energy production has also emerged.

The challenges of residue management vary across the **inland PNW**. One important factor is that residue production varies widely across the region, with estimated residue production for winter wheat ranging from roughly 0.9 ton/acre in the Grain-Fallow **agroecological class** (AEC) ■ to 8.5 ton/acre in the Annual Crop AEC ● (see Chapter 5: Rotational Diversification and Intensification). Too much residue can be problematic in the Annual Crop AEC ●. High residue levels can lead to colder, wetter

soils in the early spring, complicate planting, and create conditions that benefit soilborne pathogens. However, residue production is generally lower than desired for soil health in areas with low or intermediate yields in the Grain-Fallow AEC . Meanwhile, residue decomposition rates vary across the inland PNW and in different seasons of a year. Residue decomposition proceeds rapidly during spring, summer, and fall when soil moisture is adequate and air temperature is optimal, conditions that occur more frequently in wetter areas of the inland PNW. This is because the soil microbes responsible for decomposition are most active in warm (77–95°F) and moist (50–70% water-filled pore space) conditions (Havlin et al. 2005). Decomposition is very slow when soil temperatures are below 50°F or above 105°F, or when soil moisture is <40% water-filled pore space.

The purpose of this chapter is to provide growers with general principles about sustainable residue management practices that balance the agronomic, environmental, soil health, and economic tradeoffs of residue use. Specific objectives include: (1) discuss the benefits of crop residue in a sustainable agricultural system, (2) provide a critical evaluation of methods for estimating residue production, and (3) review current residue management practices in the inland PNW, including emerging residue management strategies and tools to help evaluate their benefits and tradeoffs.

# **Benefits of Residue Retention**

In the inland PNW, under **conventional tillage** systems such as plowing, disking, or chiseling, residues are recycled by incorporating them into the soil. Alternatively, under **conservation tillage** systems, residues are recycled by leaving them to decay on the field surface. In combination with limiting the frequency and intensity of soil disturbance by tillage, residue return plays the following important roles: (1) protecting soil from erosion, (2) improving soil health, (3) increasing soil water retention and availability, (4) moderating soil temperature, (5) providing wildlife habitat, and (6) building soil organic matter (SOM). These factors, in turn, support long-term crop productivity. Tillage is covered in more detail in Chapter 3: Conservation Tillage Systems.

## Protecting Soil Against Erosion

As discussed in Chapter 3: Conservation Tillage Systems, soil erosion is one of the biggest challenges for sustainable agricultural production in the inland PNW. Water erosion is the major concern in the Annual Crop AEC ●; wind erosion is the major concern in the Grain-Fallow AEC ■. A surface cover of crop residue can effectively reduce both water and wind erosion. The optimal ground coverage for erosion control is linked to soil topography and slope, evenness of residue distribution, tillage, type of residue, and residue decomposition rate.

Residue cover and conservation tillage reduce water erosion primarily by protecting the soil from the impact of raindrops that disperse soil **aggregates** and cause soil surface crusting. Thus, the surface residue slows rain or melting snow movement across the soil surface, allowing more time for **infiltration** and reducing the extent of soil freezing under snow cover (Dickey et al. 1986; Smil 1999; Hatfield et al. 2001).

Crop residue on the soil surface reduces wind erosion by reducing wind speeds near the soil surface to below the threshold level for lifting soil particulates. The most important factors influencing the effectiveness of residue management for controlling wind erosion include: (1) mass of residue, (2) percentage of soil covered by residue (Figure 4-1), (3) degree of residue contact with soil, which ensures residue remains in place and does not blow away (Papendick and Moldenhauer 1995), and (4) the height, diameter, and population of standing stems, because these characteristics determine the silhouette area through which the wind passes (McMaster et al. 2000).

Mass of residue is determined not only by residue production, but also by tillage practices (see Chapter 3: Conservation Tillage Systems). In general, residue level and ground cover decrease in order of **no-till** > conservation tillage > conventional tillage (Table 4-1). For the same erosion control effectiveness, more residue is needed in a conventional tillage system than in a no-till system (Figure 4-2). Moreover, a greater amount of residue is needed in a more intensive tillage system, such as moldboard plow tillage, than in a conservation tillage system, such as undercutter tillage (Figure 4-3) (Elbert et al. 1981). The Agronomy Guide from Purdue University summarizes the effects of tillage operations on the amount of post-tillage residue cover (Eck et al. 2001).





Table 4-1. Mean annual ground cover measured during winter crop growth in the Grain-Fallow
agroecological class in Umatilla County, Oregon 🔳.

Site <sup>+</sup>	Tillage	% ground cover	Tillage	% ground cover
Drainage	no-till	73a <sup>‡</sup>	traditional/ moldboard plow	44b
Hillslope	no-till	81a	minimum tillage	64b
Draw	no-till	81a	minimum tillage	59b

 $^{\rm t} The$  maximum slopes were 30%, 20%, 23%, and 4% in no-till, traditional/moldboard plow, hillslope, and draw sites, respectively.

 $^{*}Values$  in rows are significantly different at P≤0.05 with different letters. Adapted from Williams et al. 2014.



Figure 4-2. Relative soil loss from water erosion on land with surface and incorporated residues for northwest Washington where rill erosion is the dominant type of erosion on crop land. (Adapted from Papendick and Moldenhauer 1995.)



Figure 4-3. Soil loss associated with various tillage systems in a wheat-fallow rotation in Nebraska. (Adapted from Dickey et al. 1981.) Note: lab simulation study on 4% slope hill after planting wheat in a wheat-fallow rotation.

Adequate soil surface protection with crop residue cover is particularly important in the Grain-Fallow AEC during the critical periods for wind erosion, including in the fall and in April and May, when high winds and vulnerable soil conditions occur (Papendick and Moldenhauer 1995). Residue cover is generally <15% soil surface cover (<500 lb/acre) by November to March in areas where conventional tillage is practiced during summer **fallow** (Thorne et al. 2003; Williams et al. 2014). Practices that increase residue biomass production or no-till is especially important in these areas to preserve surface cover during vulnerable times. No-till with tall standing stubble is especially effective. For example, a study found that doubling the mass of 10-inch-high wheat residue (from 450 to 906 lb/acre) has been shown to cut wind erosion by more than 95% (Smil 1999).

In contrast, in the high-yield areas in the Annual Crop AEC, residue production significantly exceeds the amount required for erosion control. The concern is to retain enough residue for effective erosion control in fields where conventional tillage, or harvesting or burning residue, is practiced (see Chapter 3: Conservation Tillage Systems). The amount of residue that can be harvested or the frequency of burning should be carefully estimated so that an adequate amount of residue is retained for erosion control and soil health improvement.

Researchers generally agree that 30% residue coverage (approximately 1,000 lb/acre residue) is adequate to control both wind and water erosion in flat fields; but, coverage requirements increase to as much as 60% in sloped fields under a conservation tillage system (USDA-NRCS 2005; 2008). The Natural Resources Conservation Service (NRCS) Conservation Plan currently requires at least 30% of last year's crop residue on the soil at planting for a conservation tillage system. In addition, for best water and wind erosion management, surface residue should be spread as uniformly as possible. At harvest, straw chopped into smaller-sized pieces is more likely to be spread uniformly. However, the smaller size is also more likely to be redistributed by wind or water and will decompose faster due to greater surface area contact with soil and water.

## Improving Water Conservation

Water availability is a major limiting factor for dryland crop production. Winter wheat requires an estimated 2.32 inches of available water for vegetative growth prior to reproductive development. Each additional 0.39 inch of available stored soil water and spring rainfall (April–June) produces an average of 134 and 155 lb/acre grain, respectively, in eastern Washington (Schillinger et al. 2010).

Soil water recharge and storage is especially important in the inland PNW because an estimated 70% of the region's precipitation occurs between October and March (as discussed in Chapter 1: Climate Considerations). Because daily potential evaporation during the rainy season is low, soil water can percolate beyond the surface soil layers if water runoff can be effectively controlled (Ramig et al. 1983; Ramig and Ekin 1984). Residue and tillage management strategies can be used to increase infiltration, reduce evaporation, enhance snowfall catch, and improve **water holding capacity**, therefore increasing soil water storage.

Surface residue cover can increase infiltration and suppress evaporation. However, the extent of this effect depends largely on the AEC, the amount of residue, and the tillage system. For no-till producers in the Grain-Fallow AEC, large amounts of surface residue cover are required to effectively reduce evaporation due to the extended dry, hot summers (Wuest and Schillinger 2011). A 6-year field study conducted in this AEC concluded that, even with 4 or 7 times the regional residue average (1.4 ton/acre), evaporation reduction in no-till surface cover remained limited compared to tilled fallow ■. This limited benefit of no-till summer fallow on water storage efficiency has also been documented in other parts of the US: the percentage of precipitation that generally can be stored in soils is only 10% in Texas, 22% in eastern Colorado, and 25–30% in western Kansas for the 14-month winter wheat-summer fallow rotation (Peterson et al. 1996).

In the Annual Crop-Fallow Transition AEC, no-till that leaves residue on the soil surface provides significant benefits in soil water storage over conventional tillage. Research conducted in Pendleton, Oregon, during a dry year suggested that conserving residues results in higher water infiltration and greater soil water storage than when residues were incorporated (Figure 4-4). The average soil water storage in the 41inch profile was 7.36, 6.61, and 6.10 inches under no-till (94% ground cover), residue returned after tillage (83% ground cover), and residue incorporated with tillage (23% ground cover), respectively (Williams and Wuest 2014) ▲.



Figure 4-4. Soil water in a 41-inch profile during a dry crop year (2005) under TI (residue incorporated into soil), NT (no-till), and RR (residue returned on soil surface after tillage) treatments of annual winter wheat near Pendleton, Oregon. (Adapted from Williams and Wuest 2014.)

Increases in soil water storage in no-till that leaves residue on the soil surface have also been seen in the Annual Crop AEC. Near Troy, Idaho, soil moisture in the surface 6 inches of winter wheat, managed with no-till, was found to be significantly higher in the fall between precipitation events than winter wheat managed with no-till plus stubble reductions or with conventional tillage (Huggins and Pan 1991).

Understanding the impacts of residue on snow capture is important to understanding water storage impacts of residue. Across the inland PNW, roughly a third of precipitation is in the form of snow during the primary soil-water recharge period. Trapping more snow can increase soil water storage, and can also provide insulation that protects plants from winterkill. In the unique land topography of the Palouse, redistribution of snow by wind and snowmelt runoff can also cause substantial spatial variation in soil water availability. Ridge tops and south-facing slopes generally retain the least amount of snow, and valley areas retain the thickest snowpack regardless of tillage system (Figure 4-5).

In this topography of the Palouse, no-till retains more soil water with less spatial variation of snow depth at all topographic locations compared with conventional tillage. In Pullman, Washington, during the 2007–2008 season, no-till ridge tops and south-facing slopes (with 3.54 to 13.00 inches standing stubble) retained 3.94 to 4.72 inches and 3.94 to 5.51 inches more snow, respectively, during two separate snow events,



Figure 4-5. Average snow depth observed during January 29 through February 14, 2008, on two adjacent fields in Pullman, Washington, for (a) conventional tillage (CT) on a private farm and (b) no-till (NT) on Washington State University Cook Agronomy Farm, and departure of snow depth at ridge top and valley from the average for (c) CT and (d) NT. (Adapted from Qiu et al. 2011.)

compared with conventionally tilled fields (Qiu et al. 2011). By spring, notill stored 2.36, 1.14, and 0.51 inches more water in the 5-foot soil profile at ridge tops, south-facing slopes, and valley locations, respectively, than conventional till.

Standing crop residue, such as wheat and sunflower stubble, is more effective not only in reducing wind speed and evaporation but also in increasing snow catch than chopped residue left on the soil surface (Nielsen 2013). Snow catch generally increases as stubble height increases in no-till (Figure 4-6). A long-term study in Saskatchewan concluded that leaving 35–47 inches wide standing stubble strips of residue about 16–24 inches tall every 19.5 feet trapped 1.6 times as much snow as shorter stubble at 12 inches tall (Campbell et al. 1992).

### Improving Soil Health

In addition to conserving soil and water, residue remaining in the field positively affects soil physical, chemical, and biological properties and productivity, mostly via increasing SOM. A more complete discussion of soil health and the benefits of SOM are presented in Chapter 2: Soil



Figure 4-6. Snow depth observed at (a) ridge top route on January 15, 2008, and (b) different subsections on January 10, 2008, at the Washington State University Cook Agronomy Farm in Pullman, Washington (under no-till). (Adapted from Qiu et al. 2011.) ●

Health. Residue return and reduced tillage can be a cost-effective way to maintain soil health. Crop residue, including roots, is the primary source of organic matter for most dryland cropping systems in the inland PNW. Although, surface residue retention in no-till, arid cereal systems only has limited impact on soil organic carbon (SOC) accumulation (Gollany et al. 2011).

Adding crop residue to soil can also increase total soil porosity and reduce soil **bulk density**, surface sealing, and crust strength, which benefits crop emergence and water infiltration. Microbial decomposition of crop residue produces polysaccharides and other compounds that help bind soil particles together into stable soil aggregates, which is one of the major mechanisms of aggregate stabilization in soils (Turmel et al. 2015). Soil aggregates, in turn, can protect SOM from decomposition by making it less accessible to microorganisms.

Clearly, surface residue retention improves **aggregate stability** of the surface soils (Campbell and Souster 1982; Baker et al. 2007). Yet, the effects of residue management practices on subsoil physical quality remains unclear. Li et al. (2012) found decreased macroaggregate proportions in the 2–12 inches of subsoil under no-till. Other research found no differences in subsoil macroaggregate proportions under different tillage systems when residue was retained in the fields (Jacobs et al. 2009).

Crop residues also provide nutrients (see Chapter 6: Soil Fertility Management). Nutrient availability from decomposition of crop residue depends on residue type and quality. Pulse and canola residues contain higher concentrations of nitrogen (N) and phosphorus (P), and therefore return more of these nutrients than cereal crop residues. Research conducted in Alberta, Canada, found that canola straw returned 45 lb N per acre and pea returned 20 lb N per acre, whereas wheat only returned 14 lb N per acre (Soon and Arshad 2002). In a New Zealand study, only an estimated 7% of N in lentil straw was mineralized during the following growing season. The remaining N can become a long-term source of N (Bremer and Kessel 1992).

# **Estimating Residue Ground Coverage and Biomass**

## Estimating Residue Ground Coverage

The percentage of ground coverage by residue after planting is an important benchmark generally used to determine effectiveness of erosion control (Figure 4-7). Several methods can be used for measuring crop residue in fields, including weight per unit area (Figure 4-8), the line-transect method, the meter stick method, or the photo comparison method. Detailed descriptions of each measurement method, along with guidance for interpreting results can be found on the USDA-NRCS website: *http://www.nrcs.usda.gov/Internet/FSE\_DOCUMENTS/ nrcs144p2\_042684.pdf*.

## **Estimating Residue Biomass**

Crop residue biomass is typically estimated indirectly. Historically, these estimates have been made on the basis of **harvest index** or **residue-to-grain** (R:G) ratio. Harvest index is the ratio of crop yield to the crop's total aboveground biomass (Donaldson et al. 2001; Smil 1999). R:G ratio is simply the ratio of dry residue yield to grain yield. The equation below



Figure 4-7. Relationship between relative soil loss from water erosion and percentage of soil covered by small grain residue. (North central WA: where mixed interill/rill erosion is dominant type water erosion; Northwest WA: where rill erosion is the dominant type of water erosion on crop land.) (Adapted from Papendick and Moldenhauer 1995.)



Figure 4-8. A general relationship between percentage ground cover and residue weight per acre for common small grains and legumes in the non-irrigated areas of the inland PNW. (Adapted from Papendick and Moldenhauer 1995.)

is typically used to calculate the amount of residue production for wheat based on grain dry yield and R:G ratio.

Existing literature reports a wide range of R:G ratios. The ranges of R:G ratios commonly used are 1.10–1.70 for wheat, 0.82–2.50 for barley, 1.20–1.70 for rye, 1.08–1.32 for grain triticale, and 1.86–4.00 for canola (Koenig et al. 2011; McClellan et al. 1987; Behl and Singh 1998; Lal 2005). Using wheat production in 2012 (USDA-NASS) as an example, the ranges of estimated total wheat residue production in the inland PNW states of Washington, Idaho, and Oregon (assuming the mean test weight was 60 lb/bu) are listed in Table 4-2.

The estimation method using the R:G ratio results in a wide range of estimated residue quantities (Table 4-2). Environmental factors, nitrogen fertility, and genotype (especially crop height), greatly impact the R:G ratio.

In response to this difficulty, McClellan et al. (2012) developed improved residue-to-grain yield relationships for inland PNW dryland cereal and legume production to estimate crop residue production. These relationships were described using linear models fitted to data from a large number of research sites across eastern Washington and north-central

Chata	Total grain	Calculated	total residue pro	duction
State	production	R:G ratio = 1.1	R:G ratio = 1.7	Range
	million bushels	mil	llion metric tons -	
WA	141.02	4.22	6.52	4.22-6.52
ID	96.84	2.90	4.48	2.90-4.48
OR	57.51	1.72	2.66	1.72-2.66

Table 4-2. Estimated total wheat residue production by state in the inland PNW.

Note: total grain production was published by USDA-NASS 2012.

Oregon (Table 4-3; Figure 4-9). These linear models could explain 31% of the variation in spring wheat residue yield, and a much higher percentage (55 to 69%) of variation in winter wheat, winter barley, and spring barley residue yield. Although the model found a positive linear relationship between lentil grain yield and residue yield, it could only explain a small amount of the variation (9%) for lentils—much lower than for the cereal crops (McClellan et al. 2012). Their results suggest that the fixed R:G ratio overestimates residue production of high-yielding winter wheat by as much as 35%, and underestimates residue production of low-yielding spring wheat by as much as 66%. These differences are large enough to have implications for decisions about residue management.

Table 4-3. Linear regression analysis at a three standard deviation rejection limit for an eastern Washington dataset.

Сгор	Number of Samples	Regression Equation For Calculating Residue <sup>+</sup>	Standard Deviation	R <sup>2</sup>
			lb/acre	
Winter wheat	1135	y = 1.1274x + 1,175.3	2787	0.69
Spring wheat	112	y = 0.8613x + 2068.1	2159	0.31
Winter barley	53	y = 0.8310x + 1747.7	2089	0.65
Spring barley	737	y = 0.7013x + 1302.9	1771	0.55
Lentils	144	y = 0.4684x + 1843.8	904	0.09
Peas	117	y = 0.7187x + 940.9	975	0.29
Austrian winter peas	12	y = 1.3427x + 1327.2	1236	0.63

 $^{\dagger}x =$ grain yield (lb/acre) and y = residue dry yield (lb/acre).

Adapted from McClellan et al. 2012.



1,000

0+0

500

1,000

1,500

2,000 2,500 3,000

Grain yield (kg/ha)

Figure 4-9. Regression line, fitted equation, and 95% confidence interval (CI) for winter wheat, spring wheat, lentils, and peas in eastern Washington. (Adapted from McClellan et al. 2012.)

3,500 4,000

Lower 95% CI

4,500

Including factors such as plant height and N status, in addition to grain yield, can significantly improve the accuracy of straw yield predictions over the use of R:G ratio alone (Engel et al. 2003; Long and McCallum 2013). Research conducted on three neighboring commercial production fields in Oregon suggested that wheat height was a better predictor of residue yield for irrigated hard red spring wheat than grain yield or grain protein concentration (Long and McCallum 2013). A strong linear relationship was found between straw yield and wheat height for this cultivar and within this environment. When relationships between residue production and factors such as plant height, N status, and yield are confirmed, a GIS, on-combine lidar sensor, yield monitor, and protein monitor-equipped combine can simultaneously collect wheat height, yield, and protein data as appropriate (Long and McCallum 2013). These tools can generate maps that can be used to make site-specific decisions about sustainable residue harvest.

Remote sensing spectral indices have also been evaluated to predict crop residue cover and density (Aguilar et al. 2012). These indices include: (1) broadband spectral normalized difference indices derived using Landsat Thematic Mapper (TM) bands, such as the normalized difference tillage index, the normalized difference index 5 and 7, and the normalized differential senescent vegetation index; (2) reflectance-band height indices such as the lignin-cellulose absorption index and the cellulose absorption index; and (3) spectral angle methods. These methods work well for distinguishing crop residue from background soils, and therefore percentage of ground coverage of laying residues. However, more work needs to be done to use these technologies to measure residue density and quantify the amount of crop residue for both laying residues and tall standing stubble of stripper header harvest (Aguilar et al. 2012).

# Managing Residues in Inland PNW Dryland Cropping Systems

As described previously, the challenges for residue management vary across the region, necessitating different management strategies. In wetter areas, where too much residue can be an issue, tillage can effectively decrease residue levels by accelerating decomposition, but this strategy can diminish the benefits provided by crop residue. Mowing to cut residue into shorter pieces is one common strategy for coping with high residues without tillage. Crop rotation, for example, adding canola, pea, lentil, rapeseed, or wheat cultivars with faster decomposition genotypes into rotation can also be used to reduce overall residue levels throughout the rotation, as these crops produce less residue with a higher decomposition rate (Brown 2015). Burning or harvesting can also be used to reduce the amount of residue, though with tradeoffs for soil health and nutrients.

On the other hand, in areas with low or intermediate yields, where residue production is generally lower than desired, different management strategies are needed. When feasible, crop intensification and diversification to reduce fallow can be used to increase biomass and soil carbon (C) sequestration while increasing soil and water conservation (Gollany et al. 2013; Schillinger et al. 1999; and Young et al. 2015). Examples of crop intensification include replacing winter wheat-summer fallow with summer fallow-winter pea-winter wheat, or by replacing summer fallow by short-season, spring-planted crops such as spring wheat, barley, canola, sunflower, and others to make a winter wheatspring crop-summer fallow rotation in the Transition AEC  $\triangle$ . Research has shown that annual no-till spring cereal cropping systems can provide greater wind erosion protection and reduce SOM loss in the Grain-Fallow AEC, but the economic returns were less than winter wheat-summer fallow cropping systems (Rasmussen et al. 1998; Young et al. 2015) In addition, other management strategies such as early seeding, higher seeding rates, planting tall varieties or crops with high residues (such as barley or winter triticale), and optimizing fertility can increase residue density.

The sections below discuss several relevant management strategies in more detail: harvest with a stripper header, managing decomposition rates through utilization of different crops and varieties, burning, and harvesting residues for other uses. Intensification strategies are discussed in more detail in Chapter 5: Rotational Diversification and Intensification.

# Harvest with a Stripper Header

Use of a stripper header to conserve tall standing stubble is a promising residue management strategy that is being explored in the inland PNW

for erosion control and water conservation by research and innovative growers (Port 2016; Yorgey et al. in preparation).

Tall standing stubble in a no-till system, achieved by harvesting with a stripper header and leaving standing stubble at full-crop height, can reduce residue decomposition rates and conserve water (McMaster et al. 2000; Port 2016). Tall standing stubble is especially important for sparse stands. A 4-year study conducted in Ralston, Washington, found that stripper header winter triticale stubble in no-till chemical fallow influences the microclimate at the soil surface. The tall standing stubble can reduce soil temperatures and reduce average wind speed at the soil surface to less than one half of average wind speed. The stripper header winter triticale stubble also preserved greater amounts of soil moisture and more uniform soil moisture in the 0 to 3-inch seed zone. This allows for timely planting and establishment of fall-seeded canola (Port 2016). Another 5-year study in Fort Collins, Colorado, concluded that tall standing residue provides numerous benefits such as increased snow trapping, decreased decomposition rates, wind speed, weed pressure, soil temperature during the fallow period, and within-field variation in snow cover and water storage (McMaster et al. 2000).

# Managing Residue Decomposition Rates through Crop, Variety, and Fertility

Residue decomposition rates are influenced by a variety of management factors. An awareness of these influences is helpful and, in some cases, may offer opportunities to growers in heavy residue systems for reducing residue buildup or to those in low residue systems for preserving residue cover.

Residue structural components and chemical composition help determine residue decomposition rates in soils. Loss of simple sugars and amino acids occurs rapidly, whereas polysaccharides, proteins, and lipids take much more time to decompose. Lignin is even more resistant to decomposition, and is a major contributor to humus in soils.

Different crops have different residue structure components and chemical composition. Pulse crops and canola residues usually contain higher N concentrations and have lower **carbon-to-nitrogen** (C:N) ratios than

cereal residues, and thus decompose more rapidly. Thus, including pulses and canola in rotation with cereals can reduce residue levels across the rotation. Different environmental conditions can also result in different residue chemical composition and thus decomposition, with faster decomposition for residues grown in drier years or areas (Stubbs 2009).

Residue structural components and chemical composition can also differ significantly among varieties for a single crop, and this can impact decomposition rates. A study conducted in eastern Washington on the chemical composition of residue from different cultivars of spring barley, spring wheat, and winter wheat suggested that the percentage of acid detergent fiber (ADF), acid detergent lignin (ADL), C:N ratio, and N content all correlated with residue decomposition. The percentage of ADF and total N were both found to be best correlated with decomposition after 8 weeks of incubation. Total N was also a good indicator of decomposition at 16 weeks (Figure 4-10). Foot rot-resistant cultivars had higher ADF, ADL, and C:N ratio than foot rot-susceptible cultivars, and were therefore more resistant to decomposition.

The residue C:N ratio also determines whether net N mineralization or immobilization occurs from freshly added residue. Thus, N management should take into consideration the previous crop residue. Although soil microorganisms have a C:N ratio of 8:1, they require a crop residue C:N ratio of 24:1 for decomposition activity (of the 24 parts, 8 parts remain in microorganism biomass and 16 parts are lost as CO<sub>2</sub> during respiration). If a crop residue has a C:N ratio of  $\leq 24$ , net N mineralization occurs. If the C:N ratio is >24, a temporary net N immobilization occurs until microorganisms die and subsequently release N from their biomass. If high C:N ratio residue is repeatedly added to the soil, soil microorganisms can tie up N, increasing the likelihood of N deficiency during decomposition of high C:N crop residue. The USDA-NRCS provides typical C:N ratios of different crop residues at: http://www.nrcs.usda.gov/wps/PA\_NRCS-Consumption/download?cid=nrcs142p2\_052823&ext=pdf. For more discussion on managing soil fertility in light of mineralization and immobilization, see Chapter 6: Soil Fertility Management.

The composition of roots can be different than the above-ground portions of crops, and this also impacts decomposition rates. In canola, pea, and wheat, C:N ratios in straw are found to be higher than in roots, but lignin



Figure 4-10. Correlation of winter wheat residue decomposition with (a) percentage of acid detergent fiber (ADF) and (b) percentage of total N after 16-week incubation of six cultivars from Pullman and Dusty, Washington. (Adapted from Stubbs et al. 2009.)

content is higher in roots than in straw (Soon and Arshad 2002). Unlike above-ground residue, the decomposition of roots was neither correlated with N concentration nor C:N ratio.

## Residue Harvest

Particularly in areas where residue production is plentiful, grain residue can be harvested for livestock feed, bedding, mushroom production, as feedstock for fiberboard or paper production, and **biochar** production. Crop residue with high cellulose content, including residues of corn, wheat, sorghum, rice, and barley, was also identified by the USDA as a potential future feedstock for second generation biofuel production because of its large quantity, easy availability, and renewability (Perlack et al. 2005). Unlike first generation biofuel feedstocks such as corn grain and soybeans, using crop residues can avoid displacement of food production by allowing grain to be harvested for food or feed while the residues are harvested for ethanol production.

However, although large quantities of residue are produced, not all the residue produced can be or should be removed. Harvesting crop residues involves tradeoffs between other uses and the agroecosystem services described previously in this chapter (Laird and Chang 2013; Huggins et al. 2014). Specific considerations that can help determine how much straw should be harvested include a determination of the amount of residue needed for effective soil erosion control, maintenance of SOM and soil health, and economics.

## Determining sustainable residue harvest

Calculating the amount of residues needed for erosion control and maintenance of soil health can provide a minimum amount of residues that need to be conserved for long-term agroecosystem sustainability. Residues produced beyond that level may thus be considered for harvesting.

Changes in SOC are highly correlated with residue input in the Grain-Fallow AEC of the inland PNW (Gollany et al. 2011; Rasmussen and Parton 1994), implying that SOC sequestration is particularly sensitive to crop residue removal in this system ■. Long-term studies established

in 1931 in Pendleton, Oregon (average 15.75 inches of precipitation), estimate that 3.57 to 4.46 ton/acre/year of crop residue should be retained in this system for SOC maintenance (Rasmussen et al. 1980; 1998). However, wheat residue produced in winter wheat-summer fallow in this region was not able to maintain initial SOC levels regardless of crop rotation, fertilizer rates, and tillage practices (Machado 2011). The main reason was that growing one crop in two years did not produce sufficient biomass to maintain SOC. Harvesting wheat residue from this system would accelerate SOC depletion (Table 4-4). However, other long-term studies at the same site suggested that SOC could be maintained or increased in a continuous annual cropping system even if residues were the only SOC input (Table 4-5) (Machado 2011).

In the Annual AEC, where rotations are more diversified, a budget for sustainable cereal straw harvest should be based on the crop rotation instead of cereal residue alone (Papendick and Moldenhauer 1995; Huggins et al. 2014). For example, a comparison of three crop rotations including a 2-year rotation of winter wheat-spring pea (WW-SP), a 3-year rotation of winter wheat-spring barley-spring wheat (WW-SP-SW), and a 3-year rotation of winter wheat-spring barley-spring wheat (WW-SB-SW) indicated that harvestable residue was greatest for the WW-SB-SW rotation and least for the WW-SP rotation (Huggins et al. 2014). Tillage was also important, with smaller adverse effects of residue harvest in the 3-year rotations for no-till compared with conventional tillage.

## Economic tradeoffs for cereal residue harvesting

Once needs for erosion control and soil health maintenance are established, residue beyond these amounts may be available for baling, if economically feasible. The economic tradeoff calculated using partial budgeting (Table 4-6) is the most direct calculation that can be used to support decisions on residue baling in a given year. Using this approach, costs of residue harvest can be calculated based on the value of the nutrients removed and the cost of the baling process, and this cost should be offset by the sale of the straw for economic sustainability (Huggins et al. 2014).

The value of nutrients in crop residue is a function of the nutrient content and replacement fertilizer prices (Table 4-7). The costs of residue harvest and residue swathing, baling, and stacking vary greatly depending on Table 4-4. Tillage effects on biomass, grain yield, and soil organic carbon (SOC) in the tillage fertility long-term experiment in a winter wheat-summer fallow rotation conducted in Pendleton, Oregon.

Residue cover at seeding %	2004-2005		22b	63a	66a
Significance	level <sup>§</sup>		***	***	***
	2005	cre	22.5a	23.0a	22.6a
	1995	tric ton/a	24.9b	26.4a	25.1b
SOC <sup>‡</sup>	1984	Me	25.8a	27.1a	26.7a
SDM⁺	~	Jr	4,015a	3,747b	3,747b
GYD⁺	989-200	/acre/ye	2,498a	2,320b	2,231b
TDM⁺		<b>ql</b>	6,067a	5,621b	5,532b
	Tillage		Plow	Disc	Sweep

Note: \*\*\* indicates that SOC means in 1984 and 2005 are significantly different at  $\alpha = 0.001$ ; "TDM = total bundle dry matter, GYD = combine grain yield, SDM = bundle straw yield, SOC = soil organic carbon; <sup>\*</sup>Within columns, means followed by the same letter are not significantly different at  $\alpha = 0.05$ ; 'This column compares SOC across years. Adapted from Machado 2011.

Table 4-5. Tillage effects on biomass, grain yield, and soil organic carbon (SOC) in the wheat-pea rotation of a continuous annual cropping system in a long-term experiment conducted in Pendleton, Oregon.

	TDM⁺	GYD⁺	SDM⁺	SC	)C‡	Significance	Residue cover at seeding %
Tillage	-	995-2007		1995	2005	level⁵	2005
		o/acre/yea	Ir	Metric	ton/acre		
Maximum Tillage	8,030a	3,569ab	4,550a	26.6a	27.0b	ns	49b
Fall Plow	8,119a	3,569ab	4,639a	26.7a	27.7b	ns	27c
Spring Plow	8,208a	3,658a	4,639a	26.7a	26.8b	ns	21c
No-till	8,030a	3,390b	4,639a	26.1a	29.7a	***	97a
		7000	J	ין ז: ע.	0.001	J	

= combine grain yield, SDM = bundle straw yield, SOC = soil organic carbon; "Within columns, means followed by the same letter are not significantly Indicates that SOC means in 1995 and 2005 are significantly different at  $\alpha = 0.001$ ; ns = not significant. (1DM = total bundle dry matter, GYD different at  $\alpha = 0.05$ ; <sup>§</sup>This column compares SOC across years; Adapted from Machado 2011. Note:

Partial B Alternative: re	udgeting sidue removal
Increased cost Residue harvest Residue swathing, baling, and stacking Sensors, imageries	Increased revenue Sale of the straw
<b>Reduced revenue</b> Value of fertilizer replacement for N, P, K, S, and Cl	Reduced costs none
A. Total increased costs and reduced revenue	B. Total increased revenue and reduced costs
Expected change in	net revenue (B – A)

Table 4-6. Partial budgeting comparing residue removal and residue return to fields for growers.

the density of stubble, header width, baling method and size of bales, and field conditions. If farmers own the equipment, the cost may be lower than hiring custom operators (Duft and Pray 2002). The custom operators' rates for Idaho agricultural operations is updated by University of Idaho Extension in the BUL729 publication. If the expected change in net revenue calculated by partial budgeting is positive, then it is economically feasible to bale.

## Site-specific cereal residue harvesting

Crop residue production varies both between and within fields. In general, between-field variability can be explained by the type of crop, harvest methods, plant height and other genotype characteristics, environmental factors such as plant-available water and nitrogen fertility, and field management practices. Within-field variability can result from differences in soils, slopes, water, nutrients, **pests**, and interactions of these factors.

Because of this variability, site-specific harvesting of cereal residues may help ensure long-term economic and environmental sustainability. Over three years, within-field variability in cereal straw production in a field near Pullman, Washington, was more than twofold, and the variability in nutrient removal ranged over fivefold if all the residue was removed (Huggins et al. 2014). Site-specific harvesting could be made feasible by Table 4-7. Estimated average nutrients export and their fertilizer replacement value for cereal for a winter wheat-spring barley-spring wheat (WW-5B-SW) rotation conducted at the WSU Cook Agronomy Farm in Pullman, Washington in 2009–2011.

		Nutrient		z	utrient valu	le
nutrients	WM	SW	SB	MM	MS	SB
		Ib/acre			\$/acre	
C	1,698	1,305	1,411	na	na	na
Z	17.0	13.4	14.3	10.20	8.05	8.59
P <sub>2</sub> O <sub>5</sub>	3.0	2.3	2.5	1.89	1.44	1.55
K,O	22.3	17.8	18.7	11.84	9.47	9.95
S	2.3	1.7	1.9	0.77	0.59	0.64
Total nutrient value				24.70	19.57	20.73
Cost of harvest, \$/ton				30.73	31.46	31.22
Cost of swathing, baling, and stacking, \$/acre				14.50	11.41	12.24
Note: WW = winter wheat: SW = spring wheat: SB = spring	barlev. Nutrien	it value varies b	ased on prices	for fertilizers N	P. K. and S.	

Adapted from Huggins et al. 2014.

the use of **precision agriculture** technology, such as lidar sensors, to measure real-time wheat height to generate residue yield maps. For more information on these technologies, see Chapter 8: Precision Agriculture.

### Opportunities for harvest with biomass return after processing

One intriguing potential for reducing the downsides of harvest is to return residuals to fields after processing, along with the retained carbon and nutrients. For example, when residues from cereal systems are used for paper-making, the process results in "black liquor," an organic waste effluent that contains lignin, nutrients, and other organics. If returned to soils, black liquor can be used as a soil amendment. In an alternative example, thermochemical energy production in an oxygen-limited environment can result in bio-oil and biochar, with emphasis on one or the other products depending on conditions. Bio-oil provides energy, while biochar is a solid, carbon-rich, porous material that can be returned to soils, sequestering carbon and providing a mild liming effect. Black liquor and biochar are described in Chapter 7: Soil Amendments.

## **Residue Burning**

Grain producers in the inland PNW have burned wheat residue for a number of reasons. First, burning can eliminate seedbed tillage operations and enable producers to use existing machinery to plant winter wheat in no-till systems (McCool et al. 2008). Second, burning is sometimes perceived to positively impact crop growth and yields although this effect has not always been seen; for example, research conducted in the UK found no yield advantage from burning winter wheat straw over incorporation (Smil 1999). Third, burning can reduce the incidences of disease, weeds, and insects. Research has shown that burning can reduce seeds located on the soil surface by 97% for brome, 50% for wild oat, 61-94% for blackgrass, and 43-65% for goatgrass spikelets (Young et al. 1990), though efficacy can sometimes be impacted by non-uniform high temperatures over the soil surface during burning (McCool et al. 2008; Smil 1999; Young et al. 1990). Ongoing work has also indicated a potential role for limited burning, such as windrow burning, as one part of an integrated weed management strategy (Lyon et al. 2016; Young et al. 2010). This is discussed in Chapter 9: Integrated Weed Management.

Although there are advantages to burning residues in some cases, there are also tradeoffs, including the adverse impacts on soil health and productivity. Long-term burning can reduce total C and N pools, SOM, net N mineralization rates, C:N ratio, microbial biomass, extractable C and polysaccharides (readily available carbon sources for microbes), ammonium, and available P (Fasching 2001). Long-term crop residue burning has negative impacts on soil physical characteristics including decreased water stability of soil aggregates due to reduction of soil biological activities (glomalin, basidiomycetes, and earthworm counts) (Wuest et al. 2005), increased erodibility and soil density, and decreased water and nutrient retention (Papendick and Moldenhauer 1995; Holmgren et al. 2014). A literature review indicates that there is no measurable negative effect from occasional and short-term burning (Holmgren et al. 2014), although the practice can cause ground hardening and reduce water infiltration as a result of temporary soil surface sealing after burning.

Beyond the farm, residue burning also has negative environmental impacts. It contributes to greenhouse gas emissions including CO<sub>2</sub>, nitrous oxide (N<sub>2</sub>O), methane (CH<sub>4</sub>), and carbonyl sulphide (COS, which has a greenhouse gas potential 724 times that of CO<sub>2</sub>) (Smil 1999; Jain 2014). It also releases air pollutants including carbon monoxide (CO), ammonia (NH<sub>3</sub>), nitric oxide and nitrogen dioxide (NO<sub>x</sub>), sulfur dioxide (SO<sub>2</sub>), non-methane hydrocarbon, volatile organic compounds, particulate matter less than 10 µm (PM<sub>10</sub>) and 2.5 µm (PM<sub>2.5</sub>) in size, and smoke. These air pollutants exacerbate respiratory and lung disease with public health impacts (*http://community.seattletimes.nwsource. com/archive/?date=19981001&slug=2775191*). Research has found that there were significant increases in hospital admissions related to the increase in pollutants during agricultural crop residue burning (Agarwal et al. 2012).

### Economic tradeoffs of residue burning

The economic benefit of residue burning can best be estimated as a function of change in subsequent crop yield. However, this change is hard to identify because there are differing results of burning dependent on other field management practices (Smil 1999; Huggins et al. 2011; Young

et al. 2010). Meanwhile, the cost of residue burning can be estimated using the cost of the burning permit and the fertilizer replacement value of nutrients lost from burning, generally including N, P, K, and S. For example, based on average fertilizer prices from 2008 to 2010, the cost for fall field burning was estimated at \$28.62/acre and \$9.64/acre for spring field burning in eastern Washington (Table 4-8). The burning permit can be a substantial percentage of the total cost. In 2016, the Washington Department of Ecology charged a minimum fee of \$37.50 for the first 10 acres and \$3.75/acre for each additional acre.

In calculating the nutrient value, C content varied only a little, but other nutrients in residue varied significantly depending on time of burning, crop, water and nutrient supply, management practices, and other factors (Table 4-9). A field burning study on surface winter wheat residue conducted in Pullman, Washington, found that fall burning reduced residue by 62% whereas spring burning reduced residue by 55% (Huggins et al. 2011). The difference between fall and spring burning is a result of winter wheat residue reduction (by 36%) from decomposition and/or mixing with soil by biota between fall and spring. Spring burn resulted in greater residue N loss (40%) compared with fall burn (33%). Losses of K, P, and S from fall burning averaged 70%, 37%, 57%, respectively, and from spring burning averaged 56%, 39%, 45%, respectively (Table 4-10).

Residue nutrient	Fertilizer cost <sup>+</sup>	Fall burn nutrient loss	Spring burn nutrient loss
	\$/lb	\$/a	cre
Ν	0.45 (82-0-0)	5.27	4.95
K <sub>2</sub> O	0.62 (0-0-60)	20.40	2.83
P <sub>2</sub> O <sub>5</sub>	0.73 (10-34-0)	1.72	1.20
S	0.47 (12-0-0-26)	1.23	0.66
Nutrient replacement cost		28.62	9.64

Table 4-8. Fertilizer replacement cost for nutrient loss during fall and spring burning of winter wheat residue; research was conducted in Pullman, Washington, within the Annual Crop agroecological class.

<sup>†</sup>Average fertilizer prices for 2008–2010 from Idaho input cost publication series (*http://www.uidaho.edu/cals/idaho-agbiz*).

Source: Huggins et al. 2011.

Table 4-9. Nutrient content in harvested straw and nutrient content in one ton of harvested straw and ash from spring wheat, oats, and flax sampled in western Canada.

	Nutrien	it content ir	n straw	Nu	trient conte	nt in one to	in straw bef	ore/after bu	urn
Nutrient	Spring wheat	Oats	Flax	Spring wheat	Oats	Flax	Spring wheat	Oats	Flax
		(%)			re-burn (lb)	(		ost-burn (lb	(0
U	41	42	46	826	832	910	77	31	28
Z	0.97	0.64	0.86	22	10	28	0.4	0.1	0.05
К	1.44	2.34	0.24	29	47	4.7	24	30	2.6
Ъ	0.14	0.08	0.07	2.7	1.5	1.4	2.4	1.3	0.9
S	0.11	0.22	0.06	2.2	4.4	1.1	0.7	2.2	0.14

Adapted from Heard et al. 2006.

Table 4-10. Fall and spring burning effects on winter wheat residue loads and residue nutrient contents trials conducted in Pullman, Washington.

		% of nutrier	nt in residue			Nutrient	content	
	Fall	burn	Spring	g burn	Fall	burn	Spring	g burn
	Pre-burn	Post-burn	Pre-burn	Post-burn	Pre-burn	Post-burn	Pre-burn	Post-burn
		(o)	(0)			Ib/a	cre	
Residue					8093	3059	5168	2354
U	39.9	39.9	43.0	40.5	3228	1218	2226	955
Z	0.44	0.78	0.52	0.69	35.9	24.2	27.3	16.3
¥	0.46	0.39	0.13	0.13	38.8	11.47	6.90	3.07
Р	0.03	0.06	0.04	0.05	2.82	1.79	1.85	1.13
S	0.06	0.07	0.05	0.06	4.56	1.95	2.39	1.32

Source: Huggins et al. 2011.

# Conclusion

Crop residue is a nutrient and SOC source for soil health when returned to soil, a valuable feedstock when harvested, and a ground cover for protecting from soil erosion. Making decisions for best residue management practices is complicated because it requires balancing tradeoffs between agronomic productivity, soil health improvement, soil erosion and environmental protection, and economics. The review of benefits and tradeoffs of residue management practices and tools discussed in this chapter can be used to help growers make decisions that are best for their specific situations.

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