Dryland Agriculture's Impact on Soil Carbon Sequestration in the Pacific Northwest

T. T. Brown and D. R. Huggins

EXECUTIVE SUMMARY

Soil plays a critical role in the global terrestrial carbon (C) cycle and the soil C pool has the potential to positively or negatively influence atmospheric CO_2 concentrations and consequently, global climate change (Follett, 2001; Lal et al., 2004). Conversion of native vegetation to agriculture and other land use changes have historically reduced soil C levels, thereby releasing CO_2 to the atmosphere (Post et al., 2001). Managed ecosystems, however, have the potential to restore soil C that was lost following land use changes (West and Post, 2002; Lal et al., 2004). The overall goal of this report is to provide science-based information and assessment tools that quantify agricultural impacts on soil C sequestration for dryland cropping systems within the Pacific Northwest. Our objectives are to: (1) identify current or historic studies under diverse agricultural management and agro-ecological zones where soil C has been quantified that are relevant to dryland cropping systems in the Inland Pacific Northwest; (2) summarize research results with respect to agricultural management impacts on rates of soil carbon change over time and identify strengths and weaknesses of current knowledge bases that assess agricultural management effects on soil profile carbon; and (3) identify future efforts, if any, required to provide realistic, science-based estimates of agricultural management effects on soil C stocks.

This report focuses on dryland agriculture within agroclimatic zones of the Pacific Northwest (PNW), which are also characterized as Land Resource Region B, Northwest Wheat and Range Region (USDA, 2006). One hundred and thirty one data sets of existing soil organic carbon (SOC) data were identified within the approximately 3.3 to 4 million ha of non-irrigated cropland occurring in the PNW (i.e. northern Idaho, north central Oregon, and eastern Washington). These datasets were analyzed and synthesized to assess the influence of land management changes on SOC including the conversion of native ecosystems to agricultural crops, the conversion from conventional tillage (CT) to no-tillage (NT) and the use of alternative crop rotations and management practices.

Changes in SOC stocks were considered using depth increment means to characterize the distribution of change in SOC content with soil depth. These trends were then used to estimate total changes in SOC stocks on a soil profile basis. In addition, the expected normal scores for total profile changes in SOC were calculated using the expected score for the number of observations in each management by zone and plotted against the cumulative probability. These analyses provided a means to use a probability function when providing SOC change figures that could potentially be used for land managers, policy and marketing of SOC. The available data were sufficient to estimate changes in SOC that would occur within certain, but not all, agroclimatic zones of the PNW for: (1) conversion of native vegetation (perennial-based steppe) to cropland; (2) no-tillage (NT) compared to

conventional tillage (CT) management; and (3) use of a mixed perennial-annual rotation compared to an annual rotation.

Following conversion of native steppe vegetation to cultivation-based agriculture, total profile SOC (125-cm depth) declined an average of 0.84 (± 0.17) Mg C ha^{-1} yr^{-1} [equal to 1.24 metric tons carbon dioxide equivalent (MT CO_2e) ac^{-1} yr^{-1}] in agroclimatic zone 2, while SOC losses were less in agroclimatic zones 3 [0.53 (±0.18) Mg C ha^{-1} yr^{-1} or 0.78 MT CO_2e ac^{-1} yr^{-1}] and agroclimatic zones 5 [0.69 (±0.52) Mg ha^{-1} yr^{-1} or 1.02 MT CO_2e ac^{-1} yr^{-1}]. [1] About 50% of the SOC loss occurred in the surface 30-cm depth of the 125-cm soil profile assessed for agroclimatic zone 2 data, while 50% of the SOC loss occurred in the surface 13-cm in agroclimatic zone 3 data. The averages of SOC change had large standard deviations likely due to the influence of sampling errors and soil erosion effects and it was considered valuable to express SOC changes on a cumulative probability basis. These analyses showed that 75% of the converted native ecosystems were expected to have lost at least 0.70 Mg C ha^{-1} yr^{-1} (1.04 MT CO_2e ac^{-1} yr^{-1}) in agroclimatic zone 2. Correspondingly, in agroclimatic zone 3, a SOC loss of at least 0.35 Mg C ha^{-1} yr^{-1} (0.51 MT CO_2e ac^{-1} yr^{-1}) on 75% of converted sites and in agroclimatic zone 5, SOC losses of 0.14 Mg C ha^{-1} yr^{-1} (0.21 MT CO_2e ac^{-1} yr^{-1}) or more would be expected on 75% of sites.

Adoption of NT following CT generally resulted in SOC increases with 58% or more of the SOC change captured in the surface 5-cm and declining with depth to near zero at 20-cm. No appreciable increases in SOC content were observed for adoption of reduced tillage in either agroclimatic zone 2 or 3. In agroclimatic zone 2, SOC stocks increased by 0.71 (± 0.63) Mg C ha^{-1} yr^{-1} [1.05 (± 0.94) MT CO_2e ac^{-1} yr^{-1}] for the soil profile (all of the SOC changes occurred within the surface 20-cm) following an average of 14 years after conversion of CT to NT. Soil profile organic C increased by 0.21 (± 0.10) Mg C ha^{-1} yr^{-1} [0.32 (± 0.15) MT CO_2e ac^{-1} yr^{-1}] in the surface 20-cm of agroclimatic zone 3 with an average of 10 years following conversion of CT to NT. Given the relatively high standard deviations for these data, the cumulative probability analyses were again useful for further defining expectations for SOC changes. In agroclimatic zone 2, we predicted that for 75% of the situations where CT was converted to NT that SOC change would be at least 0.21 Mg C ha^{-1} yr^{-1} (0.31 MT CO_2e ac^{-1} yr^{-1}). Similarly for agroclimatic zone 3, increases of at least 0.12 Mg C ha^{-1} yr^{-1} (0.17 MT CO_2e ac^{-1} yr^{-1}) would be expected for 75% of the sites. Although insufficient numbers of studies occurred for this kind of analysis in agroclimatic zone 5, values of SOC change of less than 0.07 Mg C ha^{-1} yr^{-1} (0.11 MT CO_2e ac^{-1} yr^{-1}) were indicated by the few studies conducted.

Compared to annual cropping systems, mixed perennial-annual systems increased mean SOC stocks in the soil profile by 1.31 (± 0.91) Mg C ha^{-1} yr^{-1} [1.94 (± 1.35) MT CO_2e ac^{-1} yr^{-1}] in agroclimatic zone 2. No other agroclimatic zones had sufficient data to assess SOC changes. Again, considering the high standard deviations associated with these data, the cumulative probability analyses provided a more conservative estimate of SOC gains of at least 0.55 Mg C ha^{-1} yr^{-1} would be expected for 75% of the sites in agroclimatic zone 2.

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[1] MT = metric tons (1 MT = 1 Mg); MMT = million metric tons (1 MMT = 1 Tg)

There is an overall lack of existing SOC data for much of the dryland Pacific Northwest except for native conversion to cropland, adoption of NT, and use of a mixed perennial-annual rotation for agroclimatic zone 2 and to some extent agroclimatic zone 3. Furthermore, the impact of soil erosion processes on field-scale soil C stocks is poorly understood. The soil C marketing requirement for additionality exacerbates the need for baseline C data. Baseline SOC data quantifies the SOC content under "business as usual" and is the means by which SOC content under alternative management can be compared to determine net benefits. Establishment of long-term georeferenced sites representing the major agricultural systems as well as the more feasible alternatives to "business as usual" for each agroclimatic zone is needed. Initial soil C sampling would provide baseline data to be used in conjunction with temporal sampling to evaluate the rate and amount of soil C changes resulting from management. A well validated C model for the region would also aid evaluation of SOC changes due to management particularly for specific farms and sites with unique SOC history and circumstances.

13.1. INTRODUCTION: ROLE OF AGRICULTURAL SOILS IN CARBON SEQUESTRATION

13.1.1 Global Soil C Pool

Globally, soils play a critical role in terrestrial carbon (C) storage and dynamics (Follett, 2001). The soil C pool (2250 to 2500 Gt) is approximately 3 to 4 times the atmospheric (760 Gt) and biotic (560 to 600 Gt) C pools, respectively (Follett, 2001; Lal, 2004). Conversion of native ecosystems to agriculture is estimated to have reduced the global soil C pool by 40- to 100-Gt (Paustian et al., 1997; Lal, 2001; Smith et al., 2004). Lal (2004) estimated that 50 to 66% of historic C losses on agricultural and degraded soil might be restored by adopting practices that sequester soil C, thereby partially mitigating rising atmospheric CO_2 concentrations (West and Post, 2002; Purakayastha et al., 2008).

13.1.2 Management Impacts on Soil C Sequestration

Soil organic C (SOC) is a balance between C additions from unharvested plant residues and roots, organic amendments and erosional deposits, and C losses through decomposition of organic materials and soil erosion processes (Paustian et al., 1997; Follett, 2001; Post et al., 2001). Conversion of native prairie to agricultural production resulted in a 20 to 60% loss of SOC within 40 to 50 years after sod busting (Rasmussen and Parton, 1994; Lal et al., 1998; Lal, 2004). Agricultural practices that can partially restore depleted SOC include: (1) adoption of conservation tillage including no-tillage; (2) intensification of cropping by eliminating fallow, increasing cover crops and including more perennial vegetation; and (3) improving biomass production through the use of soil amendments (manures), fertilizers and high yielding crop varieties (Lal et al., 1998; Follett, 2001; Paustian et al., 2001; Post et al., 2001; West and Post, 2002; Sperow et al., 2003). Table 1 summarizes the potential for different agricultural practices to sequester soil C. Between 1982 and 1997, agricultural and land management changes in the US were estimated to sequester approximately 17 million metric tons (MMT) yr^{-1} (51 MMT CO_2e) with 8.2 MMT C yr^{-1} (30 MMT CO_2e yr^{-1}) from reducing tillage intensity (Sperow et al., 2003).[2] Sperow et al. (2003) estimated that adoption of C sequestering management practices could increase total US SOC stocks by 60 to 70 MMT C yr^{-1} (220 to 256 MMT CO_2e yr^{-1}) above the baseline 17 MMT C yr^{-1} for 15 years following adoption.

13.1.2.1 Conservation Tillage

Conversion from conventional tillage to conservation tillage (i.e. no-till, mulch-till, or ridge till) has the potential to sequester approximately 0.2 to 0.6 Mg C ha^{-1} yr^{-1} (Lal et al.,1998; Follett, 2001; West and Marland, 2001). In a paired NT-CT comparison of 39 studies reported by Paustian et al., (1997), and assuming an average study length of 12.5 years, SOC increased by 0.23 Mg C ha^{-1} yr^{-1} (0.34 MT CO_2e ac^{-1} yr^{-1}) following adoption of NT. In an analysis of 67 long-term studies, West and Post (2002) reported an average SOC increase of 0.57 ± 0.14 Mg C ha^{-1} yr^{-1} (0.85 ± 0.21 MT CO_2e ac^{-1} yr^{-1}) in the surface 30-cm

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[2] MT = metric tons (1 MT = 1 Mg); MMT = million metric tons (1 MMT = 1 Tg)

under no-tillage (NT) compared to conventional tillage (CT), excluding the wheat-fallow systems studied. No significant increases in SOC have been reported for wheat -fallow systems shifting from CT to NT (Halvorson, 2001; West and Post, 2002). Sperow et al. (2003) estimated that adoption of NT on all U.S. cropland could potentially sequester 47 MMT C yr^{-1} (172 MMT CO_2e yr^{-1}) or adoption of NT on 50% and reduced till on the remaining 50% of U.S. cropland 37 MMT C yr^{-1} (136 MMT CO_2e yr^{-1}).

The potential for agricultural practices to sequester soil C in the northwestern US was assessed by Liebig et al. (2005). They reported an average SOC increase of 0.05 Mg C ha^{-1} yr^{-1} (0.07 MT CO_2e ac^{-1} yr^{-1}) for reduced tillage and 0.27 ± 0.19 Mg C ha^{-1} yr^{-1} (0.40 MT CO_2e ac^{-1} yr^{-1}) for no-tillage under continuous dryland cropping. The Pacific Northwest Direct-Seed Association (PNDSA), in contract with ENTERGY, used a SOC sequestration rate of 0.37 Mg C ha^{-1} yr^{-1} (0.55 MT CO_2e ac^{-1} yr^{-1}) for adoption of direct-seeding in N. Idaho and E. Washington. Direct-seeding is defined by the PNDSA as "any method of planting and fertilizing done with no prior tillage to prepare the soil" and includes one and two pass systems. The C sequestration rate used by PNDSA also included diesel fuel savings as compared to conventional tillage.

Table 1. Estimated Carbon Sequestration Potential of US Cropland Soils by Improved Management Practice.

Management	**SOC Sequestration Rate**				**US Total C Sequestration†**		
	----------------------- Mg C ha^{-1} yr^{-1} -----------------------				------------ MMT C yr^{-1} ------------		
Conservation Tillage						24 - 40	17.8 - 35.7
No-Tillage	0.5	0.30 - 0.60		0.30	47		
Mulch Tillage	0.5						
Residue Management						11 - 67	11 - 67
Summer Fallow Elimination	0.10 - 0.30	0.30 - 0.60			3.2	1 - 3	1.4 - 2.7
CRP	0.30 - 0.70	0.60 - 0.90	<0.10 - >0.40		10.5	5 - 11	8.8 - 13.3
Rotation and Winter Cover Crops	0.10 - 0.30				22.8	5 - 15	5.1 - 15.3
Fertilizer Management						6 - 18	
Organic Manures and By-Products						3 - 9	
Reference	Lal et al., 1998	Follett, 2001	Paustian et al., 2001	West and Marland, 2001	Sperow et al., 2003	Lal et al., 1998	Follett, 2001

13.1.2.2 Crop Rotation and Conversion to Permanent Vegetation

Eliminating fallow, replacing continuous monocultures with diversified crop rotations and using cover crops is estimated to sequester 0.1 to 0.6 Mg C ha^{-1} yr^{-1} (0.15 to 0.89 MT CO_2e ac^{-1} yr^{-1}) (Lal et al., 1998; Follett, 2001). Elimination of all summer fallowing in the US could potentially sequester 1 to 3 MMT C yr^{-1} (3.7 to 11 MMT CO_2e yr^{-1}) over approximately 15 years (Lal et al., 1998; Follett, 2001; Sperow et al., 2003). Furthermore, Sperow et al. (2003) estimated that inclusion of a winter cover crop in annual systems could sequester a total of 22.8 MMT C yr^{-1} (83.6 MMT CO_2e yr^{-1}) over approximately 15 years in US cropland soils.

For Northwest cropland, Liebig et al. (2005) reported that rotations with high residue crops and legume green manures could increase SOC content by 0.10 to 0.22 Mg C ha^{-1} yr^{-1} (0.15 to 0.33 MT CO_2e ac^{-1} yr^{-1}). The COMET-VR interface was used by Cook (2007) to estimate C sequestration for agricultural lands in Washington State by crop type on a county by county basis. These estimates are not summarized here as they are based on total annual crop acreage rather than on a crop rotation basis.

Estimates of SOC sequestration rates for conversion of cropland to CRP or grassland have ranged from 0.10 to 0.90 Mg C ha^{-1} yr^{-1} (0.15 to 1.33 MT CO_2e ac^{-1} yr^{-1}) (Lal et al., 1998; Post and Kwon, 2000; Follett, 2001; Paustian et al., 2001). Paustian et al. (2001) reported SOC change estimates of less than 0.10 Mg C ha^{-1} yr^{-1} (0.15 MT CO_2e ac^{-1} yr^{-1}) to greater than 0.40 Mg C ha^{-1} yr^{-1} (0.59 MT CO_2e ac^{-1} yr^{-1}) in a 16-state regional analysis using the Century model which encompassed 87% of grassland and 70% of total CRP acreage. Sperow et al. (2003) estimated that converting all remaining highly erodible land currently cropped to a CRP grass cover could sequester an additional 10.5 MMT C yr^{-1} (38.5 MMT CO_2e yr^{-1}) over about 15 years.

In a regional analysis of the Northwest, Liebig et al., (2005) reported that conversion of cropland or reclaimed mineland to grass increased SOC by 0.94 ± 0.86 Mg C ha^{-1} yr^{-1} (1.39 ± 1.27 MT CO_2e ac^{-1} yr^{-1}) while grazing increased SOC by 0.16 ± 0.12 Mg C ha^{-1} yr^{-1} (0.24 ± 0.18 MT CO_2e ac^{-1} yr^{-1}). In central WA, CRP land was predicted to have a 0.30 Mg C ha^{-1} yr^{-1} increase in the surface 20-cm (Paustian et al., 2001). The Washington State Department of Agriculture (WSDA) estimated a soil C sequestration rate of 0.49 Mg C ha^{-1} yr^{-1} for the states CRP lands (Cook, 2007). This value was chosen as a mid-range of EPA estimates which range from 0.25 to 0.74 Mg C ha^{-1} yr^{-1} (Cook, 2007).

13.1.3 Additional Factors Influencing Soil C Sequestration

The amount and rate of SOC sequestered by agricultural management can be influenced by such site-specific properties as initial SOC levels, soil texture, disturbance (i.e. tillage regime), rotation intensity and erosion processes (Rasmussen et al., 1998; West and Post, 2002; Liebig et al 2005; Purakayastha et al., 2008). Furthermore, sampling protocols such as soil depth and length of time between sampling can greatly affect results and need to be evaluated for shaping science-based marketing, policy and management decisions.

13.1.3.1 Vertical Patterns of SOC Change

Management induced changes in SOC are often greatest near the surface and decrease with soil depth. In comparing NT with CT, West and Post (2002) observed statistically significant SOC increases under NT of 4.8 ± 0.87 Mg C ha^{-1} in the 0- to 7-cm depth, but only 0.73 ± 0.57 Mg C ha^{-1} for the 7- to 15-cm depth increments. No significant SOC differences between NT and CT were reported for 15- to 25- and 25- to 35-cm depth increments (West and Post, 2002). They concluded that approximately 85% of SOC sequestration occurs within the top 7-cm of agricultural soil when converting from CT to NT (West and Post, 2002). Follett (2001) reported change in SOC content that occurred when converting annual cropping to permanent vegetation under CRP that were greatest in surface depths with SOC sequestration rates of 0.57, 0.74, and 0.91 Mg C ha^{-1} yr^{-1} for 0- to 5-, 0- to 10-, and 0- to 20-cm depth increments, respectively. These studies illustrate the importance of sampling depth for evaluating rates of SOC sequestration under different management regimes. Rates of SOC change evaluated from near-surface samples (e.g. 0-10 cm) will likely be greater than the surface 30-cm and the soil profile as a whole.

13.1.3.2 Temporal Patterns of SOC Change

Soil C sequestration rates usually peak within 5 to 10 years (West and Post, 2002) and approach a new steady-state 20 to 50 years following a change in management (Horner et al., 1960; Rasmussen and Collins, 1991; Follett, 2001; Paustian et al., 2001; West and Post, 2002; Lal, 2004;) or until the soil storage capacity is reached (Lal, 2004). Initially increases in root biomass C and labile C pools might be expected, though over time increases in more resistant C pools will occur (Paustian et al., 2001). Consequently, SOC sequestration has the potential to be a short-term mitigation factor in reducing atmospheric CO_2 concentrations (Smith, 2004; Lal, 2001). Furthermore, agricultural C sequestration could potentially provide additional farm revenue through creation of carbon-emission credits that would be sold to green house gas emitters (West and Post, 2002; Willey and Chameides, 2007).

13.2. OBJECTIVES

Our overall goal is to provide science-based information and assessment tools that quantify agricultural impacts on soil C sequestration for dryland farmers within the Pacific Northwest. Our objectives are to: (1) identify current or historic studies under diverse agricultural management and agro-ecological zones where soil C has been quantified that are relevant to dryland cropping systems in the Inland Pacific Northwest; (2) summarize research results with respect to agricultural management impacts on rates of soil carbon change over time and identify strengths and weaknesses of current knowledge bases that assess agricultural management effects on soil profile carbon; and (3) identify future efforts, if any, required to provide realistic, science-based estimates of agricultural management effects on soil C stocks.

13.3. OVERVIEW OF PNW CLIMATE AND AGRICULTURE

Agricultural regions of the Pacific Northwest (PNW) have been classified by the USDA as Land Resource Region B or the Northwest Wheat and Range Region (NWRR) (USDA, 2006). The NWRR is characterized by a Mediterranean type climate with cold wet winters and warm to hot dry summers and is approximately 3.3 to 4 million hectares of non-irrigated cropland in northern Idaho, north central Oregon, and eastern Washington (Papendick, 1996; McCool and Roe, 2005). Forty-four, 29, and 27 percent of the NWRR falls within ID, WA, and OR, respectively, with a small amount occurring in UT (USDA, 2006). A semi-arid climate dominates the western edge of the NWRR and changes to a sub-humid climate at the eastern edge (Papendick, 1996). The average annual precipitation ranges from 150- to 510-mm (6- to 20- inches) and average annual temperature from 40 to 49° F. Pacific Northwest soils are dominated by Mollisol and Aridisol soil orders (USDA, 2006) derived from silt loam textured loess mixed with volcanic ash (Papendick, 1996; Rasmussen et al., 1998).

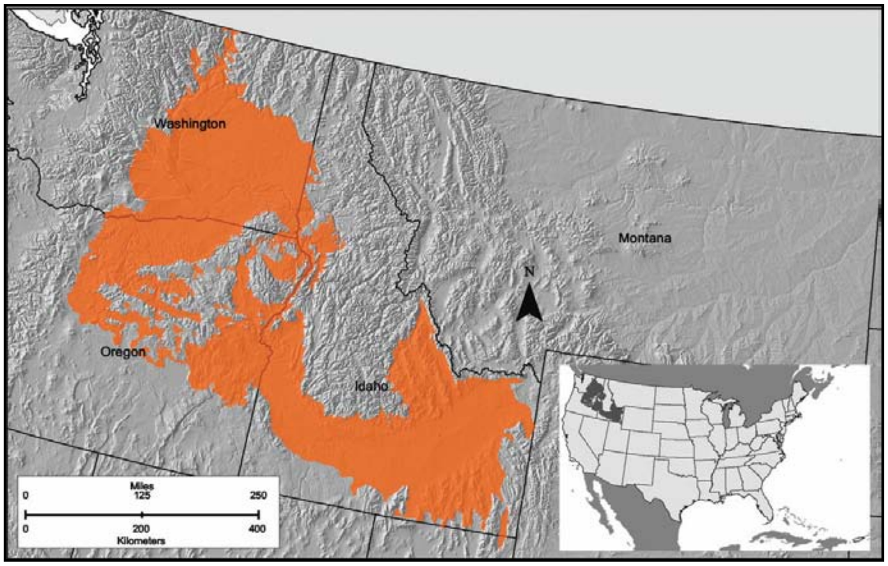

Figure 1. United States Department of Agriculture's Northwest Wheat and Range Region – Land Resource Region B (USDA, 2006).

Grazing and cropland are the major land use though relatively small amounts of forested areas exist in the NWRR (USDA, 2006). Climate is a major factor influencing the distribution of cropping systems within the NWRR (Papendick, 1996; Paustian et al., 1997). Low precipitation areas that receive less than 375-mm of water annually are typically managed using a 2-year winter wheat - summer fallow rotation (Rasmussen et al., 1998; McCool and Roe, 2005). Intermediate precipitation zones are characterized by annual rainfall of 375- to 450-mm (Rasmussen et al. 1998; McCool and Roe, 2005). The intermediate precipitation zones are typically managed using a 2- to 5-year rotation that often includes winter wheat-spring barley or spring wheat - summer fallow (Papendick, 1996). Fallow is discontinued and annual cropping is practiced in the high precipitation areas that receive greater than 450-mm of water, annually (Papendick, 1996; Rasmussen et al., 1998; McCool and Roe, 2005). Resource concerns for cropland areas of the NWRR include erosion by water and wind, maintenance of SOC content, compaction, and soil water conservation (USDA, 2006).

In the western portion of the NWRR, apples are an important crop (USDA, 2006). In the central Columbia Basin of WA and the Snake River Plains of ID, irrigation is used for potato, sugar beet, bean, and forage production (USDA, 2006). Grazing is the major land use in the drier parts of the region with approximately 29 percent of the NWRR under federally owned grazing land (USDA, 2006). Overgrazing and invasion of undesirable plant species present major resource concerns for these lands (USDA, 2006).

13.4. CHARACTERIZING CHANGES IN SOIL ORGANIC CARBON

13.4.1 Agroclimatic Zones of the Dryland Pacific Northwest

Douglas et al. (1990) defined agroclimatic zones for the PNW based on annual precipitation and growing degree-day information from National Weather Service 30-year records as well as soil depth data from published soil surveys. The six agroclimatic zone designations are summarized in Table 2 and graphically represented in Figure 2.

Table 2. Agroclimatic Zone Designations and Descriptions for the Dryland Pacific Northwest (Adapted from Douglas et al., 1990; 1992).

Zone	Description	Mean Annual Precipitation (mm)	Soil Depth (m)	Cumulative Growing Degree Days (Jan 1 to May 31)
1	Annual Crop: Wet-Cold	>400 (16 in)	Not a factor	<700
2	Annual Crop: Wet-Cool	>400 (16 in)	Not a factor	700-1000
3	Fallow-Transition	350-400 (14-16 in)	>1	700-1000
4	Annual Crop: Dry	250-400 (10-16 in)	<1	<1000
5	Grain-Fallow	<350 (14 in)	>1	Not a factor
6	Irrigated	< 250 (10 in)	Not a factor	Not a factor

13.4.2 Agroclimatic Zone Map with Soil C Study Locations

A map of Agroclimatic Zones (ACZ) for the dryland PNW was reproduced and overlain with points representing soil carbon studies identified for this report (Fig. 2). The map aids identification of areas with and without representative soil C studies. However, even areas with soil C data may lack the kind of information necessary for an accurate assessment of soil C stocks. It is important to note that in addition to climate, other factors such as cropping system and soil management, soil texture, soil structure (Lal, 2004), initial soil C content (Follett, 2001) and soil erosion processes may also influence soil C sequestration potential of a given soil.

13.4.3 Major Land Resource Areas of the NWRR

Major Land Resource Areas (MLRA's) are designated based on the interaction of physiography, geology, climate, water, soils, biological resources, and land use (USDA, 2006). The NWRR includes the following Major Land Resource Areas: Columbia Basin (7), Columbia Plateau (8), Palouse and Nez Perce Prairies (9), Central Rocky and Blue Mountain Foothills (10), Snake River Plains (11), Lost River Valleys and Mountains (12), and Eastern Idaho Plateaus (13) (USDA, 2006). Existing carbon trading programs have used MLRA

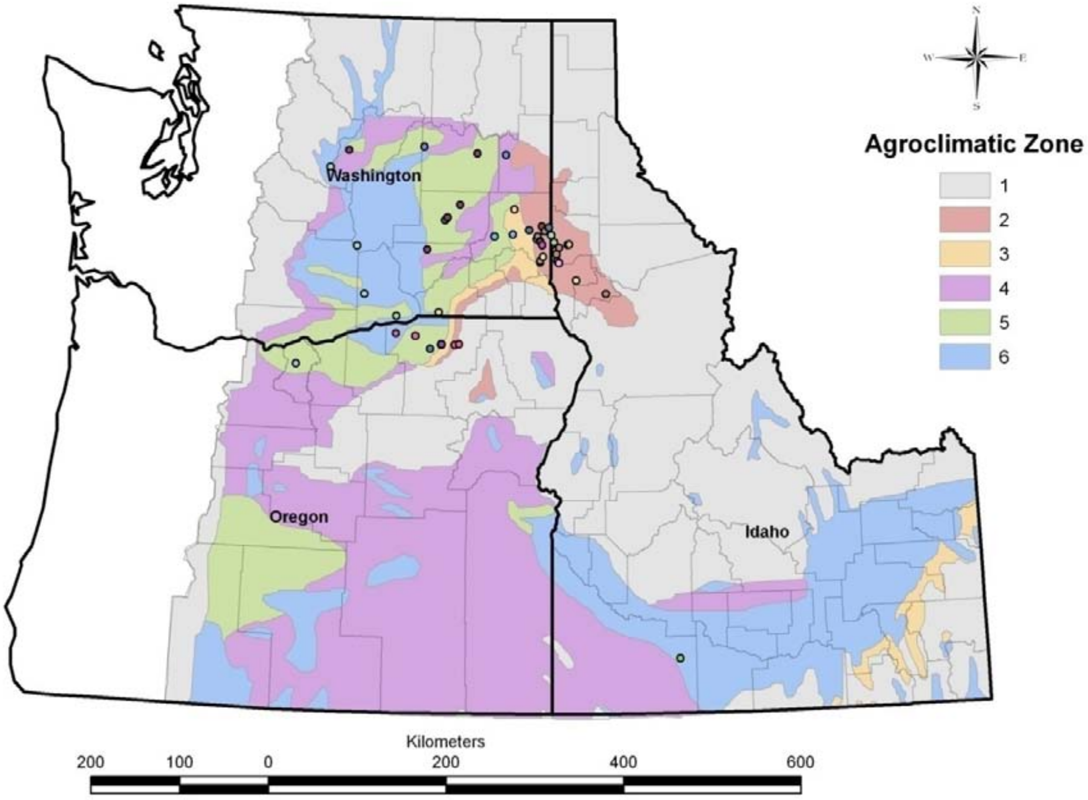

Figure 2. Agroclimatic Zone Designations for the Dryland Pacific Northwest (Adapted from Douglas et al., 1990; 1992) and locations of soil carbon studies identified by the project.

designations most likely due to their accessibility. Some trading programs may be based on regional agro-ecosystem analyses involving similar to more detail than the MLRA approach. It is our intention to consider changes in soil carbon based on agroclimatic zones delineated by Douglas et al. (1990; 1992). The agroclimatic zone delineations are based on the main climatic and edaphic conditions found to impact production of the major crop grown in the PNW (i.e., soft white winter wheat) (Douglas et al., 1990) and will be related to soil C input and decomposition processes. The agroclimatic zones mapped by Douglas et al. (1992) appear to approximately follow the boundaries for some of the MLRA designations (e.g. zone 2 and MLRA 9), but overall there appear to be differences which indicate that the two approaches may not be interchangeable with respect to estimating and predicting changes in SOC (USDA, 2006).

13. 5. METHODOLOGY

13.5.1 Data Compilation

Peer-reviewed and non-peer-reviewed literature (e.g. Agricultural Research Station Bulletins and Solutions To Environmental and Economic Problems Research Reports) addressing the influence of management changes on the amount and rate of SOC change were assembled and used to quantify SOC change under different cropland scenarios. For each site, location, ACZ, duration of management, tillage, rotation, soil C data reported, sampling depth, landscape position, soil texture, soil series, annual temperature and precipitation, and method of SOC analysis were recorded (Appendix 1). If specific information was not provided the average for the region was used based on available data (e.g. soil survey, published literature, and weather databases) or local expertise.

All data sets were converted from their original units to mass per unit volume per year (e.g. Mg C ha-cm^{-1} yr^{-1} or Mg C ha^{-1} yr^{-1}) (Appendix 2). This allowed for comparisons among different studies given that sampling depth and units of SOC content reported varied among the literature reviewed. Sufficient data were available for a more comprehensive evaluation of potential C sequestration for: (1) conversion of native vegetation (perennial) to cropland; (2) NT compared to CT management; and (3) use of a mixed perennial-annual rotation compared to an annual rotation. In addition, data for annual and fallow cropping, crop residue burning, use of green and barnyard manures, and CRP were summarized in the text.

13.5.2 Data Summary

13.5.2.1 Changes in SOC and Initial SOC

In order to evaluate the affects of initial SOC on the rates of SOC change due to management, SOC changes (Mg C ha-cm^{-1} yr^{-1}) were plotted against the initial SOC content (Mg C ha^{-1}). Changes in SOC content relative to initial C content were presented separately for the surface 30- cm and below-30 cm to identify the influence of management on surface and subsurface SOC stocks. Soil organic C stock changes were calculated relative to initial SOC stocks using long-term data when it was available or by subtraction from that of either a comparable native, conventionally-tilled or annually-cropped baseline soil at the same year of measurement when initial values were not provided. Management systems in which there were an insufficient number of studies or depth increments to perform analyses were summarized in the text. The data were also summarized by soil depth in order to: (1) account for the depth-distribution of SOC content change resulting from management systems; and (2) reduce inaccuracies arising from summarization of multiple data sets with varying soil depths.

13.5.2.2 Depth Analysis (Conversion, NT, Mixed Perennial-Annual)

In order to estimate total profile changes in SOC stocks, changes in SOC stocks were evaluated by depth increment to characterize the depth-distribution of SOC change. Exponential relationships provided the best fit for the various data sets (i.e. conversion, NT, mixed perennial-annual) and were calculated using Excel software (Appendices 3, 6, and 8). For this portion of the analysis, data sets in which SOC was sampled in more detailed depth-increments were used. In order to appropriately characterize the distribution of change in SOC content, data in which the surface was sampled at a depth increment greater than 15-cm was not included in this analysis. The relationships of SOC change with soil depth were then used to augment incomplete datasets that did not include sufficient sampling depths in order to then estimate total changes in SOC stocks on a soil profile basis. For example, if an agroclimatic zone 2 study reported the surface 20-cm changes in SOC following conversion of native prairie to annual cropping, the equations obtained for zone 2 in the depth analysis were used to estimate the change in SOC to 125-cm.

13.5.2.3 *Cumulative Probability*

The cumulative probability distribution of the total profile SOC data was determined for each zone and management in order to evaluate the probability of obtaining a change in SOC content less than or equal to a specified probability level. This approach provides the ability to address and account for inherent and management induced variations in SOC content.

13.5.3 Interpretation

13.5.3.1. Native Conversion, Adoption of NT, and Mixed Perennial-Annual Systems

A SAS proc univariate procedure was used to determine if the changes in SOC were normally distributed. From a plot of the expected score versus the observed change we concluded that the data were approximately normally distributed. A normal distribution of the change in SOC content was therefore assumed and the data interpreted using cumulative probabilities and expected normal scores. The expected normal score was calculated using the expected score for the number of observations of each management by zone dataset and plotted against the cumulative probability to obtain a distribution of the change in SOC content. By presenting the data using this methodology, a change in SOC due to management practice can be selected based on the probability of its actual occurrence. For example, one could identify the amount of SOC change that 90% of the data was either equal to or greater than.

13.6. DATASETS

Overall there were 131 location-specific SOC data sets identified from peer-reviewed and non-peer reviewed literature that addressed changes in SOC content and distribution

Table 3. Summary of Collected Literature by Management and Agroclimatic Zone.

Management	**Number of Studies**†	**Management**	**Number of Studies**†
	Total, all zones		**Total,** all zones
Zone	Zone	Zone	Zone
Conversion	**17**	***Annual cropping***	**18**
1	1	2	16
2	8	3	2
3	4	***Fallow Cropping***	**13**
5	3	2	9
6	1	3	4
NT	**26**	***Residue Burning***	**5**
2	12	2	1
3	13	3	3
5	1	5	1
RT	***7***	***No Residue Burning***	**6**
2	3	2	1
3	4	3	3
Mixed Perennial-Annual	**10**	5	2
2	9	***Barnyard Manure***	**9**
3	1	2	6
		3	2
CRP	**4**	5	1
2	2	***Green Manure***	**16**
3	1	2	14
5	1	3	2

† Number of studies by location rather than by publication (e.g. one publication may have data for 3 unique sampling locations and would be recorded as 3 studies).

under agricultural management within the dryland Pacific Northwest (Table 3; Fig. 2). For this report, conversion represents the conversion of perennial vegetation (e.g. native prairie) to annual cropping using tillage. Tillage is identified in this report as including all studies where comparisons of tillage management (e.g. no-till, reduced tillage and conventional tillage) evaluated impacts on soil organic C. There were considerably more data sets identified for ACZ's 2 and 3. In many cases there were no data identified for ACZ's 1, 4, and 6. Research quantifying or comparing SOC content under different crop rotation and alternative management practices (e.g. burning or use of green manures) for dryland agriculture was limited.

The Columbia Basin Agricultural Research Center plots, northeast of Pendleton, OR, are the only existing long-term agricultural plots for the dryland PNW (Rasmussen and Parton, 1994; Rasmussen and Rohde, 1988). Long-term research sites located in Lind, WA, Pullman, WA, Moscow, ID, and Moro, OR were terminated in the 1950's (Horner et al., 1960). These long-term studies, as well as the subsequent studies, are not adequate for a comprehensive evaluation of all major current management impacts on soil C sequestration for each ACZ. However, existing literature does provide a general understanding of management impacts on SOC and will be important in shaping future attempts to quantify SOC stocks and pools, soil C dynamics, and in evaluating management systems and practices that favor retention of soil organic matter.

13.7. RESULTS AND DISCUSSION

13.7.1 Changes in Soil Organic Carbon Content and Distribution from Conversion of Native Vegetation (Perennial) to Annual Cropping

In general, the rate of SOC loss following conversion of native ecosystems to agriculture was greatest in the surface 30-cm compared to the SOC loss at deeper depths (Fig. 3).Some cultivated landscape positions maintained or gained SOC following conversion of native perennial vegetation to cropland (Fig. 3a). This was observed for a lowland landscape position in agroclimatic zone 2 (Rodman, 1988) and for a cultivated soil with a more recent history of NT management following decades of tillage in agroclimatic zone 5 (Douglas et al., 1998). These data are likely a consequence of soil erosion processes where detached SOM is transported from eroded areas and deposited at lower-lying landscape positions.

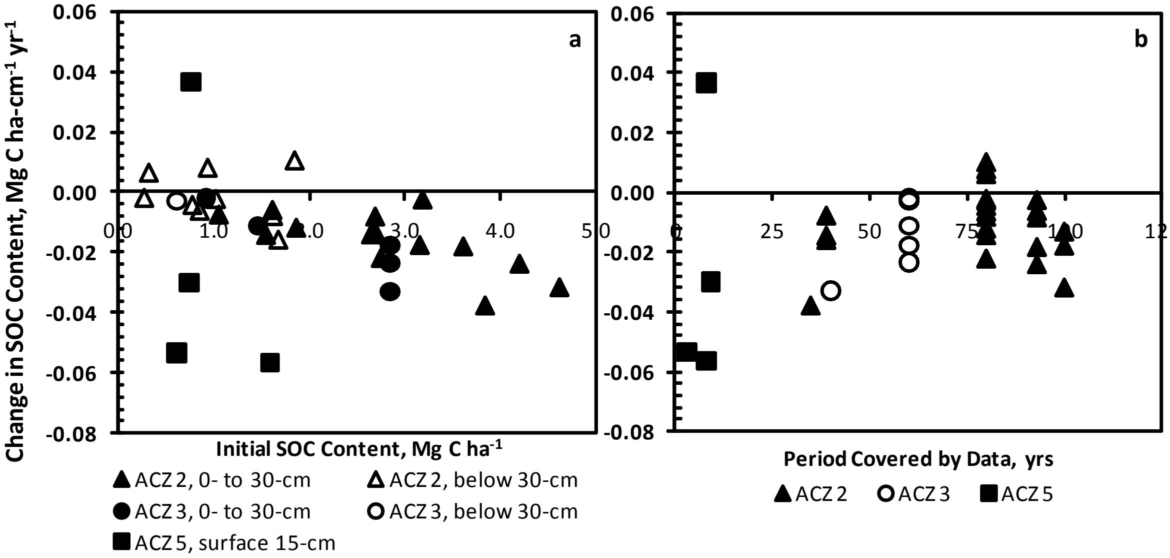

Figure 3. Agroclimatic zone changes in soil organic carbon content versus (a) initial SOC content and (b) period covered by data. Fig. 3b includes all depth increments for the respective agroclimatic zone.

No clear trend was observed between initial SOC content and the annual rate of SOC loss (Fig. 3a). Agroclimatic zones 2 and 3 generally exhibited greater initial SOC content compared to zone 5. This is likely due to differences in biomass production which is expected to be greater in dryland ACZ's with higher (i.e. ACZ's 2 and 3) compared to lower (i.e. ACZ 5) precipitation (Sievers and Holtz, 1923).

13.7.1.1 Total Profile Changes in SOC Following Conversion from Native Ecosystems to Agriculture

Total profile SOC stocks declined by an average of 0.84 (± 0.17), 0.53 (±0.18), and 0.69 (±0.52) Mg ha^{-1} yr^{-1} (1.24, 0.78, and 1.02 MT CO_2 ac^{-1} yr^{-1}, respectively) in soils converted from native vegetation to cropland for ACZ's 2, 3, and 5, respectively (Table 4). These losses represent data from 14 data sets with an average of 7 to 74 years of cropping history. Although sites that have been under cultivation for a longer amount of time may show greater overall SOC loss, relatively more recently cultivated soils will likely have greater initial rates of SOC loss until a new steady-state is approached.

Table 4. Estimated Total Profile Change in SOC Content from Conversion of Native Vegetation (Perennial) to Cropland.

Zone	Number of Studies	Period Covered by Data	Mean Profile Change in SOC Content	
	n§	mean	Mg C ha^{-1} yr^{-1}	††MT CO_2e ac^{-1} yr^{-1}
2	7	74	-0.84 (± 0.17)†	-1.24 (± 0.28)
3	4	55	-0.53 (± 0.18)	-0.78 (± 0.27)
5	3	7	-0.69 (± 0.52)	-1.02 (± 0.77)

†Parenthesis values represent ± 1 standard deviation

††Unit is metric tons (MT) of carbon dioxide equivalents per acre per year, MTCO_2e ac^{-1} yr^{-1}, not an SI unit

§ number of profiles used to calculate mean, standard deviation, and cumulative probability.

13.7.1.2 Cumulative Probability of SOC Changes Following Conversion from Native Ecosystems to Agriculture

Figure 4 shows the change in SOC content following conversion of native vegetation to cropland for the 0th, 25th, 50th, 75th and 100th percentile (i.e., 0, 0.25, 0.50, 0.75, and 1.0 cumulative probability, respectively) for ACZ's 2, 3 and 5. At the 25th, 50th, and 75th percentile in ACZ 2, SOC would be expected to decline by less than or equal to 0.70, 0.82, and 0.92 Mg C ha^{-1} yr^{-1}, respectively. Another way to interpret and use these results is that if these probability plots are representative of the SOC changes, then we would expect 75% of the converted native ecosystems to have lost at least 0.70 Mg C ha^{-1} yr^{-1} (the value for the 25th percentile where 75% of the data are greater than this value). Therefore, the values of SOC change for the lower percentiles in the cumulative probability function represent more certainty that a given

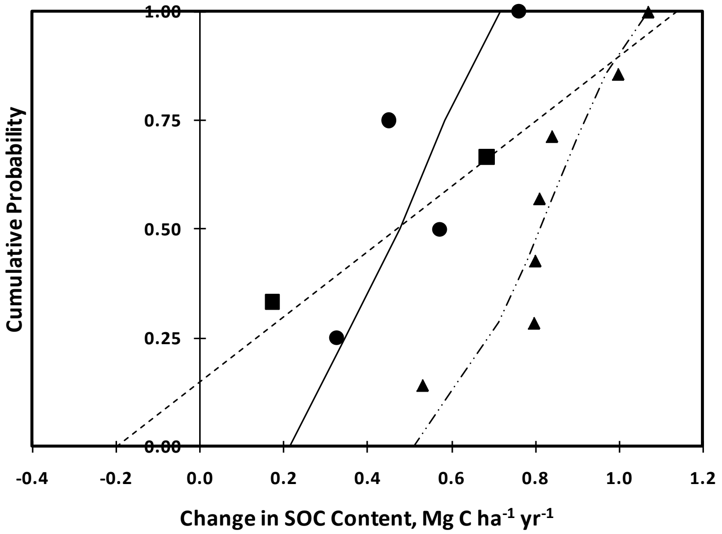

Figure 4. Cumulative probability plots for change in SOC content following conversion of native vegetation to cropland for ACZ 2 (triangle), 3 (circle) and 5 (square). Solid symbols are observed values and lines represent the expected normal score values.

amount of SOC change has occurred. By using these results and methodology, the degree of uncertainty can therefore be incorporated into management and policy scenarios.

In ACZ 3, the SOC content declined by less than or equal to 0.35, 0.48, and 0.58 Mg C ha^{-1} yr^{-1} at the 25th, 50th, and 75th percentiles, respectively. For ACZ 5, an estimated 0.14, 0.47, and 0.80 Mg C ha^{-1} yr^{-1} would be expected 25, 50, and 75 percent, respectively, of the time following conversion of native vegetation to cropland.

The following are the results of conversion of native ecosystems to agriculture for each agroclimatic zone.

13.7.1.3 Agroclimatic Zone 1

Only one comparison of SOC content in a cropped compared to a native soil was identified for ACZ 1 (Douglas et al., 1998). The initial SOC in the surface 20-cm was relatively high (90.2 Mg C ha^{-1}) and declined with depth to 60-cm (18.8 Mg C ha^{-1}) (Fig. 3). Douglas et al. (1998) reported a SOC content decrease of 43.4, 10.7, and 9.0 Mg C ha^{-1} at 0- to 20- cm, 20- to 40- cm, and 40- to 60-cm, respectively (Appendix 1). This data set was not used for further analyses because the length of time under cropland management was not reported and consequently, no SOC changes over time can be estimated.

13.7.1.4 Agroclimatic Zone 2

Annual losses of SOC ranged from as little as 0.006 to as much as 0.038 Mg C ha-cm^{-1} yr^{-1} in the surface 30-cm of studies comparing different cropping scenarios to native, virgin, or otherwise near native conditions (i.e. cemetery sites) in ACZ 2 (Appendix 1). Changes in subsurface SOC ranged from a loss of 0.016 to a gain of 0.010 Mg C ha-cm^{-1} yr^{-1} (Appendix 1). Though the data for the subsurface (below 30-cm) primarily exhibit declining SOC content, Rodman (1988) reported SOC increases of 0.010, 0.008, and 0.006 Mg C ha-cm^{-1} yr^{-1} at 20- to 50-cm, 50- to 100-cm, and 100- to 150-cm, respectively, in a lowland position of a soil cropped for over 80 years (Fig. 3a). These results likely arise from soil erosion redistributing SOC within a given field. The rate of SOC loss was less for the surface 20-cm of the lowland position (0.003 Mg C ha-cm^{-1} yr^{-1}) compared to that of the paired upland position (0.014 Mg C ha-cm^{-1} yr^{-1}). This illustrates the need to consider landscape position in addition to management history when studying changes in SOC content. Quantifying this contribution to the SOC balance would be appropriate for determining the net C sequestration potential across the landscape. However, little is currently known about the fate of soil C that is transported from the field via erosion processes.

There was no clear trend in SOC change with length of time since conversion to cropland (Fig. 3b). However, the studies identified did not capture the initial 40 years following conversion of native vegetation. Sievers and Holtz (1922) reported a 34.5% change in SOC, relative to initial SOC content, within the surface 60-cm after 39 years of cropping near Pullman, WA. After approximately 40 years these soils may have been approaching a new steady state and large detectable SOC changes would only be expected with a management change (e.g. inversion tillage to NT). The large variation for 80 to 100 years is largely due to different rates of SOC change within a soil profile (Fig. 3). Greater rates of SOC change occurred in the surface 10- to 20-cm and the depth analyses showed that 50 % of the change was captured in the surface 30-cm for ACZ 2 (Fig. 3c).

13.7.1.5 Agroclimatic Zone 3

Losses in SOC content ranged from 0.002 to 0.033 Mg C ha-cm^{-1} yr^{-1} in the surface 30-cm and was near zero (0.003 Mg C ha-cm^{-1} yr^{-1}) for the one point below 30-cm (Fig. 3a). The greatest losses were observed in the surface 20-cm and declined dramatically between 20- to 40- and 40- to 60-cm (Appendix 1). As with ACZ 2, there was no clear trend in SOC change with length of time since conversion to cropland but the initial 40 years following sodbusting were not captured by the data (Fig. 3b). Approximately 50% of the change was captured within the surface 15-cm of zone 3 which is half of the depth needed to capture 50% of the change in zone 2 (Fig. 3c). This is most likely related to the biomass production, climatic and management differences between ACZ's 2 and 3.

13.7.1.6 Agroclimatic Zone 5

Changes in SOC content ranged from a loss of 0.057 to a gain of 0.037 Mg C ha-cm^{-1} yr^{-1} within the surface 15-cm of zone 5 (Fig. 3a). These gains and losses occurred in the same soil profile sampled by Schillinger et al. (2007) where SOC content decreased by 0.057 Mg C ha-cm^{-1} yr^{-1} in the surface 5-cm but increased by 0.037 Mg C ha-cm^{-1} yr^{-1} at 5- to 10-cm depth (Appendix 1). The management history of the cropped soil was 8 years of annual NT spring cropping following decades of WW-SF and may explain the distribution of SOC changes in the near surface profile studied. After 8 years of NT, SOC in the surface 5-cm remained below native SOC values and decades of residue burial were still elevating SOC contents at 5- to 10-cm compared to native values. Because of the more recent change in management practice and fewer studies for ACZ 5, the mean rates of change and standard deviation was relatively high especially considering the low initial SOC content and lower rainfall compared to the ACZ's 2 and 3 (Fig. 3b). The high standard deviation indicates that the cumulative probability function would be useful to assess more certain expectations for SOC change than the mean for ACZ 5.

13.7.2 Changes in Soil Organic Carbon Content and Distribution from Adoption of No-Tillage

Adoption of NT included increases, decreases and maintenance of SOC compared to conventional tillage (Fig. 5). However, adoption of NT generally resulted in SOC increases (Appendix 1). Within any ACZ there was no clear trend between SOC content increase and initial SOC content. Soil organic C data, limited to ACZ's 2, 3, and 5, focused on the surface 10- to 20-cm, largely ignoring the potential impact of management on whole profile SOC. However, no differences in SOC were detected below 25-cm for comparisons of NT *versus* CT (Fig. 5c). No data were identified for ACZ's 1, 4, and 6.

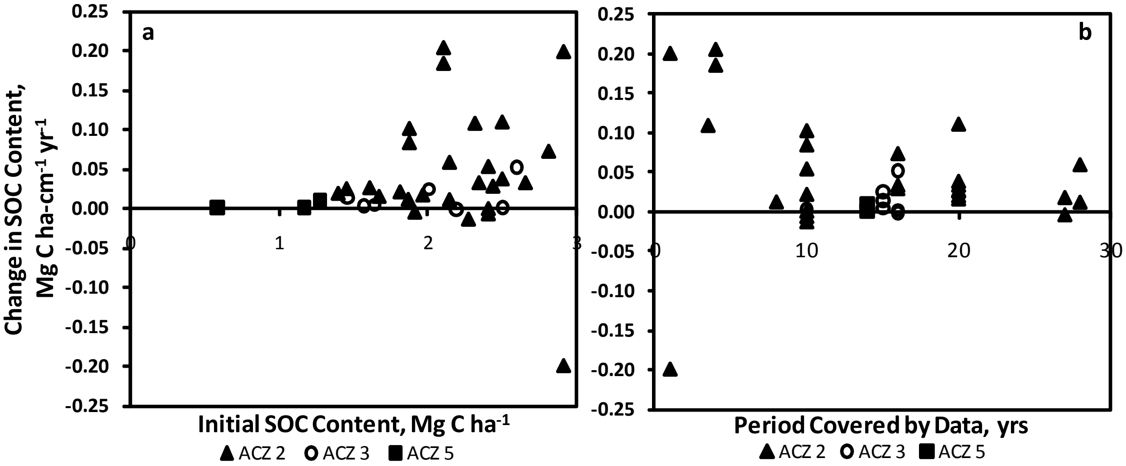

Figure 5. Change in soil organic carbon content with adoption of no-tillage (increase over conventional tillage) versus a) initial SOC content and b) period covered by data.

13.7.2.1 Total Profile Changes in SOC Following Conversion from Conventional Tillage (CT) to No-Tillage (NT)

In ACZ 2, SOC stocks increased an average of 0.71 (± 0.63) Mg C ha^{-1} yr^{-1} (1.05 (± 0.94) MTCO$_2$e ac^{-1} yr^{-1}) in the surface 20-cm over an average of 14 years under NT management (Table 5). After an average of 10 years under NT, soil profile C stocks increased by 0.21 (± 0.10) Mg C ha^{-1} yr^{-1} (0.32 (± 0.15) MTCO$_2$ ac^{-1} yr^{-1}) in the surface 20-cm of ACZ 3 (Table 5). About 58% and 91% of the change in SOC content occurred in the surface 5-cm of ACZ 2 and 3 soils, respectively. The 0.21 to 0.71 Mg C ha^{-1} yr^{-1} sequestration estimate for agroclimatic zones 2 and 3, respectively, are at the extreme ends of the global range (0.3 to 0.8 Mg C ha^{-1} yr^{-1}) reported by Smith (2004) for improved management practices. The ACZ 2 rate of change (0.71 Mg C ha^{-1} yr^{-1}) exceeds the upper limit of the 0.3 to 0.6 Mg C ha^{-1} yr^{-1} used by Follett (2001) for NT adoption on CT cropland. The ACZ 2 sequestration rate is also higher than surface 30-cm rate increase (0.57 ± 0.14 Mg ha^{-1} yr^{-1}) reported by West and Post (2002) and the 0.5 Mg C ha^{-1} yr^{-1} estimate for the surface 20-cm reporter by Lal et al. (1998) in a global and national analysis, respectively, of NT compared to CT. Furthermore, the ACZ 2 value is much higher than the 0.23 Mg C ha^{-1} yr^{-1} reported by Paustian et al. (1997) and the 0.3 Mg C ha^{-1} yr^{-1} estimated by West and Marland (2001) comparing NT to CT sites nationally. However, the 0.21 Mg C ha^{-1} yr^{-1} sequestration rate estimated for conversion from CT to NT in ACZ 3 is similar to these lower rates reported (Liebig et al., 2005; Smith, 2004; Follett, 2001; West and Post, 2002; Lal et al., 1998; Paustian et al., 1997; West and Marland, 2001). Factors that could contribute to the relatively high rates of SOC change reported as well as the large range and standard deviation include soil sampling biases and the influence of soil erosion. Sampling biases can arise if soil sampling occurs soon after a recent addition of biomass from residues, for example after harvest. Here, residues and root sources of C can become mixed with the sample and difficult to remove prior to total C analysis. The significance of this sampling issue increases with greater crop yields and associated residue and root inputs. Soil erosion redistributes SOC within the landscape as a function of detachment, transport and deposition processes. The high rates of soil erosion that have been historically typical of farming practices in much of the dryland region of the PNW have been a major determinant of how much SOC occurs at a given location. For example, assuming a SOC of 1 to 2% and an annual soil erosion rate of 25 Mg ha^{-1} means that 0.25 to 0.5 Mg C ha^{-1} yr^{-1} could be either lost from eroded landscape positions or gained in landscape positions where deposition occurred. Furthermore, it is unknown as to whether or not eroded SOC contributes more or less to atmospheric CO_2 than SOC that remains in place. Consequently, soil erosion impacts on greenhouse gas (GHG) production are largely unknown. However, the change in SOC that is measured through soil sampling at a given location includes contributions of C inputs and losses from both soil erosion and biological processes. At this time, only the biological processes are directly linked to GHG production, consequently, field measurements need to be carefully and conservatively evaluated with respect to GHG production. Process-oriented modeling can aid this situation by only simulating SOC changes due to biological processes. With respect to the data presented here, rather than the average value of SOC change, more conservative values along the cumulative probability function should be used for assessing expectations for SOC change relevant to GHG production.

Table 5. Average Total Profile Change in Soil Organic Carbon Stocks with Adoption of No-Tillage Compared to Tillage (full width inversion tillage) Management.

Zone	Number of Studies	Period Covered by Data	Profile Change in SOC Content	
	n§	mean yrs	Mg C ha^{-1} yr^{-1}	$MTCO_2e$ ac^{-1} yr^{-1}
2	11	14	0.71 (± 0.63)†	1.05 (± 0.94)
3	5	10	0.21 (± 0.10)	0.32 (± 0.15)

†Parenthesis values represent ± 1 standard deviation

§ number of profiles used to calculate mean, standard deviation, and cumulative probability.

13.7.2.2 Cumulative Probability of SOC Changes Following Conversion from Conventional Tillage (CT) to No-tillage (NT)

Fig. 6 shows the change in SOC content following adoption of NT for the 0th, 25th, 50th, 75th and 100th percentile (i.e., 0, 0.25, 0.50, 0.75, and 1.0 cumulative probability, respectively) for ACZ's 2 and 3. In ACZ 2, SOC increases less than or equal to 0.21, 0.64, and 1.04 Mg C ha^{-1} yr^{-1} were observed at the 25th, 50th and 75th percentiles, respectively. Consequently, one would expect that at least 75% of the situations where CT was converted to NT that SOC change would be 0.21 Mg C ha^{-1} yr^{-1} (0.31 $MTCO_2$ ac^{-1} yr^{-1}). This value is similar to the 0.37 Mg C ha^{-1} yr^{-1} used by the Pacific Northwest Direct Seed Association. In ACZ 3, increases of 0.12, 0.19, and 0.25 Mg C ha^{-1} yr^{-1} for the 25, 50, and 75th percentiles, respectively, were observed (Fig. 6). Using the 25th percentile for both ACZ 2 and 3 would provide C sequestration rates that are more in line with those from the literature and provides a conservative value, 75% of the data is at least at that level or above, for SOC sequestration possible in dryland systems of the PNW.

The following are the results of the change in SOC following the conversion of CT to NT for each agroclimatic zone that had reported data.

13.7.2.3 Agroclimatic Zone 2

In ACZ 2, SOC increased by as much as 0.205 Mg C ha-cm^{-1} yr^{-1} and decreased by as much as 0.200 Mg C ha-cm^{-1} yr^{-1} (Appendix 1). The 0.205 Mg C ha-cm^{-1} yr^{-1} gain in SOC was observed in the surface 5-cm after 4 years under NT (Purakayastha et al., 2008). The 0.200 Mg C ha-cm^{-1} yr^{-1} loss occurred in the surface 5-cm of a soil where NT had been in place for one year following 3 years of CT and 10 years of NT prior to the CT treatment (Purakayastha et al., 2008). In a few instances NT was reported to have less SOC than the CT counterpart (Fuentes et al., 2004; Bezdicek et al. 1998; Granatstein et al., 1987). Fuentes et al. (2004) noted a 0.017 Mg ha-cm^{-1} yr^{-1} SOC increase at 0- to 5-cm but a 0.004 Mg ha-cm^{-1} yr^{-1} decrease at 5- to 10-cm after 27 years under NT (Appendix 1). This distribution of SOC changes may be explained by residue burial at the plow depth under CT that is absent in a NT system. The change in SOC content appears to decrease with length of time under NT management and may take more than 30 years to reach a new SOC steady-state (Fig. 5b). The change in SOC was greatest for the surface 5-cm and declined to zero near 20-cm depth (Appendix 5).

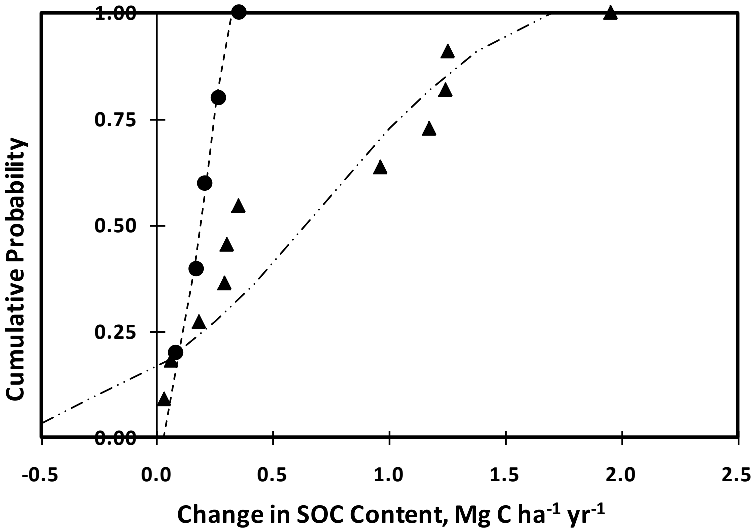

Figure 6. Cumulative probability plots for change in SOC content following adoption of NT for ACZ 2 (triangle) and 3 (circle). Solid symbols are observed values and lines represent the expected normal score values.

13.7.2.4 Agroclimatic Zone 3

Increases in SOC content following conversion to NT in ACZ 3 ranged from a gain of 0.053 Mg ha-cm^{-1} yr^{-1} to a loss of -0.001 Mg ha-cm^{-1} yr^{-1}. The gain and small loss in SOC content was reported by Bezdicek et al., (1998) at 0- to 5- and 10- to 25-cm, respectively, following 16 years of NT compared to CT management. Changes in SOC content from adoption of NT were smaller for ACZ 3 and declined to zero at a shallower depth compared to ACZ 2 (Appendix 5).

13.7.2.5 Agroclimatic Zone 5

Only one study, by Bezdicek et al. (1998), was identified in ACZ 5 that reported SOC changes under NT compared to CT management (Fig. 5a). Increases in SOC content from adoption of NT ranged from 0.011 Mg ha-cm^{-1} yr^{-1} in the surface 5-cm and declined to 0.002 and 0.001 Mg ha-cm^{-1} yr^{-1} at 5- to 10- and 10- to 25-cm, respectively (Appendix 1). The total profile changes in SOC stocks were 0.07 Mg C ha^{-1} yr^{-1} (0.11 MTCO$_2$ ac^{-1} yr^{-1}). The initial SOC content and rate of change with adoption of NT were lower for ACZ 5 compared to ACZ's 2 and 3. There was no appreciable gain in SOC below 5-cm following 14 years of NT in this zone (Appendix 5).

13.7.3 Changes in Soil Organic Carbon Content and Distribution from Alternative Management Practices

13.7.3.1 Mixed Perennial-Annual Crop Rotation

The inclusion of a perennial crop into an otherwise annual crop rotation (mixed perennial-annual rotation) resulted in gains, losses, and maintenance of SOC within the surface 30-cm of soils in ACZ's 2 and 3 (Fig. 7a). Overall, the rate of SOC content change was greatest for the surface 30-cm. The influence of a mixed perennial-annual system was generally

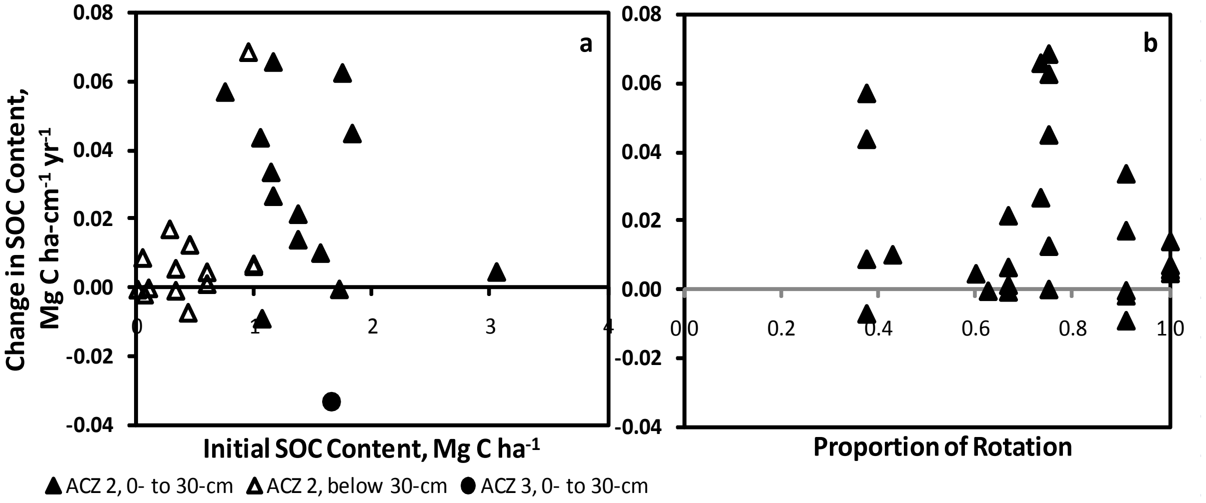

Figure 7. Influence of mixed perennial-annual crop rotations on soil organic carbon content and distribution in ACZ 2 versus a) initial SOC content and b) proportion of rotation under perennial crop.

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positive for ACZ 2. Soil organic C increases of up to 0.066 Mg C ha-cm^{-1} yr^{-1} and losses as high as 0.009 Mg C ha-cm^{-1} yr^{-1} were observed in ACZ 2 (Appendix 1). There was no clear trend between the change in SOC content and length of time (data not shown) or proportion of the mixed perennial-annual rotation in a perennial crop (Fig. 7b). In ACZ 3, a SOC content decrease of 0.03 Mg C ha-cm^{-1} yr^{-1} was reported by Horner et al. (1960) in a 6 year rotation that included 3 years of alfalfa.

13.7.3.2 Total Profile Analysis and Cumulative Probability of SOC Changes of Mixed Perennial-Annual Crop Rotations

Compared to annual cropping systems, mixed perennial-annual systems increased mean SOC stocks in the soil profile by 1.31 (± 0.91) Mg C ha^{-1} yr^{-1} (1.94 (± 1.35) MT CO_2 ac^{-1} yr^{-1}) (Table 6). The value obtained in this analysis is higher than the 0.33 Mg C ha^{-1} yr^{-1} global estimate for converting agricultural land back to grassland vegetation reported by Post and Kwon (2000) and also higher than the 0.94 ± 0.86 Mg C ha^{-1} yr^{-1} regional rate reported by Liebig et al. (2005) for conversion of cropland or reclaimed mining land to grass.

Table 6. Total Change in Soil Organic Carbon Stocks under Mixed Perennial-Annual Compared to Annual Crop Rotations for Agroclimatic Zone 2.

Zone	Number of Studies	Period Covered by Data	Profile Change in SOC Content	
	n	mean	Mg C ha^{-1} yr^{-1}	$MTCO_2e$ ac^{-1} yr^{-1}
2	9	12	1.31 (± 0.91)	1.94 (± 1.35)

Figure 8 shows the SOC content increases observed at the 0th, 25th, 50th, 75th, and 100th percentiles. From the cumulative probability, gains of up to 0.55, 1.18, and 1.76 Mg C ha^{-1} yr^{-1} at the 25th, 50th and 75th percentiles, respectively might be expected. The high standard deviation indicates that the cumulative probability function would provide more certain expectations for SOC change than the mean for this management practice in ACZ 2. Using the 25th percentile would provide a C sequestration value close to that reported by Leibig et al. (2005) for conversion of cropland to grass but still higher than the values reported by Post and Kwon (2000).

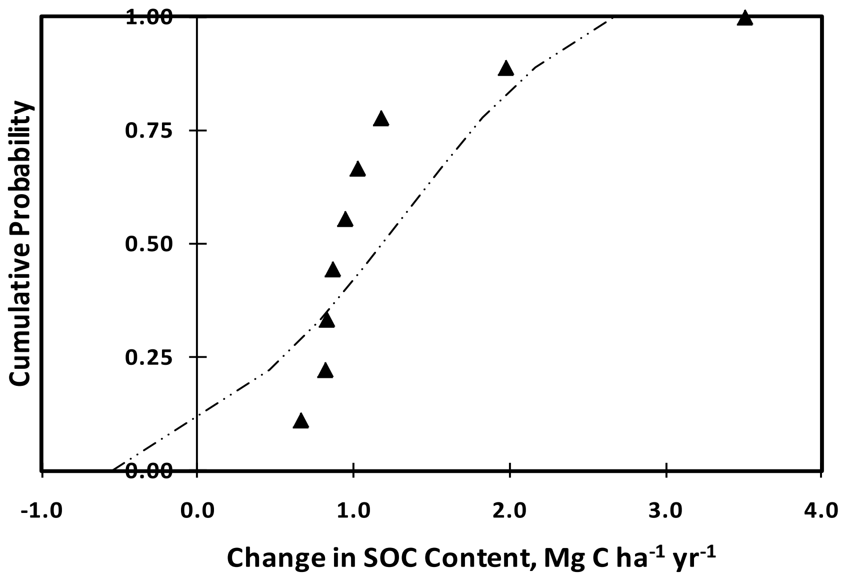

Figure 8. Cumulative probability plots for change in SOC content under mixed perennial-annual compared to annual rotations in ACZ 2. Solid symbols are observed values and lines represent the expected normal score values.

13.7.3.3 Soil Organic Carbon Changes under Annual and Fallow Cropping

Overall, SOC decreased under both annual and fallow management (Fig. 9a). Annual cropping with the use of fertilizers reduced SOC by 0.001 to 0.017 Mg C ha-cm^{-1} yr^{-1} while annual cropping without fertilizers reduced SOC by 0.010 to 0.018 Mg C ha-cm^{-1} yr^{-1} in ACZ 2. In ACZ 3, SOC losses ranged from 0.001 to 0.15 Mg C ha-cm^{-1} yr^{-1}under annual cropping. Data on the influence of fallow practices on SOC were confined to the surface 15- to 30-cm of ACZ 2 and 3 (Appendix 1). In ACZ 2, the rate of SOC decline ranged from approximately 0 to 0.02 Mg C ha-cm^{-1} yr^{-1} in the surface 30-cm after 10 to 31 years of fallow cropping

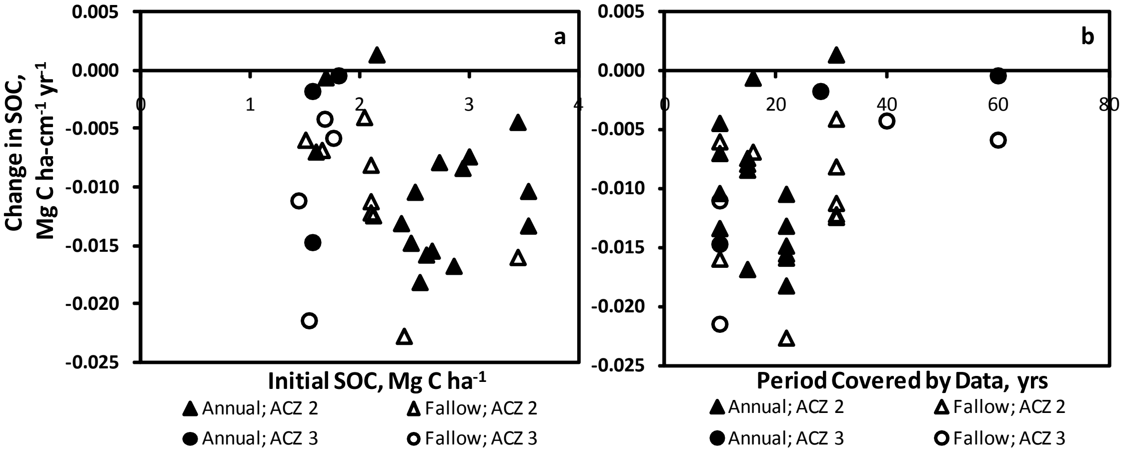

Figure 9. Changes in SOC under annual and fallow cropping versus a) initial SOC content and b) period covered by data.

(Horner et al., 1960). Fallow cropping in the long-term Pendleton, OR plots (ACZ 3) resulted in SOC declines of 0.006 and 0.004 Mg C ha-cm^{-1} yr^{-1} in the surface 20-cm after an average of 60 and 40 years of winter wheat (WW) -summer fallow (SF) cropping, respectively (Rasmussen and Albrecht, 1998). Horner et al. (1960) observed higher rates of SOC declines in the surface 30-cm at Pendleton, OR after 10 years of fallow cropping (0.022 and 0.011 Mg C ha-cm^{-1} yr^{-1} under WW-SF and WW-WW- SF, respectively) compared to Rasmussen and Albrecht (1998). A portion of this discrepancy may be due to the different lengths of time under fallow management with greater rates of SOC change occurring during the initial 10 years compared to those after 40 and 60 years of fallow cropping.

13.7.3.4 Conservation Reserve Program

The Conservation Reserve Program (CRP) is a voluntary U.S. Farm Bill program administered by the Farm Service Agency of the United States Department of Agriculture. The purpose of the program is to encourage farmers to convert highly erodible cropland or other environmentally sensitive acreage to conservation vegetation, such as introduced or native grasses, trees, filter strips, or riparian buffers. In return, farmers receive an annual rental payment for the term of the contract. Most contracts are originally signed for 10 years though extensions may be granted.

No information for agroclimatic zones 1, 4 and 6 were identified from the literature. Purakayastha et al. (2008) noted a SOC gain of 0.07 and 0.005 Mg C ha-cm^{-1} yr^{-1} at 0- to 5-cm and 5- to 10-cm, respectively, after 11 years in the CRP (Fig. 10). In a study of 20 WA soils, an average 0.024 Mg C ha-cm^{-1} yr^{-1} gain in SOC was reported after 4.5 to 5.5 years in the CRP (Karlen et al., 1999). In a 7.5-cm profile this would result in a C sequestration potential of approximately 0.18 Mg C ha^{-1} yr^{-1} (Appendix 1). This value is similar to the 0.20 Mg C ha^{-1} yr^{-1} value used by Cook (2007) but much less than the 0.94 ±0.86 Mg C ha^{-1} yr^{-1} estimated by Liebig et al. (2005) for conversion of cropland to grass. Furthermore, Sanchez de-Leon (2007) observed that annual changes in SOC under CRP remained 0.11, 0.18, and 0.15 Mg C ha^{-1} yr^{-1} below those of native Palouse prairie for the 0- to 10-, 10- to 20-, and 20- to 30-cm depth increments, respectively, after approximately 23 years in CRP conservation cover (Appendix 1).

13.7.3.5 Crop Residue Burning

Burning generally accelerated SOC losses beyond that from cropland management practices that did not use burning for residue management (Fig. 10). Burning resulted in a loss of 0.03 Mg C ha-cm^{-1} yr^{-1} within the surface 15-cm for a soil in ACZ 2 (Horner et al., 1960). However, SOC content also declined under cropland management in which residue was not burned but the rate of SOC loss was reduced by approximately 0.01 Mg C ha-cm^{-1} yr^{-1} (Appendix 1) (Horner et al., 1960).

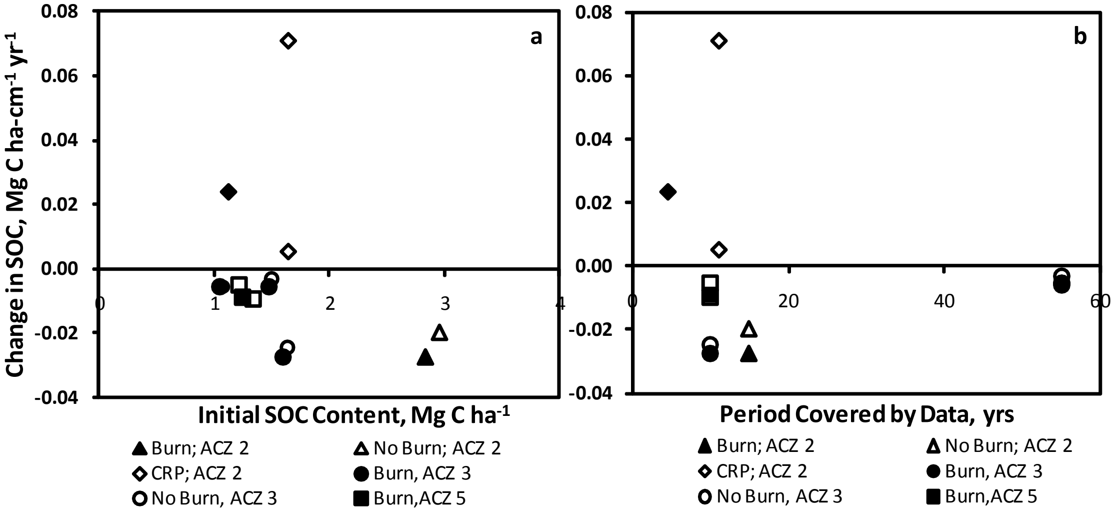

Figure 10. Changes in SOC under CRP and crop residue burning versus a) initial SOC content and b) period covered by data.

For ACZ 3, Rasmussen and Parton (1994) reported reduced SOC losses in the surface 30-cm of approximately half from not burning crop residue compared to crop residue burning over 55 years (Fig. 10). Horner et al. (1960) showed similar SOC content losses for both burned and non-burned treatments in ACZ 3 after 10 years of residue burning. The difference between the rate of SOC decline reported by Horner et al. (1960) and Rasmussen and Parton (1994) is most likely due to the different lengths of time under burning management and depth of soil sample (30- versus 20-cm for Horner et al. (1960) and Rasmussen and Parton (1994), respectively). From the ACZ 5 data it appears that losses in SOC content were similar for residue burning (0.009 Mg C ha-cm^{-1} yr^{-1}) and plowing with no burning (0.010 Mg C ha-cm^{-1} yr^{-1}) in the surface 30-cm.

13.7.3.6 Barnyard and Green Manures

13.7.3.6.1 Agroclimatic Zone 2

The surface 30-cm exhibited a range of near maintenance, losses, and gains in SOC resulting from application of barnyard manures (Fig. 11). Soil organic C changes following addition of barnyard manure ranged from slight declines (-0.005 to -0.001 Mg C ha-cm^{-1} yr^{-1}) to a 0.017 Mg C ha-cm^{-1} yr^{-1} increase within the surface 30-cm (Appendix 1). Addition of barnyard manure to soils under continuous wheat exhibited increases in SOC content while rotations adding barnyard manure but fallow cropping continued to deplete or maintain SOC stocks (Horner et al., 1960). Rotations with green manures, as compared to rotations that did not include a green manure crop, generally showed increases in SOC content for ACZ 2 (Fig. 11). Changes in SOC under green manure management ranged from a loss of 0.04 to a gain of 0.04 Mg C ha-cm^{-1} yr^{-1} which occurred in the same soil profile (0- to 10- and 24- to 55-cm, respectively) (Appendix 1). However, the rotation using the green manures included a fallow component and was compared to a system with no green manure crop and no fallow phase (Huggins et al., unpublished). Overall, barnyard and green manures show some potential for increasing SOC content.

13.7.3.6.2 Agroclimatic Zone 3

Rasmussen and Parton (1994) observed continued SOC declines in the surface 30-cm following 55 years of barnyard manure and pea vine residue incorporation, respectively, in a winter wheat- summer fallow system (Fig. 11). There was also little change in SOC content at 30- to 60-cm depth (Rasmussen and Parton, 1994). Similarly, use of green manures did not reverse the decline in SOC for a winter wheat- summer fallow system and losses ranged from 0.003 to 0.005 Mg C ha-cm^{-1} yr^{-1} at 0- to 30- and 30- to 60-cm, respectively (Rasmussen and Parton, 1994). The SOC declines were greater over the 10-year study by Horner et al. (1960) compared to the Rasmussen and Parton (1994) 55-year study.

13.7.3.7 Reduced Tillage

In ACZ 2 and 3, one and four data sets addressing changes in SOC content with adoption of reduced tillage were identified, respectively (Appendix 1). In ACZ 2, use of RT resulted in a 0.045 Mg C ha^{-1} yr^{-1} (0.003 Mg C ha-cm^{-1} yr^{-1} * 15-cm) increase in SOC for the surface 15-cm compared to CT. In ACZ 3, RT exhibited a relatively large increase in the surface 7.5-cm that declined to near zero between 7.5- to 22.5-cm. However, the change in SOC compared to CT increased at 22.5 to 45-cm depth and may indicate that RT is more efficient at increasing SOC stocks in the subsurface compared to NT.

13.7.4 Conclusions

13.7.4.1 Native Conversion, No-Tillage and Mixed Perennial-Annual

These results and methodology provide a reasonable estimate of SOC change for native conversion, NT, or perennial-annual rotations in zones 2, 3, or 5 but data were limited for zones 1 and 4 as well as for other management practices across all zones. Expressing profile data on cumulative probability basis provided a method for selecting the degree of certainty in obtaining a particular SOC change. Using the 25th percentile of the cumulative probability function provides a conservative estimate of SOC change as 75% of soils would be expected to be greater than this value.

Table 7. Summary of profile changes in SOC calculated from the mean and cumulative probability function for native conversion, adoption of NT, and use of a mixed perennial-annual rotation.

Management	**Number of Studies**	**Period Covered by Data**	**Mean and Cumulative Probability Function Estimates of Profile Change in SOC**							
			Mean	***Cumulative Probability†***			***Mean***	***Cumulative Probability***		
	n	Mean	(±1 std dev)	25th	50th	75th	(±1 std dev)	25th	50th	75th
			--------------- Mg C ha^{-1} yr^{-1} -------------				------------- MTCO$_2$e ac^{-1} yr^{-1} -------------			
Native Conversion										
2	7	74	-0.84 (± 0.17)	-0.70	-0.82	-0.92	-1.24 (± 0.28)	-1.04	-1.22	-1.36
3	4	55	-0.53 (± 0.18)	-0.35	-0.48	-0.58	-0.78 (± 0.27)	-0.51	-0.71	-0.86
5	3	7	-0.69 (± 0.52)	-0.14	-0.47	-0.80	-1.02 (± 0.77)	-0.21	-0.70	-1.19
No-Tillage										
2	12	14	0.71 (± 0.63)	0.21	0.64	1.04	1.05 (± 0.94)	0.31	0.95	1.54
3	5	10	0.21 (± 0.10)	0.12	0.19	0.25	0.32 (± 0.15)	0.17	0.28	0.36
Mixed Perennial-Annual										
2	9	12	1.31 (± 0.91)	0.55	1.18	1.76	1.94 (± 1.35)	0.82	1.75	2.61

† 25th, 50th, and 75th percentiles of the cumulative probability function.

Conversion of native ecosystems to cropland decreased mean profile SOC stocks by 0.84, 0.53, and 0.69 Mg C ha^{-1} yr^{-1}. On a cumulative probability bases, 75% of converted native ecosystems have lost at least 0.70, 0.35, and 0.14 Mg C ha^{-1} yr^{-1} in zones 2, 3, and 5, respectively (based on the 25th percentile). Profile SOC stocks increased, on average, by 0.71 and 0.21 Mg C ha^{-1} yr^{-1} in zone 2 and 3 under NT compared to CT management, respectively. At the 25th percentile we would expect 75% of zone 2 and 3 would gain at least 0.31 and 0.17 Mg C ha^{-1} yr^{-1}, respectively, under NT compared to CT management. Compared to annual cropping systems, mixed perennial-annual systems increased mean profile SOC stocks by 1.31 Mg C ha^{-1} yr^{-1} and we would expect zone 2 soils to gain at least 0.55 Mg C ha^{-1} yr^{-1} for 75% of the locations under this management.

There was conflicting data with regard to SOC changes with depth under NT compared to CT and additional profile research is needed to ascertain SOC differences at the plow depth. From this analysis we might predict that decreases in SOC under NT compared to CT have more potential to occur in ACZ 2 but less chance in ACZ 3 or 5. Granatstein et al. (1987) reported declines in SOC under NT compared to CT soils at 10- to 15-cm and 20- to 25-cm in ACZ 2. However, Bezdicek et al. (1998) found higher SOC in NT compared to CT soils at 10- to 25-cm for 3 sites in ACZ 2. The use of NT in ACZ 3 and 5 increased SOC stocks at all depth increments reported.

Because of the scatter in the data, the length of time in a perennial crop needed to optimize SOC gains under a mixed perennial-annual systems compared to an annual rotation could not be evaluated (Fig. 7).

13.7.4.2 Additional Management Practice Impacts on Surface Changes in SOC

These data generally contain SOC changes for the surface 15-cm to 30-cm with sampling increments of 15-cm and the distribution of change for the soil profile could not be characterized or the degree of certainty addressed using cumulative probabilities. Overall, annual cropping, fallow cropping and burning tended to decrease SOC while use of green manures, application of barnyard manure, and CRP enrollment increased SOC stocks. Nitrogen fertilization appeared to reduce SOC losses under both annual and fallow cropping.

Reduced tillage may have the potential to increase SOC though the rates reported are generally much less than those observed under NT as compared to CT. These data indicate that more research is needed to assess the impact of RT on C sequestration, particularly near the plow depth.

13.8. STRENGTHS AND WEAKNESSES OF EXISTING DATA

13.8.1 Strengths

These data include many of the common current cropping system practices utilized in dryland agricultural production of the PNW. Furthermore, it also includes some historical cropping system components that might be incorporated in current agricultural systems if they show promise in improving the environmental (i.e. C sequestration and nutrient cycling) and economic performance (i.e. yield increase or stability) of PNW dryland agriculture.

13.8.2 Weaknesses

13.8.2.1 Lack of Soil Bulk Density Data

Soil bulk density, oven dry soil mass per unit volume (i.e. g soil cm^{-3} soil), is necessary to determine total SOC stocks. As noted in Table 14.1, several studies did not report bulk density values (Sievers and Holtz, 1926; El-Haris et al., 1983; Granatstein et al., 1987; Rodman, 1988; Douglas et al., 1998; Gewin et al., 1999; Bezdicek et al., 1998; Fuentes et al., 2004). Therefore, bulk density values were assumed from the best available data in order to convert the SOC concentration (e.g. g C per mg soil) to a SOC content basis (Mg C per hectare or acre). These assumptions can lead to over or under estimation of SOC content and perhaps cause greater scatter in the data if the actual bulk density differs from the assumed value.

Table 8. Summary of the range in SOC changes for management practices in which a profile or cumulative probability function analysis could not be performed.

Management	Number of Studies	Period Covered by Data	Range in SOC Change†
Agroclimatic Zone	n	Mean yrs	Mg C ha-cm^{-1} yr^{-1}
Annual			
2, with fertilizer	11	15	0.001 to -0.017
2, without fertilizer	5	22	-0.010 to -0.018
3, with fertilizer	2	33	-0.001 to -0.015
Fallow			
2, with fertilizer	7	23	-0.004 to -0.016
2, without fertilizer	2	27	-0.011 to -0.023
3, with fertilizer	4	30	-0.004 to -0.022
Residue Burning			
2	1	15	-0.027
3	2	40	-0.006 to -0.027
5	1	10	-0.009
No Residue Burning			
2	1	15	-0.020
3	2	40	-0.003 to -0.025
5	2	10	-0.005 to -0.010
CRP			
2	1	11	0.005 to 0.071
3	1	60	0.008
5	1	4.5	0.024
Green Manure			
2	14	15	-0.039 to 0.072
3	2	40	-0.003 to -0.005
Barnyard Manure			
2	6	25	-0.001 to 0.017
3	2	40	-0.006 to 0.001
5	1	10	-0.001
RT			
2	1	8	0.003
3	4	42	-0.004 to 0.011

† Range includes SOC changes from all depths under the specified management.

13.8.2.2 Depth Increment of Sampling

The data contained in this analysis includes incremental depth sampling, sampling by horizon, and whole plow zone sampling. These different sampling schemes will produce very different results since SOC naturally declines with depth. The SOC content will be different if sampling includes deeper layers of the soil profile than if only near surface samples are studied. Comparing whole plow zone values to incremental values would create bias since the whole plow zone sampling includes subsoil samples that are typically lower in SOC content than the surface. Furthermore, sampling by genetic horizon will produce different values than sampling by arbitrary depth increments. To the best of our ability these factors were taken into consideration and documented during the synthesis of these data.

13.8.2.3 Length of Time under Management

Many data sets do not share similar sampling schematics with respect to time after a change in management. The rate of change in SOC content is dependent on the time following adoption of a new management practice. Changes in SOC content tend to occur more rapidly during the first 10 to 15 years following a management change (Paustian et al., 2001; Rasmussen and Collins, 1991; Horner et al., 1960). Following the initial relatively rapid changes, the rate of SOC change will decline until a new steady-state is established or the SOC storage capacity is reached (Lal, 2004). The time between sampling (long term plot) or length of time under management (across the fence row comparisons) varied greatly for the comparisons in this report. For example, in agroclimatic zone 2 the period covered by data ranged from 10 to 100 and 1 to 28 years for the cultivated and NT data sets, respectively. Comparing data with different lengths of time following adoption of a management practice or different sampling frequency can be problematic. For example, total SOC stocks may be greater after 20 years of NT compared to 10 years but the rate of change may be greater in the 10 year data set. Though we recognize the influence of time on rates of SOC change, zones with limited amounts of data points and covering a few years following management change might show higher rates of annual SOC change than we would expect for the long term.

13.8.2.4 Methodology

Variation arising from different approaches to sample preparation and analysis are another inherent weakness in a data compilation and synthesis such as this. Generally, the data in this report were analyzed for soil organic matter by the modified Walkley-Black (Machado et al., 2006; Rodman, 1988; El-Haris et al., 1983) or loss on ignition (Petersen et al., 2002; Rasmussen and Albrecht, 1998) and for soil organic carbon by dry combustion (Purakayastha et al., 2008;Kennedy and Schillinger, 2006; Fuentes et al., 2004; Guy et al., 2006; Douglas et al., 1998; Granatstein et al., 1987). Comparing data generated using different analytical methods might increase the variation within a data set. Another weakness of these data might be differences in sample preparation and also lack of information on sample preparation methodology. For example, the methodology specified by Machado et al. (2006) included roots in their analysis of the surface 40-cm whereas Rasmussen and Albrecht (1998) did not include roots in their 20-cm analysis of SOC changes. This emphasizes the need for adoption of consistent methodology in handling, processing, and analyzing soil organic C. This would strengthen the utility of these data for any C based accounting program (e.g. C trading or Conservation Stewardship Program) in the dryland PNW.

Overall, there is a lack of SOC data for most agroclimatic zones except zone 2 and in some instances zone 3. Where data exists there are differences in the number of years under management, sampling frequency as well as sample collection, preparation and analysis that may influence the outcome of this synthesis. Furthermore, this data set is not amenable to traditional or even non-traditional statistical analysis such as analysis of variance and meta-analysis, respectively.

13.9. CONSIDERATIONS AND FUTURE NEEDS

From a carbon credit trading standpoint, SOC content should be measureable, transparent, and verifiable (IPCC, 2003). In order to develop and maintain a C sequestration market that is both economically and environmentally lucrative, future soil organic carbon studies in the PNW should consider developing a process oriented strategy for measuring, verifying, and monitoring management impacts on SOC stocks. Many carbon credit programs depend on additionality. Additionality is the requirement that a project show SOC is sequestered beyond business as usual or emissions are avoided by maintaining a SOC sequestering practice (Willey and Chameides, 2007). The requirement for additionality emphasizes the need for baseline SOC data. Baseline SOC data quantifies the SOC content under business as usual and is the means by which SOC content under alternative management can be compared to the determine net project benefits (i.e., offsets) (Willey and Chameides, 2007).

13.9.1 Depth and Increment of Sampling

Most of the change in SOC content will occur in the surface 15-cm but it is important to sample the entire plow zone at a minimum (i.e. 20- to 30-cm) (Blaisdell et al., 2003; Willey and Chameides, 2007). Samples should be taken beyond the plow zone if SOC changes (gains or losses) are expected deeper in the soil profile, for example upon conversion from a perennial CRP planting back to annual cropping (Willey and Chameides, 2007). Several protocols use a more refined depth increment for the surface 10-to 15-cm and follow with a less refined increment below the surface. Soil C data is often collected using arbitrary depth increments but may be collected using genetic soil horizons (Davidson and Ackerman, 1993). Davidson and Ackerman (1993) concluded that sampling by genetic horizon provided more reliable data than sampling by fixed depth increments. The authors explain that sampling based on a fixed depth may result in sampling material from a horizon in the cultivated soil that may not occur within the depth increment of the uncultivated soil (i.e. may reach deeper genetic horizons exposed by cultivation practices). However, if an arbitrary depth increment sampling scheme is used it would be beneficial to record basic soil horizon characteristics (i.e. horizon boundary and thickness) (Blaisdell et al., 2003).

13.9.2 Timing and frequency

Soil carbon sequestration is finite with impacts declining over time. The rate of SOC increase typically has a maximum sequestration occurring 5 to 20 years following a management change (Lal et al., 2004). Therefore, samples should be taken every 5 to 10 years following a change in management for the first 10 to 15 years in order to capture SOC content changes (Willey and Chameides, 2007). Sampling should occur during periods with low biological activity with repeated sampling occurring during the same season and environmental conditions if possible (Stolbovoy et al., 2005) and also within the growing season (Blaisdell et al., 2003). Bulk density determination, oven dry soil mass per unit volume (i.e. g soil cm^{-3} soil), is crucial for total carbon stock measurement (Blaisdell et al., 2003). Sampling should be planned for a time when bulk density can be measured reliably and root biomass is minimal (Blaisdell et al., 2003).

13.9.3 Landscape Position and Management History

Current land use and management history of fertilization, residue management, tillage, crops, and animal integration must be document and considered (Blaisdell et al., 2003). Soil properties will also vary with landscape position (i.e., landform- SU, SH, BS, FS, TS, floodplain; slope gradient and length) and therefore must also be considered and documented (Blaisdell et al., 2003).

13.9.4 Residue Accumulation

Residue accumulation at the soil surface through alternative management practices such as NT represents a C pool that has not been adequately quantified to date. When feasible, this layer should be identified and sampled separately from the mineral soil surface using a consistent approach (Blaisdell et al., 2003).

13.9.5 SOC Analysis

Historically soil organic carbon content data was obtained by using the Walkley-Black or loss on ignition methods. The use of high-temperature dry combustion is more commonly used currently and is recommended for total SOC analysis (Nelson and Sommers, 1996; Willey and Chameides, 2007). However, total C data must be corrected for inorganic carbonates in order to assess changes in organic C. When sampling and analysis are cost prohibitive modeling can be used to estimate baseline values. Several models are in circulation that estimate SOC values under different management and environment scenarios.

13.9.5.1 Statistical Procedures

In assessing changes in SOC content from changes in management practices it is important to also assess the level of uncertainty surrounding measurements (Willey and Chameides, 2007). This not only applies to field measurements but also modeled changes in SOC content (Willey and Chameides, 2007). Willey and Chameides (2007) recommend a 90% confidence level which would produce a 10% or less error in the mean.

13.9.6 Soil Organic Carbon Pools

Though this report has focused on total SOC content it is recognized that total SOC is composed of different SOC fraction which differ in characteristic and pedo-function. Soil organic carbon fractions may be disrupted and separated by physical or chemical methods alone or in combination to identify the kinds of organic matter present and the location of organic matter in the soil environment (Elliott and Cambardella, 1991). Macroorganic matter, also referred to as particulate organic matter (POM), is a sand sized (50 – 2000 μm) fraction separated by size alone that represent a more labile pool of SOM (Gregorich et al., 2006; Mirsky et al., 2008). Particulate organic matter shows greater sensitivity to soil management changes compared to total SOM (Mirsky et al., 2008) and may be useful tool is distinguishing C sequestration potential of different soil management.

13.9.7 Establishment of Long-term Study Sites

From this literature review it is clear that long-term research quantifying soil organic C content under different management practices is limiting. There is concern that estimates of agricultural soil C sequestration based on a limited soil depth might over estimate the actual sequestration potential resulting from changes in tillage management. The increase in sample size from sampling deeper in the soil profile will most likely be cost prohibitive for land managers. Long-term plots could provide a mechanism for achieving the kind of rigorous sampling needed to more definitely answer such remaining questions.

Establishment of long-term sites representing the major agricultural systems as well as the more feasible alternatives to “business as usual” for each agroclimatic zone is needed. Included in the establishment of these long-term sites would be georeferenced sampling locations and a minimum of 150-cm sampling depth. Initial soil C sampling would provide baseline data to be used in conjunction with temporal sampling to evaluate the rate and amount of soil C changes resulting from management.

Conversion of CRP program ground back to cultivation would result in much of the sequestered C being released back into the atmosphere. However, if converted land goes into a NT systems SOC losses may be minimized (Karlen, 1998). Long-term studies could help determine the impacts from changing back to previous management practices (i.e. breaking out CRP or converting from NT to conservation tillage) and offer alternative that may be less disturbing.

While long-term research on agricultural experiment stations may not always capture economic and socio-political influences on management decisions, the influence of environmental conditions under traditional and alternative agricultural management practices can be considered with less risk to the farm.

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13.12. GLOSSARY

Carbon sequestration: any net increase in organic C storage over the management system (e.g. rotation) for purposes of mitigating atmospheric CO_2 concentration

Continuous cropping: refers to crop rotation that includes no fallow period

Conventional Tillage (CT): includes and refers to use of moldboard plow or full width inversion tillage

Cumulative Probability Distribution: a probability distribution that describes the proportion of all observations that are less than or equal to the upper limit of a specified value or range.

Expected Normal Score: mean value expected from a normal distribution with a mean value μ and standard deviation σ.

No-Tillage: refers to use of no full width soil inversion

Reduced Tillage: includes use of non-moldboard plow operations such as disking

Appendix 1. Changes in Soil Organic Carbon Content and Distribution by Agroclimatic Zone and Management.

ACZ	Location	Depth	Duration	Treatment[†]	Annual Change in SOC			Reference
		cm	yrs		Mg C $ha\text{-}cm^{-1}$	Mg C ha^{-1}	$MTCO_2e$ ac^{-1}	
				Conversion to Cropland				
1	NR	0-20		native vs. cropped				Douglas et al., 1998[§,#,¶]
		20-40						
		40-60						
2	NR	0-20	93	native vs. cropped	-0.008	-0.165	-0.25	Douglas et al., 1998[§,#]
		20-40	93		-0.006	-0.122	-0.18	
		40-60	93		-0.002	-0.049	-0.07	
	near Colton, WA	0-5	93	native prairie (KPNA) vs. CT WW-SW-SP; Upland	-0.024	-0.119	-0.18	Fuentes et al., 2004[§]
		5-10	93		-0.018	-0.091	-0.13	
	NW of Palouse, WA	0-10	80	Cemetary (native grass and shrub) vs. CT WW-P	-0.022	-0.220	-0.33	Huggins et al., unpublished
		10-22	80		-0.012	-0.144	-0.21	
		22-60	80		-0.006	-0.238	-0.35	
	near Colton, WA	0-5	100	native prairie (KPNA) vs. CT	-0.032	-0.158	-0.23	Purakayastha et al., 2008
		5-10	100		-0.018	-0.088	-0.13	
		10-20	100		-0.013	-0.130	-0.19	
	near Colton, WA	0-20	80	native prairie (KPNA) vs. W-P (80+ yrs); Lowland	-0.003	-0.052	-0.08	Rodman, 1988[§]
		20-50	80		0.010	0.308	0.46	
		50-100	80		0.008	0.393	0.58	
		100-150	80		0.006	0.312	0.46	
	near Colton, WA	0-20	80	native prairie (KPNA) vs. W-P (80+ yrs); Upland	-0.014	-0.284	-0.42	Rodman, 1988[§]
		20-50	80		-0.008	-0.241	-0.36	
		50-100	80		-0.004	-0.218	-0.32	
		100-150	80		-0.002	-0.102	-0.15	
	Pullman, WA	0-15	39	virgin vs. cropped; Upland	-0.014	-0.215	-0.32	Sievers & Hotlz, 1922
		15-30	39		-0.008	-0.114	-0.17	
		30-60	39		-0.016	-0.474	-0.70	
	Palouse region, WA	0-15	35	virgin vs. cropped	-0.038	-0.566	-0.84	Sievers and Holtz, 1926[§]
3	Pendleton, OR	0-20	60	grass pasture (60 yrs) vs cropped	-0.011	-0.228	-0.34	Douglas et al., 1998[§,#]
		20-40	60		-0.002	-0.041	-0.06	
		40-60	60		-0.003	-0.057	-0.08	
	Pendleton, OR	0-20	60	virgin grassland vs. WW-SF	-0.024	-0.470	-0.70	Rasmussen and Albrecht, 1998
	Pendleton, OR	0-20	40	virgin grassland vs. WW-SF	-0.033	-0.660	-0.98	
	Pendleton, OR	0-20	60	virgin grassland vs. Cont. WW	-0.018	-0.353	-0.52	
5	Ritzville, WA	0-5	8	native vs. annual NT crop (8 yrs) - decades WW-SF	-0.057	-0.283	-0.42	Schillinger et al., 2007
	Ritzville, WA	5-10	8		0.037	0.183	0.27	
	Rock Island,	0-15	9	virgin vs. cropped	-0.030	-0.450	-0.67	Sievers & Hotlz, 1926

ACZ	Location	Depth	Duration	Treatment†	Annual Change in SOC			Reference
		cm	yrs		Mg C ha-cm^{-1}	Mg C ha^{-1}	MTCO$_2$e ac^{-1}	
	WA							
	Prosser, WA	0-15	3	virgin vs. cropped	-0.053	-0.800	-1.19	Sievers & Hotlz, 1926
6	NR	0-20		native vs. cropped				Douglas et al., 1998[§,#]
		20-40						
		40-60						
				Tillage				
2	Colfax, WA	0-5	10	NT mostly W, some lentil vs. CT	0.102	0.510	0.76	Bezdicek et al., 1998[§]
		5-10	10		0.084	0.419	0.62	
		10-25	10		0.021	0.320	0.47	
	Palouse, WA	0-5	20	NTW-B-P vs. 1st yr NT	0.110	0.551	0.82	Bezdicek et al., 1998
		5-10	20		0.038	0.189	0.28	
		10-25	20		0.033	0.494	0.73	
	Pullman, WA	0-5	16	NT cont. W vs CT	0.073	0.365	0.54	Bezdicek et al., 1998[§]
		5-10	16		0.033	0.165	0.24	
		10-25	16		0.029	0.428	0.64	
	Pullman, WA	0-15	8	NT vs. CT	0.012	0.176	0.26	El-Haris et al., 1983[§]
	20 km N Pullman, WA	0-5	27	NT WW-SW-L vs. CT WW-SW-SP	0.017	0.087	0.13	Fuentes et al., 2004[§]
		5-10	27		-0.004	-0.022	-0.03	
	Moscow, ID	0-5	10	NT vs. CT; WW-SP; WW-SB-SP; WW-SP+red clover and alfalfa	0.054	0.268	0.40	Granatstein et al., 1987[§]
		5-10	10		0.000	0.000	0.00	
		10-15	10		-0.007	-0.033	-0.05	
		15-30	10		-0.013	-0.201	-0.30	
		0-10	3.5	NT vs. CT	0.109	1.086	1.61	Guy et al., 00 to 06
	Colfax, WA	0-5	20	NT:SW-CSF-WW vs. CT:WW-SW; lowland	0.027	0.133	0.20	Kennedy and Schillinger, 2006
		5-10	20		0.016	0.078	0.12	
	Colfax, WA	0-5	20	NT:SW-CSF-WW vs. CT:WW-SW; upland	0.025	0.127	0.19	Kennedy and Schillinger, 2006
		5-10	20		0.019	0.097	0.14	
	near Palouse, WA	0-5	28	NT WW-SB-SP or L	0.059	0.294	0.44	Purakayastha et al., 2008
		5-10	28		0.011	0.057	0.08	
	Pullman, WA	0-5	1	1 yr NT - 3 yrs CT - 10 yrs NT	-0.200	-0.999	-1.48	Purakayastha et al., 2008
		5-10	1		0.200	0.999	1.48	
	Pullman, WA	0-5	4	NT WW-SB-SW	0.205	1.024	1.52	Purakayastha et al., 2008
		5-10	4		0.185	0.924	1.37	
3	LaCrosse, WA	0-5	2	NT:SW-CSF-WW vs. CT:WW-SF; lowland	0.418	2.091	3.10	Kennedy and Schillinger, 2006[#]
		5-10	2		0.287	1.433	2.13	
	LaCrosse, WA	0-5	2	NT:SW-CSF-WW vs. CT:WW-SF; upland	0.060	0.299	0.44	Kennedy and Schillinger, 2006[#]
		5-10	2		-0.023	-0.117	-0.17	
	near Colfax, WA	0-5	7	NT:SW-CSF-WW vs. CT:WW-SF; lowland	0.075	0.376	0.56	Kennedy and Schillinger, 2006[#]
		5-10	7		0.111	0.554	0.82	
	near Colfax, WA	0-5	7	NT:SW-CSF-WW vs. CT:WW-SF; upland	0.024	0.121	0.18	Kennedy and Schillinger, 2006[#]
		5-10	7		0.006	0.029	0.04	
	Pendleton, OR	0-20	10	NT Cont. WW	0.004	0.080	0.12	Rasmussen and Albrecht, 1998
	St. John, WA	0-5	15	NT WW-SF vs. CT WW-SF	0.025	0.125	0.18	Bezdicek et al., 1998[§]
		5-10	15		0.004	0.021	0.03	
		10-25	15		0.014	0.207	0.31	

ACZ	**Location**	**Depth**	**Duration**	**Treatment**[†]	**Annual Change in SOC**			**Reference**
		cm	yrs		Mg C ha-cm^{-1}	Mg C ha^{-1}	MTCO$_2$e ac^{-1}	
	Lewiston, ID	0 -5	16	NT WW (1980-92), 3 yr rot. since vs. conventional	0.053	0.264	0.39	Bezdicek et al., 1998[§]
		5-10	16		0.002	0.010	0.01	
		10-25	16		-0.001	-0.016	-0.02	
	Pendleton, OR	0-40	6	NT vs. CT; Cont. WW fertilized	-0.045	-1.782	-2.64	Machado et al., 2006[#]
	Pendleton, OR	0-40	6	NT vs. CT; Cont. WW unfertilized	0.029	1.177	1.75	
	Pendleton, OR	0-40	6	NT vs. CT; Cont. SW fertilized	-0.023	-0.938	-1.39	
	Pendleton, OR	0-40	6	NT vs. CT; Cont. SW unfertilized	-0.014	-0.558	-0.83	
	Pendleton, OR	0-40	6	NT vs. CT; Cont. SB fertilized	-0.095	-3.793	-5.63	
	Pendleton, OR	0-40	6	NT vs. CT; Cont. SB unfertilized	-0.074	-2.940	-4.36	
5	Touchet, WA	0-5	14	NT SW vs. WW-SF	0.011	0.054	0.08	Bezdicek et al., 1998
		5-10	14		0.002	0.008	0.01	
		10-25	14		0.001	0.012	0.02	
				Reduced Tillage				
2	Pullman, WA	0-5	20	Chisel-till vs. NT	0.025	0.123	0.18	Petersen et al., 2002
	Pullman, WA	5-15	20		-0.009	-0.085	-0.13	
	Pullman, WA	0-15	8	Chisel vs. CT	0.003	0.051	0.08	El-Haris et al., 1983[§]
	Pendleton, OR	0-7.5	44	Disk vs plow; WW-SF	0.011	0.085	0.13	Rasmussen and Rohde, 1988
		7.5-15	44		0.001	0.005	0.01	
		15-22.5	44		0.000	0.000	0.00	
		22.5-45	44		0.002	0.050	0.07	
	Pendleton, OR	0-7.5	44	Sweep vs. plow; WW-SF	0.011	0.080	0.12	Rasmussen and Rohde, 1988
		7.5-15	44		0.001	0.008	0.01	
		15-22.5	44		-0.001	-0.004	-0.01	
		22.5-45	44		0.001	0.028	0.04	
	Pendleton, OR	0-20	28	W-P; mulch tillage	0.004	0.071	0.11	Rasmussen and Albrecht, 1998
	Pendleton, OR	0-20	40	W-F; mulch tillage	-0.004	-0.080	-0.12	Rasmussen and Albrecht, 1998
				Annual Cropping				
2	Pullman, WA	0-30	31	Continuous WW; A-13	0.001	0.040	0.06	Horner et al., 1960[§]
	Moscow, ID	0-15	15	Cont. WW; A-16	-0.017	-0.252	-0.37	Horner et al., 1960[§]
	Moscow, ID	0-15	15	Cont. WW + N (150 lbs/ac); A-16	-0.008	-0.119	-0.18	Horner et al., 1960[§]
	Moscow, ID	0-15	15	WW-SP; A-16	-0.008	-0.126	-0.19	Horner et al., 1960[§]
	Moscow, ID	0-15	15	W-W-SP; A-16	-0.007	-0.111	-0.17	Horner et al., 1960[§]
	Pullman,	0-15	10	ContiuousW W; A-17	-0.010	-0.156	-0.23	Horner et al., 1960[§]

ACZ	Location	Depth	Duration	Treatment[†]	Annual Change in SOC			Reference
		cm	yrs		Mg C ha-cm^{-1}	Mg C ha^{-1}	MTCO$_2$e ac^{-1}	
	WA							
	Pullman, WA	0-15	10	WW-SP; A17	-0.013	-0.200	-0.30	Horner et al., 1960[§]
	Pullman, WA	0-15	10	WW-SP-O; A-17	-0.004	-0.067	-0.10	Horner et al., 1960[§]
	Pullman, WA	0-15	16	Cont. W (10yrs) following WW-SF (6yrs); A-18	-0.001	-0.009	-0.01	Horner et al., 1960[§]
	Pullman, WA	0-15	10	WW-SP (10 yrs); A-19	-0.007	-0.105	-0.16	Horner et al., 1960[§]
	Moscow, ID	0-30	22	W-O-C, NaNO3 (40lbs/ac); A-15	-0.015	-0.445	-0.66	Horner et al., 1960[§]
	Moscow, ID	0-30	22	Cont. WW, no fert; A-15	-0.010	-0.314	-0.47	Horner et al., 1960[§]
	Moscow, ID	0-30	22	W-O-SP, no fert; A-15	-0.016	-0.475	-0.71	Horner et al., 1960[§]
	Moscow, ID	0-30	22	W-O-C, no fert; A-15	-0.013	-0.395	-0.59	Horner et al., 1960[§]
	Moscow, ID	0-30	22	W-O-potato, no fert; A-15	-0.016	-0.465	-0.69	Horner et al., 1960[§]
	Moscow, ID	0-30	22	W-O-sunflower, no fert; A-15	-0.018	-0.546	-0.81	Horner et al., 1960[§]
3	Pendleton, OR	0-20	28	WW-SP;plowed	-0.002	-0.036	-0.05	Rasmussen and Albrecht, 1998
	Pendleton, OR	0-20	60	Cont. W; plowed	-0.001	-0.010	-0.01	Rasmussen and Albrecht, 1998
	Pendleton, OR	0-30	10	WW-SP	-0.015	-0.444	-0.66	Horner et al., 1960[§]
				Fallow				
2	Pullman, WA	0-15	10	WW-F; A-17	-0.016	-0.240	-0.36	Horner et al., 1960[§]
	Pullman, WA	0-15	10	WW-SF; A-19	-0.006	-0.090	-0.13	Horner et al., 1960[§]
	Pullman, WA	0-15	16	WW-F; A-18	-0.007	-0.103	-0.15	Horner et al., 1960[§]
	Pullman, WA	0-30	31	WW-SF, 60N(NaNO3); A-13	-0.012	-0.366	-0.54	Horner et al., 1960[§]
	Pullman, WA	0-30	31	WW-SF, 2700 straw; A-13	-0.012	-0.373	-0.55	Horner et al., 1960[§]
	Pullman, WA	0-30	31	WW-SF, 2700 st+60N (NaNO3); A-13	-0.008	-0.244	-0.36	Horner et al., 1960[§]
	Pullman, WA	0-30	31	WW-SF, 2700 straw+60N (NH4)2SO4; A-13	-0.004	-0.122	-0.18	Horner et al., 1960[§]
	Moscow, ID	0-30	22	W-O-F, no fertilizer; A-15	-0.023	-0.682	-1.01	Horner et al., 1960[§]
	Pullman, WA	0-30	31	WW-SF, no fert; A-13	-0.011	-0.337	-0.50	Horner et al., 1960[§]
3	Pendleton, OR	0-20	60	WW-SF; plowed	-0.006	-0.117	-0.17	Rasmussen and Albrecht, 1998

ACZ	Location	Depth	Duration	Treatment[†]	Annual Change in SOC			Reference
		cm	yrs		Mg C ha-cm^{-1}	Mg C ha^{-1}	MTCO$_2$e ac^{-1}	
	Pendleton, OR	0-20	40	WW-SF; plowed	-0.004	-0.085	-0.13	Rasmussen and Albrecht, 1998
	Pendleton, OR	0-30	10	WW-SF; A-20	-0.022	-0.645	-0.96	Horner et al., 1960[§]
	Pendleton, OR	0-30	10	WW-WW-SF; A-20	-0.011	-0.333	-0.49	Horner et al., 1960[§]
				Burning				
2	Moscow, ID	0-15	15	WW-SF Burn; A-16	-0.027	-0.410	-0.61	Horner et al., 1960[§]
	Moscow, ID	0-15	15	WW-SF No-Burn; A-16	-0.020	-0.300	-0.45	Horner et al., 1960[§]
3	Pendleton, OR	0-30	55	WW-SF; Burn	-0.006	-0.168	-0.25	Rasmussen and Parton, 1994
	Pendleton, OR	30-60	55	WW-SF; Burn	-0.006	-0.170	-0.25	Rasmussen and Parton, 1994
	Pendleton, OR	0-30	10	WW-SF; Burn; A-20	-0.027	-0.822	-1.22	Horner et al., 1960[§]
	Pendleton, OR	0-30	55	WW-SF; No-burn	-0.003	-0.098	-0.15	Rasmussen and Parton, 1994
	Pendleton, OR	30-60	55	WW-SF; No-burn	-0.006	-0.166	-0.25	Rasmussen and Parton, 1994
	Pendleton, OR	0-30	10	WW-SF; No-burn; A-20	-0.025	-0.735	-1.09	Horner et al., 1960[§]
5	Moro, OR	0-30	10	WW-SF Burn; A-21	-0.009	-0.270	-0.40	Horner et al., 1960[§]
	Moro, OR	0-30	10	WW-SF, No-burn, binder stubble plowed under; A-21	-0.005	-0.156	-0.23	Horner et al., 1960[§]
	Moro, OR	0-30	10	WW-SF, No-burn, all straw plowed under; A-21	-0.010	-0.289	-0.43	Horner et al., 1960[§]
				Mixed Perennial-Annual System				
2	Pullman, WA	0-15	7	alf & grass (3yrs)-WW-WW-P-WW; A-19	0.010	0.150	0.22	Horner et al., 1960[§]
	Pullman, WA	0-15	16	grass (10yrs) following 6 yrs WW-SF; A-18	-0.001	-0.009	-0.01	Horner et al., 1960[§]
	Moscow, ID	0-15	5	crested wheatgrass (3 yrs)-flax-WW; A-16	0.004	0.067	0.10	Horner et al., 1960[§]
	NW Genesee, ID	0-10	6	WW (barley)-P-alf (4 to 5 yrs) vs. CT WW-P	0.045	0.450	0.67	Huggins et al., unpublished
		10-25	6		0.063	0.941	1.40	
		25-45	6		0.069	1.372	2.04	
		45-105	6		0.013	0.751	1.11	
		105-180	6		0.000	-0.010	-0.01	

ACZ	Location	Depth	Duration	Treatment[†]	Annual Change in SOC			Reference
		cm	yrs		Mg C ha-cm^{-1}	Mg C ha^{-1}	MTCO$_2$e ac^{-1}	
	W of Palouse, WA	0-10	16	WW (barley)-P (lentils); 10 yrs ago alf-bromegrass (6yrs) vs. CT WW (barley)-WW-L	0.044	0.438	0.65	Huggins et al., unpublished
		10-20	16		0.057	0.571	0.85	
		20-47	16		-0.007	-0.196	-0.29	
		47-180	16		0.009	1.158	1.72	
	SW Johnson, WA	0-10	11	NT W (1 yr)-bluegrass (10 yrs) vs. CT W-P	0.034	0.336	0.50	Huggins et al., unpublished
		10-24	11		-0.009	-0.130	-0.19	
		24-68	11		0.017	0.749	1.11	
		68-127	11		-0.002	-0.116	-0.17	
		127-180	11		-0.001	-0.028	-0.04	
	near Uniontown, WA	0-5	15	NT (4 yrs)- bluegrass	0.066	0.330	0.49	Purakayastha et al., 2008
		5-10	15		0.027	0.133	0.20	
	near Dayton, WA	0-20	18	WW-SP-WW-SF vs. 12 yrs blugrass-6 yrs WW	0.021	0.428	0.63	Rodman, 1988[§]
		20-50	18		0.006	0.189	0.28	
		50-100	18		0.001	0.056	0.08	
		100 -120	18		-0.001	-0.017	-0.02	
	near Dayton, WA	0-20	18	WW-SP-WW-SF vs. 18 years bluegrass	0.014	0.278	0.41	Rodman, 1988[§]
		20-50	18		0.007	0.206	0.30	
		50-100	18		0.005	0.228	0.34	
		100 -120	18		0.006	0.111	0.16	
3	Pendleton, OR	0- 30	6	alfalfa(3yrs)-fallow-WW-C; A-20	-0.033	-1.000	-1.48	Horner et al., 1960[§]
				CRP				
2	near Albion, WA	0-5	11	Grass Stand	0.071	0.354	0.53	Purakayastha et al., 2008
		5-10	11		0.005	0.027	0.04	
	eastern Palouse region	0-10	22.5	native prairie (Tomer Butte, Paradise Ridge, Smoot Hill) vs. CRP	-0.011	-0.107	-0.16	Sanchez de-Leon, 2007[††]
		10-20	22.5		-0.018	-0.184	-0.27	
		20-30	22.5		-0.015	-0.151	-0.22	
3	Pendleton, OR	0-20	60	grass pasture	0.008	0.163	0.24	Rasmussen and Albrecht, 1998
5	Columbia Plateau, WA	0-7.5	4.5	CRP vs. cropland	0.024	0.178	0.26	Karlen et al., 1999
				Barnyard Manure				
2	Pullman, WA	0-30	31	WW-SF; 13,452 kg barnyard manure/ha every other yr; A-13	-0.001	-0.022	-0.03	Horner et al., 1960[§]
	Moscow, ID	0-30	22	W-Oats-F; 37,070 kg barnyard manure/ha every 3rd yr ; A-15	-0.005	-0.152	-0.23	Horner et al., 1960[§]
	Moscow, ID	0-30	22	Cont. W; 37,070 kg	0.017	0.516	0.77	Horner et al., 1960[§]

ACZ	Location	Depth	Duration	Treatment†	Annual Change in SOC			Reference
		cm	yrs		Mg C ha-cm^{-1}	Mg C ha^{-1}	MTCO$_2$e ac^{-1}	
				barnyard manure/ha every 3rd yr; A-15				
	Pullman, WA	0-30	31	Cont. WW; 13,452 kg barnyard manure/ha every yr; A-13	0.014	0.406	0.60	Horner et al., 1960§
	Moscow, ID	0-30	22	W-Oats-peas; 37,070 kg barnyard manure/ha every 3rd yr; A-15	0.007	0.223	0.33	Horner et al., 1960§
	Moscow, ID	0-30	22	W-Oats-corn; 37,070 kg barnyard manure/ha every 3rd yr; A-15	-0.003	-0.081	-0.12	Horner et al., 1960§
3	Pendleton, OR	0-30	55	WW-SF; no-burn; 22.40 kg barnyard manure ha^{-1} crop^{-1}	0.001	0.027	0.04	Rasmussen and Parton, 1994
		30-60			-0.005	-0.158	-0.23	
	Pendleton, OR	0-30	10	WW-SF; 24,713 kg barnyard manure ha-1 every other yr; A-20	-0.006	-0.177	-0.26	Horner et al., 1960§
5	Moro, OR	0-30	10	WW-SF, straw+ 24,713 kg barnyard manure/ ha every other year; A-21	-0.001	-0.044	-0.07	Horner et al., 1960§
				Green Manure				
2	Pullman, WA	0-30	31	Cont. WW with alfalfa residue; A-13	0.002	0.068	0.10	Horner et al., 1960§
	Pullman, WA	0-30	31	WW-SF with alfalfa residue; A-13	-0.008	-0.237	-0.35	Horner et al., 1960§
	Moscow, ID	0-30	22	P+Sweetclover-Sweetclover hay- O - C silage- WW; A-15	-0.013	-0.384	-0.57	Horner et al., 1960§
	Moscow, ID	0-30	22	2 yrs Sweetclover hay- O- WW- C-B; A-15	-0.009	-0.283	-0.42	Horner et al., 1960§
	Moscow, ID	0-15	15	P+sweetclover-Sweetclover plowed under- WW- WW; A-16	0.000	0.007	0.01	Horner et al., 1960§
	Pullman, WA	0-15	10	WW- P + Sweetclover gm; A-17	0.032	0.480	0.71	Horner et al., 1960§
	Pullman, WA	0-15	16	P + Sweetclover - Sweetclover gm - WW-SW; A-18	0.007	0.111	0.17	Horner et al., 1960§
	Pullman, WA	0-15	10	Sweetclover-Sweetclover gm-WW-SW; A-18	0.015	0.223	0.33	Horner et al., 1960§

ACZ	Location	Depth	Duration	Treatment†	Annual Change in SOC			Reference
		cm	yrs		Mg C ha-cm^{-1}	Mg C ha^{-1}	$\text{MTCO}_2\text{e ac}^{-1}$	
	Pullman, WA	0-15	10	WW-P green manure; A-19	0.002	0.033	0.05	Horner et al., 1960§
	Pullman, WA	0-15	10	clover green manure; A-19	0.003	0.045	0.07	Horner et al., 1960§
	Pullman, WA	0-15	10	WW-P-WW-sweetclover & grass green manure(2 yrs); A-19	0.009	0.134	0.20	Horner et al., 1960§
	Culdesac, ID	0-10	10	WW-SP w/ underseeded alf plowed in next spring-SF vs. CT WW-O-SB-WP (30 yrs)	0.039	0.390	0.58	Huggins et al., unpublished
		10-24	10		0.036	0.510	0.76	
		24-55	10		-0.039	-1.209	-1.79	
		55-107	10		0.014	0.706	1.05	
	Culdesac, ID and Lapwai, ID	0-10		WW-P w/ underseeded sweet clover (red) plowed in next spring-SF vs. CT WW-P				Huggins et al., unpublished
		10-19						
		19-37						
		37-117						
	Pullman, WA	0-15	5	peas-alfalfa green manure (3 yrs) and SW-WW vs. Cont. WW	0.072	1.080	1.60	El-Haris et al., 1983§
3	Pendleton, OR	0-30	55	WW-SF, no-burn, pea vine manure	-0.003	-0.087	-0.13	Rasmussen and Parton, 1994
		30-60	55		-0.005	-0.164	-0.24	
	Pendleton, OR	0-30	10	Sweetclover hay (2yrs)-WW				Horner et al., 1960§

† NT, no-tillage; CT, conventional tillage; RT, reduced tillage; WW, winter wheat; SW, spring wheat; SP spring pea; WP, winter pea; SB, spring barley; L, lentil; SF, mechanical summer fallow; CSF, chemical summer fallow; O, oats; C, corn; Saf, safflower; YM, yellow mustard; alf, alfalfa; SC, sweet clover; gm; green manure; No-B, no burn; KPNA, Kramer Palouse Natural Area; Cont., continuous.

‡ Negative values indicate SOC loss.

§ Bulk density values were not provided in original data source and were assumed using the best available data.

¶ All textures were silt loam except this soil which was a fine sandy loam.

Data not used due to insufficient information or unresolved discrepancies.

†† All textures were silt loam except this soil which was a silty clay loam.

Appendix 2. Conversion Table for Commonly Expressed Carbon Units.

Convert From	To	Equation	Multiply	
			first by multiplier	**then by sampling depth (cm)**
Mg C ha-cm^{-1}yr^{-1}	lbs C ac^{-1} yr^{-1}	1	892	i.e. 15 cm, 30 cm, 10 cm
	kg C ac^{-1} yr^{-1}	2	405	
	kg C ha^{-1} yr^{-1}	3	1000	
	MMT† CO$_2$ ac^{-1} yr^{-1}	4	0.0000015	

†MMT, million metric tons; not an SI unit

Example Calculations:

(-0.025 Mg C ha-cm^{-1} yr^{-1} change) x (892) x (30 cm) = 669 lbs C lost ac^{-1} yr^{-1} (***Eqn. 1***)

OR

-0.025 Mg C	0.405 ha	1,000,000 g C	1 lb C	30 cm
ha-cm yr	1 ac	1 Mg C	454 g C	

= 669 lbs C lost ac^{-1} yr^{-1}

(-0.025 Mg C ha-cm^{-1} yr^{-1} change) x (405) x (30 cm) = 303.75 kg C lost ac^{-1} yr^{-1} (***Eqn. 2***)

OR

-0.025 Mg C	0.405 ha	1,000 kg C	30 cm
ha-cm yr	1 ac	1 Mg C	

= 303.75 kg C lost ac^{-1} yr^{-1}

(-0.025 Mg C ha-cm^{-1} yr^{-1} change) x (1000) x (30 cm) = 750 kg C lost ha^{-1} yr^{-1} (***Eqn. 3***)

OR

-0.025 Mg C	1,000 kg C	30 cm
ha-cm yr	1 Mg C	

= 750 kg C lost ha^{-1} yr^{-1}

(-0.025 Mg C ha-cm^{-1} yr^{-1} change) x (0.0000015) x (30 cm) = MMT CO$_2$ ac^{-1} yr^{-1} (***Eqn.4***)

OR

-0.025 Mg C	0.405 ha	1,000,000 g C	1 lb C	1 ton C	1 MMT C	44 MMTCO$_2$	30 cm
ha-cm yr	1 ac	1 Mg C	454 g C	2204.6 lbs C	1,000,000 tons C	12 MMTC	

= 1.11 x 10^{-6} MMT CO$_2$ ac^{-1} yr^{-1}

Appendix 3. Example Calculations for Cumulative Probability Analysis

The observations are ordered from smallest to largest and the expected scores are obtained from a statistics table in order to calculate the expected normal score.

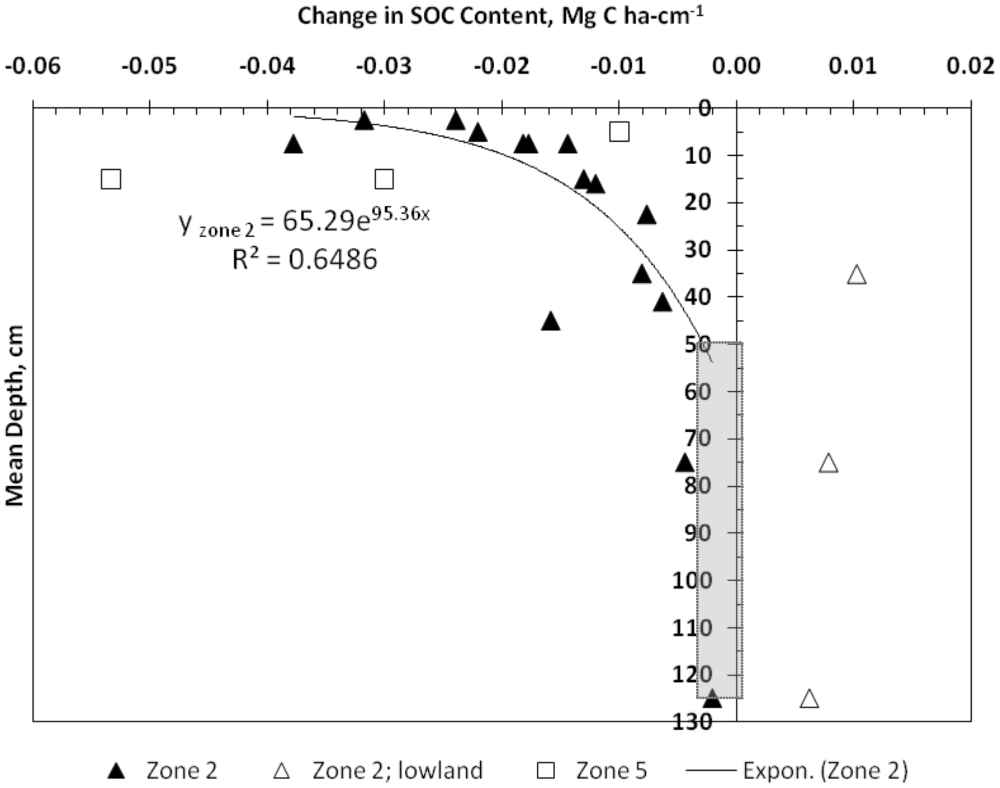
Expected Normal Score = μ + (corresponding expected score for $\mu=0$, $\sigma=1$)*σ

Example Calculation for Native Conversion in ACZ 2 where there were 7 observation (n=7)

Observed Change in SOC	**Mean Change**	**Standard Deviation**	**Expected Score for $\mu=0,\sigma=1$**[†]	**Expected Normal Score,** μ+(Exp. Score)*σ
--------------- Mg C ha^{-1} yr^{-1} ---------------				Mg C ha^{-1} yr^{-1}
0.53	0.84	0.17	-1.3522	0.61
0.80	0.84	0.17	-0.7574	0.71
0.80	0.84	0.17	-0.3527	0.78
0.81	0.84	0.17	0	0.84
0.84	0.84	0.17	0.3527	0.90
1.00	0.84	0.17	0.7574	0.97
1.07	0.84	0.17	1.3522	1.07

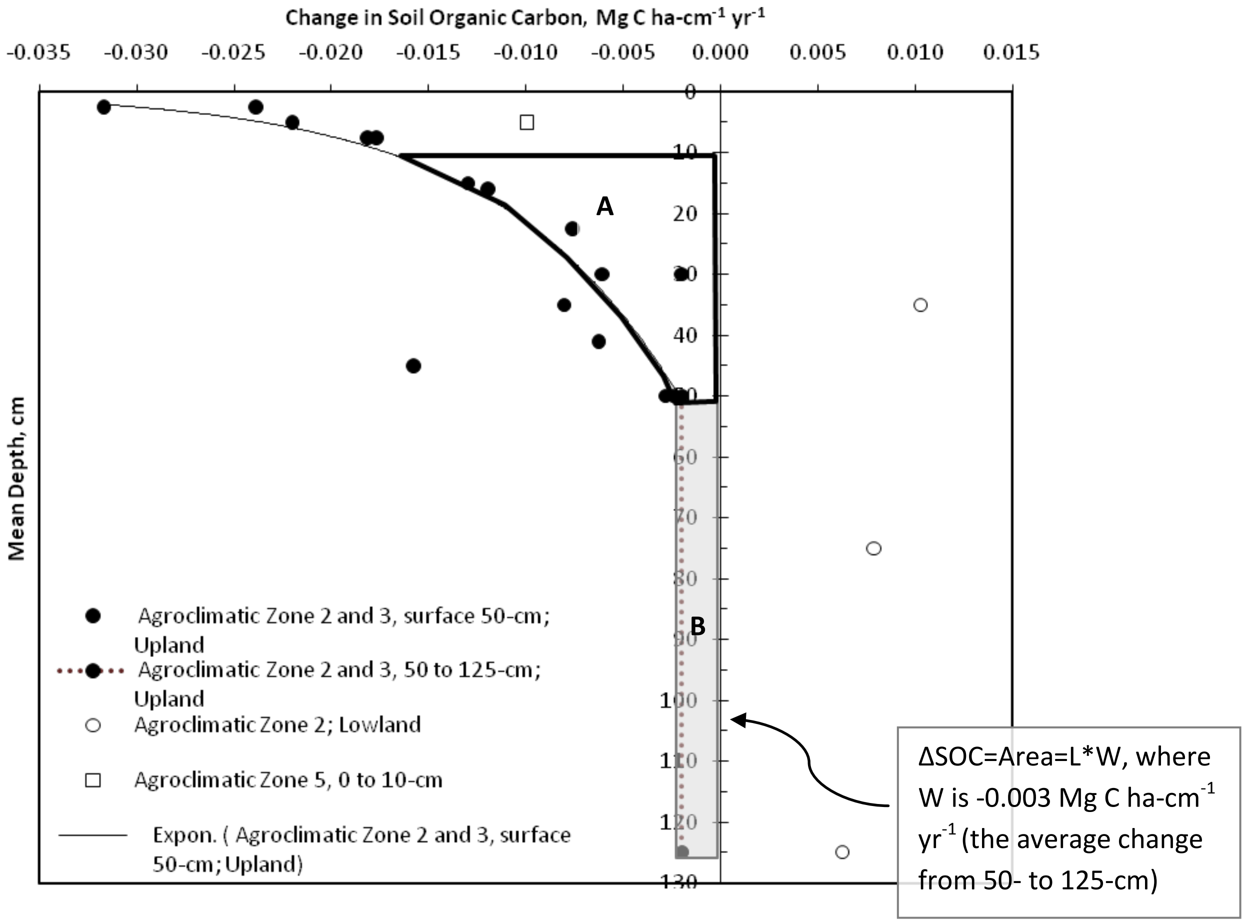
[†] The corresponding expected normal score for $\mu=0$ and $\sigma=1$ is obtained from a statistics table and based on the number of observations.

Appendix 4. Trends and Distribution of Soil Organic Carbon Content Change in Cultivated Soils as Compared to Native or Near Native Conditions.



The profile change in SOC was calculated by integrating the exponential equation to 50-cm and/or taking the area of the rectangle from 50- to 125-cm to obtain the changes in SOC stocks for studies in which SOC was not reported to these depths. This allowed for SOC changes to be expressed on a 125-cm profile depth basis.

Appendix 5. Example Calculation for Profile Change in SOC Stocks from Conversion of Native Vegetation to Cropland.



ΔSOC=Area=L*W, where W is -0.003 Mg C ha-cm^{-1} yr^{-1} (the average change from 50- to 125-cm)

10-cm change provided in data set = 0.21 Mg C ha^{-1} yr^{-1}

A: Area Under Exponential Curve, from 10- to 50-cm

$y = 65.29e^{95.36x} = \int 65.29e^{95.36x}\,dx = 65.29/95.36\ [e^{(95.36* -0.0197)} – e^{(95.36* -0.003)}]$

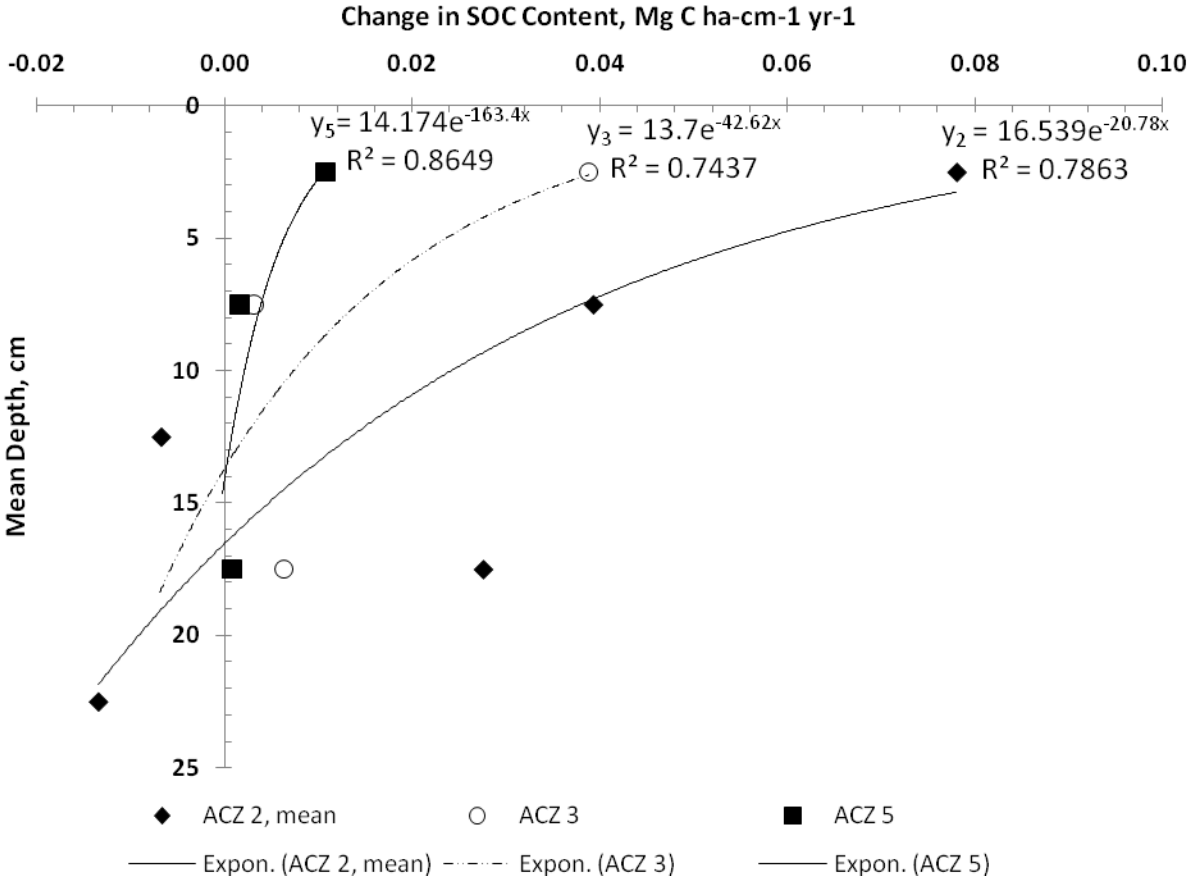
$y = -0.41$ Mg C ha^{-1} yr^{-1}

B: Area of Rectangle

Area = Length x Width = -0.003 Mg C ha-cm^{-1} yr^{-1} x (50-cm -125-cm) = -0.225 Mg C ha^{-1} yr^{-1}

Total Change in SOC Stocks (provided+A+B) = -0.21 + -0.41 + -0.225 = 0.845 Mg C ha^{-1} yr^{-1}

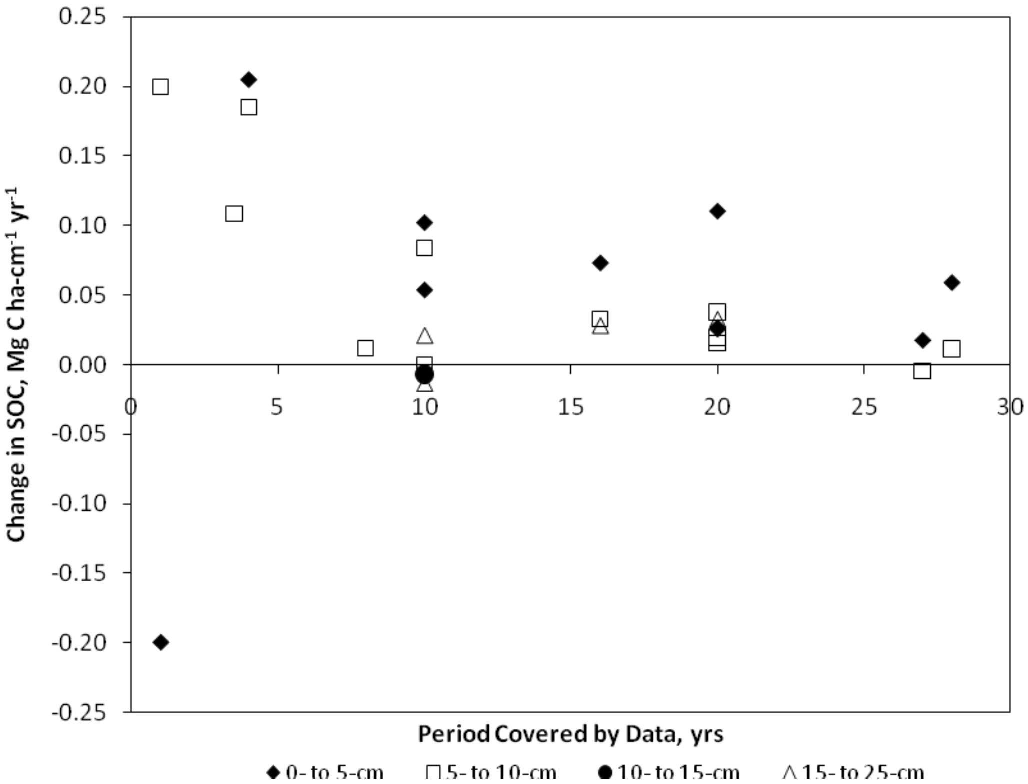
Appendix 6. Trends and Distribution of Soil Organic Carbon Content Change in No-Till Compared to Tilled (full width inversion tillage) Soils.†



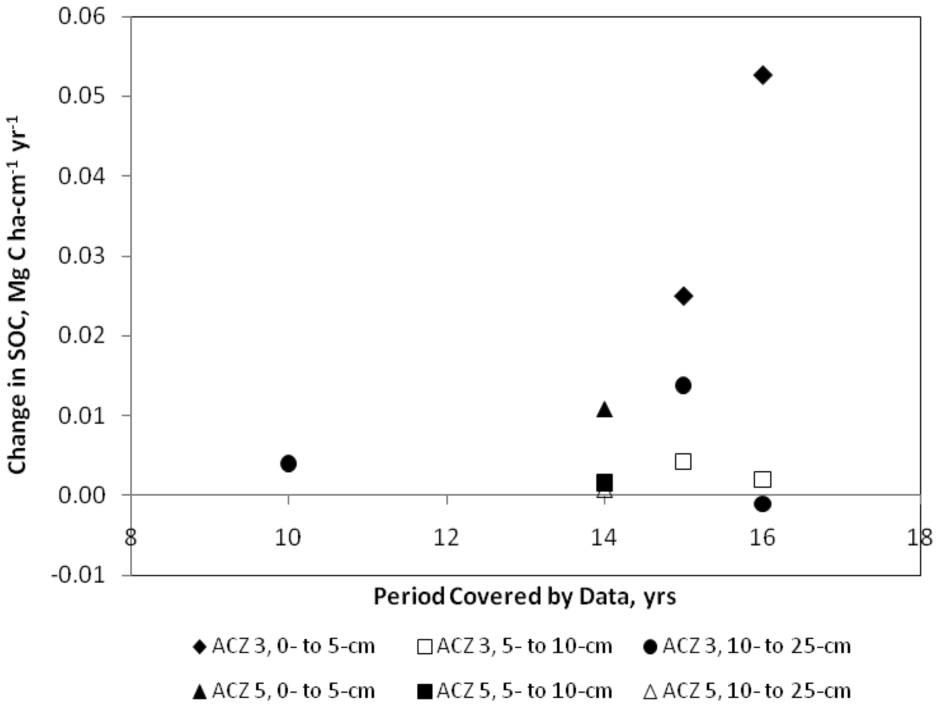
†This figure includes only those data sets in which SOC was sampled in more detailed depth increments. Data sets with surface sampling depth increments greater than 15-cm were not included in order to appropriately characterize the distribution of SOC content changes.

The profile change in SOC was calculated by integrating the exponential equation to a depth of 20-cm to obtain profile changes for studies in which SOC was not reported to these depths. From these data we do not expect a difference in SOC between NT and CT from approximately 20- to 125-cm. This allowed for SOC changes to be expressed on a 125-cm profile depth basis.

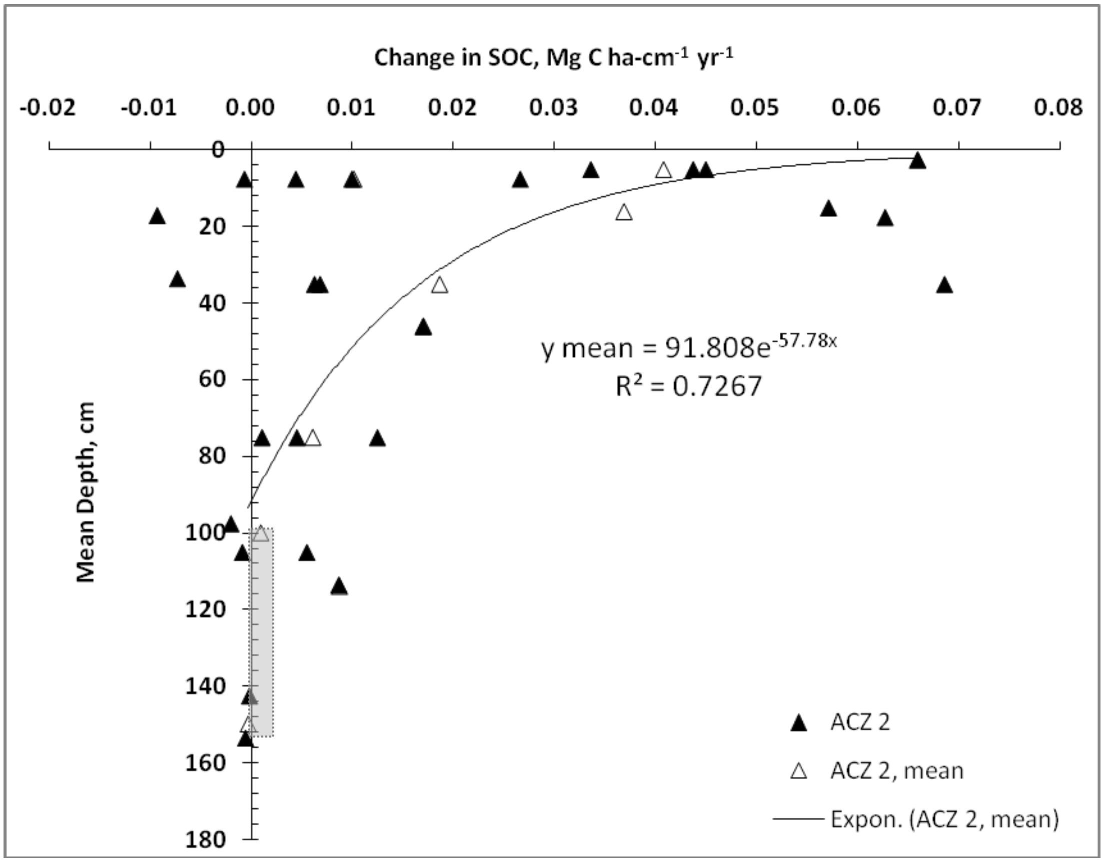
Appendix 7. Change in Soil Organic Carbon Following Adoption of No-Tillage versus Period of Time Under No-Tillage by Depth for ACZ 2.



Appendix 8. Change in Soil Organic Carbon Following Adoption of No-Tillage versus Period of Time Under No-Tillage by Depth for ACZ 3 and 5.

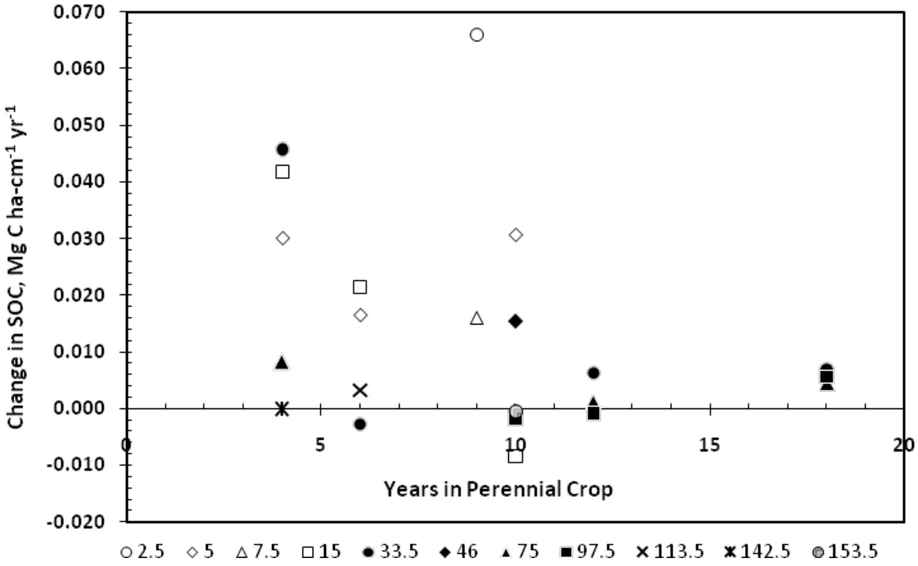


Appendix 9. Distribution of Soil Organic Carbon Content Change for All Data Points in a Mixed Perennial-Annual Compared to Annual Crop Rotation Management for ACZ 2.



The profile change in SOC was calculated by integrating the exponential equation to 100-cm and/or taking the area of the rectangle from 100- to 155-cm to obtain the changes in SOC stocks for studies in which SOC was not reported to these depths. This allowed for SOC changes to be expressed on a 155-cm profile depth basis.

Appendix 10. Change in Soil Organic Carbon under a Mixed Perennial-Annual Compared to an Annual Crop Rotation versus Period of Time in Perennial Crop for ACZ 2.



Appendix 11. Total Cropland Estimates by Agroclimatic Zone and State.

Agroclimatic Zone	Total Land		AMT. in cropland†	Total Cropland Est.	
State	million			million	
	ac	ha	%	ac	ha
Zone 1 Total	54.98	22.25	< 20	11.00	4.45
ID	32.86	13.30		6.57	2.66
OR	9.85	3.99		1.97	0.80
WA	12.28	4.97		2.46	0.99
Zone 2 Total	2.98	1.21	95	2.83	1.15
ID	1.62	0.66		1.54	0.62
OR	0.24	0.10		0.23	0.09
WA	1.11	0.45		1.06	0.43
Zone 3 Total	2.16	0.87	90-95	1.94	0.79
ID	1.26	0.51		1.13	0.46
OR	0.13	0.05		0.11	0.05
WA	0.78	0.32		0.70	0.28
Zone 4 Total	30.27	12.25	50	15.13	6.12
ID	4.44	1.80		2.22	0.90
OR	22.73	9.20		11.37	4.60
WA	3.09	1.25		1.55	0.63
Zone 5 Total	9.91	4.01		6.45	2.61
ID	0	0			
OR adj to WA	1.84	0.75	90	1.66	0.67
S. OR	3.52	1.42	< 20	0.70	0.28
WA	4.54	1.84	90	4.09	1.65
Zone 6 Total	22.56	9.13	not reported	-	-
ID	13.12	5.31	-	-	-
OR	4.10	1.66	-	-	-
WA	5.34	2.16	-	-	-

† Adapted from Douglas et al., 1990

Appendix 12. Estimated Total Soil Organic Carbon Loss During the Average Number of Years Covered by Data for Native Conversion to Cropland by ACZ and State.

ACZ	Total Est. Cropland	Period Covered by Data	Estimated Total SOC Loss Over Mean Period Covered by Data			
State	million ha	yrs	Mean (±1 std dev)	25th Percentile‡	Mean (±1 std dev)	25th Percentile
			-------------- MMT --------------		---------- $MMTCO_2e$† ----------	
2, total	1.15	74	-73.74 (16.10)	59.33	-270.15 (59.00)	217.36
ID	0.62		-40.17 (8.77)	32.32	-147.15 (32.14)	118.40
OR	0.09		-6.04 (1.32)	4.86	-22.14 (4.84)	17.82
WA	0.43		-27.53 (6.01)	22.15	-100.85 (22.03)	81.15
3, total	0.79	55	-26.83 (9.95)	16.44	-98.29 (36.46)	60.24
ID	0.46		-15.60 (5.79)	9.56	-57.14 (21.20)	35.02
OR	0.05		-1.55 (0.58)	0.95	-5.69 (2.11)	3.49
WA	0.28		-9.68 (3.59)	5.93	-35.46 (13.15)	21.73
5, total	2.61	7	-12.61 (9.50)	2.56	-46.20 (34.82)	9.37
ID						
OR adj. to WA	0.67		-3.24 (2.44)	0.66	-11.88 (8.95)	2.41
S. OR	0.28		-1.38 (1.04)	0.28	-5.04 (3.80)	1.02
WA	1.65		-7.99 (6.02)	1.62	-29.28 (22.07)	5.94

†$MMTCO_2e$, million metric tons of carbon dioxide equivalents; trading unit.

‡ Represents SOC changes at the 25th percentile of the cumulative probability function.

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