Soil Carbon Storage in Willamette Valley Grass Seed Systems: A review

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Abstract

Agricultural systems have potential to store carbon (C) when soil C management practices are in place. Some of these practices may include the production of perennial crops, inclusion of grass species in a crop rotation, reduced tillage, and leaving post-harvest crop residues in the field. Increases in soil C could be beneficial to enhance soil fertility, soil biodiversity, and soil structure, and could also provide opportunities for participation in future C markets. There is great interest to determine the C storage of Oregon grass seed systems and the role of management practices on C cycling for potential involvement in cap-and-trade, soil C, or soil health incentive programs. A better understanding of these factors should help inform future offset projects and help establish the potential for the grass seed industry to participate in incentive programs that may reward management decisions that lead to reduced greenhouse gas emissions or greater C storage. This review presents the current state of knowledge on C storage in both perennial and annual grass seed cropping systems and identifies knowledge gaps as a resource for C storage estimates. Soil C discussions are focused on two main themes: 1) overall estimates of soil C storage and the factors that influence this parameter in the topsoil of grass seed production fields, and 2) comparison of how soil C storage in grass seed cropping systems compare to intensively managed and uncultivated/minimally managed cropping systems.

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BACKGROUND

Agricultural systems have potential to store carbon (C) when soil C management practices are in place. Some of these practices may include the production of perennial crops, inclusion of grass species in a crop rotation, reduced tillage, and leaving post-harvest crop residues in the field. Increases in soil C could be beneficial to enhance soil fertility, soil biodiversity, and soil structure, and could also provide opportunities for participation in future C markets. There is great interest to determine the C storage of Oregon grass seed systems and the role of management practices on C cycling for potential involvement in cap-and-trade, soil C, or soil health incentive programs. A better understanding of these factors should help inform future offset projects and help establish the potential for the grass seed industry to participate in incentive programs that may reward management decisions that lead to reduced greenhouse gas emissions or greater C storage.

This review presents the current state of knowledge on C storage in both perennial and annual grass seed cropping systems and identifies knowledge gaps as a resource for C storage estimates. Soil C discussions are focused on two main themes: 1) overall estimates of soil C storage and the factors that influence this parameter in the topsoil of grass seed production fields, and 2) comparison of how soil C storage in grass seed cropping systems compare to intensively managed and uncultivated/minimally managed cropping systems.

APPROACH

A literature review was conducted to obtain estimates of C stocks in Willamette Valley (WV) grass seed cropping systems. Reviewed literature included peer reviewed journal articles, theses, dissertations, Extension publications, and OSU Seed Production Research Reports. The literature was reviewed for two key pieces of information: the total C at a specified depth (topsoil; 0-8 inches), and the soil bulk density (oven dried mass of soil per unit volume). Studies with vaguely described soil collection and C measurement methods were excluded.

The reviewed studies in the WV included all of the major grass seed species (tall fescue, annual ryegrass, perennial ryegrass, fine fescue, and orchardgrass) with the most representation of tall fescue and annual ryegrass seed systems (Table 1; Table 4). For comparison purposes, studies that evaluated WV soil C in intensively managed cropping systems (Table 2), as well as uncultivated or minimally managed systems (Table 3) were also included in the review. Intensively managed agricultural systems were defined as non-grass seed cropping systems where annual tillage is a common practice, such as row crops. Total C estimates for all studies reviewed were reported primarily for 0-6 and 0-8 inch soil depths and were presented as total carbon (C), total organic C (TOC), and organic matter (OM). Several assumptions were used to calculate total C from OM and TOC values reported in the literature. When the original data were reported as OM, values were divided by a factor of 1.72 to estimate total C concentration, based on the commonly applied assumption that OM compounds consist of approximately 58% C based on the proportion of C, hydrogen, and oxygen elements in most OM compounds. It was also assumed that values reported as TOC were equivalent to total C as the soil pH values were all lower than 5.9, indicating an absence of carbonates, a non-organic C form commonly found in alkaline and calcareous soils. It was further assumed that soil C concentrations and bulk density for either the 0-6 or the 0-8 inch soil depths are similar, therefore studies where soil C was analyzed at either of those depths were included and compared in our analyses. Soil bulk density measurements are also needed to accurately estimate amount of C for a specific area and soil depth. Reported bulk density values and depths were used for C stock calculations in this review. When bulk density was not reported, a bulk density of 1.2 g/cm^3 was used for grass seed and intensively managed cropping systems (Verhoeven et al., 2020; Trippe et al., 2020; Horwath et al., 1998), and bulk density of 0.95 g/cm^3 was used for the minimally managed systems (Lawrence and Kay, 2007; Horwath et al., 1998).

Soil C findings were compared statistically for cases where there was sufficient data to be analyzed. Differences between the impact of soil C by factors including grass species, annual vs. perennial cropping, soil texture, and grass seed cropping vs. other contrasting land uses, were analyzed using t-tests for group comparisons in R Studio (R Core Team, 2018). Mean differences were considered to be significant when p-values were <0.05.

Table 1. Grass species, soil carbon (C) analysis method, soil depth, bulk density, and soil series information for twelve soil C studies conducted in Willamette Valley grass seed cropping systems from 1978 to 2021.

Publication	Grass species	C analysis method	Soil depth (inch)	Bulk density (g/cm^3)	Soil series
Chapin, 1992	ARG*	Combustion	0-6.7	1	Dayton
Chastain et al., 2017	ARG	Combustion	0-8	NA	Woodburn
Griffith et al. 2011	PRG/TF/FF*	Combustion	0-8	NA	Amity/Woodburn/Nekia
Hart et al., 2011	ARG	NA-%C	0-6	NA	Dayton
Horwath et al. 1998	PRG*	NA-g/kg C	0-6	1.3	Dayton/Holcomb
Knight and Dick, 2004	ARG	Combustion	0-6	NA	Dayton
Laurent, 1978	ARG	Walkely Black	0-6	NA	Dayton/Amity/Concord/ Woodburn
Makepeace, 2021	TF*	Walkely Black	0-6	NA*	Aloha/Amity/Awbrig/Bashaw/ Bellpine/Camas/Concord/ Conser/ Cornelius/Cove/Dayton/Jory/ Malabon/ Natroy/Nekia/Salem/ Willamette/Woodburn
Mellbye et al. 1997	ARG	NA-%OM*	0-8	NA	Woodburn
Qureshi, 1994	TF	Walkely Black	0-6	NA	Amity/Woodburn
Trippe et al., 2020	ARG/OG*/ TF/PRG	Combustion	0-8	0.9-1.4	Amity/Awbrig/Coburg/Concord/ Conser/Dayton/Holcomb/Malabon/ Willamette/Waldo/Willakenzie/ Woodburn
Verhoeven et al, 2020	TF/PRG	Combustion	0-8	1.0-1.4	Aloha/Amity/Bashaw/Dayton/ Helvetia/Malabon/Laurelwood/ Nekia/Quatama/Woodburn

*PRG=perennial ryegrass, ARG=annual ryegrass, TF=tall fescue, FF=fine fescue, OG=orchardgrass, LOI=loss on ignition; OM=organic matter; NA=an assumed bulk density of 1.2 g/cm^3 was used for C stock calculations in these studies.

Table 2: Crop rotation, soil carbon (C) analysis method, soil depth, bulk density, and soil series information for three soil C studies conducted for intensively managed Willamette Valley cropping systems from 1998 and 2002

Reference	Crop rotation	C analysis method	Soil depth (inch)	Bulk density (g/cm^3)	Soil series
Ndiaye, 1998	Vegetable rotation**	Combustion	0-6	NA*	Willamette
Schutter and Dick, 2002	Vegetable rotation**	LOI	0-6	NA	Chehalis
Whalen et al. 2000	Vegetable rotation**	Combustion	0-6	NA	Willamette

*NA=an assumed bulk density of 1.2 g/cm^3 was used for C stock calculations in these studies
** Summer vegetable rotation (sweet corn, broccoli, green bean), with either winter fallow or a winter cover crop (oat, common vetch, red clover or triticale)

Table 3: Land use, soil carbon (C) analysis method, soil depth, bulk density, and soil series information for eight soil C studies conducted in minimally managed Willamette Valley cropping systems from 1978 to 2020.

Reference	Land use	C analysis method	Soil depth (inch)	Bulk density (g/cm^3)	Soil series
Chapin, 1992	Grassland	Combustion	0-6.7	1.0	Dayton
Day, 2015	Prairie	Combustion	0-6	NA*	Santiam
Horwath et al. 1998	Riparian area	NA-g/kg C	0-6	1.1	Dayton/Holcomb
Knight and Dick, 2004	Grassland	Combustion	0-6	NA	Dayton
Laurent, 1978	Pasture	Walkley Black	0-6	NA	Dayton/Amity/Concord/ Woodburn
Lawrence and Kay, 2006	Prairie	LOI	0-6	0.8-0.1	Burlington/Bellpine/ Chehulpum/Jory/Steiwer/ Dixonville
Sharrow and Ismail, 2004	Pasture	Combustion	0-6	0.97	Philomath
Trippe et al. 2020	Homestead/ Cemetery	Combustion	0-8	0.9-1.5	Salkum/Salem

*NA=an assumed bulk density of 0.95g/cm^3 was used for C stock calculations in these studies

CARBON STORAGE POTENTIAL IN WILLAMETTE VALLEY GRASS SEED CROPPING SYSTEMS

Reported average topsoil C storage was 24.2 tons/acre for WV perennial grass seed production for all species and 21.9 tons/acre for WV annual ryegrass production (Table 4). Specifically, perennial grass seed cropping systems had 11.8% more topsoil C stocks than annual ryegrass ($p=0.045$). Lower soil C stocks in annual ryegrass seed production systems compared to perennial grass seed cropping systems could be a result of differences in root development. Estimates of root biomass density in perennial grass seed crops range between 0.34 and 2.16 oz/ft^3 at a 12-inch depth (Chastain et al., 1999). In comparison, Griffith et al. (1997) estimated annual ryegrass root biomass to be relatively lower at an average of 0.68 oz/ft^2, although these root biomass estimates may require validation because the sampling depth was not specified in that study. Regular physical soil disturbance may also explain the reduction in soil C in annual ryegrass seed crops given that at least half of the annual ryegrass fields included in this review were frequently tilled. Tillage breaks up the soil and increases aeration that can promote faster degradation of soil C, although tillage may not be as influential at roots. The specific effects of tillage in grass seed systems are discussed in a later section. Further research is needed to understand how roots, tillage, and other factors in both perennial and annually produced grass seed cropping systems contribute to soil C storage potential.

Within the different perennial grass seed crops, tall fescue was the most widely represented in our dataset and comprised 64 of the 72 fields evaluated (Table 4). These fields covered 22 different soil series across the WV, resulting in a wide range of soil C stocks that spanned from 15.9 to 48.1 tons/acre (1.9% C and 5.9% C respectively) (Makepeace, 2021), with an average of 23.5 tons/acre (2.8% C). Statistical comparisons of soil C stocks amongst perennial grass seed crops was only possible for tall fescue and perennial ryegrass given the limited number orchardgrass and fine fescue fields sampled (Table 4). The average C concentrations and C stocks of perennial ryegrass were 26.4 tons/acre and 2.8%, respectively. These data for perennial ryegrass did not differ from the averages reported for tall fescue ($p>0.47$). The similarity between C concentration and C stock of tall fescue and perennial ryegrass may be attributed to similarities in rooting structure. It should be noted that a large number of the soil C studies reviewed only focused on one grass species instead of multiple species. Future studies on soil C storage potential may need to simultaneously evaluate multiple grass species to understand how soil C stocks are impacted by species.

Table 4: Reported average topsoil carbon (C) concentrations and C stocks at the 0-6 inch or 0-8 inch soil depths in Willamette Valley grass seed fields, summarized from twelve published studies described in Table 1.

Species	No. of studies	No. of fields	Mean soil C%	Mean C stock (ton/acre)
----------------------------Perennial grass seed production---------------------------				
Tall fescue	5	64	2.8	23.5
Perennial ryegrass	4	5	2.8	26.4
Orchardgrass	1	2	3.8	37.7
Fine fescue	1	1	2.9	31.5
Perennial grass seed, all species	**11**	**72**	**2.8**	**24.2**
--------------------------Annual grass seed production-----------------------------				
Annual ryegrass seed	**7**	**26**	**2.4**	**21.9**

SOIL CHARACTERISTICS AND CROP MANAGEMENT EFFECTS

Soil texture and soil drainage class

There are two main soil and site factors that can inherently affect soil C concentrations at a local scale: the soil texture and drainage capacity. Fine textured soils (with high silt and clay contents) tend to have more C because organic material is better protected from microbial decomposition. This is due to the binding of organic matter with clay particles, and the protection of C inside of soil aggregates. Specific amounts and types of clays will differ in their capacity to bind and stabilize OM, therefore texture can be a key factor that limits the level of C that can accumulate in a specific soil system. In terms of drainage class, it has been theorized that poorly drained soils are likely to store more C than similar textured soils that are well-drained, because lower oxygen content decreases potential C turnover and release (Weil and Brady, 2017).

Grass seed production takes place across a large variety of soil series that have a wide range of clay contents (10-47%, Figure 1) and for the most part can be categorized as silt loams or silty clay loams. The clay content and therefore the potential for soil C accumulation is expected to differ between silt loams and silty clay loams. Some of the predominant soil series in WV grass seed production include clays/silty clay loam soils such as Bashaw, Conser, Malabon, McBee, Verboort, Cove, Wapato, Steiwer and Hazelair, and silt loams/loams such as Dayton, Willamette, Amity, Woodburn, Chehalis, Clackamas, Newberg, Nekia, Jory, Stayton, Helmick, Laurelwood, and Aloha (Hart et al., 2012; Hart et al., 2011; Anderson et al., 2014). Past studies have found that OM concentrations across several of these soil series were positively correlated (R^2=0.56) to clay content in 52 tall fescue and 12 annual ryegrass seed fields sampled at an 8-inch depth (Figure 1; Verhoeven et al., 2020; Makepeace, 2021; Gonzalez Mateu et al., 2022 unpublished).

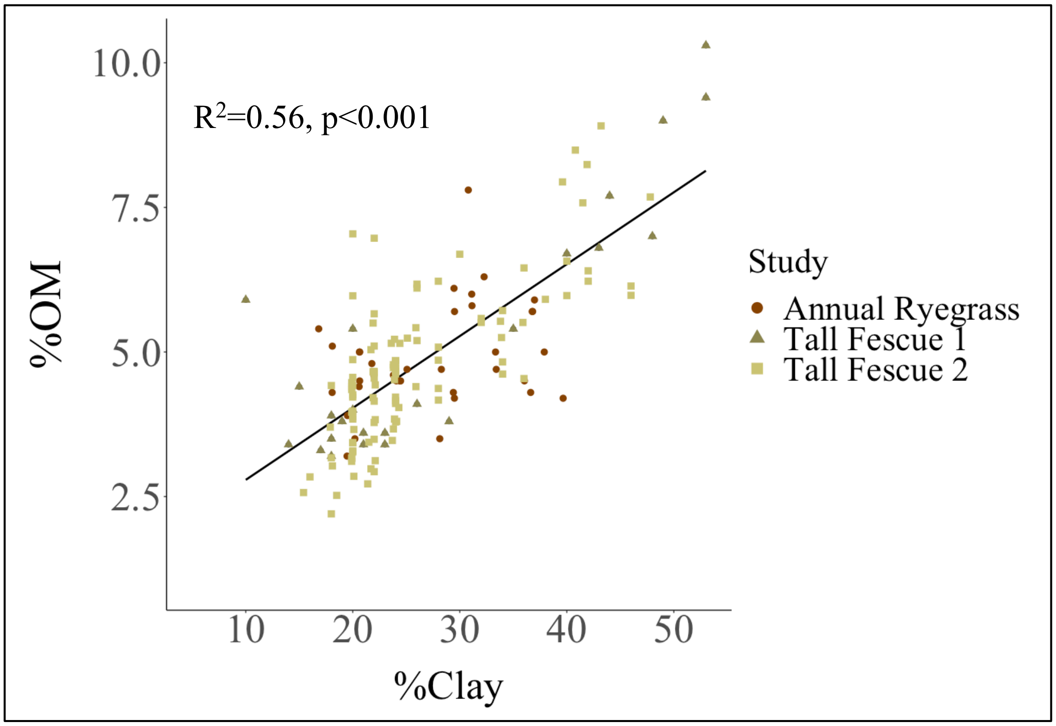

Figure 1. Comparison between topsoil clay content and organic matter (OM) concentration from 64 grass seed production fields. Data originates from two tall fescue studies (Tall Fescue 1-Verhoeven et al., 2020 and Tall Fescue 2-Makepeace, 2021) and one annual ryegrass study (Gonzalez Mateu et al., 2022 unpublished).

Further analysis of the soil C data from the studies presented in Table 1 showed differences in soil C concentration and stocks between silt loams (average 20.4% clay) and silty clay loams (average 31.8% clay). Silty clay loam textured soils store more C at the 0-8 inch depth (31.7 tons/acre, 3.6% C) than silt loam textured soils (20.14 tons/acre, 2.2% C) ($p<0.001$) (Figure 2). Specifically, average values were 20.4 and 27.4 tons/acre for annual ryegrass in silt loam and silty clay loam respectively, and 20.4 and 32.7 tons/acre for perennial grass seed crops in silt loams and silty clay loams respectively. The observed difference in soil C between textures is most likely related to inherent soil properties that can affect C accumulation and degradation in soils such as texture and drainage. Therefore, comparisons of soil C between grass seed systems that are often grown in high clay soils (like fine fescue) and other grass seed systems should be done with caution and considering soil texture effects on C storage.

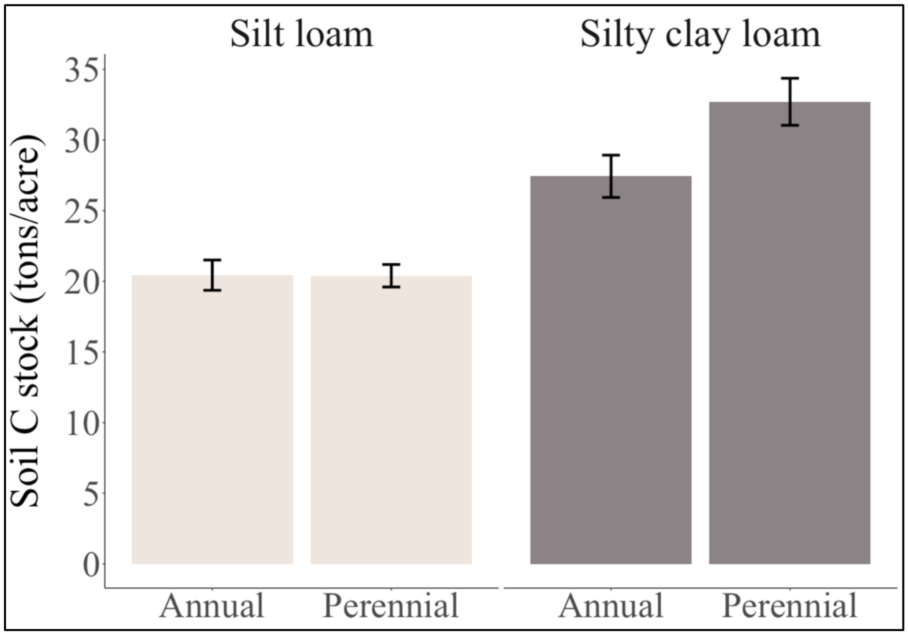

Figure 2. Topsoil carbon (C) stocks in Willamette Valley annual and perennial grass seed cropping systems for 43 silt loam and 23 silty clay loam soil textures. Data originated from studies presented in Table 1.

Topsoil C concentrations in WV soils have also been found to differ between well drained and poorly drained soil types. Pomerening (1961) surveyed 114 sites under different land uses across the WV and found that mean soil C concentration was significantly lower (0.7% less) in poorly drained Dayton soils compared to better-drained Amity, Woodburn, and Willamette soils. Similarly, in perennial and annual grass seed systems, Laurent (1978) reported that poorly-drained soils (Dayton and Concord) had on average 0.6% less C than moderately well-drained soils (Amity and Woodburn). Griffith et al. (2011) found on average 2.9% less C concentration in soils of perennial grass seed crops growing in Amity and Woodburn soils compared to a well-drained Nekia soil in fine fescue seed production. In general, the previous studies suggest an overall trend of greater topsoil C concentration with improved drainage in WV soils. These observations could be due to higher plant productivity in well-drained systems, but further studies would be needed to verify this.

Tillage management

Conventional tillage is a common method used to establish annual and perennial grass seed crops in the WV. Conventional tillage types, including disking and plowing, can accelerate soil C decomposition by increasing aeration and breaking up soil aggregates, making C more accessible to microbes (Weil and Brady, 2017). Conventional tillage has been shown to impact several soil abiotic and biotic factors in Oregon grass seed production systems including soil water content and nitrogen mineralization (Nelson et al., 2006). Therefore, tillage practices could have the potential to affect overall C storage in grass seed systems. Alternative methods of grass seed crop establishment include no-till planting as well as volunteering seedlings from shattered seeds of the previous year's crop (Hart et al., 2011).

There are two field studies that addressed the effects of tillage on topsoil C storage. The first study was focused on annual ryegrass (Chastain et al. 2017) while the other study was focused on tall fescue and perennial ryegrass (Griffith et al. 2011). Annual ryegrass is often grown continuously in poorly drained WV soils where tillage is common between crops. Chastain et al. (2017) assessed the effects of tillage and establishment methods after nine years of continuous annual ryegrass seed production. Overall, the authors found that conventional tillage did not significantly reduce soil C concentration at a 0-8 inch soil depth in comparison to other tillage and establishment methods which included no-till and volunteering. Griffith et al. (2011) reached a similar conclusion that tillage may not be detrimental to long-term C sequestration, and found that there was no effect of increased tillage on soil C concentration at a 0-4 inch depth in a poorly drained perennial ryegrass location. However, that same study also observed mixed results on soil C concentration in a moderately well-drained site planted to tall fescue.

Overall, the studies by Chastain (2017) and Griffith (2011) suggest minimal effects of tillage on topsoil C. These studies support the views expressed by Banowetz et al. (2009) that agronomic management practices have little effect on C sequestration because WV soils are generally rich in C. However, it is important to highlight that total C is a metric that can sometimes take decades to change following the implementation of new management practices. Therefore, assessment of other C pools that can be more responsive to management changes may be of interest. Some alternative metrics include assessment of labile C pools like dissolved organic C (DOC), microbial biomass C (MBC), or estimating the overall pools of readily oxidizable C by measuring active C (POXC).

In some instances, the effects of tillage on soil C may become more evident if additional C pools or longer time periods are evaluated. For example, the previously presented study by Griffith et al. (2011) reported a negative effect of tillage on topsoil C (0-4inch depth) in one of the three study locations. At that location, SOM, DOC and MBC decreased by 15.4%, 33.0% and 42.5%, respectively, in a 6-year continuous tall fescue cropping system relative to the grass/legume and grass/legume/cereal rotations used for comparison. Similar results were observed by Nelson et al. (2006) who found 20-30% lower MBC in conventionally tilled fine fescue and tall fescue seed crops compared to no-till grass seed rotations. Furthermore, preliminary data from Gonzalez Mateu et al. (2022, unpublished) illustrated that a combination of tillage and post-harvest straw removal on three annual ryegrass seed fields significantly decreased OM and POXC by 12.5 and 18%, respectively, in comparison to three no-till annual ryegrass seed fields with no straw removal when on silt loams. In contrast, there was no significant effect of combined tillage and straw removal when a similar comparison was made for annual ryegrass seed fields on silty clay loams. In addition, preliminary data from annual ryegrass seed fields sampled at different years since implementation of conservation farming practices (tillage only every 7-13 years), suggests that total soil C and POXC increased by 15.7%

and 28.8%, respectively, after 25 years of using such practices (Trippe et al. 2020, unpublished). Future studies of soil C in WV should include multiple measurements of different C pools to evaluate the effects of management practices in shorter time scales.

A summary of the available data of soil C in till and no-till annual ryegrass seed cropping systems is presented in Table 5. Analysis of this data suggests that there are no differences in topsoil C concentrations between conventionally tilled (2.2% C) and no-till (2.6% C) annual ryegrass seed crops in the WV ($p=0.35$). Although differences in soil C were not significant, it is possible that agronomic management could have an effect on other C pools that are more responsive to changes in management practices as suggested previously. However, the available data do not allow for this comparison.

To summarize, this review only found two published studies that compared conventional tillage and no-till practices in grass seed cropping systems, but both were <9 years in duration (Griffith et al., 2011; Chastain et al., 2017). This is a challenge when trying to estimate changes in soil C from tillage practices given that changes in soil C can take many years to be detected. For example, a recent metanalysis suggested that no-till practices could increase soil OM concentration by 34-39% when implemented for 8-16 years, but found no differences between tillage practices when experimental duration was less than 8 years (Kan et al. 2021). Assessment of other C pools could help aid in this respect, but implementation of long-term studies using standardized methodologies would be necessary to help further evaluate the effects of tillage on soil C in WV grass seed cropping systems.

Table 5. Reported topsoil carbon (C) concentrations in Willamette Valley perennial and annual grass seed cropping systems as influenced by straw management, tillage, and soil texture.

Grass	No of fields	Soil depth (inch)	Management	C%	References
Tall fescue	22	0-8	Straw	2.2	Verhoeven et al. 2020; Griffith et al. 2011; Trippe et al. 2020
	21		Bale	2.3	
Annual ryegrass	13	0-8	No till	2.6	Chastain et al. 2017; Trippe et al. 2020
	12		Till	2.4	
Fine fescue	2	0-4	Straw	3.4	Griffith et al. 2011; Dick and Christ, 1996
	2		Bale	3.1	
Perennial ryegrass	2	0-8	Straw	2.8	Griffith et al. 2011; Verhoeven et al. 2020 (unpublished)
	1		Bale	1.6	

Straw residue management

Postharvest residue management in grass seed cropping systems was historically reliant on residue burning. However, after legislative restrictions were imposed on open-field burning for most WV grass seed crops in the mid-1980s, the predominant methods now used to manage residue are either baling and removing it, or chopping the full straw load and uniformly spreading it onto the field to decompose. Long-term return of residue-C would be expected to increase C sequestration as levels of soil organic C can be linked to fresh OM inputs (Kong et al., 2005; Paustian et al., 1997). However, studies on the effect of residue management on C pools in grass seed cropping systems show variable results.

Some studies have found positive effects of full straw management on various C pools in grass seed cropping systems in silt loams. For example, total C, OM, DOC, and MBC concentrations increased in the top 0-4 inches under full straw management compared to baled treatments in a 6-year continuous tall fescue seed field rotation (Griffith et al. 2011). The same pattern of increased DOC and MBC was observed at the 0-4 inch soil depth in a 3-year continuous perennial ryegrass seed production system with a full straw load management (Barry, 1999; Dick and Christ, 1996). Similarly, a study in annual ryegrass reported a small increase in OM of 0.15% at the 0-8 inch depth after 3 years with a full straw load compared to continuous baling treatments (Mellbye et al., 1997). The overall findings of increased soil C when straw residue remains in the field are further supported by Hart et al. (2012) who suggested that OM can slowly increase in the top 1-2 inches of soil when switching from baling to full straw management.

In contrast, other studies found no effect of straw residue retention on various C pools. Verhoeven et al. (2020) carried out a survey across various soils in the WV in 14 paired tall fescue fields that were either baled or had a history of full straw management. The authors found no differences between the two postharvest residue management practices for total C, OM or POXC concentration in soils sampled at a 0-8 inch depth. Further analysis of some of these soil samples at a 0-3 inch depth also reflected no differences in total or POXC carbon pools. In addition, some of the previously referenced studies that showed some positive effects of full straw loads on C pools, also had some examples were straw residue management did not affect soil C. For example, Dick and Christ (1996) found no effects of straw management on C or OM in a perennial ryegrass seed field, while Griffith et al. (2011) reported no effects of straw residue on soil C, MBC and DOC in a perennial ryegrass seed field or on any of the evaluated C pools in a fine fescue seed field.

The available data on the effects of post-harvest residue management practices on soil C in the topsoil of grass seed systems is summarized in Table 5. Of the three different perennial grass species evaluated for the effects of straw residue management, only tall fescue had enough replicates to allow for statistical comparisons of residue management practices (Table 5). Baled tall fescue fields had 2.3% C, while full straw tall fescue fields had 2.2% C ($p=0.86$). Therefore, data compiled in this review suggest that post-harvest residue management practices have no effect on total C in the topsoil. Limited data were available for perennial ryegrass and fine fescue, and although full straw fields appeared to have higher soil C concentration compared to baled fields, more data are needed to determine if those differences are statistically significant.

The effects of post-harvest residue management practices on the different pools of soil C were found to be variable between studies, within studies, and also between grass seed systems. These mixed results suggest that site specific characteristics (such as soil type and drainage) are relevant to determine the outcome of these practices. Although full straw management has been reported to have both positive and neutral effects on soil C pools compared to baling, it is important to note that none of the studies reported negative effects of this practice on soil C.

COMPARISON OF SOIL CARBON STORAGE IN GRASS SEED CROPS AND CONTRASTING LAND USES

Row crops and other intensively managed cropping systems

Mean soil C concentration at the 0-6 inch depth for intensively managed cropping systems in the WV was 1.7% C and 13.7 ton C/acre, based on three studies across three row crop vegetable production fields (Table 6). More research is needed to validate these C stock estimates in other intensively managed cropping systems in the WV, such as wheat, corn, mint, specialty seed crops, and other vegetables. For the purpose of this literature review, we compared grass seed systems to the mean C values from Table 6, understanding that these comparisons may shift as more studies on C stocks in other agricultural systems are conducted. A greater sampling size will also help confirm that differences in C stocks is caused by the crop species more so than inherent differences in C storing potential between soil types and textures.

This preliminary evaluation implies greater potential for C accumulations in both annual and perennial grass seed cropping systems compared to vegetable production systems grown in similar soils. Specifically, perennial (2.8% C) grass seed fields and annual (2.4% C) grass seed fields had 1.1% and 0.7% greater soil C concentrations than vegetable production systems (1.7% C) at the 0-6 inch soil depth, respectively (Figure 3). This is an encouraging finding, suggesting that grass seed production, either annual or perennial, could increase C storage potential compared to some other intensively managed crops. The observed differences could be related to increased plant biomass inputs (primarily from roots) or possibly differences in tillage practices. Perennial crops in general have been shown to increase soil C through reduced tillage and greater root biomass inputs compared to annual crops (Bray, 1963; Paustian et al. 1997; Bolinder et al. 2002). Similarly, the observed difference in annual ryegrass and the intensively managed crops assessed here may be caused by shallow and limited root systems developed by vegetable crops like broccoli, sweet corn and green beans compared to annual ryegrass, which could limit root C contributions (Lott and Hammond, 2013; Kristensen and Thorup-Kristensen, 2004). We strongly emphasize that more data are needed in order to solidify these comparisons. In addition, soil C research is also needed in other intensively managed non-grass seed crops in the WV like corn, wheat, canola, specialty seed, various cover crop species, etc., to better quantify variations in root systems, cultural practices, and other factors that may influence topsoil C storage potential.

Table 6. Reported topsoil carbon (C) concentrations and C stocks at the 0-6 inch soil depth in intensively managed Willamette Valley agricultural production systems, summarized from three published studies described in Table 3.

System	No of studies	No of fields	C%	C stock (ton/acre)
Vegetable rotation*	3	3	1.7	13.7
Overall mean			**1.7**	**13.7**

* Sweet corn, broccoli, green bean rotation with either winter fallow or a winter cover crop (oat, common vetch, red clover or triticale).

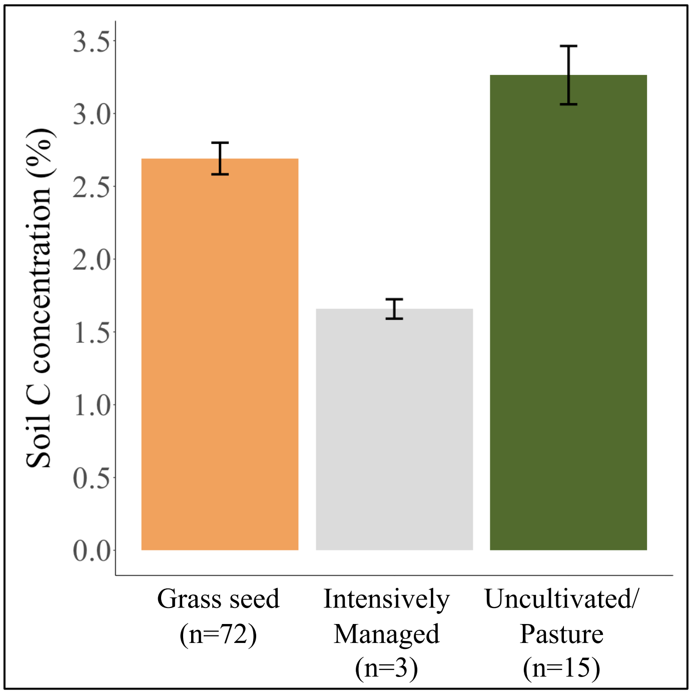

Figure 3. Topsoil carbon (C) concentration in published Willamette Valley grass seed, intensively managed and minimally managed systems. Data originated from studies listed in Tables 1, 2, and 3.

Prairies, pastures, grasslands, and other minimal management systems

Our findings showed that topsoil C concentrations in WV grass seed cropping systems were lower than in minimally managed areas on similar soil types ($p=0.02$). Specifically, topsoil C concentration in minimally managed areas were higher (3.5% C) than perennial and annual grass seed fields (2.8 and 2.4% C respectively). The increase in mean C value of 1% concentrations in the minimally managed areas compared to grass seed cropping systems may be attributed to lack of soil disturbance that could enhance C decomposition, and/or year-round photosynthetic activity leading to increased plant residue inputs to the soil.

Table 7. Reported topsoil carbon (C) concentrations and C stocks at the 0-6, 0-6.7, and 0-8 inch soil depths in Willamette Valley uncultivated or minimally managed systems, summarized from eight studies described in Table 3.

System	No of studies	No of sites	C (%)	C stock (ton/acre)
Prairie	2	6	3.1	26.4
Riparian area	1	2	3.2	19.0
Pasture	2	5	3.1	12.9
Grassland	2	2	2.3	13.9
Cemetery and Homestead	1	2	3.2	35.3
Overall mean			**3.5**	**23.9**

Although total C concentrations were higher in minimally managed systems compared to grass seed production systems, estimated C stocks did not differ ($p=0.47$). This discrepancy is due to increased bulk density estimates in grass seed cropping systems. Again, bulk density for minimally managed systems was estimated at 0.95 g/cm^3 and 1.2 g/cm^3 for grass seed cropping systems, based on findings from other studies conducted in similar management systems (Horwath et al., 1998; Lawrence and Kay, 2006; Verhoeven et al., 2020; Trippe et al., 2020 unpublished). Possible reasons for lower bulk density in the minimally managed system compared to grass seed cropping systems may include lack of tillage that can lead to soil compaction in annual cropping systems, and higher OM and root structures that promote soil porosity in minimally managed systems. In the future, both bulk density and C concentration analyses are needed to accurately estimate and compare C sequestration capabilities of these important production systems. In either case, if the lower bulk densities can be validated on other minimally managed sites, then the combination of higher C and lower bulk density could illustrate that C stocks are actually very similar in these systems. Minimally managed and uncultivated systems are generally considered to have a high capacity for C sequestration compared to agricultural fields (Weil and Brady, 2017), further suggesting that grass seed cropping systems may be more similar to minimally managed systems in their C sequestration capacity than annual cropping systems, like row crop production.

Additional studies that assess bulk density and soil C in both intensively and uncultivated/minimally managed systems would help further assess the conclusion presented in this review.

FUTURE RESEARCH CONSIDERATIONS

Soil sampling approach

In order to standardize the methodology for future C stock estimates in grass seed fields we recommend following the guidelines from the Food and Agricultural Organization FAO (2019). These guidelines include sampling strategies (for example, stratified sampling by soil series), sample processing, and C stock calculations. Briefly, to obtain accurate C stocks, researchers must measure three parameters: C% of soil that passes through a 2mm mesh, the coarse mineral fraction (>2mm size), and the bulk density of the soil. The guidelines further recommend that bulk density be estimated from the same cores used to collect soil for the C analysis because sampling of soils by coring almost inevitably results in some compaction (Ellert et al. 2001). In terms of analytical methodology, FAO (2019) recommends using combustion analysis when possible; alternatively, wet oxidation (Walkley Black method) may be used. Lastly, choosing a standardized sampling depth would allow comparisons over time and between systems and studies. Future sampling efforts should aim to obtain deeper (>12 inches) soil samples to meet the recommendations established by FAO and the Intergovernmental Panel for Climate Change (IPCC).

Although soil C stocks decrease with depth, there can still be large amounts of C found deep in the soil profile that can contribute to C sequestration. The studies by Laurent (1978) and Chapin (1992) (Figure 4) illustrate the substantial amount of C found in the deeper soil layers of annual ryegrass seed fields. More studies in a variety of grass seed crops, intensively managed systems, and uncultivated systems should include deep soil C measurements for future C accounting efforts.

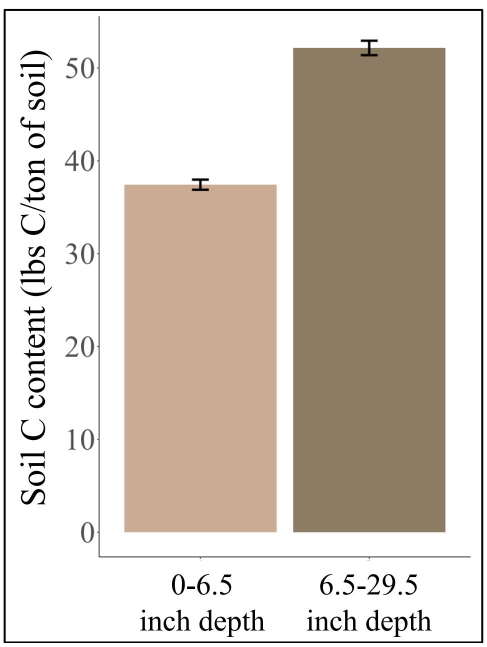

Figure 4. Reported soil carbon (C) stocks in surface and subsoil horizons for Willamette Valley annual ryegrass grass seed fields (Laurent, 1978; Chapin, 1992).

Accounting for plant biomass carbon in perennial and annual grass seed crops

Preliminary estimates of plant C in grass seed cropping systems based on total crop biomass (shoots, seeds and roots) and total acreage of grass seed crops in Oregon suggest a total C capture of over 2.2 million tons/year (Chastain, personal communication). Although this provides a rough estimate of C in the standing biomass, seeds are exported from the system and therefore total C is at least slightly overestimated when seed biomass is considered. Furthermore, it is important to note that straw residue C would only potentially contribute to soil C pools in full straw load management systems, while that C would be mostly lost from the system if the straw is removed. Therefore, contributions of crop biomass to total C should be limited to the biomass that would actually remain in the system. In addition, C accounting for potential Cap-And-Trade opportunities relies on long-term C sequestration in the soil, so it would be valuable to assess how much of the C in the above and belowground biomass is not only returned to the soil system but how stable it is over time.

FINAL SUMMARY

Carbon in grass seed systems

- Carbon stocks were greater in perennial grass seed crops than annual ryegrass seed crops (24.2 and 21.9 tons/acre, respectively).
- Limited data were found for some of the grass seed species (fine fescue, perennial ryegrass and orchardgrass). Our estimates of C stocks in tall fescue (23.5 tons/acre) and annual ryegrass (21.9 tons/acre) should be considered the most accurate and reliable of all of the species surveyed.
- More data on soil C in some perennial species (perennial ryegrass, orchardgrass, and fine fescue), would help improve estimates of C storage in grass seed crops across the different species grown in the WV.
- Soil texture can influence C storage potential. Grass seed fields on silty clay loams can store more C than ones on silt loams.
- Management practices related to tillage and post-harvest straw residue did not have a significant effect on total soil C in grass seed crops. However, consideration of other soil C pools and longer evaluation time periods may be helpful to more accurately determine the effects of those practices on topsoil C in WV grass seed cropping systems.

Comparison of carbon in grass seed systems and contrasting land uses

- Carbon concentrations were lowest in intensively managed systems (1.7% C) compared to annual ryegrass and perennial grass seed (2.4% C and 2.8% C, respectively) or minimally managed systems (3.6% C)
- For intensively managed crops, it would be useful to gather more data across a larger area in the WV and include a greater variety of crops given that the data assessed in this review was limited to three studies of vegetable rotations. Studies including other

regionally important perennial crops would also be useful (hazelnuts, berries, orchard crops).

- Minimally managed systems had greater C concentrations than grass seed systems, but C stocks that take into account bulk density did not differ between these (23.9 and 24.2 tons/acre, respectively).
- Inclusion of studies that report bulk density would improve our assessments of C stocks across all systems, and further verify our observations.

Other considerations

- Future sampling efforts should adhere to recommended C sampling guidelines provided in this review to make C stocks comparable across systems and to comply with C accounting depth requirements set by the IPCC and FAO.
- For potential Cap-and-Trade involvement, conservation management practices evaluated in this review (no-till planting and full straw load management) did not increase topsoil C. We also found evidence that grass seed cropping systems are capable of greater C storage than intensively managed cropping systems, such as vegetable production systems, and had similar C stocks when compared to minimally managed/uncultivated systems in similar soil types. If more data in intensively managed systems in the WV is obtained, and similar C stocks are found, then one could argue that a switch from intensively managed crops to grass seed might promote C sequestration.

REFERENCES

Anderson, N.P., Chastain, T.G., Hart, J.M., Young, W.C., Christensen, N.W. (2014). Tall fescue grown for seed. Nutrient Management Guide. Oregon State University, EM 9099.

Banowetz G.M., Griffith, S.M., Steiner, W.E., Mueller-Warrant, G.W. (2009). Sustainability in seed production enterprises-what we've learned. In: 2009 Seed production research at Oregon State University, W. C. Young (ed.), Department of Crop and Soil Science, Ext/CrS 129, 35-37. Corvallis, OR.

Barry, A. N. (1999). Soil biological, chemical, and physical dynamics during transition to non-thermal residue grass-seed management systems. Undergraduate Honors thesis. Oregon State University, Corvallis.

Bolinder, M. A., Angers, D. A., Bélanger, G., Michaud, R., and Laverdière, M. R. (2002). Root biomass and shoot to root ratios of perennial forage crops in eastern Canada. *Canadian Journal of Plant Science, 82(4)*, 731–737. https://doi.org/10.4141/P01-139

Bray, J. R. (1963). Root Production and the estimation of net productivity. *Canadian Journal of Botany, 41(1)*, 65–72. https://doi.org/10.1139/b63-007

Chapin, M. F. (1992). Effects of ryegrass residue management on Dayton soil organic carbon content, distribution and related properties. MS thesis. Oregon State University, Corvallis.

Chastain, T. G., Young, W. C., Garbacik, C. J., Silberstein, T. B. (1999). Root productivity and seed production in grass seed crops. In: 1999 Seed production research at Oregon State University, W. C. Young (ed.), Department of Crop and Soil Science, Ext/CrS 114, 15-18. Corvallis, OR.

Chastain, T. G., Garbacik, C. J., and Young, W. C. (2017). Tillage and establishment system effects on annual ryegrass seed crops. *Field Crops Research, 209,* 144–150. https://doi.org/10.1016/j.fcr.2017.04.017

Day, E.S. (2015). Soil property effects on Willamette Daisy (*Erigeron decumbens*) within William L. Finley National Wildlife Refuge. Undergraduate Honors thesis. Oregon State University, Corvallis.

Dick and Christ (1996). Soil biological, chemical, and physical dynamics during transition to nonthermal residue management in grass seed systems. In: 1996 Seed production research at Oregon State University, W. C. Young (ed.), Department of Crop and Soil Science, Ext/CrS 110, 20-23. Corvallis, OR.

Ellert, B. H., Janzen, H. H., and McConkey, B. G. (2001). Measuring and comparing soil carbon storage. In R. Lal, J. M., Kimble, R. F. Follett, and B. A. Stewart (Eds.), *Assessment methods for soil carbon* (pp. 131-146). Lewis Publishers, Boca Raton, FL.

FAO (2019). Measuring and modelling soil C stocks and stock changes in livestock production systems (Version 1). Livestock Environmental Assessment and Performance (LEAP) Partnership. Rome, FAO. 170 pp. Licence: CC Y-NC-SA 3.0 IGO.

Griffith, S. M., Alderman, S. C., and Streeter, D. J. (1997) Italian ryegrass and nitrogen source fertilization in Western Oregon in two contrasting climatic years. I: Growth and seed yield. *Journal of Plant Nutrition, 20:4–5,* 419–28. https://doi.org/10.1080/01904169709365263.

Griffith, S. M., Banowetz, G. M., Dick, R. P., Mueller-Warrant, G. W., and Whittaker, G. W. (2011). Western Oregon grass seed crop rotation and straw residue effects on soil quality. *Agronomy Journal, 103(4),* 1124-1131. https://doi.org/10.2134/agronj2010.0504

Hart, J. M., Mellbye, M. E., Young III, W. C., Silberstein, T. B. (2011). Annual ryegrass grown for seed. Nutrient Management Guide. Oregon State University, EM 8854.

Hart, J. M., Anderson N.P., Hulting, A. G., Chastain, T.G., Mellbye, M.E., Young III, W.C., Silberstein, T. B. (2012). Postharvest residue management for grass seed production in Western Oregon. Oregon State University, EM 9051.

Horwath, W., Elliott, L., Steiner, J., Davis, J., & Griffith, S. (1998). Denitrification in cultivated and noncultivated riparian areas of grass cropping systems. *Journal of Environmental Quality, 27(1),* 225-231. https://doi.org/10.2134/jeq1998.00472425002700010032x

Knight, T. R., and Dick, R. P. (2004). Differentiating microbial and stabilized β-glucosidase activity relative to soil quality. *Soil Biology and Biochemistry, 36(12),* 2089–2096. https://doi.org/10.1016/j.soilbio.2004.06.007

Kong, A. Y. Y., Six, J., Bryant, D. C., Denison, R. F., & Kessel, C. van. (2005). The relationship between carbon input, aggregation, and soil organic carbon stabilization in sustainable cropping systems. *Soil Science Society of America Journal, 69(4),* 1078–1085. https://doi.org/10.2136/sssaj2004.0215

Kristensen, H. L., and Thorup-Kristensen, K. (2004). Root growth and nitrate uptake of three different catch crops in deep soil layers. *Soil Science Society of America Journal, 68(2),* 529-537. https://doi.org/10.2136/sssaj2004.5290

Laurent, T.E. (1978). The status of organic materials in several southern Willamette Valley grassland soils. MS thesis. Oregon State University, Corvallis.

Lawrence, B., and Kaye, T. (2006). Habitat variation throughout the historic range of golden paintbrush, a Pacific Northwest prairie endemic: Implications for reintroduction. *Northwest Science, 80(2)*, 140-152.

Lott, D.E., and Hammond, V. E. (2013). Water wise vegetable and fruit production. UNL Nebraska Extension Publications, G2189. University of Nebraska Press, Lincoln, NE. https://extensionpubs.unl.edu/publication/9000016368841/water-wise/

Kan, Z.-R., Liu, Q.-Y., Virk, A. L., He, C., Qi, J.-Y., Dang, Y. P., Zhao, X., & Zhang, H.-L. (2021). Effects of experiment duration on carbon mineralization and accumulation under no-till. *Soil and Tillage Research*, *209*, 104939. https://doi.org/10.1016/j.still.2021.104939

Makepeace, C. A. (2021). Estimating lime requirement for Oregon soils with non-hazardous soil test methods. M.S. thesis. Oregon State University, Corvallis.

Mellbye, M. E., Young, W. C., Chastain, T. G., Silberstein, T. B., Garbacik, C. J. (1997). The effect of straw removal and different establishment systems on soil fertility levels in annual ryegrass seed fields. In: 1997 Seed production research at Oregon State University, W.C. Young III (ed.), Department of Crop and Soil Science, Ext/CrS 111, 7-10. Corvallis, OR.

Ndiaye, A. (1998). Impact of a red clover winter cover crop on carbon and nitrogen mineralization by microorganisms in soil aggregates. MS thesis. Oregon State University, Corvallis.

Nelson, M. A., Griffith, S. M., and Steiner, J. J. (2006). Tillage effects on nitrogen dynamics and grass seed crop production in Western Oregon, USA. *Soil Science Society of America Journal, 70(3),* 825–831. https://doi.org/10.2136/sssaj2005.0248

Paustian, K., Andrén, O., Janzen, H. H., Lal, R., Smith, P., Tian, G., Tiessen, H., Noordwijk, M. V., and Woomer, P. L. (1997). Agricultural soils as a sink to mitigate CO_2 emissions. *Soil Use and Management, 13(s4),* 230–244. https://doi.org/10.1111/j.1475-2743.1997.tb00594.x

Pomerening, J.A. (1961).A test of differentiation of soil series within the Willamette catena. PhD thesis. Oregon State University, Corvallis.

Qureshi, M. H. (1994). Tall fescue growth and nitrogen uptake as influenced by non-thermal residue management. MS thesis. Oregon State University, Corvallis.

R Core Team (2018). R: a language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing; https://www.R-project.org/.

Schutter, M. E., and Dick, R. P. (2002). Microbial community profiles and activities among aggregates of winter fallow and cover-cropped soil. *Soil Science Society of America Journal, 66(1),* 142–153. https://doi.org/10.2136/sssaj2002.1420

Sharrow, S. H., and Ismail, S. (2004). Carbon and nitrogen storage in agroforests, tree plantations, and pastures in western Oregon, USA. *Agroforestry Systems, 60(2),* 123–130. https://doi.org/10.1023/B:AGFO.0000013267.87896.41

Verhoeven, E.C., Gonzalez Mateu, M., Moore, A.D., Sullivan, D.M (2020). Effects of straw removal, clay content, and stand age on soil health in tall fescue seed production: final report. Anderson, N., Hulting, A., Walenta, D., Mallory-Smith, C. (Eds), Seed prod. rep. Crop Sci. Ext. 164, 12-16, Corvallis, OR.

Weil, R. R., and Brady, N. C. (2017). *The nature and properties of soil* (15th ed.). Pearson.

Whalen, J. K., Bottomley, P. J., and Myrold, D. D. (2000). Carbon and nitrogen mineralization from light- and heavy-fraction additions to soil. *Soil Biology and Biochemistry, 32(10),* 1345–1352.