Carbon sequestration potential in cropland soils in the Pacific Northwest:

A summary of what we know and what gaps there are

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Abstract

Cropland agricultural soils have the potential to either release (be a source of) or capture and sequester (become a sink for) carbon. We provide a summary of existing experimental and modeling evidence for the potential that cropland soils in the Pacific Northwest have for sequestering organic carbon, and identify remaining knowledge gaps. The purpose of this summary is to provide context for regional policy discussions intent on fostering farming practices that show the best potential for carbon sequestration. We review regional research on the impacts of agricultural management strategies on carbon sequestration, including tillage, crop rotation, fallowing, perennial crops, crop fertilization, soil amendments, reduced burning, and reduced erosion. Our summary suggests that a number of practices can provide real but modest contributions to carbon sequestration. The opportunities to build soil organic carbon are greater in annually cropped systems with higher productivity, though the benefits of particular management practices are variable and depend on multiple environmental and physical conditions. Therefore, there is a need to establish credible estimates of carbon fluxes for Northwest agricultural systems. These estimates must also be accompanied by monitoring to determine whether cropland soils are achieving carbon sequestration goals. Thoughtful consideration of the environmental and production contexts surrounding Pacific Northwest agriculture, combined with targeted research to identify the most effective carbon sequestration practices, could lead to the development of policies that can realize the real contributions that croplands in the Pacific Northwest can make to climate change mitigation efforts.

Introduction

The science and the discussion about climate change—its causes, effects, and the paths forward to adapt to and mitigate its negative impacts—have progressed significantly over the last three decades, in many regions of the world, at different scales, and for different decision-making purposes. Agriculture is an economic sector that plays an important role in the balance of different carbon forms, and therefore on climate change. Cropland agriculture affects the carbon balance through production and use of nitrogen-based fertilizers that can generate greenhouse gases, photosynthesis that extracts carbon dioxide from the air, and management practices that impact how much carbon dioxide is released from soils back into the atmosphere versus captured in forms that can be sequestered in the soil (Smith et al., 2008). The consumption of agricultural products, either by livestock or people, eventually releases carbon back into the atmosphere as well. Agriculture is also a very important economic driver in the northwestern states of Washington, Idaho, and Oregon, being valued at close to $24 billion in 2015 (WSDA, 2016; ISDA, 2016; Sorte and Rahe, 2015), and farms comprise close to 43 million acres in the region (USDA, 2014).

Agricultural soils have the potential to either release (that is, be a source of) or capture and sequester (that is, become a sink for) carbon (Smith et al., 2008). As of mid-2017, some resources exist that inform policy makers on management strategies that could increase the "sink" potential of agricultural soils. Yet policy makers must search multiple sources of information, each providing conclusions for a particular set of conditions, many with specifics and caveats that make drawing overall conclusions to inform policies on climate change mitigation potential difficult.

The purpose of this white paper is to summarize existing experimental and modeling evidence for the potential that cropland soils in the Pacific Northwest have for sequestering organic carbon, and to identify where gaps in knowledge remain. Due to the lack of systematic and comprehensive data for the area west of the Cascade Mountains, the synthesis we provide focuses mainly on the inland Pacific Northwest (more details below). Note that the focus in this white paper is on organic carbon; while some types of soils may also have high content of inorganic carbon, inorganic carbon has different dynamics, and is generally not as responsive to management as organic carbon is.

This summary can help inform what farming practices or strategies show the best potential for carbon sequestration, providing context for regional discussions on policies that might lead to incentives for their adoption. It can also help identify what research tracks might be most informative for such policies, thereby providing incentive to fund such research in this region.

Why Soil Carbon?

With the growing recognition that an atmospheric doubling of carbon dioxide is inevitable (IPCC, 2014), interest in methods for reducing the amount of carbon dioxide in the atmosphere have also been growing. Globally, the amount of carbon (C) stored in soils is roughly three times the amount stored in the atmosphere (USDOE, 2008). Thus, a relatively small change in the size of the soil carbon pool could significantly influence atmospheric carbon dioxide concentrations. Globally, 89% of the technical mitigation potential from agriculture is estimated to result from strategies that increase soil carbon storage (Smith et al., 2008).

Croplands' carbon sequestration potential is a reflection of the fact that, historically, converting land to agriculture resulted in large carbon losses, with total losses since conversion estimated to be roughly 20-70% (Flach et al., 1997; Paustian et al., 1997; Lal, 2001; Franzleubbers and Follett, 2005). This matches well with estimates of carbon loss for dryland (non-irrigated) soils in the inland Pacific Northwest (Figure 1). A review of field studies in the inland Pacific Northwest found that mean losses of soil organic carbon after conversion of native vegetation ranged from 0.53 to 0.84 Mg of carbon ha-1 yr-1, depending on the agro-ecological zone, which are used to classify the region based on soils, rainfall, and cropping systems (Brown and Huggins, 2012).

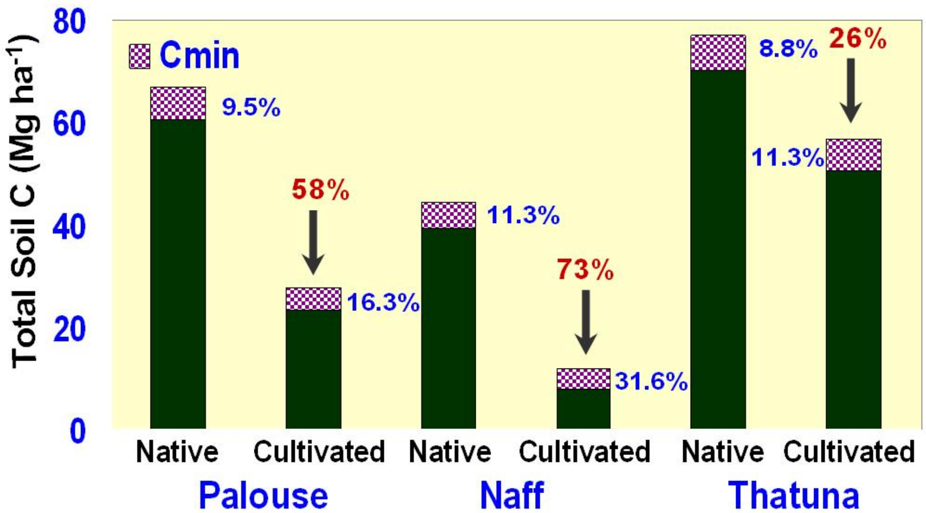

Figure 1. Figure 1. Carbon content of soils near Pullman, Washington. Black bars reflect soil carbon in three different soil types (Palouse, Naff, and Thatuna), comparing native and cultivated soils. The hatched bars quantify mineralizable carbon, less persistent in the soil. Percentages in red are estimates of carbon loss from conversion of native soils to dryland agriculture in each soil type. Portions of these data have been previously published in Purakayastha et al. (2008).

The loss of soil carbon when native vegetation is converted to agriculture results from factors such as lower inputs of organic matter in annual cropping systems, increases in the release of carbon as carbon dioxide due to increased decomposition and, in some cases, erosion losses (note that losses from erosion may or may not contribute to greenhouse gas emissions; in some cases, erosion simply moves the soil carbon across the landscape, sequestering it somewhere else).

While this pattern of carbon loss in agricultural soils has occurred across much of the United States, there are important exceptions to this general rule. One key exception includes the irrigated Columbia Basin. In this arid environment, where plant productivity and soil organic carbon levels are low in natural ecosystems, a comparison of agricultural and native soils in Grant County, Washington, showed that soil organic carbon levels were higher in fields that had been cultivated for two or three years than in soils under native shrub steppe (Figure 2, Cochran et al., 2007). Increases in organic soil carbon were influenced by irrigation and the resulting increased plant productivity, cultivation, crop residue incorporation, and dairy manure compost amendments. These factors are discussed in more detail below, as they are the basis for practices by which producers can and do increase soil carbon sequestration in agricultural soils.

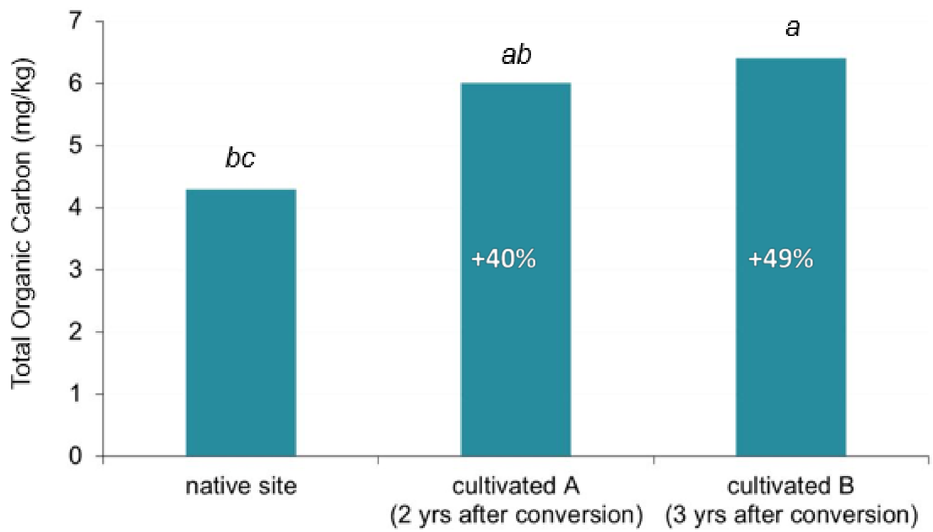

Figure 2. Total organic carbon in native shrub-steppe soils (native site) and two sites recently converted to irrigated agriculture. Percent changes reflect increases relative to the organic carbon in the native site. Based on data published by Cochran et al. (2007).

It is important to note that although this white paper focuses on carbon sequestration in soils, changes in management practices could also reduce emissions of other greenhouse gases from croplands, in particular nitrous oxide. Nitrous oxide's global warming potential is 298 times higher than carbon dioxide's (IPCC, 2007). The United States' nitrous oxide emissions were estimated to be equivalent to 82 million tons of carbon dioxide in 2010, and the country is expected to be the second largest emitter of cropland-based nitrous oxide by the 2030s, with this gas accounting for 6% of the U.S.'s non-carbon dioxide greenhouse gas emissions (USEPA, 2014).

Nitrous oxide emissions represent a significant challenge for those seeking to reduce greenhouse gas emissions from cropland agriculture, as losses that are negligible from an agronomic perspective can represent a substantial impact from a greenhouse gas perspective. For example, if fertilizer is applied at 150 kg ha^{-1} of nitrogen, a commonly observed loss of only 1% of the applied nitrogen would lead to greenhouse gas emissions comparable in effect to the over half the mitigation benefit obtained from converting from conventional to no-till management (Post et al. 2012, Venterea et al., 2012). Though technologies also exist for reducing nitrous oxide emissions, significant obstacles still exist for effectively achieving such reductions. These include:

- An incomplete understanding of how nitrous oxide is produced in soils (Venterea et al., 2012).
- High variability in measurements of nitrous oxide fluxes from soils, with variability both from location to location and from one point in time to another (Henault et al., 2012; Nicolini et al., 2013).
- Difficulty in accurately measuring nitrous oxide emissions from soils (partly due to the variability identified above), which leads to difficulty in tracking changes in emissions due to changes in nitrogen management (Henault et al., 2012). However, recent advances in methodology (e.g. Waldo et al. 2016) continue to improve our ability to measure nitrous oxide (Brian Lamb, personal communication).
- In the inland Pacific Northwest, there are very few direct measurements of nitrous oxide emissions from agricultural systems, and existing studies range in terms of the conclusions they reach as to how nitrous oxide emissions in this region compare to climate-change related benchmarks (e.g. Stockle et al., 2012; Waldo et al., 2016).

These challenges currently complicate efforts to quantify whether management practices can reduce nitrous oxide emissions effectively. So, although it is an important topic, it is beyond the scope of this white paper.

It is also important to note that although climate impacts are the focus of this white paper, there are a number of other important benefits to be gained from management strategies that increase soil carbon, including reduced erosion, improved ability to store water in soils, increased microbial activity, and in some cases enhanced crop productivity (e.g., Johnston, 1986). These additional benefits could help transform a climate mitigation strategy into a win-win opportunity for producers, helping offset some of the additional costs and operational hurdles that may need to be overcome to increase soil organic carbon. And if site-specific and year-to-year variabilities, or uncertainties related to the mitigation potential of specific strategies lead to only moderate climate impacts, these strategies can still have a significant impact on the sustainability of cropping systems, thanks to the benefits identified above.

The Fundamentals of the Carbon Cycle

Any climate mitigation policy intending to provide incentives for increased carbon sequestration in agricultural soils must be based on an understanding of some of the basics of soil carbon dynamics. This understanding is also critical for correctly interpreting experimental and modeling data relevant to soil carbon in the Pacific Northwest, which we summarize in later sections of this white paper.

Soil scientists consider the amount of carbon stored in the soil as one or more carbon "pools," and the additions and losses of carbon from each pool as "fluxes" or "flows." It can therefore be helpful to visualize carbon as water flowing into and out of a bathtub (Figure 3). The size of the soil carbon pool is analogous to the amount of water in the bathtub. The rate of water flowing into the tub—which can be changed by strategies that open or close the faucet—represents the rate of carbon additions to the soil carbon pool. The rate of carbon losses is represented by the size of the drain, which again can be changed in the tub design, or by using a plug.

Soil carbon levels at any given time are a reflection of ongoing gains and losses from the soil. If additions of carbon are greater than the losses, the soil carbon pool will increase in size—what researchers call a "carbon sink." If, on the other hand, losses are greater than additions, the soil carbon pool will shrink, becoming a "carbon source," mainly producing carbon-based greenhouse gases, like carbon dioxide or methane.

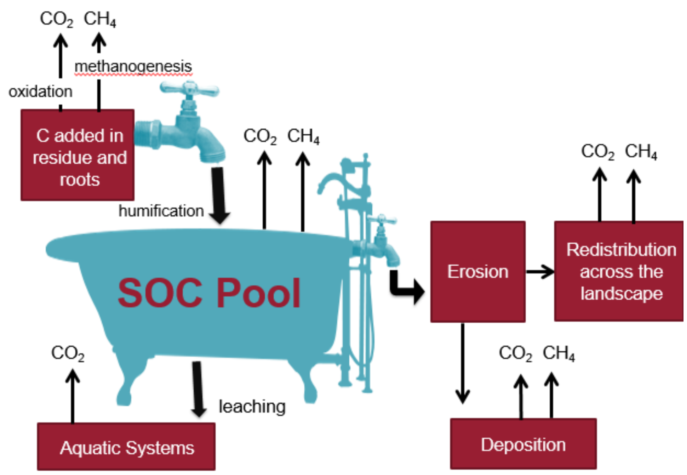

Figure 3. Conceptual schematic of the soil organic carbon pool, with the pool size at any given time reflecting the size of ongoing carbon additions and losses. Each soil type at each geographic location has a soil organic pool that has an upper limit that reflects the point at which all the available soil surface area is interacting with soil carbon, and a practical lower limit, where the remaining soil carbon is very hard to decompose. Figure by Elizabeth Allen, adapted from Lal (2001).

Additions of carbon to soils can come from a variety of sources, including:

- Unharvested plant residues and roots,
- Root exudates,
- Living and dead microorganisms or other soil biota,
- Animal residues (e.g. manures), either from animals that graze the site, or added as soil amendments,
- Other organic amendments. In addition to the animal residues described above, other amendments could include compost, biochar, etc., and
- Erosional deposits.
- Meanwhile, losses of soil carbon result from a number of processes, including:
- Decomposition of organic materials, with oxidation and release of carbon dioxide,
- Leaching of some types of soil organic carbon (i.e. soluble carbon), and
- Soil erosion processes, where these lead to emissions of greenhouse gases.

What Practices Can be Used to Increase the Soil Carbon Pool in Cropland Soils?

Based on the understanding of soil carbon dynamics described above, mitigation occurs if agricultural management is changed in ways that increases the inputs of carbon, reduces the losses, or both. Strategies to increase inputs can include (Lal, 2004a, 2004b; Smith et al., 2008; Lal, 2015):

Increasing the crop residues, which can be achieved through a number of practices. Varieties of the same crop that produce more residues can be chosen, for example. Or crop rotations can be changed to alternate the primary revenue-producing crop with crops that leave greater residues (e.g. Kirby et al., 2017). If nutrient availability is constraining crop growth, then fertilization generally increases carbon inputs to the soil by increasing biomass production, including the residues left after harvest.

Intensifying production by eliminating fallow. If a crop is grown every year, total residues being added to the soil would be greater than if one crop is grown every other year, with a fallow in between. There are of course limitations to this strategy, as there are usually good reasons why producers fallow their fields, such as lack of sufficient rainfall.

Adding manure or other organic amendments. Carbon-rich soil amendments, such as manure, compost, and biochar, provide an additional, new flux of carbon—a new faucet to the soil carbon pool bathtub. Under current agricultural patterns in the inland Pacific Northwest, livestock and cropping systems are frequently spatially isolated, so the costs of transporting and applying organic amendments is one important barrier to their more widespread use (Yorgey et al., 2017a).

Using cover crops. Cover crops are crops grown specifically to add residues to the soil and are not harvested, though in some cases they may be grazed. If grazed, a portion of the organic carbon may be harvested (though another portion may be cycled back to the soil, as manure from the grazing animals). Although there has been widespread interest in cover cropping in the Midwest, and although there are some viable irrigated cover cropping systems (e.g. Yorgey et al., 2017b), existing research with single- and multiple-species cover crops in eastern Washington and semiarid eastern Colorado has not found agronomic or economic benefits (Thompson and Carter, 2014; Nielsen et al., 2015; Roberts et al., 2016).

Replacing annual crops with perennial crops. Perennial crops tend to produce more and deeper rooting systems, which add more organic carbon to the soil. They are also tilled less, even if under conventional tillage, as tillage only occurs, generally, when the crop is renewed, rather than every year as with annual crops. However, many of the most widespread cropping systems are based on annual crops, and while efforts are underway to develop perennial crops for wheat, for example, these efforts are not guaranteed to be successful, or economically viable (e.g. Bell et al., 2008).

Strategies to *reduce losses* include (Lal, 2004a, 2004b; Smith et al., 2008; Lal, 2015):

Reducing the amount or intensity of tillage. Tillage leads to aeration of the soil, accelerating decomposition, which releases carbon in inorganic forms, such as carbon dioxide. Soils are tilled for multiple reasons, including weed suppression, and accelerating the release of the nitrogen and other nutrients held in the organic matter where they are inaccessible to the crop. In the driest parts of the inland Pacific Northwest, tillage can also suppress loss of water during the fallow year, by severing capillaries in the soil that bring water to the surface, making it susceptible to evaporative losses (Hammel et al., 1981; Wuest 2010; Wuest and Schillinger, 2011).

Reducing the burning of residues. Burning of the carbon-rich organic residues volatilizes that carbon, mostly as carbon dioxide. Burning has declined in the Pacific Northwest in recent years due to air quality concerns, but has been used in some cases to improve seedbed preparation and to reduce viable weed seed (Tao et al., 2017; Burke et al., 2017).

Strategies that reduce erosion will reduce in-field losses of carbon, though the ultimate fate of the eroded and re-deposited soil carbon—and therefore its impact on regional-scale soil carbon—is not well understood (see, for example, Lal, 2003 and Van Oost et al., 2007).

Cropping systems are complex, and their different components are interrelated. One key consideration is how future climate itself may affect what strategies to increase carbon sequestration are feasible in particular locations. Kaur and colleagues, for example, studied which climatic variables best allow us to determine agro-ecological classes in the inland Pacific

Northwest. They then used climate model projections for those climatic variables to evaluate how those classes might shift in the future. They found that dynamic classes (i.e. those with different cropping systems during different time periods) and fallow-based agro-ecological classes increased in area, while stable classes (i.e. those consistently maintaining a particular cropping system) and annual cropping classes were expected to shrink (Kaur et al., 2017). These shifts would likely lead to an increase in fallowing, increased erosion hazards, and potentially decreased flexibility in rotations (Kaur et al., 2017), with the potential for negative impacts on carbon storage in soils.

Independently Karimi et al. (2017) used a process-based cropping system model to evaluate likely future shifts in cropping systems in response to climate change. They found that the direct effects of increased carbon dioxide concentrations on wheat and the earlier start to the growing season would more than compensate for the negative effects of increased temperature and decreased water availability, leading to higher wheat yields. Higher crop yields are usually associated with higher residue yields, and therefore carbon inputs to soils. Karimi and colleagues concluded that overall shifts away from crop-fallow towards annual cropping systems would be expected (Karimi et al., 2017). The contradictory results of these two studies highlight the uncertainties that remain, with each emphasizing different key factors needed to accurately project changes in agro-ecological classes: the effects of increased atmospheric carbon dioxide (Karimi et al., 2017), and the impacts of socio-economic factors driving farmers' cropping decisions (Kaur et al., 2017).

A third study focused specifically on the soil organic matter content in soils, relating values from long-term experiments in the inland Pacific Northwest to mean annual precipitation and temperature (Morrow et al., 2017). They found that these climatic variables were more influential than either tillage or cropping intensity in determining organic matter levels, and that the direction these variables are expected to change as the climate changes would lead to declines in organic matter in surface soils (Morrow et al., 2017). However, one important limitation to this study is that it does not incorporate the impacts of higher carbon dioxide levels in the atmosphere on plant growth.

In sum, these studies point to a need for ongoing work to clarify how future climate may affect what strategies to increase carbon sequestration are feasible in particular locations and cropping systems in the future, as well as the likelihood that they will be adopted by farmers.

Constraints on the Carbon Sequestration Potential of Cropland Soils

There is an upper limit to the amount of carbon that can be stored in soils. This is partly because of the environmental constraints on the maximum size of the soil carbon pool, as described below. However, it is also because the losses from the soil carbon pool depend on the size of the pool itself. The more carbon in the pool that can decompose, or erode, or leach, the more carbon that will generally be decomposed, eroded, or leached. Generally speaking, when a change in management increases carbon inputs, this leads to higher outputs. If the constraints and management stay constant, these will eventually balance out, and thus, the system may approach a new steady state over time. This is when carbon input rates equal carbon output rates, such that the size of the soil organic carbon pool remains steady over many years.

The maximum size of the soil organic pool—the size of your bathtub—depends on a number of environmental constraints, including:

- **Temperature –** more organic carbon is stored in cooler climates, as decomposition is slower.
- **Moisture –** more organic carbon is stored in wetter soils, as there is less oxygen available to aid its decomposition.
- **Soil texture –** more organic carbon is stored in finely textured soils, as clay particles help stick to and protect organic material from microbes that decompose it.
- **Soil structure –** more organic carbon is stored in well aggregated soils, as again, the aggregates protect the organic material inside them from decomposition.

From a climate change perspective, mitigation only occurs if the size of the soil organic pool (the amount of water in the bathtub) *increases.* It is not sufficient to increase inputs, if losses also increase by the same magnitude. It is also not sufficient to maintain soil organic carbon levels in healthy soils. Maintaining soil carbon levels can avoid further outputs, and therefore be a worthy goal; however, it is important to understand that it does not sequester more carbon, and therefore cannot mitigate other greenhouse emissions.

What do the fundamentals of the carbon cycle mean for climate change mitigation efforts that focus on building soil organic carbon in cropland soils in the Pacific Northwest?

Implication #1: Soil organic carbon benefits vary geographically

Soil organic carbon varies across the Pacific Northwest. For example, there is a strong environmental gradient from west to east across the region, with high annual precipitation on the west side of the Cascade Mountains, low precipitation just east, in the mountains' rain shadow, and then increasing amounts of precipitation further east-northeast across the region. These environmental gradients, which extend well beyond the Pacific Northwest, not only influence the maximum amounts of carbon that can be stored in soils, but also influence the management strategies that are appropriate at each location. Both these influences affect the potential for sequestering carbon in cropland soils.

Beyond this, the carbon levels of soils at the time that particular practices are implemented vary widely across the region, and this can have very significant impacts on the ability of those soils to store *additional* carbon. Results of a modeling study that examined the carbon benefit over the first 50 years after adopting no-till management for two locations in the inland Pacific Northwest—Colfax, Washington and Heppner, Oregon—illustrate this variation (Kemanian and Stockle, 2010). Colfax is a relatively wet location for the region, with higher residue production than the drier Heppner site. In addition to looking at the change in management from conversion to no-till, they added one additional important variable: how much organic carbon was in the soil before management changed to no-till; that is, how full the soil carbon pool (the bathtub) was to begin with. The team ran the model a number of different times for each location, using a range of different values for initial soil organic carbon. These values were selected based on the range of soil carbon values found in each area, as documented in SSURGO, a soils database developed by the US Department of Agriculture's Natural Resources Conservation Service (https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/?cid=nrcs142p2_053627).

When the same initial soil organic carbon levels were used at both locations (for example, 6 g kg^{-1} of soil, in Figure 4), there was a greater change in soil carbon in Colfax (approximately 14 Mg ha^{-1} in 50 years) than in Heppner (approximately 5 Mg ha^{-1} in 50 years), illustrating how soil carbon benefits vary based on regional-scale factors such as precipitation and the resulting differences in the amount of residue inputs to the soil. However, when they compared results across the range of initial soil carbon values, they found that within each location, soils would gain carbon over 50 years (positive change) if the initial soil carbon was low, but would lose carbon (negative change) if soil organic carbon was initially high (Figure 4). The magnitude of these differences led the researchers to conclude that initial soil organic carbon levels at each site were more important than the differences in residue inputs between the two sites—a reflection of the difference in precipitation—in terms of determining the changes in soil organic carbon levels (Kemanian and Stockle, 2010).

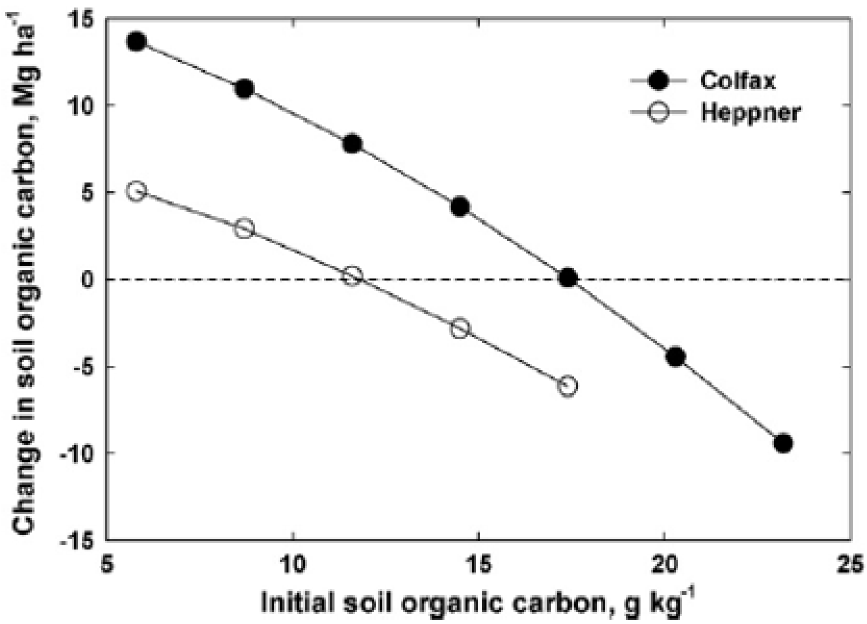

Figure 4. Modeled changes in soil organic carbon over 50 years after adoption of no-till at two inland Pacific Northwest locations. Changes in soil organic carbon were modeled for different values of initial soil organic carbon expected at each location. Figure reproduced from Kemanian and Stockle (2010).

Implication #2: Soil organic carbon benefits from a management change will change over time

The new soil organic carbon stored due to a change in management will vary over time, because there is an upper limit to the amount of carbon that can be stored in soils. Tracking changes in soil organic carbon over time is best illustrated through long-term experiments, of which there are few anywhere in the world. One such long-term experiment in our region is in Pendleton, Oregon. Another, which will be used here to illustrate this point, was established in 1843 in Rothamsted, in the United Kingdom (Jenkinson et al., 1990). Plots were set up in previously cropped ground, and three different treatments were applied to continuous winter wheat:

- Annual additions of inorganic fertilizer
- Annual additions of farmyard manure
- No soil amendments

Plots receiving farmyard manure gained carbon over time, while the other two treatments maintained or lost carbon (Figure 5). The field data collected from these soils (the symbols in Figure 5) were complemented with modeling studies. The outputs of the models (the lines in Figure 5) allow a more detailed visualization of how soil organic carbon changed through time, and shows how the rate of change of plots where manure was added—the slope of the FYM line at different points in time—decreased through the life of the experiment, as soil organic carbon increased. Models can also help predict the steady state values that such soils might achieve.

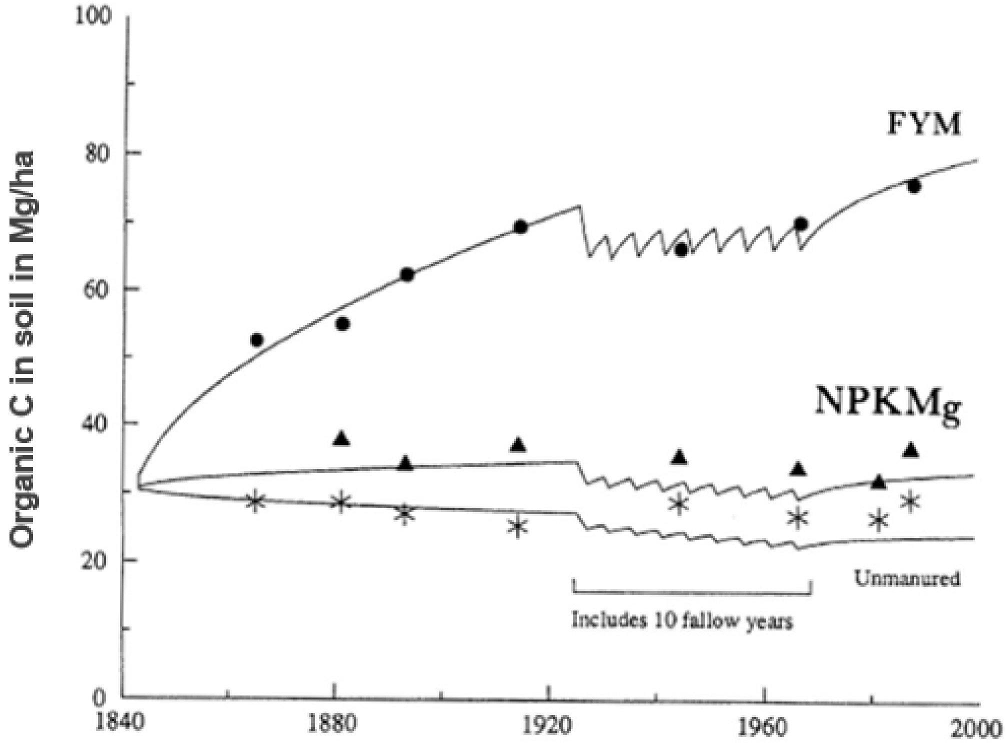

Figure 5. Results of a long-term experiment in winter wheat crops in Rothamsted, United Kingdom. Plots were untreated (stars), had annual additions of inorganic fertilizer (triangles), or annual additions of farmyard manure (circles). Symbols represent experimental data and lines represent modeled data. Figure reproduced from Jenkinson et al. (1990).

Beyond carbon – Additional principles of cropland's greenhouse gas emissions

Management changes that impact soil carbon can also impact other agricultural greenhouse gases. For example, reducing the amount of tillage might reduce decomposition (carbon outputs), increasing the amount of soil organic carbon. But this reduction in tillage might also:

- Reduce fuel use, as fewer tractor passes are made over the field. This would further reduce greenhouse gas emissions.
- Change emissions of nitrous oxide from the soil, where the direction and magnitude of the change depends on soil conditions, which are influenced by tillage.
- Change emissions from fertilizer and pesticide production, as different fertilizer and pesticide application rates may be used.

Zaher and colleagues completed a life-cycle assessment study in an effort to evaluate the potential carbon benefits from no- and reduced-tillage when fertilizer production and use of machinery are considered as well (Zaher et al., 2013). They found that accounting for fuel consumption, emissions of nitrous oxide, and up-stream emissions from fertilizer production have significant impacts on the total carbon footprint of the agricultural system. These other emissions surpassed the amount of carbon sequestered in the soil under some conditions (Figure 6). This study highlights the importance of understanding the full production system, and establishing the boundaries of the system based on the question that is being asked.

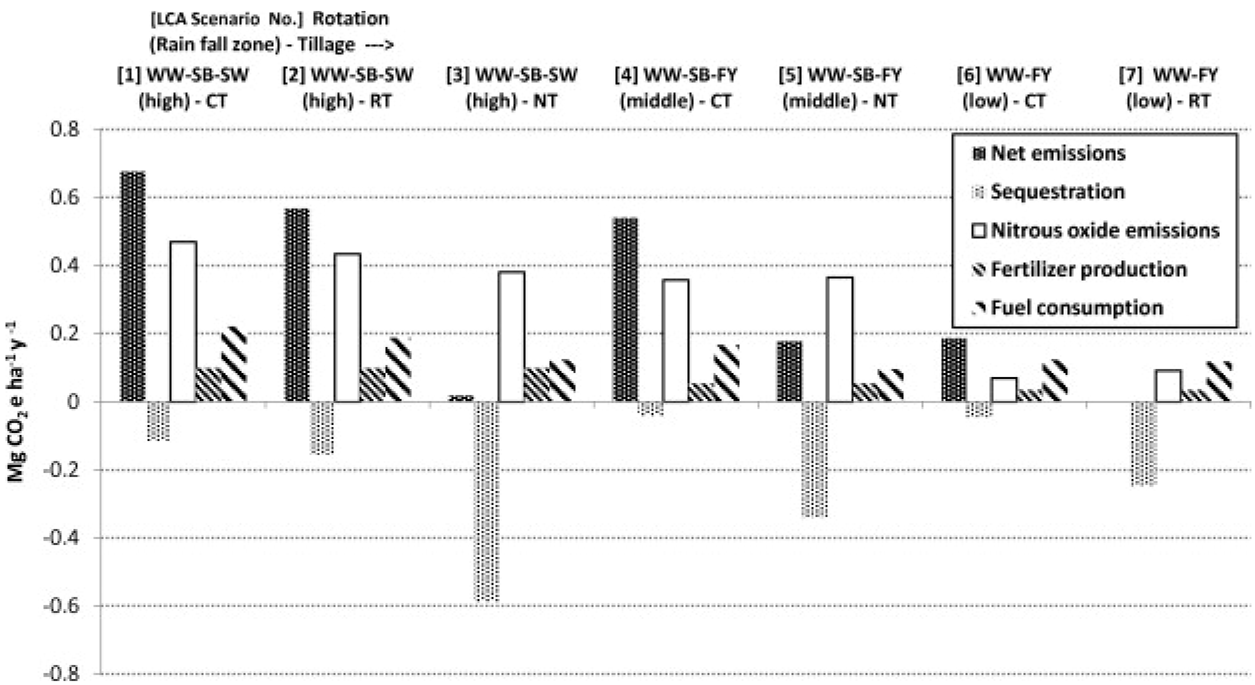

Figure 6. Greenhouse gas emissions from a life-cycle assessment study to evaluate the potential carbon benefits from no- and reduced-tillage when fertilizer production and use of machinery are considered as well. Figure reproduced from Zaher et al. (2013).

Agriculture in the Pacific Northwest

Agriculture in the Pacific Northwest is diverse and productive, and varies across the region, following variations in climatic, soils, and geographic characteristics. In 2015, agriculture accounted for $10.7 billion in Washington (WSDA, 2016), $7.5 billion in Idaho (ISDA, 2016), and $5.5 billion in Oregon (Sorte and Rahe, 2015), with the associated food processing industry more than doubling those amounts. Regional production includes over 300 agricultural products (WSDA, 2016), ranging from milk and livestock, fruits and vegetables, to grains and forage. Production systems also vary, including extensive and intensive dryland production, irrigated agriculture, organic production, livestock and dairy production, and more. The coastal portion of the region, west of the Cascade Range, is generally characterized by deep soils and a mild, maritime climate, and produce a wide range of fruits and vegetables. As mentioned earlier, few comprehensive studies exist on the carbon sequestration potential in the western portion of the Pacific Northwest.

East of the Cascades, and inland through the Snake River Plains and towards the Rocky Mountains, the climate is drier and more continental, with warmer summers and colder winters. Precipitation is lowest in the direct rain shadow of the Cascades and the high plains of southern Oregon and Idaho, and increases eastward and northward, respectively, towards the Rocky Mountains (Douglas et al., 1992). Soils also vary across the region, following patterns of glacial and glacial flood silty deposits transported to the region by prevailing westerly winds tens of thousands of years ago (Schillinger et al., 2010; Phillips, ND). Researchers have classified this part of the region—known as the inland Pacific Northwest—into agro-ecological classes where the climatic, topographic, and soils differences across the regions have led to distinct agricultural patterns. Dryland agricultural production has been classified into three major agro-ecological classes (Yorgey and Kruger, 2017, following Huggins et al., 2014):

- Grain-fallow, defined as areas with greater than 40% fallow,
- Annual crop-fallow transition, with 10 to 40% of the area using fallow, and
- Annual crop, with less than 10% fallow.

The differences among these classes—and the cropping systems and geographic regions they are currently associated with—affect the carbon sequestration potential of soils, so it is important to analyze studies within the context of each class.

Irrigation is another driving factor influencing agricultural systems in the region, leading to an additional agro-ecological class (Huggins et al., 2014). However, overall, there are fewer data available for the irrigated region than for the dryland agro-ecological classes. Therefore, the majority of the research on carbon sequestration in agricultural soils described in the following section has occurred in the three dryland classes.

Evidence supporting strategies to increase carbon sequestration in cropland soils in the inland Pacific Northwest

In general, there are three types of research that provide evidence about the impacts of various management strategies on carbon sequestration in agricultural soils in the Pacific Northwest:

- Field experiments, where data is collected either from research plots or from cultivated fields on commercial farms. These studies usually involve collecting soil samples, measuring the carbon content of the soil, and exploring the relationships between carbon content and the biophysical context, management practices, cropping history, and other key factors, to draw conclusions on the impact of different strategies on carbon sequestration. Valuable studies include Brown and Huggins (2012), who summarized the results of existing field experiments on carbon sequestration in dryland systems in the inland Pacific Northwest (see sidebar). A long-term experiment established in 1931 in Pendleton, Oregon (Rasmussen and Smiley, 1997; see sidebar) is also particularly valuable, given that changes in soil carbon can take decades to occur and stabilize.
- Eddy covariance studies, where an array of sensors are deployed on towers above specific fields of interest. These sensors quantify small variations in the concentrations of gases in the air—such as carbon dioxide—above each field, and these variations allow researchers to quantify and infer changes in the relative fluxes of carbon (and other elements) to and from the plants and soil. As of 2016 there were five such towers on agricultural lands in the inland Pacific Northwest, one close to Lind, Washington, in a grain-fallow system, under reduced tillage; two near Pullman, Washington, in the annual cropping system (one under no-till management, one under conventional tillage), one near Moscow, Idaho, also in the annual cropping system, and under conventional management, and one near Moses Lake, Washington, in irrigated and conventionally managed cropland (Chi, 2016; see sidebar).

- Modeling studies, where simulation models—which synthesize current understanding of the processes that govern the flows of water, carbon and other nutrients between the atmosphere, the crops and the soil, and quantify the size of the pools and the rates of the flows—are used to quantify carbon inputs, outputs, and pool sizes under defined environmental and management conditions. Modeling studies depend on existing experimental measurements, and can be used to look at carbon changes over wider spatial and time scales than can be measured experimentally. A crop system model developed by Dr. Claudio Stockle at Washington State University—CropSyst—has been used extensively to explore these kinds of questions in the inland Pacific Northwest (Stockle et al., 1994, 2003; See sidebar).

Carbon sequestration in Pacific Northwest cropland soils – What we know

This section summarizes the existing field, eddy covariance, and modeling studies that provide evidence about the effects of different practices or strategies on soil organic carbon. These studies then allow us to make better inferences on the potential for increasing carbon sequestration in agricultural soils in the inland Pacific Northwest. As discussed earlier, the difference between soil carbon in agricultural lands and those under native vegetation may be very different for dryland and irrigated agriculture. First, we discuss evidence in dryland systems, which has been a major focus of recent research, and then we synthesize what is known in irrigated systems, which have not yet been studied as extensively.

Dryland cropping systems

No-till and reduced tillage: Reducing tillage can increase soil organic carbon, particularly in the higher rainfall, annual cropping agro-ecological class. Conversion from conventional tillage to no-till has greater impact than reduced tillage, and carbon gains occur mainly in the first decade after the change is implemented.

Brown and Huggins (2012), in their synthesis of existing field experiments on carbon sequestration in agricultural soils of the inland Pacific Northwest, analyzed the impact of conversion from conventional tillage to no tillage or to reduced tillage. Conversion to no-till generally resulted in soil organic carbon gains in the top 30 cm (11.8 in), where the majority of carbon accumulates when soils are not turned over. It is worth noting that these datasets include data from the Pendleton, Oregon long-term experiment, where Albrecht and colleagues found that no-till continuous wheat gained soil carbon (at a rate of 0.08 Mg ha^{-1} yr^{-1}) while soils under conventional tillage lost carbon (-0.01 Mg ha^{-1} yr^{-1}) (Figure 7, Albrecht et al., 2008).

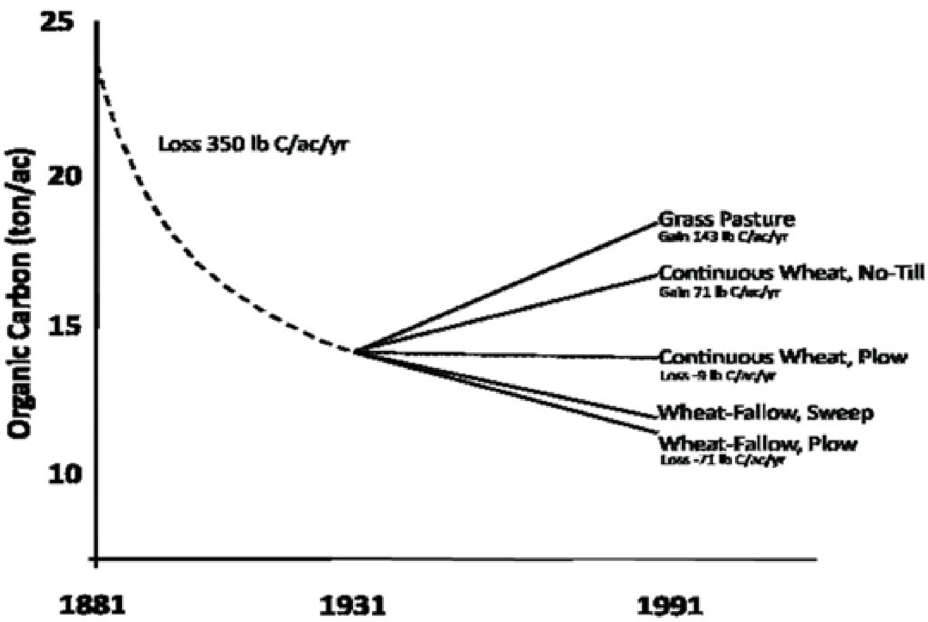

Figure 7. Extrapolated trends in soil organic carbon in the Pendleton, Oregon long-term experiments. Figure reproduced from Albrecht et al. (2008).

Brown and Huggins (2012) found that gains from conversion to no-till were not related to initial carbon content of the soil (Figure 8a). However, the rate of change in soil carbon tended to decrease after the initial 10 years following conversion (Figure 8b). In the annual cropping class (ACZ 2 in Figure 8 and Table 1), soil carbon stocks across the soil depth profile increased an average of 0.71 (± 0.63) Mg C ha^{-1} yr^{-1} over an average of 14 years following conversion from conventional tillage to no-till, with all changes occurring within the surface 20 cm (Table 1; Brown and Huggins, 2012). In the annual crop-fallow transition class (ACZ 3 in Figure 8 and Table 1), increases in carbon across the soil profile were less, averaging 0.21 (± 0.10) Mg C ha^{-1} yr^{-1} in the surface 20 cm over an average of 10 years following conversion (Table 1; Brown and Huggins, 2012).

Given the relatively high standard deviation for these data, a cumulative probability analysis was used to define expectations for soil organic carbon changes. Cumulative probabilities allow for an evaluation of results based on the probability of their occurrence. For example, a change in soil organic carbon of 0.21 Mg C ha^{-1} yr^{-1} or more would be expected on 75% of annual cropping sites over the first 14 years following conversion (Table 1, see cumulative probability estimates for no-till). There were not enough studies to carry out a probability analysis in the grain-fallow class (ACZ 5 in Figure 8 and Table 1). However, soil organic carbon was observed to accumulate at a rate of less than 0.07 Mg C ha^{-1} yr^{-1} with no appreciable gains observed below 5 cm following 14 years of no-till (Bezdicek et al., 1998, as cited in Brown and Huggins, 2012).

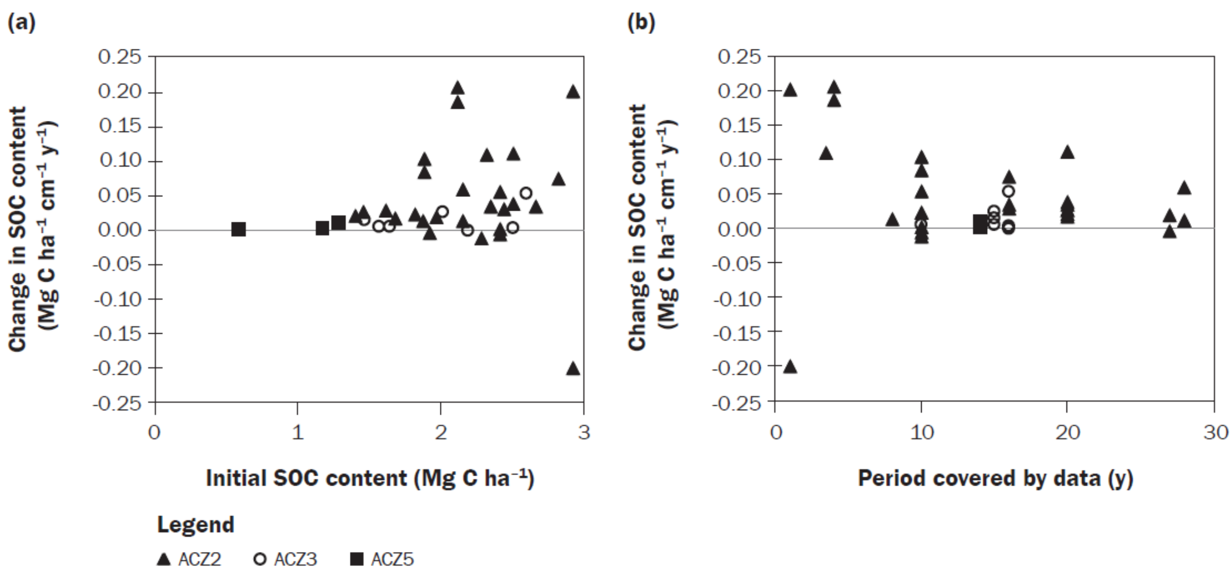

Figure 8. Changes in soil organic carbon when converting from conventional tillage to no-till. (a) Changes do not appear to vary with initial soil carbon content; (b) Changes were most significant during the first 10 years after conversion. Reproduced from Brown and Huggins (2012).

Table 1. Changes in soil organic carbon across studies evaluating changes in tillage and inclusion of perennials in the crop rotation, in the inland Pacific Northwest. Reproduced from Table 2 in Brown and Huggins (2012).

Management	Agroclimatic Zone	Number of studies	Period covered by data (mean y)	Mean SOC change (Mg C ha^{-1} yr^{-1})[a]	Cumulative probability of SOC change (Mg C ha^{-1} yr^{-1})[b] 25th	50th	75th
No-tillage	2	12	14	0.71 (±0.63)	0.21	0.64	1.04
	3	5	10	0.21 (±0.10)	0.12	0.19	0.25
Mixed perennial-annual	2	8	12	1.03 (±0.41)	0.69	0.94	1.12

[a] Values in parenthesis indicate plus or minus one standard deviation from mean value.

[b] The 25th, 50th, and 75th percentiles of the cumulative probability function.

Brown and Huggins note that the 0.71 Mg C ha^{-1} yr^{-1} estimated for the annual cropping class is at the extreme high end or exceeds other national and global estimates for conversion from conventional tillage to no-till (Smith, 2004; West and Post, 2002; Follett, 2001; West and Marland, 2001; Paustian et al., 1997, all as cited in Brown and Huggins, 2012). In contrast, the 0.21 Mg C ha^{-1} yr^{-1} estimated for the annual crop fallow transition class is similar to lower rates reported in other studies (Liebig et al., 2005; Smith, 2004; Follett, 2001; West and Marland, 2001; Paustian et al., 1997, all as cited in Brown and Huggins, 2012). Brown and Huggins attribute the high estimates in the annual cropping class and the large range and standard deviation to the influence of sampling biases (e.g. sampling just after residue incorporation) and soil erosion processes. These caveats are important to understand when looking to change management practices to increase carbon sequestration. Though not a straight-forward task (see Awale et al., 2017), monitoring to determine the actual impact of management changes on carbon sequestration in the particular context changes are made in is necessary to complement such understanding.

Brown and Huggins (2012) found limited regional datasets addressing changes in soil organic carbon with the adoption of reduced tillage: five datasets, mostly in the annual crop fallow transition class. However, the available data did indicate that gains in soil carbon when converting to reduced tillage may be less than for conversion to no-till. In the annual cropping class, the use of reduced tillage resulted in a 0.045 Mg C ha^{-1} yr^{-1} gain in soil organic carbon in the surface 15 cm (Brown and Huggins, 2012).

An important aspect that they note is that reduced tillage led to increases in carbon at greater depths than no-till, which can be overlooked when measuring the top few centimeters of soil only. At a national and global level, the impact of where in the soil's depth profile carbon accumulates or not is a key question that still leads to uncertainty as to whether no-till and reduced tillage lead to overall soil carbon accumulation, or simply a redistribution in depth, with increases in the top 20 to 30 cm, and decreases below that (Syswerda et al., 2011; Powlson et al., 2014).

Stockle and colleagues investigated the impact of converting cropland from conventional tillage to no-till and reduced tillage in the inland Pacific Northwest through a modelling approach using CropSyst (Stockle et al., 2012). They simulated the changes in soil organic carbon at three dryland locations with varying amounts of rainfall—Lind, in the grain-fallow class, St. John, in the annual crop-fallow transition class; and Pullman, in the annual cropping class. The team looked at average changes in soil carbon during the first 12 and 30 years after the change in tillage. To accommodate real-world variability, the modeling scenarios were completed twice, using a lower and upper boundary value to represent the range of possible impacts that tillage could have on oxidation rates of agricultural soil carbon. Together, the two sets of results can thus be interpreted as showing a range of possible expected changes in soil organic carbon.

In general, modeling results were consistent with the lower mid-range of results found by Brown and Huggins (2012) described above. Annual changes in soil organic carbon after conversion to no-till were all positive, with conversion to no-till in the annual cropping class (Pullman) producing the largest increase in soil carbon (Figure 9). Change in soil organic carbon was less with lower annual precipitation and greater fallow frequency. Again, in accordance with the field data summarized by Brown and Huggins (2012), Stockle et al. (2012) found that the rate of change in soil organic carbon decreased over time, with the increases almost all occurring within the first 12 years after conversion (Figure 9).

Annual changes in soil organic carbon after conversion to reduced tillage were also almost all positive, except for the lower value at the Pullman (annual cropping) site. Reduced tillage includes a wide range of tillage strategies in the inland Pacific Northwest, which can result in a corresponding wide range of carbon gains estimates. As with conversion to no-till, the magnitude of values obtained by Stockle et al. (2012) was largely consistent with the (limited) values found by Brown and Huggins (2012).

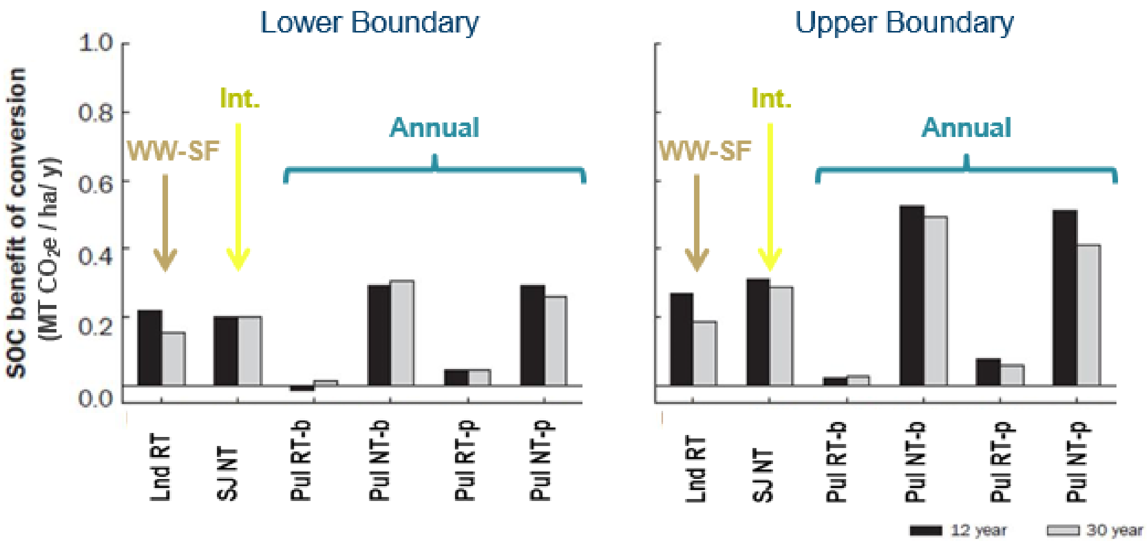

Figure 9. Modeled changes in soil organic carbon in soils 12 years (black bars) and 30 years (gray bars) after conversion to reduced tillage (RT) or no-till (NT), in different agro-ecological classes and with different rotations. The left panel shows the lower boundary of soil carbon changes, and the right panel shows the upper boundary. Reproduced from Stockle et al. (2012).

Crop rotation: Where possible, including crops that produce higher aboveground or belowground residues in annual crop rotations could increase soil organic carbon. The increase will depend on other factors, such as tillage and rainfall.

As part of a broader modeling study investigating the impacts of tillage on soil carbon in the inland Pacific Northwest, Stockle and colleagues (Stockle et al., 2012) addressed rotation to some extent. They carried out two simulations in Pullman (the annual cropping class), one with spring barley and one with spring pea as part of the winter and spring wheat rotation. They found that, when spring barley was included, more soil organic carbon was stored in the soil than when spring pea was included, likely because of the increased residue generated from barley compared to pea (Stockle et al., 2012). The differences were most noticeable in no-till sites when focused on the top 15 cm.

Eddy covariance results also suggest rotation may impact carbon sequestration potential. For example, Waldo and colleagues estimated that fields in high and low rainfall sites (Pullman and Lind, Washington) were carbon sinks—that is, were accumulating carbon in the soil—when grown with winter wheat, but were carbon neutral—that is, sequestered or emitted a little carbon, but close to zero—when growing garbanzos (Pullman) or fallowed (Lind) (Waldo et al., 2016). Chi (2016) reached similar conclusions through a combination of eddy covariance and modeling work, though her results also highlight that interactions are important. Thus, the potential to sequester carbon depends on the specific combination of crop, management practices, and climatic conditions (Chi, 2016).

Fallowing: Cropping intensity and resulting residue inputs matter, so eliminating fallow where feasible can increase soil organic carbon, potentially as much as conversion to no-till.

The impact of fallow years on soil carbon storage is underlined by Albrecht and colleagues (2008), who compared the effects of reducing fallow to those of reducing tillage. Several different experiments were established at the Columbia Basin Agricultural Research Center in Pendleton, Oregon between 1931 and 1981. Albrecht et al. (2008) compared data from these experiments, extrapolating the data as if all experiments had been initiated at the same time, in 1931 (though they were not[1]) (Figure 7). They found that the winter wheat-fallow systems had lost carbon over time, and there was little difference between the sites that were tilled with a moldboard plow and those that utilized a less intense sweep plow operation. In contrast, the continuous wheat systems (in which wheat was planted every year) maintained or even increased (depending on tillage practices) their carbon content over time, as carbon-rich crop residues are added to the system each year.

Waldo and colleagues' eddy covariance study reached similar conclusions on the impact of fallow years on cropland soils' ability to sequester carbon. They concluded that during wheat-

[1] CT continuous wheat was established in 1931. The CT and MT (minimum tillage) WW-SF was established in 1940. WW-NT was in place for 10 years prior to Rasmussen and Albrecht, established in 1981 (so it's possible these numbers are inflated).

growing years both high and low rainfall sites (Pullman and Lind, respectively) were sinks for carbon, but that fallow years at Lind were close to neutral (Waldo et al., 2016). In theory this would mean that eliminating fallow would increase the carbon sequestration at Lind. However, it is important to highlight once again the interaction with climatic conditions: rainfall at Lind is generally not sufficient to support annual wheat crops, which is why fields are fallowed on alternate years. It is also important to note that these results, though based on frequent measurements during the year, are only from one or two seasons under each crop. The researchers point out the need for longer-term studies to fully understand the potential of soils as long-term carbon sinks (Waldo et al., 2016).

In summary, these data indicate that opportunities to build soil organic carbon seem to lie mostly in higher intensity annual cropping systems, and tillage appears to be one important factor affecting the magnitude of the carbon sequestration potential.

Perennial crops: *Where economically and biologically feasible, mixed perennial-annual systems could increase soil organic carbon.*

Brown and Huggins (2012) analyzed the impact of adding perennial crops to an otherwise continuous annual crop rotation (Table 1). These mixed annual-perennial rotations include crops such as alfalfa or grasses (bluegrass, wheatgrass, alfalfa-grass mix) in an otherwise annual wheat rotation. Compared to annual cropping systems, mixed perennial-annual systems in the annual cropping class increased mean soil organic carbon in the soil profile by 1.03 (± 0.41) Mg C ha^{-1} yr^{-1}. Though this value is somewhat higher than estimates made by other groups (e.g., Liebig et al., 2005; West and Post, 2002; Follett, 2001; Paustian et al., 1997), those other estimates still suggest that shifting to a mixed annual-perennial rotation can provide soil carbon benefits that are equivalent to, or higher than, the benefit obtained from a conversion to no-till in annual systems. Such mixed annual-perennial systems are not common in the inland Pacific Northwest due to economic and market factors, as well as logistical barriers (for example, harvesting alfalfa requires different equipment, leading to greater investment needs). However, successful models used by some innovative growers include, for example, growing dryland alfalfa in rotation with wheat (Yorgey et al., 2017c).

Cover crops: The inputs of carbon from cover crops can increase carbon sequestration, but its ability to reverse losses depends on other management practices, such as fallowing and crop rotation.

No comprehensive studies exist on the effects of cover crops on carbon sequestration. Brown and Huggins (2012) discussed two studies (Horner et al., 1960; Rasmussen and Parton, 1994, as cited in Brown and Huggins, 2012) where cover crops (called "green manure") did not reverse the loss in soil organic carbon. They concluded that, though using green manure could lead to increases in soil organic carbon, the impact of this practice is dependent on other practices, such as whether there is fallowing or not (Brown and Huggins, 2012).

Crop fertilization: It is difficult to maintain carbon in low rainfall areas characterized by winter wheat-fallow cropping systems, and nitrogen additions in this system do not appear to increase carbon inputs sufficiently to reverse losses of soil carbon.

A tillage-fertility study was initiated as part of the Pendleton long-term experiments in 1940, which included six fertility treatments (Machado, 2011). Machado analyzed changes in soil organic carbon from 1984 to 2005, and found that soils under the nitrogen addition treatments (between 0 and 180 kg ha^{-1}) lost between 7.5 and 10.6 Mg ha^{-1} over that time frame. Of all the other treatments evaluated in the Pendleton residue-management experiment (nitrogen application, residue burning, pea vine and manure application in winter wheat-summer fallow under conventional tillage) only the treatment with added manure maintained (though did not build) soil carbon over the length of the experiment (see Soil amendments, below; Machado, 2011).

Soil amendments: Additions of carbon-rich materials can maintain, or potentially increase, soil organic carbon. The amount of carbon added appears to be more important than the type of material. Continued research into different types of amendments is important, however, because these amendments can have other effects on the production system or on the environment, as well *as the potential to help solve other management challenges (e.g. manure management challenges for some livestock operations).*

Overall, the results of the Pendleton long-term experiments show clearly the difficulty of maintaining soil carbon in a winter wheat-fallow system, as all treatments except one lost soil carbon (Table 2; Figure 10; Machado 2011). One of the more promising insights arising from these experiments, however, was that the treatment that added manure maintained (though did not build) soil carbon over the length of the experiment. In such grain-fallow cropping systems, the land lies fallow every other year, and thus there are no carbon additions during those years. Meanwhile, microbial activity continues, and may increase due to the availability of additional water during the fallow year. Fallow ground is also normally tilled for weed control, contributing to carbon losses. Further analysis (not shown here) suggests that the organic carbon levels in the soils are related to the amount of carbon added in crop residues and other amendments, while the differences in types of material are less important.

Table 2. Crop residue management effects on soil organic carbon (SOC) in a winter wheat-summer fallow system, at the Pendleton long-term experiment. Reproduced, with modifications, from Machado (2011).

N† kg ha^{-1}	Burn	SOC 1976‡ Mg ha^{-1}	SOC 2005‡ Mg ha^{-1}	Significance level§
0	No burn	64.8ab	56.1c	***
45	No burn	63.5ab	55.6c	**
90	No burn	64.3ab	57.6bc	*
Pea⁋	No burn	69.6a	61.3b	**
Manure#	No burn	69.4a	68.8a	ns††
0	Fall burn	59.1b	48.9d	**
se		2.3	1.5	

* Indicates that SOC means in 1976 and 2005 are significantly different at the 0.05 probability level.
** Indicates that SOC means in 1976 and 2005 are significantly different at the 0.01 probability level.
*** Indicates that SOC means in 1976 and 2005 are significantly different at the 0.001 probability level.
† N, nitrogen; SOC, soil organic carbon.
‡ Within columns, means followed by the same letter are not significantly different according to LSD (0.05).
§ This compares SOC across years.
⁋ Pea vines = 2.24 Mg ha^{-1} field weight; 87.8% dry matter; 0.82 Mg C ha^{-1} and 0.037 Mg N ha^{-1}; applied 1-3 days before plowing.
Manure = 22.4 Mg ha-1 wet wt; 47.5% dry matter; 1.69 Mg C ha-1 and 0.14 Mg N ha-1; applied 1-3 days before plowing in April or May of plow year.
††ns = not significant.

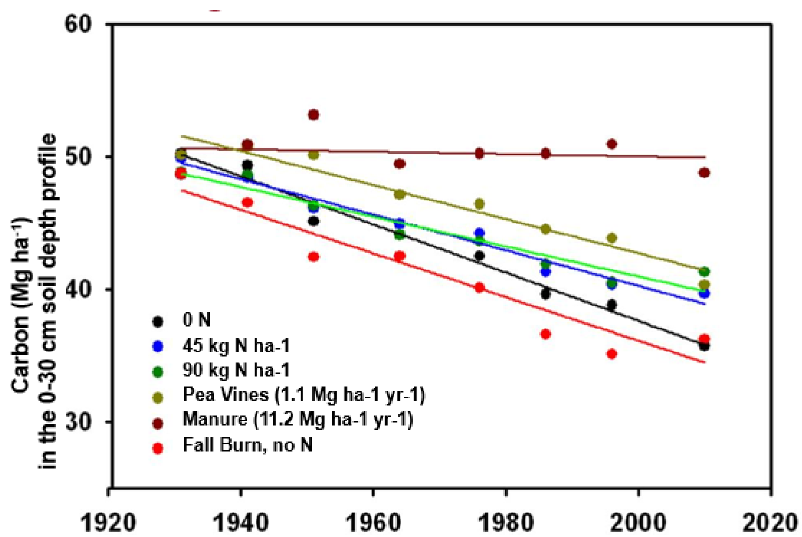

Figure 10. Soil carbon in the top 30 cm of soil in plots in the long-term residue management experiment at Pendleton, Oregon (1931-2010) (Machado et al., unpublished data)

Reduced burning: Practices that incorporate greater amounts of residue into the soil, where they contribute to soil carbon, are preferable to residue burning, from a carbon sequestration perspective.

The Pendleton long-term experiments include residue burning as a treatment. As mentioned above, only the manure additions led to maintained soil carbon, with the burning treatment showing among the highest losses in soil carbon (Figure 7; Albrecht et al., 2008). Follow-up studies at Pendleton confirmed that soil organic carbon was lowest under a fall burning treatment, and that eliminating burning can improve sustainability of winter wheat production (Ghimire et al., 2015). Brown and Huggins (2012) discuss two studies that looked at the effects of burning on soil organic carbon (the same ones as discussed green manure: Horner et al., 1960, and Rasmussen and Parton, 1994, as cited in Brown and Huggins, 2012). In both these studies the loss of carbon with burning was notably larger than without burning (0.45 vs. 0.15 Mg C ha^{-1} yr^{-1} in the annual cropping class [Horner et al., 1960]; 50% reduction in losses of soil carbon in annual crop-fallow transition class [Rasmussen and Parton, 1994]). These results were not unexpected, given that burning the crop residues leads to release of carbon in the form of carbon dioxide, reducing the inputs of carbon into the soil. Burning of residues was common until the 1990s, but is now limited in the inland Pacific Northwest (Machado, 2011).

Reduced erosion: The impact of soil redistribution through erosion and deposition on carbon sequestration is not yet well understood. Though reducing erosion has known benefits for agricultural fields, the net impact of soil redistribution may also act as a carbon sink.

Modeling studies in other areas, such as in the United Kingdom and in Maryland, United States, suggest that erosion and deposition together could lead to a watershed-level increase in carbon sequestration. This increase could be due either to increased carbon sequestration in eroded areas, due to shifting the balance of carbon sequestration in the soil (McCarty and Ritchie, 2002), or to increased rates of carbon sequestration in wetland deposition areas (Quine and Van Oost, 2007). We are unaware of field studies in the Pacific Northwest that specifically investigate the impact of efforts to reduce erosion on the soil's ability to sequester carbon. In the inland Pacific Northwest, however, Stockle et al. (2012), using the CropSyst model, concluded that even if erosion-deposition increased the oxidation of soil organic carbon by an unlikely 50%, erosion would only contribute modestly to changes in soil organic carbon, even under conventional tillage, where erosion values are high.

Irrigated cropping systems

Entry et al. (2002) estimated net carbon gains under irrigated agriculture in southern Idaho. Among other variables, the team measured carbon in soils for sites that had long-term cropping histories of irrigated cropland under moldboard plow, irrigated cropland under conservation tillage, and irrigated pasture. They compared the carbon pools under these different cropping systems to those of native sagebrush steppe. Carbon stored in soils was greatest in irrigated pasture, followed by irrigated crops under conservation tillage, irrigated crops under moldboard plow, and all cultivated sites has more carbon stored than the native sagebrush steppe (gray bars in Figure 11), even if aboveground plant biomass—in the native sagebrush and perennial pasture—was included in the accounting (red bars in Figure 11).

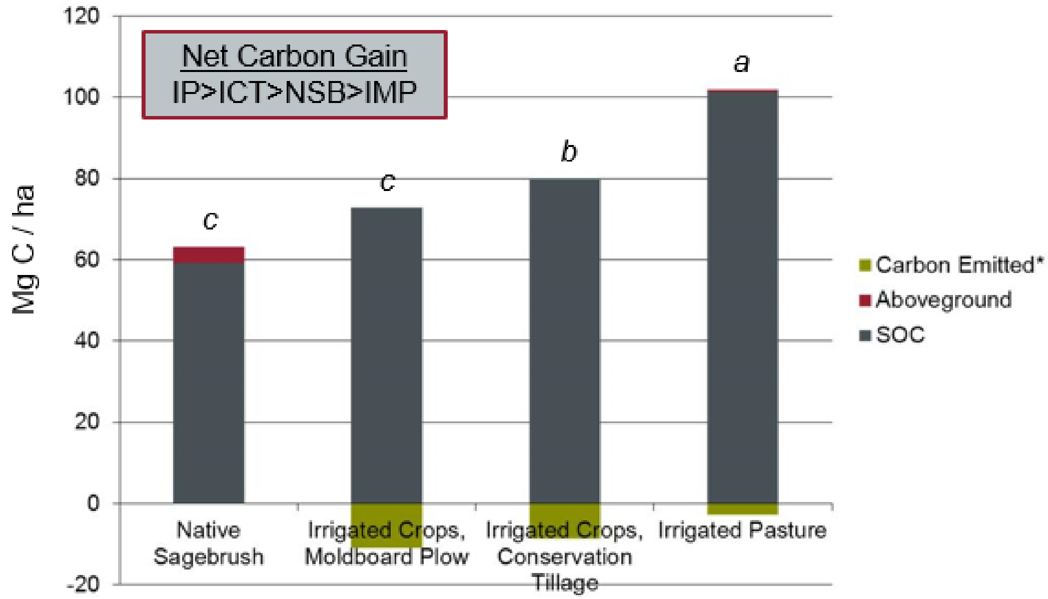

Figure 11. Organic carbon in soils and aboveground biomass in native sagebrush steppe and different cropping systems in southern Idaho, and carbon emitted during fertilizer production, farm operations, and dissolved in irrigation water over a 30-year period. Data from Entry et al. (2002).

In addition to measuring carbon in soils and aboveground plant biomass, Entry et al. (2002) explicitly considered some of the carbon losses associated with agricultural use, resulting from fertilizer production, farm operations, and carbon dioxide lost via dissolved carbonate in irrigation water over a 30-year period (green bars in Figure 11). Once these losses are considered, the order of net carbon gain is somewhat different, with irrigated pasture storing the most net carbon, followed by irrigated crops under conservation tillage, native steppe, and irrigated crops managed with moldboard plow.

Different results were obtained using eddy covariance methods (Chi, 2016). When comparing net carbon fluxes in an irrigated site near Moses Lake, Washington, to the other four, dryland sites with eddy covariance towers in the inland Pacific Northwest (see sidebar), Chi (2016) found that the irrigated agriculture site lost more soil carbon over the period of study (2014) than the dryland sites. When she explored what processes would explain these differences, she found that, though irrigated crops had higher gross primary productivity—which results directly from photosynthesis, and captures carbon in the plants—they also had much higher respiration overall—which releases carbon from plants and soils (Chi, 2016). If a large part of this additional respiration in irrigated cropping systems comes from the soil (rather than the plants themselves), these results would support the conclusion that irrigation leads to increased residues being added to the soil, but would point to the potential for increased decomposition releasing more carbon from those residues and other soil organic material. As with the other eddy covariance studies, Chi (2016) emphasizes the need for longer-term studies to fully understand the impacts of management activities on soil carbon, and their interaction with climatic conditions (Chi, 2016).

In addition to the experimental and eddy covariance results discussed above, Stockle et al. (2012) modeled the soil organic carbon change resulting from conversion to reduced tillage in an irrigated system in Paterson, Washington. They used a representative rotation (rather than a rotation chosen for its ability to generate residue or to store carbon), and found that overall carbon gains in this irrigated system fell between the values for reduced tillage in Lind and reduced tillage in Pullman (Figure 12). Note that true no-till may be limited as an option for some irrigated crops. For example, potatoes require tillage for harvest.

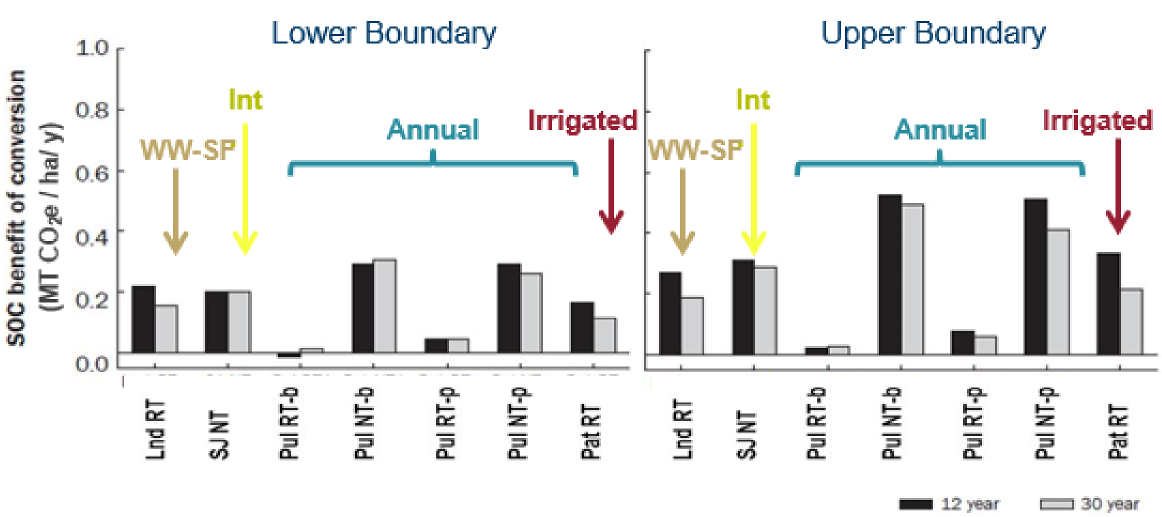

Figure 12. Modeled changes in soil organic carbon in soils 12 years (black bars) and 30 years (gray bars) after conversion to reduced tillage (RT) or no-till (NT), in different agro-ecological classes and with different rotations. The left panel shows the lower boundary of soil carbon changes, and the right panel shows the upper boundary. All bars except those marked "irrigated" were in Figure 9, above. Reproduced from Stockle et al. (2012).

Conclusions

The Pacific Northwest—particularly the inland Pacific Northwest—has benefited from a variety of field experiments, eddy covariance studies, and modeling work that provides insights into the potential for carbon sequestration in cropland soils. Summarizing existing studies and their resulting conclusions highlights several key points that can provide the basis for discussions around policies and incentives for efforts to mitigate climate change through soil carbon sequestration:

- Reducing tillage (particularly conversion to no-till), incorporating perennial crops into rotations, or adding carbon-rich soil amendments can provide real but modest contributions to carbon sequestration in the Pacific Northwest.

- Benefits from conversion to no-till could reach on the order of hundreds of kilograms of carbon per hectare per year in annual cropping systems.

- In dryland systems, shifting to a mixed annual-perennial rotation can provide soil carbon benefits that are equivalent to, or higher than, the benefit obtained from a conversion to no-till in annual systems.

- Integrating livestock manures or other organic amendments in both dryland and irrigated cropping systems could significantly increase soil carbon sequestration on a per hectare basis, where this is economically viable.

- Greater opportunities exist to build soil organic carbon in annually cropped systems, where higher annual rainfall allows crop production every year, and therefore annual residue additions to the soil. These opportunities are mirrored, to some extent, in irrigated systems. It is difficult to maintain, let alone build, soil organic carbon in areas with lower annual precipitation, with greater fallow frequency.

- The soil organic carbon benefits of particular management practices can vary depending on the initial soil organic carbon levels, the environmental and physical constraints of a site, and the amount of time after the management changes are made.

- Soils with high initial organic carbon levels will accumulate further carbon at lower rates.

- Rainfall is a key environmental condition, with greater carbon sequestration potential at higher rainfall sites.

- It is likely that most increases in soil organic carbon due to management changes occur in the first decade or so after the change is implemented.

In addition to the insights that this white paper's summary of evidence provides, it is critical that policy discussions keep in mind the context within which such policies would take effect. Interactions occur between management changes and the environment, so that the potential to sequester carbon depends on the specific combination of crop, management practices, and climatic conditions. Any policy targeting particular changes in management practices must consider the variations in climatic conditions across the region—and variations to come as the climate changes—as well as the agro-ecological classes and production systems within which such practices may or may not be implemented. Policies targeting management practices can directly impact individual farmers, who on a day-to-day basis consider and evaluate opportunities, risks and trade-offs posed by a variety of options. Farmers are constantly subject to financial, operational and market conditions and constraints. Policy discussions should therefore consider these same conditions and constraints, as they may impact the feasibility of adoption of particular practices in particular locations or under particular market conditions.

It is clear from the emphasis this white paper gives to the inland Pacific Northwest, as well as to certain management practices, that there are gaps in the available evidence supporting different carbon sequestration strategies in different areas. Similarly, the range of values—and researchers' emphasis in evaluating a range of values—highlights the variability in existing data (e.g. Brown and Huggins, 2012). And interactions between factors are hard to comprehensively capture and understand. These gaps, variability, and interactions all support the need to establish credible estimates of carbon fluxes for Northwest agricultural systems so that further innovation in and adoption of greenhouse gas reduction strategies can occur. This has been highlighted as a top priority for research and extension in the region (Yorgey et al., 2017d).

Credible estimates must also be accompanied by monitoring to determine whether cropland soils are achieving carbon sequestration goals. Such monitoring requires methods that are sensitive to short-term changes in soil organic carbon (e.g. Awale et al., 2017). It also requires an understanding of the impact the management practices have on other greenhouse gas emissions, from other parts of the life-cycle of inputs.

Thoughtful consideration of the environmental and production contexts surrounding Pacific Northwest crop production, combined with targeted research to facilitate the adoption of the most effective carbon sequestration practices, could lead to the development of policies that can realize the real contributions that croplands in the Pacific Northwest can make to climate change mitigation efforts in the region.

Sidebar: Review of Regional Experimental Datasets

Brown and Huggins (2012) surveyed existing datasets on soil organic carbon changes in the inland Pacific Northwest. The authors found 131 datasets in the peer-reviewed and non-peer-reviewed literature (e.g. bulletins and project reports), with data concentrated in annual cropping and annual crop-fallow transition classes and, to a lesser extent, the grain-fallow class (Table 1, reproduced from Brown and Huggins, 2012). These authors used the agro-climatic zones that were defined by Douglas et al. (1992), where ACZ1 is mountain/forest (wet-cold), ACZ2 is annual cropping (wet-cold), ACZ3 is annual cropping (fallow-transition), ACZ4 is annual crop (dry), ACZ5 is grain-fallow, and ACZ6 is dryland (in the irrigated/very dry region). Zones 2, 3, and 5, which contain most of the data, correlate with the annual cropping, annual crop-fallow transition, and grain-fallow classes used in this white paper.

Table 1. Summary of collected soil organic content literature by management practice (native conversion [NC], no-tillage management [NT], reduced tillage management [RT], mixed perennial-annual system [Mixed P-A], Conservation Reserve Program planting [CRP], annual cropping, fallow cropping, residue burning, no residue burning, barnyard manure application, and green manure application) and Pacific Northwest agroclimatic zone (ACZ). Numbers of studies listed are by location rather than publication. Modified from Brown and Huggins (2012).

ACZ*	NC	NT	RT	Mixed P-A	CRP	Annual cropping	Fallow cropping	Residue burning	No residue burning	Barnyard manure	Green manure
1	1	—	—	—	—	—	—	—	—	—	—
2	8	12	3	9	2	16	9	1	1	6	14
3	4	13	4	1	1	2	4	3	3	2	2
4	—	—	—	—	—	—	—	—	—	—	—
5	3	1	—	—	1	—	—	1	2	1	—
6	1	—	—	—	—	—	—	—	—	—	—

*The agro-climatic zones (ACZ) used here are those that were defined by Douglas et al. (1992), where ACZ1 is mountain/forest (wet-cold), ACZ2 is annual cropping (wet-cold), ACZ3 is annual cropping (fallow-transition), ACZ4 is annual crop (dry), ACZ5 is grain-fallow, and ACZ6 is dryland (in the irrigated/very dry region).

The authors converted each dataset from its original units to mass per unit volume of soil per year, allowing them to (a) compare the values of different studies, (b) assess the depth-distribution of soil organic carbon change, and (c) estimate the total profile changes in soil organic carbon. Where they found adequate data with particular combinations of management changes and agro-ecological conditions, they carried out a comprehensive analysis to estimate mean soil organic carbon change, as well as the cumulative probability of that change. Their methods are described in detail in Brown and Huggins (2012). For other management practices where only limited data existed, they provided summaries of experimental results.

Sidebar: Pendleton Long-Term Experiments

One of the best resources for understanding long-term soil carbon dynamics in the dryland soils of the Pacific Northwest comes from a set of long-term experiments established at the Columbia Basin Agricultural Research Center (http://cbarc.aes.oregonstate.edu/) in Pendleton, Oregon. The longest-standing of these experiments, investigating residue management in a winter wheat-summer fallow cropping system, was established in 1931. Prior to the establishment of the trial, all plots were cultivated for about 50 years, and presumably were losing carbon over that time period. This experiment considers several methods for managing residues, including the following:

- No nitrogen added, no special management (the control)
- Fall burn, no nitrogen added (burning increases losses of carbon from the system)
- Two different rates of nitrogen addition, 45 kg ha^{-1} and 90 kg ha^{-1} (added nitrogen will result in higher yields and more residues, with the residues, and their incorporated carbon, being incorporated back into the soil during tillage operations)
- Pea vines added (at a rate of 1.1 Mg ha^{-1} yr^{-1})
- Manure added (at a rate of 11.2 Mg ha^{-1} yr^{-1})

Sidebar: Eddy covariance towers in the inland Pacific Northwest

As part of the Regional Approaches to Climate Change project for Pacific Northwest agriculture (https://www.reacchpna.org), a network of five towers was deployed to continuously measure carbon dioxide and water fluxes over wheat-cropping systems in the inland Pacific Northwest, as well as nitrous oxide emissions at two of the sites. These data can be used to evaluate whether agricultural cropping systems are net carbon sinks or sources, and whether cropland fertilization leads to enhanced nitrous oxide emissions.

All five sites were wheat-based cropping systems where crop rotation typically consists of winter wheat and spring crops such that spring crops are seeded into winter wheat residue. Two paired towers were located at the Washington State University Cook Agronomy Farm (CAF) near Pullman, Washington, which is located in the high rainfall zone in the inland Pacific Northwest. Both sites have the same crop rotations (winter wheat-spring garbanzos-winter wheat-spring canola during the crops years of 2012-2015) and similar meteorological conditions, but one site has been in continuous no-till management (CAF-NT) since 1998 while the other site has been under conventional tillage practices (CAF-CT) for the same time period. A third site (MMTN) is located in a higher rainfall area near Moscow, Idaho. Conventional tillage practices have been applied since the tower was set up in 2012. MMTN also has a crop rotation of winter wheat-spring crops. A fourth site (LIND) is situated in a low-rainfall, crop-fallow area in Lind, Washington. Due to low precipitation (~280 mm annually), winter wheat (WW)-tillage fallow (TF) has been the predominant farming practice in this dry area of the inland Pacific

Northwest. Undercut and reduced tillage practices have been used at this site. The fifth site (MSLK) is located in an irrigated continuous-cropping area in Moses Lake, Washington, and irrigation has been applied during each growing season at this site.

Note: The description of the eddy covariance sites, above, and the details in Figure 1 and Table 1 were reproduced from Chi (2016) with only slight modifications.

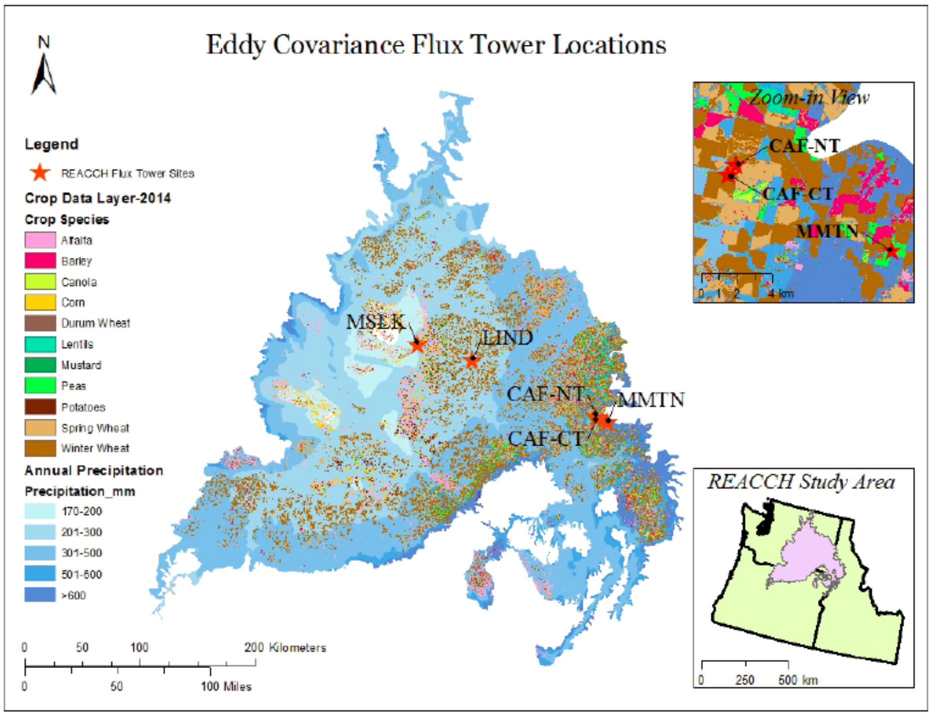

Figure 1: Location of five eddy covariance flux towers in the inland Pacific Northwest region of the US.

Table 1: Site characteristics, local meteorology, and management practices at the five eddy covariance flux tower sites in the inland Pacific Northwest region of the US.

Site	MSLK	LIND	CAF-NT	CAF-CT	MMTN
Latitude	47º00'N	46º59'N	46º47'N	46º46'N	46º45'N
Longitude	119º14'W	118º35'W	117º04'W	117º04'W	116º56'W
Elevation (m)	349	475	807	799	817
Date tower installed	6/19/2013	10/18/2011	8/19/2011	6/27/2012	7/11/2012
Soil type‡	Mollisols	Mollisols	Mollisols	Mollisols	Mollisols
Soil texture‡	Timmerman coarse sandy loam	Silt loam (Shano and Ritzville Series)	Silt loam (Naff, Thatuna and Palouse Series)	Silt loam (Naff, Thatuna and Palouse Series)	Silt loam (Latahco-Thatuna complex, Southwick and Larkin Series)
Annual temperature (ºC) ‡	11	10	9	9	9
Annual precipitation (mm) ‡	230	280	550	550	680
Crop rotation*	SW-CC-P	WW-TF	WW-SG-WW-SC	WW-SG-WW-SC	WW-SB-Pea
Tillage practices†	CT	RT	NT	CT	CT
Tillage fallow	No	Yes	No	No	No
Irrigation	Yes	No	No	No	No

‡Annual temperature and precipitation were averaged based on historical records from 1981 to 2010, National Climatic Data Center, NOAA. Soil types and textures were from Soil Survey Staff (1999) and Web Soil Survey (2013).

* SW (spring wheat), CC (cover crops, i.e., mustard), P (potato), WW (winter wheat), TF (tillage fallow), SG (spring garbanzo), SC (spring canola), SB (spring barley).

† CT (conventional tillage), RT (reduced tillage), NT (no-till).

Sidebar: CropSyst – a simulation model

CropSyst is a crop growth simulation model, developed with an emphasis on a friendly user interface (Stockle, 1996). The model is basically an analytical tool which can be used to study the effect of cropping systems management on crop productivity and the environment—for the purposes of this white paper, we focus on soils. CropSyst simulates—and quantifies—a variety of processes that determine how quickly crops grow and accumulate biomass, and move through different stages of development, what happens with water in the soil; what happens to nitrogen that is added to the cropping system, absorbed by the crop, and then recycled into the soil or released, how much residue is left after harvest, and what happens to that residue and the carbon it contains. These processes are affected by weather, soil characteristics, crop characteristics, and cropping system management options such as crop rotation, cultivar selection, irrigation, nitrogen fertilization, soil and irrigation water salinity, tillage operations, and residue management. Many of these management options are strategies that could increase the ability of agricultural soils to sequester carbon, helping mitigate climate change impacts. CropSyst is therefore a useful modeling tool to explore the carbon sequestration potential of agricultural soils in the Pacific Northwest, and has been used extensively in the region. For more details on CropSyst, please visit: http://modeling.bsyse.wsu.edu/CS_Suite/CropSyst/index.html.

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