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Soil organic carbon stocks in three Canadian agroforestry systems: From surface organic to deeper mineral soils

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ABSTRACT

Our understanding of the effect of agroforestry systems on soil organic carbon (SOC) is largely limited to the upper layer of the mineral soil, while LFH (litter, partially decomposed litter and humus) and deeper soil layers are poorly studied. In this study, the effects of three different agroforestry systems (hedgerow, shelterbelt, and silvopasture) and their component land-cover types (treed area and adjacent herbland) on SOC stock in LFH and mineral soil layers (0–75 cm) were investigated across 36 sites in central Alberta, Canada. The SOC stock of mineral soil (0–75 cm) was not affected by agroforestry systems but by land-cover type. The treed area had greater ($p < 0.001$) SOC in the 0–75 cm mineral soil (25.5 kg C m^{-2}) than the herbland (19.4 kg C m^{-2}), driven by the greater ($p < 0.001$) SOC level in the top 0–30 cm rather than that in the deeper layers (30–75 cm). Within the treed area, the silvopasture system that was dominated by broad-leaf deciduous trees had 56–70% more SOC in the 0–10 cm soil than in the hedgerow and shelterbelt systems. The SOC stock in the 0–10 cm layer was positively ($p = 0.025$) related to the C stock of the overlying LFH layer in the silvopasture system. These results together with the 22–24% higher dissolved organic carbon (DOC) concentration in the silvopasture than in the other systems suggest that the greater SOC stock in the 0–10 cm mineral soil could be attributed to the higher rates of translocation of DOC from the LFH in the silvopasture than that in shelterbelt or hedgerow. We conclude that SOC stock in the top mineral soil (e.g., 0–30 cm) is more responsive to changes in land-cover type and the LFH layer plays an important role in increasing SOC stock in the surface mineral soil of the agroforestry systems in central Alberta.

1. Introduction

Agroforestry is a land-use system that combines perennial vegetation such as trees and shrubs (referred to as "treed area" hereafter) with annual crops and/or grazed pasture (herbland area) on the same land unit (Montagnini and Nair, 2004; Nair et al., 2009). In Alberta, three agroforestry systems (hedgerow, shelterbelt, and silvopasture) are common, and each of them consists of two land-cover types: a treed area with trees and understory vegetation (shrubs, forbs and other plant species), and a herbland comprised of annual crops or grazed grassland (Baah-Acheamfour et al., 2015). The hedgerow system typically consists of a 3–5 m wide strip of natural vegetation containing trees, shrubs and grasses along the edge of the cropland (Van Vooren et al., 2017). In the shelterbelt system, trees are planted to protect soils, crops, and animals from wind (Kort and Turnock, 1998). The silvopasture is a system that contains a mosaic of open grassland and natural forest with understory for livestock grazing (Abbas et al., 2017).

Agroforestry systems may sequester more soil organic carbon (SOC) than annual cropping systems because perennial woody vegetation continuously returns plant litter to the soil and tree removal occurs less frequently than annual crop harvesting (Paul et al., 2002; Montagnini and Nair, 2004; Oelbermann et al., 2004; Lenka et al., 2012; Abbas et al., 2017). For example, treed areas in Florida silvopasture contained 33% more SOC than adjacent open herblands (Haile et al., 2008). In our previous studies (Baah-Acheamfour et al., 2014, 2015), up to 30% more SOC was found in the 0–30 cm layer of mineral soil in the treed area

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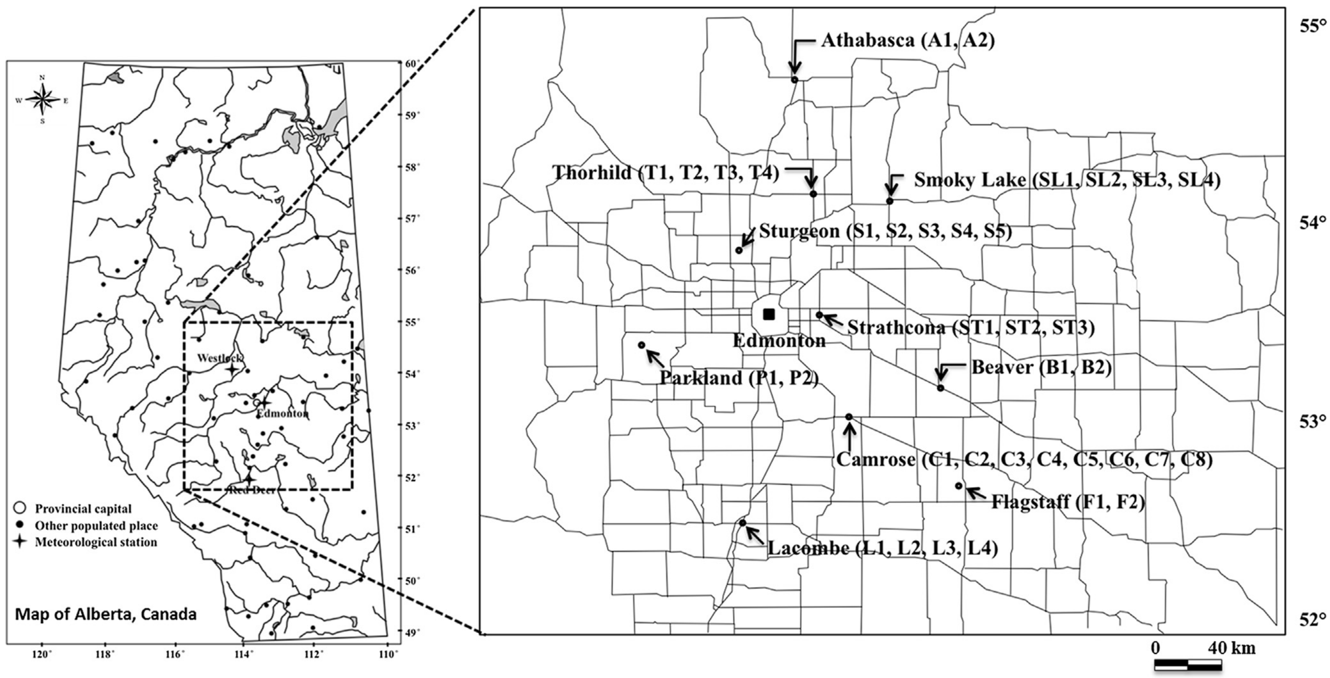

Fig. 1. Soil sampling locations across central Alberta, Canada. Detailed information about county and agroforestry system types of the location codes are provided in Table S1.

compared to the cropland in western Canada. However, in these studies, SOC stock in soil layers below 30 cm depth has rarely been considered. Though studies investigated deeper soil layers are available, these studies are limited to a certain agroforestry system such as silvopasture (Haile et al., 2008, 2010; Upson and Burgess, 2013; Upson et al., 2016; Cardinael et al., 2017, 2018) or hedgerow systems (Cardinael et al., 2015; Thiel et al., 2015). Therefore, our overall understanding of the effect of different types of agroforestry systems on SOC sequestration is limited to the top mineral soil layers (typically 0–30 cm), and it remains unclear if the observed trends in SOC extend to deeper soil layers. The SOC in deeper layers may be particularly important for treed areas as compared with herblands because of the deep-rooting habit of woody plants (Batjes, 1996; Jobbagy and Jackson, 2000), even though the majority of the roots are found in the upper 30 cm of soil in boreal forests (Jackson et al., 1996).

The surface organic soil layer (LFH, the litter, partially decomposed litter and humus) has also rarely been considered in studying SOC stock in agroforestry systems largely due to the LFH being susceptible to loss by fire and other surface disturbances (Baah-Acheamfour et al., 2015). Nevertheless, where present the LFH can represent about 10% of the total C in forested area (Birdsey et al., 1993) and is an important source of SOC for mineral soils, although it is possible for some for agroforestry systems to have little LFH due to a low tree density or fast litter decomposition. Due to the difference in litter quantity and quality between tree species (Prescott et al., 2000), the contribution of LFH to SOC stock in mineral soil could differ between deciduous vs. coniferous dominated agroforestry systems. In our previous studies (Baah-Acheamfour et al., 2014, 2015), agroforestry systems (e.g., hedgerow and silvopasture) containing deciduous trees were found to have higher SOC stock in mineral soil than that dominated by conifer trees (e.g., shelterbelt). This difference in SOC stock in the mineral soil was attributed to deciduous trees generating a large amount of high-quality litter (i.e., less recalcitrant, and thus more likely to be stabilized in the mineral soils via microbial processes), while coniferous trees produce a lower quantity of litter with more recalcitrance to microbial processes (Miltner et al., 2012; Cotrufo et al., 2013). However, we still do not understand how LFH influences the SOC stock in the mineral soil of agroforestry systems containing functionally different trees. One possible mechanism is the vertical migration of SOC into the surface mineral soil in the form of dissolved organic C (DOC) following a partial decomposition of surface organic matter in the LFH (Neff and Asner, 2001; Chantigny, 2003); however, patterns of DOC concentration in the soils of agroforestry systems have rarely been investigated.

This study was conducted to investigate (1) the effect of different agroforestry systems (hedgerow, shelterbelt, and silvopasture) and their land-cover types (treed area and herbland) on SOC stock across the LFH and the 0–75 cm soil layers and (2) the difference in DOC concentration in the top mineral soils among different agroforestry systems. We hypothesized that (1) the SOC benefit of agroforestry would be greater when deeper soil layers are accounted for due to the deep-rooting habit of trees and the contribution of deep roots to SOC stock and (2) DOC concentrations would be greater for agroforestry systems dominated by deciduous trees (e.g., hedgerow and silvopasture) than that for systems with coniferous trees (e.g., shelterbelt) due to more readily decomposability of deciduous litter than coniferous litter as well as the greater quantity of litter of the first than that of latter as mentioned previously.

2. Materials and methods

2.1. Site description

This study is part of a larger project investigating soil physicochemical and microbiological properties, including the SOC stock size and its stability in different agroforestry systems and land-cover types in central Alberta, Canada (Baah-Acheamfour et al., 2014, 2015; Banerjee et al., 2016). We selected 12 sites for each of the three common agroforestry systems (total of 36 sites): hedgerow, shelterbelt, and silvopasture, along a 270-km long north-south soil/climatic gradient (54° 60′ N to 52° 33′ N latitude; 111° 52′ W to 114° 42′W longitude and 533–850 m above mean sea level), spanning the prairie and parkland regions (Fig. 1; Table S1). Temperature and precipitation data were obtained from 26 Environment Canada climate stations adjacent to the study sites. During the past 30 years (1984–2013), annual precipitation varied from 448 to 463 mm, and mean annual temperature ranged from 1.9 to 2.4 °C (Environment Canada, 2014). Dominant soils were Black Chernozems in the southern, Dark Gray Chernozems in the central, and Gray Luvisols in the northern parts of the study area (Soil Classification Working Group, 1998).

Detailed characteristics of the agroforestry systems are described in Baah-Acheamfour et al. (2014, 2015) and Banerjee et al. (2016). Briefly, the hedgerow system was dominated by 40- to 100-year old broadleaf deciduous species such as trembling aspen (*Populus tremuloides* Michx.) and Balsam poplar (*Populus balsamifera* L.). In the shelterbelt system, one or two rows of trees were planted along the border of croplands, and the treed areas were comprised of 20- to 50-year old coniferous trees (> 70%) dominated by needle-leaved white spruce (*Picea glauca* (Moench) Voss) and deciduous trees dominated by narrow-leaved acute willow (*Salix acutifolia* L.) and box elder (*Acer negundo* L.). The silvopasture system was comprised of native aspen trees; about 95% of the treed area was dominated by deciduous trees and understory shrubs such as trembling aspen, balsam poplar, white birch (*Betula papyrifera* Marshall), box elder, and acute willow (Baah-Acheamfour et al., 2015) while the herbaceous part of the system was dominated by a mix of perennial grasses and forbs. Consequently, the silvopasture system had more diverse and abundant understory vegetation than hedgerow and shelterbelt systems, and the treed area of the shelterbelt system had the lowest abundance of understory vegetation among the three systems. Average tree density and age measured in two plots (size: 100 to 510 m^2) established in each site were 7776 ± 1425 ha^{-1} and 28.1 ± 1.4 yrs for hedgerow, 6323 ± 1858 ha^{-1} and 34.1 ± 1.8 yrs for shelterbelt, and 6492 ± 1014 ha^{-1} and 30.2 ± 1.7 yrs for silvopasture, respectively (Table S1).

2.2. Experimental design and field sampling

Sampling was conducted in a completely randomized split-plot design, with 12 replicates of each agroforestry system as the main plot, and two land-cover types (treed and herbland areas) as nested subplots. At each agroforestry site, one 30-m long transect was established in each of the treed and paired herbland subplots (30 m from the forest edge). Both LFH and mineral soil samples were collected from each subplot in June, 2014. Within the treed subplots, LFH samples (approximately 500 g) were collected from two randomly selected quadrats (25 × 25 cm) along the transect and bulked. To collect mineral soil samples, two soil pits at the LFH sampling points were dug to 50 cm depth using a shovel. Samples were taken from three intervals (0–10, 10–30, and 30–50 cm) from the surface of the mineral layer by inserting two (for 0–10 cm) or four (for 10–30 and 30–50 cm) soil-cores (4.7 cm diameter × 5.8 cm long) horizontally (evenly distributed along the depth) into each soil layer. For the 50–75 cm layer, soil samples were collected using a soil auger (diameter: 4.5 cm) at the bottom of pit. For the herbland area where a surface organic layer was less apparent, particularly in the cropland, only mineral soil samples were collected from two soil pits located at random points along the transect, similar to the procedure described for treed areas. In addition, for both treed and herbland areas, soil samples from the top 10 cm of mineral soil at two points at each site were collected three times in June, July, and August 2014 to determine the temporal dynamics of DOC concentrations with water extraction of the soil samples. Water extractable organic C has been reported to be well correlated with the leaching of DOC (Ghani et al., 2010). Though vertical movement of DOC could be more precisely measured with water samples collected in zero-tension lysimeters, in this study we used water extractable organic C as a surrogate for DOC as lysimeter installation is extremely invasive; lysimeters need to be installed via soil pits, and then ideally sit and settle for 9 months to 1 year. Because our study included fields that were actively maintained for agricultural production, the lysimeters would have to have been installed and removed before the lysimeters were able to settle in the ground. In addition, the number of sites and the fact that this study has been conducted on privately owned lands prevented us from pursuing lysimeter installation.

All soil samples were placed in plastic bags, transported to the laboratory, and refrigerated until analyzed. For bulk density (D_b) measurement, additional soil cores were taken at each corresponding soil depth of the pits; these were collected horizontally for the 0–50 cm and vertically for the 50–75 cm soil layers. Care was taken to minimize soil compaction when hammering the soil cores. The D_b was determined after oven-drying at 105 °C for 48 h to a constant weight.

2.3. Analyses of SOC and DOC

Samples of LFH were oven-dried at 60 °C for 72 h and weighed for dry matter content. The samples were ground to fine powder with the ball mill, and analyzed for C and N concentrations using the elemental analyzer described above. To assess the stability of the LFH against microbial decomposition, we determined the degree of chemical stability, an indicator of recalcitrance of organic matter to microbial decomposition, following a modified Klason lignin method (López et al., 2010). Chemical stability degree was calculated as the portion (%) of resistant organic matter that was not hydrolysable by sulfuric acid, to the total organic matter in LFH samples.

A portion (about 300 g) of mineral soil was air-dried and passed through a 2-mm sieve. For samples collected at sites where the surface soils (0–10 cm) were found to have a pH > 6.4 in previous studies (Baah-Acheamfour et al., 2014, 2015), soils were pretreated with acid (0.5 mol L^{-1} HCl) to remove inorganic carbonates before measurement (Harris et al., 2001) and then washed with distilled water and dried again. Soil samples were ground to a fine powder with a ball mill (MM200, Retsch GmbH, Haan, Germany) and analyzed for C concentration using an elemental analyzer (LECO Tru-Spec CN analyzer, Leco Corp., St. Joseph, MI, USA). The SOC stock (kg C m^{-2}) at each depth interval was calculated using the bulk density of the corresponding soils and then summed to obtain SOC for all soil layers:

$$\text{SOC stock}(\text{kg C m}^{-2}) = SOC \times D_b \times th$$

where *SOC* is the soil organic C concentration (g kg^{-1}), D_b is the bulk density of the soil layer (range: 1.12 ± 0.03 to 1.33 ± 0.03 Mg m^{-3}), and *th* is the thickness of the soil layer (m). In this calculation, coarse fragments and root debris were not considered as soils < 2 mm were analyzed for C.

To determine DOC of soils (0–10 cm) collected monthly from June to August, field-moist soil (5 g on dry basis) was shaken with 50 mL of distilled water (1:10 w:v, soil-to-water ratio) for 1 h. at 150 rpm and filtered using a Whatman No. 42 filter paper. The filtrate was measured for C using a high-temperature combustion analyzer (TOC-V_{CSN}, Shimadzu, Scientific Instruments, Tokyo, Japan).

2.4. Statistical analysis

All data were analyzed using the Statistical Analysis Software (SAS v. 9.3, SAS Institute Inc., NC, USA) after being tested for normality and homogeneity of variance using Shapiro-Wilk's and Levene's tests, respectively. No transformation of data was required as the data were homogenous and normally distributed. Analysis of variance (ANOVA) was conducted using the following mixed model to test the fixed effects of agroforestry system, land-cover type, and their interaction:

$$Z_{ijk} = \mu + A_i + (A\gamma)_{ik} + L_j + A_iL_j + \varepsilon_{ijk}$$

where Z_{ijk} is the response variable (such as SOC) at *i*th (=1, 2, 3) agroforestry system (A) and *j*th (=1, 2) land-cover type (L), μ is the overall mean, and $(A\gamma)_{ik}$ and ε_{ijk} are the random variable errors within the experiment. When the main- and subplot effects were significant ($p < 0.05$), means were separated by a Fisher's protected least significant difference (LSD) test. Pearson correlation coefficients ($p < 0.05$) were determined between C stock in LFH metrics and that of the top (0–10 cm) mineral soil layer to examine the relationship between LFH and mineral soil.

3. Results

3.1. The SOC in the LFH layer

The concentration of C of the LFH was greater in shelterbelt system than in the other two systems; however, the total C stock of the LFH layer in treed areas was not different among the agroforestry systems (Table 1). The total N concentration and C/N of the LFH was not different among agroforestry systems. The LFH in shelterbelts had a lower ($p = 0.018$) chemical stability than those in hedgerow or silvopasture systems (Table 1).

3.2. The SOC and DOC in mineral soil layers

The SOC stock across the entire mineral soil profile from 0 to 75 cm was affected ($p < 0.001$) by land-cover type, but not by agroforestry systems or their interactions (Table 2). Comparing the SOC stock of the entire soil depth (0–75 cm) averaged across three agroforestry systems, treed areas had 32% (38.5% for hedgerow, 27.5% for shelterbelt, and 29.1% for silvopasture) more SOC than herbland areas (Fig. 2a). This value is lower than the value when the SOC stock was limited to the top 0–30 cm (53.1% for hedgerow, 35.1% for shelterbelt, and 49.2% for silvopasture) (Table S2).

Vertical distribution of SOC stock in the mineral layers showed that about 70–80% of SOC was stored in the top 0–30 cm of mineral soil, with slightly less in herbland (67–74%) than in treed areas (74–79%) (Fig. 2; Table S2). In the 0–10 cm layer, the SOC stock was affected by agroforestry system ($p = 0.014$) and land-cover type ($p < 0.001$) (Table 2). The SOC stock in the 0–10 cm layer of the herbland did not differ between agroforestry systems, but was 56% and 70% higher ($p = 0.014$) in the treed area of silvopastures than in hedgerow and shelterbelt systems, respectively (Fig. 2b). In the 10–30 cm layer, the SOC stock was also affected by agroforestry system ($p < 0.001$) and land-cover type ($p = 0.007$) (Table 2). The SOC stock in the 10–30 cm layer of herbland did not differ between agroforestry systems as was the case in the 0–10 cm layer (Fig. 2b). However, unlike the 0–10 cm layer, SOC stock in the 10–30 cm layer of treed areas in the silvopasture was around 50% that found in the hedgerow and shelterbelt. In the deeper soil layers (30–50 cm and 50–75 cm), SOC stock (Table S2) was not affected by either agroforestry system or land-cover type (Table 2). The SOC stock in the top (0–10 cm) mineral soil layer was positively correlated with the C stock in the LFH layer for silvopastures ($r^2 = 0.41$, $p = 0.025$, n = 12), but not in the other agroforestry systems (Fig. 3).

Monthly average DOC concentrations in the 0–10 cm soil were affected by both agroforestry system ($p < 0.05$) and land-cover type ($p < 0.001$) at each sampling, but the effect of agroforestry system was not significant in July (Table 3). Average DOC concentrations were typically greater in silvopasture than in hedgerow and shelterbelt systems (Fig. 4). Treed areas had 29% greater DOC concentration than the neighboring herbland areas.

4. Discussion

4.1. Effects of land-cover type on SOC in mineral soils

The higher SOC stock (by 32% to 75 cm depth) in treed areas than in neighboring herbland in agroforestry systems (Fig. 2 and Table S2) is consistent with our previous results of the C stock benefit of agroforestry systems in Canada (Bambrick et al., 2010; Baah-Acheamfour et al., 2014, 2015) as well as other studies in Europe (Howlett et al., 2011; Cardinael et al., 2015, 2018), South America (Maia et al., 2007), and the US (Haile et al., 2008). However, many previous studies have focused primarily on the surface (mostly 0–30 cm) mineral layers (Maia et al., 2007; Baah-Acheamfour et al., 2014, 2015, and references cited in Lorenz and Lal, 2014) or examined only one type of agroforestry system (e.g., Maia et al., 2007; Haile et al., 2008; Howlett et al., 2011). The greater SOC stock in treed areas over neighboring herbland areas is often attributed to greater plant residue input in treed areas and contrasting land management practices that also affect SOC input and protection (Paul et al., 2002; Oelbermann et al., 2004). For example, in treed areas, there is continuous SOC input to the soil via above- and belowground litterfall, and the resulting SOC is better protected under minimum disturbance (Baah-Acheamfour et al., 2014, 2015). In the herbland, however, plant residues are frequently removed by mechanical harvesting and land-use practices such as tillage and traffic that disturbs the upper soil, leading to SOC loss by respiration and erosion (Paustian, 2000; Lal, 2005).

Table 1
Dry matter, total carbon (C) and nitrogen (N), C/N ratio, and chemical stability degree (CSD) of LFH from the forest floor layer of three agroforestry systems (hedgerow, shelterbelt, and silvopasture systems).

Agroforestry systems[a]	Dry matter ($kg\,m^{-2}$)	C concentration ($g\,C\,kg^{-1}$)	C stock ($kg\,C\,m^{-2}$)	N concentration ($g\,N\,kg^{-1}$)	C/N	CSD
Hedgerow	6.4 (0.7)a	397.9 (3.2)b	2.5 (0.3)a	13.1 (1.0)a	32.6 (3.2)a	20.5 (2.2)a
Shelterbelt	8.8 (1.3)a	430.9 (11.9)a	3.7 (0.5)a	12.3 (1.0)a	36.8 (3.7)a	12.8 (2.7)b
Silvopasture	7.8 (0.8)a	398.0 (11.5)b	3.1 (0.3)a	14.6 (0.8)a	28.1 (1.7)a	22.2 (2.2)a
$LSD_{0.05}$	2.56	3.34	2.38	1.72	2.76	4.54
Prob > *F*	0.228	**0.048**	0.100	0.195	0.078	**0.018**

Values are means with the standard error of the means in parentheses (n = 12); *p* values less than 0.05 and the corresponding *F* values are in bold. Values with the same lowercase letters are not different at $p < 0.05$ between agroforestry systems according to the Fisher's protected least significant difference (LSD) test.

[a] The LFH sample was collected only from treed areas in the agroforestry system.

Table 2
Analysis of variance (*F* and *P* values) of the effect of agroforestry system (hedgerow, shelterbelt, and silvopasture systems), land-cover type (treed area and herbland), and their interactions, on soil organic carbon (SOC) stock ($g\,C\,m^{-2}$) in different soil layers.

Soil layer (cm)	Agroforestry system			Land-cover type			Agroforestry × land-cover type		
	df	*F*	*p*	*df*	*F*	*p*	*df*	*F*	*p*
0–10	2	**4.91**	**0.014**	1	**16.6**	**< 0.001**	2	3.09	0.059
10–30	2	**9.25**	**< 0.001**	1	**8.20**	**0.007**	2	2.67	0.084
30–50	2	2.54	0.094	1	0.03	0.86	2	0.15	0.86
50–75	2	1.13	0.34	1	0.05	0.82	2	0.97	0.39
Total (0–75)	2	0.22	0.80	1	**14.1**	**< 0.001**	2	0.16	0.85

P values less than 0.05 and the corresponding *F* values are in bold.

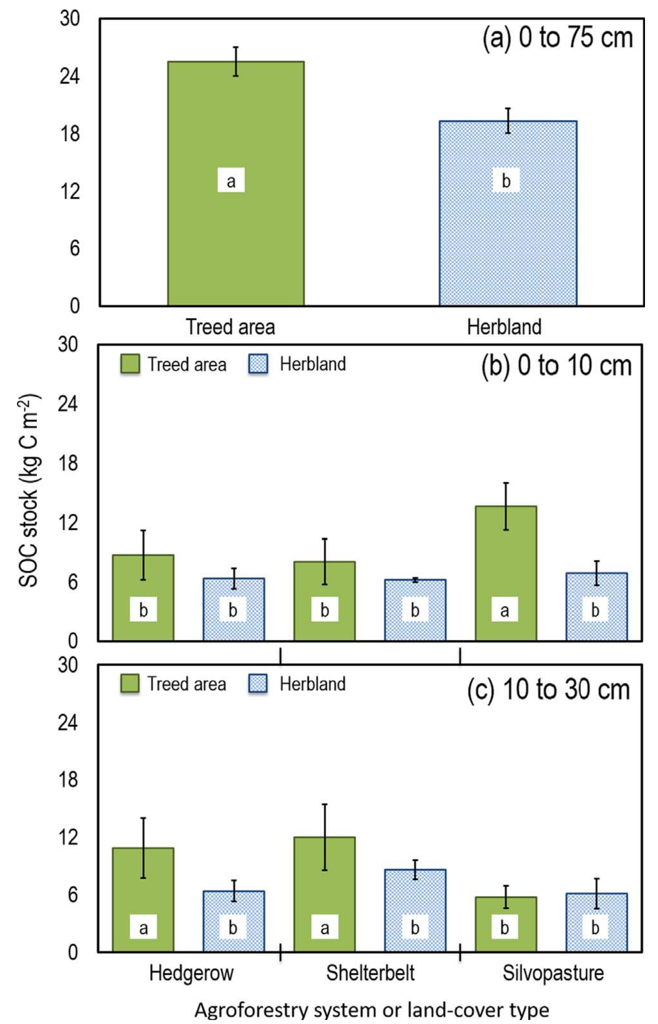

Fig. 2. Soil organic carbon (SOC) stock in various soil layers under different agroforestry systems (hedgerow, shelterbelt, and silvopasture) and land-cover types (treed area and herbland): (a) 0–75 cm (the entire soil profile), (b) 0–10 cm, (c) 10–30 cm, and (d) 30–50 cm. Data for the 30–50 cm and 50–75 cm layers are not presented in this figure but are shown in Table S2 as there is no differences among treatments. Vertical bars are standard of the means (n = 12). For the 0–75 cm layer, data for land-cover types were averaged across agroforestry systems as SOC stock was affected only by land-cover type. For the 0–10 cm and 10–30 cm soil layers, data were presented for each land-cover type and agroforestry system as both agroforestry system and land-cover type affected SOC stock. The ANOVA are presented in Table 2, and within each soil layer, different letters indicate significant differences ($p < 0.05$).

In our study, however, the smaller difference (32%) in SOC stock between the treed area and herbland in the 0–75 cm layer than that (46%) in the 0–30 cm layer (Fig. 2 and Table S2) suggests that the upper soil layer (0–30 cm) is more responsible for the differences in SOC stock associated with the tree presence among the agroforestry systems studied. Therefore, these data do not support our first hypothesis that the benefit of agroforestry in accumulating SOC would be greater when deeper soil layers are included. Instead, our findings are supported by the notion that the majority of roots (80–90%) in boreal forests are found in the upper 30 cm of soils (Jackson et al., 1996), and thus, the influence of these roots on soil C stock may be greatest in the upper mineral soil layers, even though roots can also influence SOC below 30 cm of the soil (Callesen et al., 2016).

The greater SOC stock in the 0–10 cm layer in silvopasture than in the other two agroforestry systems was also consistent with our previous findings (Baah-Acheamfour et al., 2014, 2015). This result can be attributed to greater organic matter productivity in treed areas associated with a highly diverse understory vegetation (Howlett et al., 2011) as well as rapid incorporation of litter into mineral soil layers by ongoing grazing activity in silvopastures (Reeder and Schuman, 2002). However, such benefit of silvopasture in terms of SOC stock was not evident in the 10–30 cm layer (Fig. 2c), suggesting that the SOC sequestration benefit in silvopasture is limited to the 0–10 cm soil layer, in part due to its location directly beneath the LFH and resulting ability to continuously receive a supply of soil organic matter input from the LFH. Other studies also showed that tree planting on grasslands did not affect SOC stock as much as it was expected due to the high initial SOC stock under the existing grassland vegetation (Beckert et al., 2016; Upson et al., 2016; Cardinael et al., 2017).

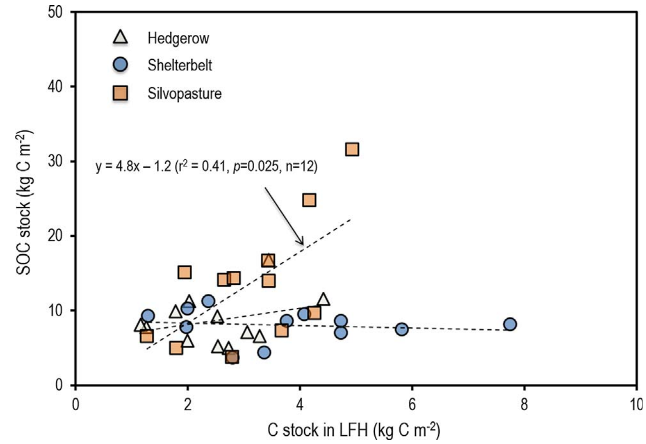

Fig. 3. Relationship between SOC stock in the 0–10 cm mineral soil and that in the overlying LFH layer for treed areas in three agroforestry systems (hedgerow, shelterbelt, and silvopasture).

4.2. Effects of the LFH on SOC in the top mineral soil layer in the treed area

As the LFH is inherently unstable and susceptible to loss by microbial decomposition and burning (Parfitt et al., 2003), the LFH has rarely been considered in estimating SOC stock in agroforestry systems (Lorenz and Lal, 2014). However, in this study, the amount of C in the LFH was substantial, corresponding to 9.5–14.6% of the total SOC in the entire soil profile (to 72 cm mineral depth) in the agroforestry systems (Table 1), making this a potentially important source of SOC for the underlying mineral soil (Neff and Asner, 2001; Chantigny, 2003).

In our study, the non-significant difference in C stock of the LFH in treed areas (Table 1) suggests that tree species type, stem density and tree age did not affect LFH. However, the positive correlation between the SOC stock in the LFH and that found in the 0–10 cm layer of the silvopasture system dominated by broadleaf deciduous trees (Fig. 3) suggests that the LFH maybe an important C source for the surface mineral soil layer in this system. In this context, the greater DOC concentration in the 0–10 cm layer of the silvopasture than in the hedgerow (Fig. 4) partially supports our second hypothesis, and suggests that translocation of DOC from the LFH to the surface mineral soil may be a mechanism to increase SOC within the 0–10 cm layer in the silvopasture system (Guggenberger et al., 1994). This might be further aided by physical mixing of LFH and the mineral soil by soil fauna such as earthworm (Frouz et al., 2014) and by the contributions of root litter (Vesterdal et al., 2013). It is well recognized that deciduous litter decomposes faster than needle litter due to a lower lignin concentration (Cole and Rapp, 1981; Klemmedson, 1992; Prescott et al., 2000; Berg and Meentemeyer, 2002). Therefore, the forest floor of deciduous forests could supply more C to the underlying mineral soil layer in the form of DOC, which is stabilized through association with mineral particles when compared with coniferous litter (Prescott et al., 2000; Rasse et al., 2005). The greater decomposability of deciduous litter than coniferous litter in turn is supported by the higher degree of chemical

Table 3
Analysis of variance (*F* and *p* values) of the effect of agroforestry system (hedgerow, shelterbelt, and silvopasture systems), land-cover type (treed area and herbland), and their interactions, on dissolved organic carbon (DOC) concentration in the 0–10 cm mineral soil layer.

Sampling time	Agroforestry system (AF)			Land-cover type (LCT)			AF × LCT		
	df	*F*	*p*	*df*	*F*	*p*	*df*	*F*	*p*
June	2	**17.0**	**< 0.001**	1	**41.8**	**< 0.001**	2	2.33	0.113
July	2	1.40	0.259	1	**22.7**	**< 0.001**	2	1.23	0.305
August	2	**4.30**	**0.022**	1	**18.9**	**< 0.001**	2	0.42	0.659
Mean	2	**7.45**	**0.002**	1	**39.4**	**< 0.001**	2	1.43	0.254

P values less than 0.05 and the corresponding *F* values are in bold.

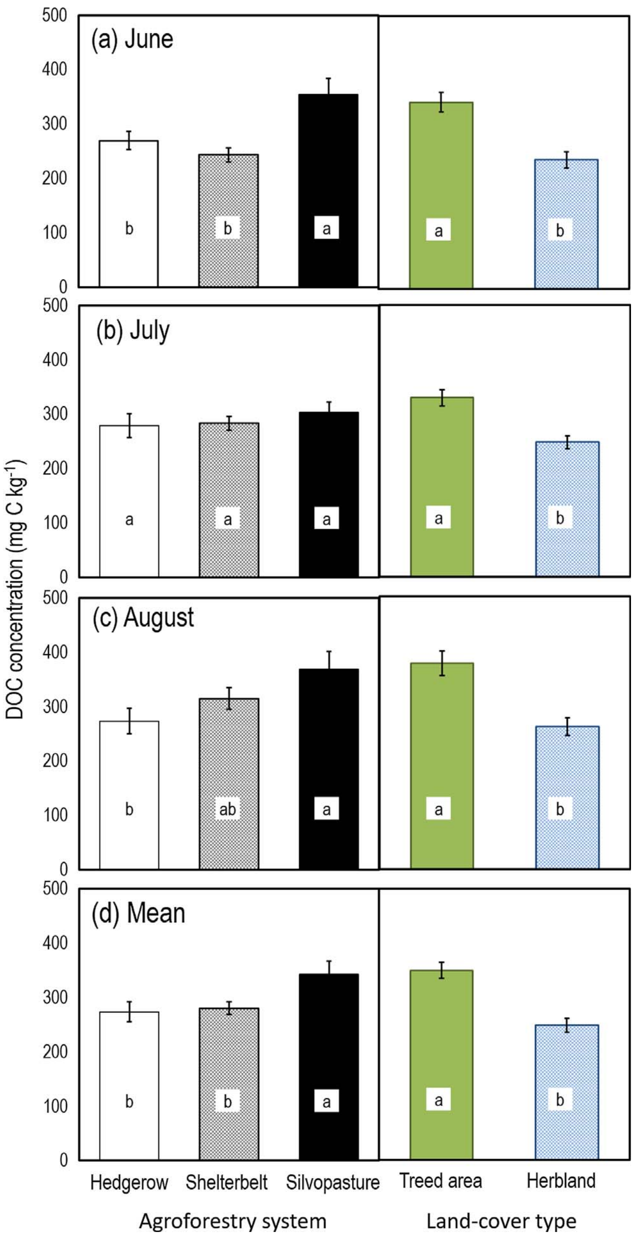

Fig. 4. Dissolved organic carbon (DOC) concentrations in the 0–10 cm mineral soil layer in (a) June, (b) July, (c) August, and (d) their mean values as affected by agroforestry system (hedgerow, shelterbelt, and silvopasture) and land-cover type (treed area and herbland). Vertical bars are standard of the means (n = 12). The detailed data are shown in Table S3. Different letters indicate significant differences ($p < 0.05$).

stability of the LFH layer within the treed areas of hedgerow and silvopasture than in the shelterbelt (Table 1). This is due to an increased recalcitrant fraction with litter decay in the LFH under deciduous trees; as less recalcitrant fractions decompose faster, and this would increase chemical stability of the remaining organic matter while decreasing C stock in the LFH (Prescott et al., 2000; Berg and McClaugherty, 2003). However, the influence of tree species on DOC concentration in the top mineral soil layer was not apparent for hedgerows, which were also dominated by deciduous trees (Fig. 3). This could be attributed to a relatively greater C/N ratio of LFH material in the hedgerow compared to that in the silvopasture system (Table 1) as litter with a high C/N ratio is disadvantageous for the decomposition of litter in soil (Paul et al., 2002).

5. Conclusions

We conclude that the treed area has greater SOC stock than the herbland when the soil was sampled to 75 cm depth; however, the difference in SOC in the 0–75 cm layer between the two land-cover types was smaller than when it was compared to SOC in the 0–30 cm layer. This suggests that root contributions in affecting the amount of SOC in the mineral soil are smaller at deeper depth (below 30 cm) compared to in shallower soil layers. Similarly, the effect of aboveground litterfall in altering SOC in treed areas is restricted to the surface mineral soil layer. The greater DOC concentration in the 0–10 cm mineral soil of treed areas than in the herbland suggests that translocation of DOC from the LFH layer to underlying mineral soil layers could play an important role in increasing SOC in mineral soil. Such a mechanism was more evident in the silvopasture system dominated by diverse deciduous species than the other two systems as indicated by greater DOC concentrations, as well as the positive relationship between C concentration of the LFH and 0–10 cm mineral soil of silvopastures. These results highlight the important role of the LFH layer in affecting SOC stock in mineral soils within the treed areas of agroforestry systems, particularly in the silvopasture. We also note that the current study does not report the SOC stock of the overlying mulch layer in perennial grassland in the silvopasture system, as the LFH was often either missing or too small to measure in the pastures. This layer has properties similar to the LFH in the treed areas, and is therefore an additional potential source of C stock, and warrants further research. In addition, the effect of tree species in the treed area of each agroforestry system on SOC stock needs to be further explored.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.foreco.2018.02.050.

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