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Soil carbon fractions in short rotation poplar and black locust coppices, Germany

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Abstract Short rotation coppice (SRC) is seen as a successful management system, which in addition to energy wood production may enhance soil carbon sequestration. The objective of this study was to investigate total, labile and stable soil carbon fractions at SRCs composed of poplar clones *Max 1* (*Populus nigra x P. maximowiczii*), *Muhle Larsen* (*Populus Trichocarpa*), and black locust (*Robinia pseudoacacia* L.). Study was conducted at three SRC sites (Allendorf, Dornburg, and Forst) varying in age (1–4 years old), soil texture and climatic characteristics, in Germany. Composite soil samples collected at SRCs from 0 to 3; 0–10; 10–30; and 30–60 cm depth layers were compared with soils collected from adjacent crop strips. Samples were analysed for total organic carbon (TOC), hot-water extractable carbon (HWC), and organic carbon (OC) at 250–2,000; 53–250; and <53 µm soil-size aggregates. Total OC stocks in 0–60 cm soil layer were the highest at the site with the heaviest texture, Dornburg, followed by Forst and Allendorf, comprising 92–107; 59–74; and 53–64 Mg ha^{-1}, respectively. Although no significant differences in the total OC stocks between SRCs and adjacent crops were found for the 0–60 cm layer, a significantly ($p < 0.05$) higher TOC, HWC, OC at macro-aggregates (250–2,000 µm), and the amount of macro-aggregates were found in the top 0–3 cm layer in all SRC sites (except the youngest poplar SRC in Forst) compared to adjacent crop strips. A greater macro-aggregate formation in SRCs related to the lower soil disturbance compared to the tilled crops, revealed a potential of SRC for C sequestration, as C occluded within soil aggregates has a slower decomposition rates and longer residence time.

Keywords Soil carbon sequestration · Soil particle size fractions · Labile and stable carbon fractions · Hot water-extractable C

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Introduction

Short rotation coppice (SRC) composed of fast growing tree species is considered to be a promising land-use system at agricultural marginal lands and reclamation sites. In addition to production of energy-wood as a substitute to fossil fuels, SRCs may mitigate the greenhouse gas CO_2 and enhance soil carbon sequestration (Lal 2004; Nair et al. 2010). Compared to conventional crop systems, greater quantities of assimilated carbon may be stored in woody biomass and translocated to soil with litterfall or via extensive root systems (Montagnini and Nair 2004). Organic matter originated from lignified tree branches and roots has slower decomposition rates, and therefore has longer residence time in soils than crop residue.

SRCs may be planted as stands or in a form of alley-cropping, with tree coppices established as strips on arable crop land, and crops cultivated in the alleys in between the tree strips. Among the tree species used for alley-cropping, fast growing trees - black locust (*Robinia pseudoacacia* L.) and poplar (*Populus* spp. L.) have received much interest in Germany (Quinkenstein et al. 2011). While poplar is suitable for sites adequately supplied with water, black locust shows a comparable well growth performance also at sites susceptible to drought stress. Furthermore, black locust has the ability to fix nitrogen and grows also at infertile and acidic sites (Redei et al. 2008). It produces nutrient rich and well decomposable litter, which may enhance soil organic matter levels.

Numerous studies have reported increase in soil OC content after establishment of SRCs. According to Nii-Annang et al. (2009), soil OC in 0–3 cm layer at black locust and poplar strips were two times higher compared to adjacent rye strips after 9 year of establishment of alley-cropping systems in a post mining site of Lusatia, Germany. Quinkenstein et al. (2011) reported an increase in soil organic carbon (OC) content after 14 years of establishment of SRC on degraded mine reclamation site in Lower Lusatia, Germany, with an average rate of soil C sequestration in the 0–60 cm layer of 7.0 Mg ha^{-1} year^{-1}. Mungai et al. (2006) also reported higher C sequestration in 19 years-old tree rows of alley-cropping system in Missouri, with 13 % higher soil OC in pecan (*Carya illinoinesis*) rows compared to adjacent strips of bluegrass (*Poa trivialis*).

Soil carbon has a complex and heterogeneous composition. It exists in soils in various fractions varying in decomposability and residence time: labile fraction (mean residence time MRT—1–2 year), slow fraction (MRT—25 year), and a passive, recalcitrant fraction (MRT 100–1,000 year) (Parton et al. 1987). The extent to which carbon is sequestered varies between alley-cropping systems and depends on species composition, soil properties, and physical protection of carbon within soil aggregates (Montagnini and Nair 2004; Nair et al. 2009). Organic matter occluded within the soil aggregates is better protected from microbial decomposition than that located outside the aggregates (Six et al. 2000). Fractionation of soil into macro- (>250 μm), micro- (53–250 μm), and clay and silt (<53 μm) particle-size aggregates, followed by carbon determination in these aggregates allows detection of decomposable and recalcitrant OC fractions (Elliot 1986; Christensen 1992). This procedure was successfully adopted in a number of studies (Haile et al. 2008, 2010; Gama-Rodrigues et al. 2010; Howlett et al. 2011). While it may take a long time for the changes in total C to be detectable, a determination of labile C fraction may show short-term changes in soil C. In this regard, hot water extractable OC (HWC) was found to be a sensitive measure for detection of land-use change effect on soil OC (Ghani et al. 2003; Böhm et al. 2009).

In order to understand the C sequestration potential of alley-cropping systems, it is important to know C storage in variable fractions at different soil depth layers. The objective of this study was to quantify and compare total and labile OC stocks as well as OC storage in different soil–size aggregates (250–2,000, 53–250, and <53 μm) at four depth layers (0–3, 3–10, 10–30, and 30–60 cm) at SRCs in comparison with adjacent crop strips in Germany. An attempt was made to distinguish if trends in OC sequestration were comparable across SRC sites, varying in soil and climatic characteristics.

Methods

Study sites

The study was conducted at three SRC sites located along a rainfall gradient stretching from west to east across Germany: Allendorf, Dornburg, Forst. The sites vary in age, soil properties and climatic characteristics (Table 1). The details regarding land-use systems at different sites are presented in Table 2. At each study site, soil samples were collected from four vegetation types, representing SRCs and adjacent to them crop strips.

In Allendorf, two SRC coppices: poplar *Max 1* (*Populus nigra x P. maximowiczii*) (1.2 ha) and poplar *Muhle Larsen* (*Populus Trichocarpa*) (3.7 ha), and two adjacent to them wheat fields: C1 (3.3) and C2 (3.1 ha) were sampled. SRC coppices were established in 2008 on former agricultural lands. At the time of sampling in November 2011, poplar *Max* 1 was 1 year after harvesting (roots/shoots 3/1) with trees approximately 1.4 m high, and poplar *Muhle Larsen* was not harvested (roots/shoots 3/3) with trees approximately 3 m high.

In Dornburg alley-cropping site, samples were collected from two poplar (clone *Max 1 Populus nigra x P. maximowiczii*) coppices planted as alleys and varying in densities: 10.000 and 3.300 trees ha^{-1}, and from adjacent

Table 1 Characteristics of study sites

Site	Geographical coordinates	Soil type	MAP[a]	T °C[b]	Soil texture			Soil textural type
					Clay %	Silt	Sand	
Allendorf	51°04' N 8°73′E	Cambisols	630	9	18.2	34.4	47.4	Loam
Dornburg	51°0' N 11°39′N	Luvisol	585	8.8	28.0	67.5	4.5	Silty loam
Forst	51°47' N 14°37′E	Gleysol	590	8.3	10.6	32.7	51.8	Sandy loam

[a] Mean annual precipitation (mm)

[b] Mean annual temperature

to them crop strips. Alleys of trees were 12 m wide with the length varying between 642 and 680 m. The width of the crop strips located in-between trees alleys varied between 48 and 114 m. Alleys of trees were planted in 2007. Higher density poplar coppices were harvested in 2011 (roots/shoots 4/1), and at the sampling time in March 2012, trees were about 3 m high. Lower density poplar trees were not harvested yet (roots/shoots 4/4), and at the sampling time trees were about 6 m high.

In Forst alley-cropping site, samples were collected from black locust (*Robinia pseudoacacia* L.), and poplar (clone *Max 1 Populus nigra x P. maximowiczii*) alleys and from adjacent to them crop strips. Alleys of trees were 11 m wide and 660 m long. The width of crop strips located in-between tree alleys varied between 24 and 96 m. In 2010 and 2011, maize silage was planted in the crop strips. Although both black locust and poplar trees were planted in 2010, due to the low rate of survival, poplar trees were replanted in 2011. At the time of sampling in March 2012, black locust (roots/shoots 2/2) trees were about 2.2 m high, and poplar trees (roots/shoots 1/1) were about 1.2 m high.

Soil sampling

In Forst and Dornburg alley-cropping systems, soil samples were collected from replicate plots (10 × 10 m) located along tree alleys and along adjacent crop strips (five replicate plots for each vegetation type). At crop strips, replicate plots were located at 12 m distance from the tree alleys. This distance was chosen, as it presents a middle of the narrowest crop strip. In Allendorf, soil samples were collected from four replicate plots located in SRC coppices and in adjacent to them crop fields. Replicate plots from each particular vegetation type had comparable climatic, and soil characteristics.

At each replicate plot, composite soil samples were randomly collected from 0–3; 3–10; 10–30; and 30–60 cm depth layers with a stainless steel auger. Each composite sample composed of four subsamples bulked together and mixed thoroughly. Samples were collected from the interior of 10 × 10 m plots to reduce edge effects. At tree plots, two samples were collected directly beside trees and two in between the trees. Samples were air-dried and sieved <2 mm.

At each vegetation type, soil bulk density was determined with a core method (two samples for each soil depth layer) (Blake and Hartge 1986). For this, soils were collected with cylinders of a known volume, dried at 105 °C for 48 h, and weighed. The dry soil mass was divided by the volume of soil collected (g cm^{-3}). Adjustment was made for rock volume.

Soil analyses

Soil samples were analysed for total C by gas chromatography (Vario El Elemental Analyser), inorganic C with 10 % HCl using Scheibler device (DIN 2007), and hot water-extractable OC according to Körschens et al. (1990) using a TOC analyser (Schimadzu). Organic carbon (OC) was calculated as a difference between total C and inorganic C. Soil samples were physically fractionated into three fraction size classes: macro- (250–2,000 µm), micro- (53–250 µm), and clay- and silt- sized fraction (<53 µm) (referred as 'clay + silt' thereafter) by wet-sieving using disruptive forces of slaking by Elliott (1986). An attempt was made to use comparable energy input and not to disrupt water-stable aggregates. This procedure yielded water-stable aggregates. The recovery of mass percentage of soil fractions after the wet sieving procedure was on average 97.5 % of the initial soil mass. Total carbon

Table 2 Characteristics of land-use systems at study sites

Site	Land-use system	Year of establishment	Sampling plots	Abbreviation	Characteristics of tree alleys				Land-use prior to establishment
						Distance between:		Density tree/ha	
						Tree rows (m)	Trees in a row (m)		
Allendorf	SRC[*]	2008	Poplar (*Max 1*)	P1	Single rows	2	0.4	12500	Agricultural farming:
			Poplar (*Muhle Larsen*)	P2	Single rows	2	0.4	12500	Wheat
			Crop: wheat	C1					
				C2					
Dornburg	Alley-cropping	2007	Poplar (*Max 1*)	P1	6 single rows	2	0.5	10000	Agricultural farming:
			Poplar (*Max 1*)	P2	4 single rows	3	1.5	3300	Winter wheat,
			Crop: winter wheat, spring barley	PC1[a]					Spring barley,
				PC2[b]					Winter rape
Forst	Alley-cropping	2010 black locust	Black locust (*Robinia pseudoacacia L.*)	BL	4 double rows	1.8	0.9	8715	Agricultural farming:
		2011 poplar	Poplar (*Max 1*)	P	4 single rows	2.5	0.4	9804	Winter wheat, barley,
			Crop: maize	BLC[c]					Silage maize, canola,
				PC[d]					Potatoes, oats

[*] Indicates short rotation coppice

[a,b,c,d] Indicate crop strips adjacent to P1, P2, BL, and P, respectively

Table 3 Soil bulk density and amount of soil without stones at 0–10, 10–30, and 30–60 cm soil depth layers in SRCs and crops at Allendorf, Dornburg and Forst sites

	Allendorf		Dornburg		Forst	
	SRC	Crop	SRC	Crop	SRC	Crop
Soil bulk density (g/cm^3)						
Soil depth (cm)						
0–10	1.4 (0.13)*	1.5 (0.2)	1.4 (0.08)	1.1 (0.09)	1.4 (0.09)	1.2 (0.01)
10–30	1.5 (0.04)	1.6 (0.01)	1.4 (0.03)	1.3 (0.04)	1.4 (0.01)	1.3 (0.01)
30–60	1.6 (0.08)	1.6 (0.1)	1.4 (0.01)	1.5 (0.01)	1.5 (0.09)	1.5 (0.01)
Amount of soil without stones (%)						
Soil depth (cm)						
0–10	86 (1)	94 (1)	100	100	92 (3)	97 (2)
10–30	84 (6)	90 (1)	100	100	99 (0)	95 (3)
30–60	88 (3)	95 (1)	100	100	93 (1)	94 (3)

* Data are presented as mean values with standard deviation values given in brackets

storage (Mg ha^{-1} in 1 cm soil layer) was calculated by multiplying the C concentration (g kg^{-1}), bulk density, thickness of soil layer (1 cm), and percent weight of soil without stones. To calculate carbon storage at different particle-size aggregates, the above was multiplied by the percent weight of the fraction. Soil bulk density values and the amounts of soil without stones at different depth layers in SRCs and crops at different study sites are presented in Table 3.

Statistical analyses

Data was analyzed for normality by Shapiro–Wilk Test. As not all the data were normally distributed, a Mann–Whitney *U* test was done to compare the mean differences between vegetation types in C stocks. Statistical analyses were performed separately for each depth layer. Differences were considered significant at $p < 0.05$. Spearman correlation coefficients were determined to test correlations between variables. All analyses as well as descriptive data statistics (mean, standard deviation) were done with SPSS (2012) program (version 21, IBM).

Results

Total OC stocks

Total OC stocks in 0–60 cm soil depth layer varied between the sites, showing the highest OC stock at the

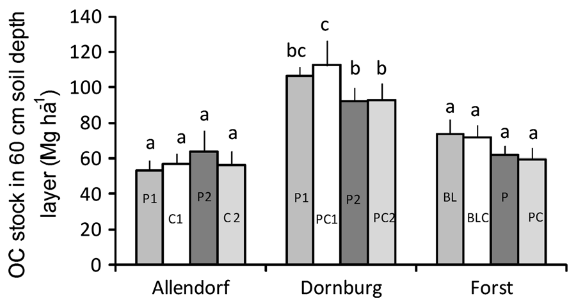

Fig. 1 Organic carbon stocks in 0–60 cm soil depth in SRCs and adjacent crops in Allendorf, Dornburg, and Forst sites. *Bars* present mean values; *vertical lines* present standard deviations. Different letters (*a*–*c*) indicate significant ($p < 0.05$) difference between sampling areas

site with the highest amount of silt and clay, Dornburg, followed by Forst and Allendorf, comprising 92–107; 59–74; and 53–64 Mg ha^{-1}, respectively. At all study sites, no significant differences for the total OC in 0–60 cm soil depth layer were found between SRC and adjacent crop strips (Fig. 1).

Although no differences between the vegetation plots were found for total stocks in the 0–60 cm soil layer (Fig. 1), a determination of OC stocks at different layers revealed significantly ($p < 0.05$) higher OC stocks at SRCs compared to adjacent crop strips for 0–3 and 3–10 cm layers in Dornburg (Fig. 2). In Allendorf, crop C1 had significantly ($p < 0.05$) lower OC stock than other sampling plots in 0–3 cm layer. In Forst, no differences in OC stocks between SRCs and adjacent crops at different soil

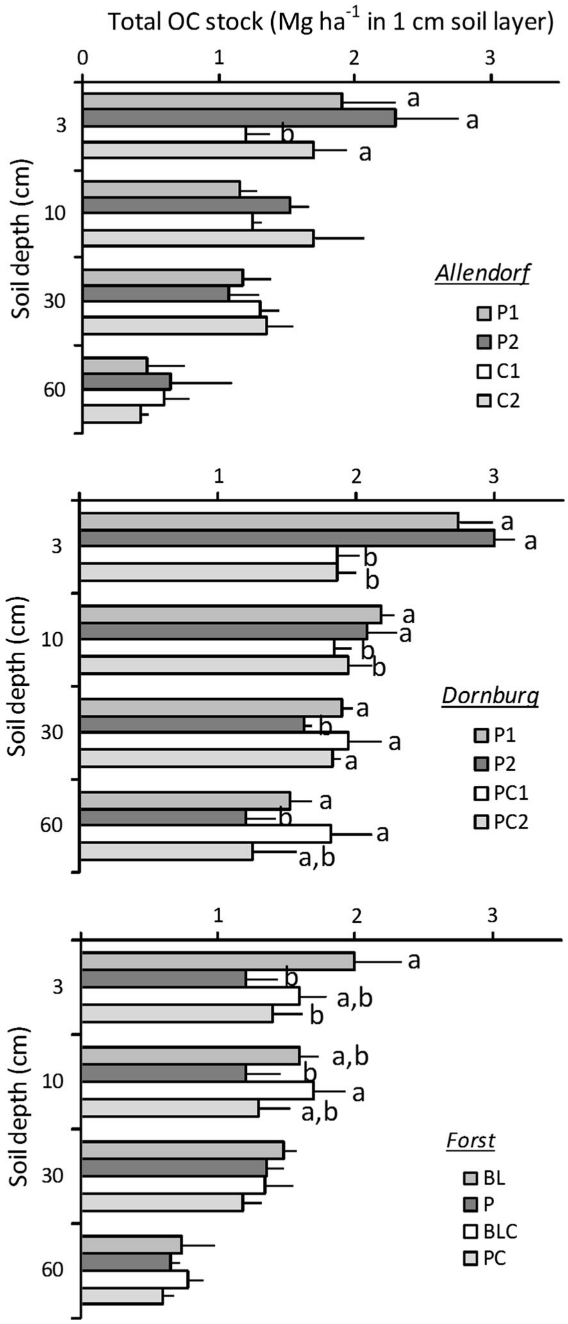

Fig. 2 Total OC stocks at different soil depth layers in SRCs and adjacent crops at Allendorf, Dornburg, and Forst sites. *Bars* present mean values; horizontal lines-standard deviation. Different letters (*a*, *b*) indicate significant ($p < 0.05$) difference between sampling areas for a particular depth layer

layers were observed, although there was a difference at 0–10 cm depth between tree coppices: BL had significantly ($p < 0.05$) higher OC stocks compared to *P*. In all SRCs sites, except *P* in Forst, OC stocks showed a vertical gradient with the highest values in 0–3 cm depth, which gradually decreased with soil depth. In contrast, under crops, OC stocks were similar between different soil depth layers up to 30 cm depth (Fig. 2).

Soil OC stocks at different particle-size fractions

Soil OC stocks in macro-aggregates (250–2,000 μm) in 0–3 cm soil depth were about two times higher in SRCs compared to crops at all three study sites, except poplar SRC in Forst (Fig. 3). In Allendorf, OC in macro-aggregates (250–2,000 μm) in SRC was also higher at 3–10 cm depth, while OC in micro-aggregates (53–250 μm) was significantly ($p < 0.05$) lower in SRCs compared to crops at 3–10 and 10–30 cm depth. In Dornburg, OC stocks at macro-(250–2,000 μm) and at clay + silt-sized aggregates were significantly ($p < 0.05$) higher in SRCs compared to crops at 0–3 cm depth. In Forst, OC stocks in macro-(250–2,000 μm) and micro-aggregates (53–250) were significantly higher in BL compared to the other vegetation types at 0–3 cm depth.

In Allendorf's SRC at 0–10 cm depth and in Dornburg's SRC at 0–3 cm depth, OC was mostly allocated within macro-sized aggregates. While OC in crops at these study sites was mostly allocated within micro-sized aggregates. In Forst, no clear differences in OC distribution within different particle size aggregates were observed between vegetation types. In all vegetation types in Forst, OC was mostly allocated within micro-sized and clay + silt aggregates (Fig. 3).

Distribution of water-stable aggregates in soils

The amount of soil macro-aggregates (250–2,000 μm) was significantly ($p < 0.05$) higher, and the amount of micro-aggregates (53–250 μm) was lower in Allendorf and Dornburg SRCs compared to adjacent crops in 0–10 cm depth (Fig. 4). In Forst, a difference in the amount of soil aggregates was observed only between BL and adjacent crops. In BL the amount of macro-aggregates (250–2,000 μm) was higher at 0–3 and 30–60 cm soil depth, while the amount of clay + silt-sized aggregates (<53 μm) at 0–3 cm and 30–60 cm soil depth and the amount of micro-aggregates (53–250 μm) at 30–60 cm depth were lower.

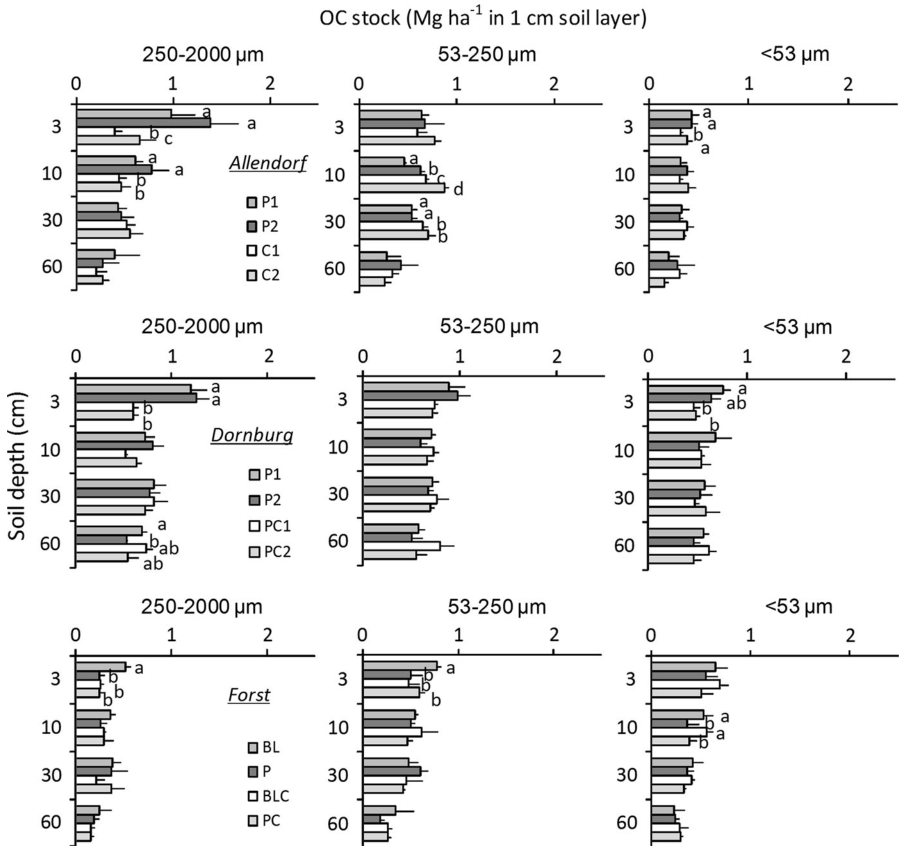

Fig. 3 Organic carbon stocks at 250–2,000, 53–250 and <53 µm soil particle-size aggregates at 0–3, 3–10, 10–30, and 30–60 cm soil depth layers in SRCs and crops at Allendorf, Dornburg, and Forst sites. *Bars* present mean values; horizontal lines-standard deviation. Different letters (*a*–*d*) indicate significant ($p < 0.05$) difference between sampling areas for a particular depth layer

Hot water-extractable OC

Hot water-extractable OC showed similar patterns to the total OC stocks, exhibiting a depth gradient with higher values at the top 10 cm soil layers, and gradual decrease with depth. This trend was more evident at SRCs at Allendorf and Dornburg sites. HWC was significantly ($p < 0.05$) higher in SRCs compared to adjacent crops in Allendorf at 0–3 cm depth, and in Dornburg at 0–3 and 3–10 cm depth (Fig. 5). In Forst, HWC was significantly higher ($p < 0.05$) at BL compared to poplar at 0–3 and 3–10 cm depth. SRC in Forst had the lowest ($p < 0.01$) amount of HWC at 0–3 cm depth compared to other study sites, comprising 396 mg kg^{-1}, compared to 536 mg kg^{-1} in black locust SRC in Forst, 909–941 mg kg^{-1} in poplar SRCs in Allendorf, and 905–1,048 mg kg^{-1} in poplar SRCs in Dornburg.

Relationships between OC fractions

In all study sites, total OC stocks were significantly ($p < 0.01$) correlated with HWC and OC stocks at different particle size fractions, showing the highest correlation with OC stock in macro-aggregates at Allendorf, micro-aggregates at Dornburg, and clay + silt aggregates at Forst (Table 4). Hot water-extractable OC was also significantly ($p < 0.01$) correlated with OC fractions at different particle-sized aggregates, showing the highest correlation with macro-aggregates in Allendorf, and Dornburg, and with clay + silt-sized (< 53 µm) aggregates in Forst (Table 4).

Discussion

It may take a long time for the differences in total organic carbon (TOC) stocks to be detectable after the land-use change. SRCs investigated in present study are young, and the time passed after establishment of SRCs was probably too short for the changes in TOC stocks at the 0–60 cm soil depth layers to be detectable. The differences in TOC stocks between the sites may be attributed to soil texture. A positive correlation

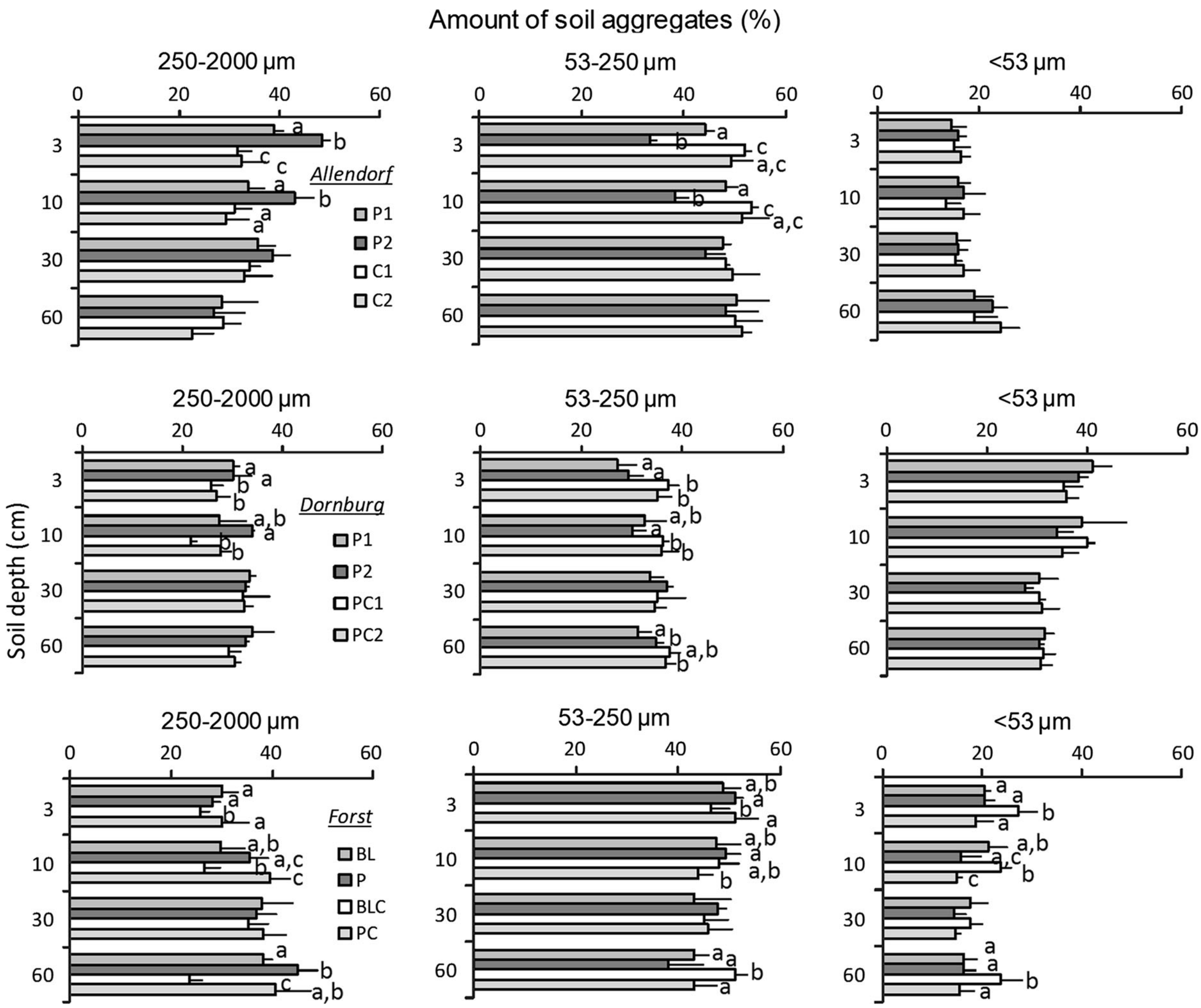

Fig. 4 Distribution of 250–2,000, 53–250, and <53 µm soil particle-size aggregates at 0–3, 3–10, 10–30, and 30–60 cm soil depth layers in SRCs and crops in Allendorf, Dornburg, and Forst sites. *Bars* present mean values; horizontal lines-standard deviation. Different letters (*a*–*c*) indicate significant ($p < 0.05$) difference between sampling areas for a particular depth layer

between soil OC and clay contents have been reported by a number of studies (Schimel et al. 1985; Spain 1990). This is because clay particles have a large surface area on which OC compounds can be adsorbed and stabilized against microbial decomposition (Baldock and Nelson 2000). In the study, Dornburg with the highest clay (28 %) and clay + silt (95 %) content had the highest TOC stocks (Fig. 1). Although Allendorf has higher clay (18 %) and clay + silt (52 %) content than Forst (10 % clay, and 42 % clay + silt), the TOC stocks in Allendorf for 0–60 cm were slightly lower than in Forst. This can be related to the higher amount of stones at Allendorf site (Table 3).

Despite no significant differences in the OC at 0–60 cm depth were found between sampling areas, there was a trend of higher TOC stocks in top 0–3 cm soil in SRCs, with a gradual decrease with depth. This trend is consistent with numerous studies (Nii-Annang et al. 2009), and could be a reflection of litter return to the topsoils. By contrast, in crops, soil tillage mixes and redistributes litter within soil till the depth of 20–30 cm, leading to more even OC distribution. In addition, tillage may enhance soil aeration, promoting microbial activity and organic matter mineralization, reducing SOM levels in the topsoil of crop strips.

Similar to the TOC stocks, a vertical gradient in OC distribution at macro-aggregates was observed at

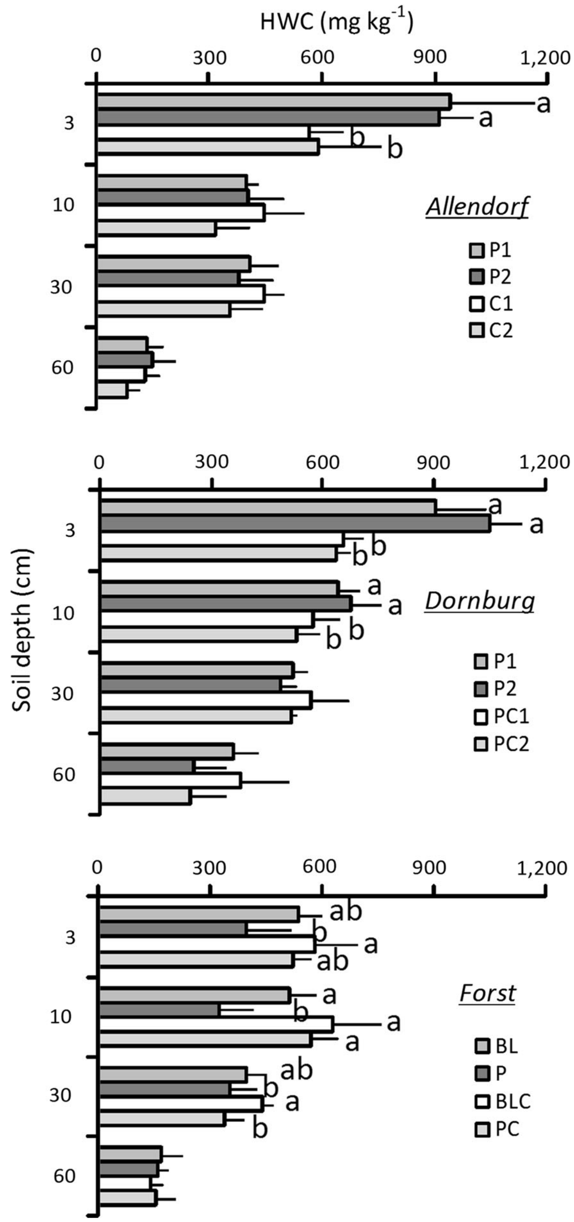

Fig. 5 Hot water-extractable organic carbon at 0–3, 3–10, 10–30, and 30–60 cm soil depth layers in SRCs and crops at Allendorf, Dornburg, and Forst sites. *Bars* present mean values; *horizontal lines*-standard deviation. Different letters (*a*, *b*) indicate significant ($p < 0.05$) difference between sampling areas for a particular depth layer

SRCs. In all study sites, except poplar in Forst, OC stocks in macro-fractions in the top 0–3 cm soil layer were about two times higher at SRCs compared to crops. This pattern was similar to other studies (Haile et al. 2008; Howlett et al. 2011), and may be attributed to the greater litter returns, as marco-sized OC particles represent a partly decomposed litter material. In addition, this pattern may also be related to the greater amount of macro-aggregates observed in the topsoils of SRCs, which resulted from the lower soil disturbance at SRCs compared to the tilled crop strips (Fig. 3). According to Six et al. (2000) a conversion from till to no-till land use enhances soil aggregation. A formation of macro-aggregates from smaller-sized aggregates, explains a concomitant decrease of micro- and clay + silt aggregates at a particular soil depth layer (Fig. 4). Macro-aggregates, formed from micro, and clay- and silt- sized aggregates, contain stable OC bond to clay and silt particles, as well as labile partly decomposed organic material occluded within soil aggregates. A greater inclusion OC in macro-aggregates may result in greater C sequestration in SRCs, as C occluded within soil aggregates is better protected from microbial decomposition and has longer residence time in soils (Six et al. 2000). Management practices conserving soil aggregates in SRCs, such as zero tillage may enhance sequestration of OC within soil aggregates, and therefore enhance soil potential to C sequestration.

Among the study sites, Dornburg showed the highest potential for C sequestration. This is because stabilization of soil OC is associated with binding to clay- and silt- sized particles (Six et al. 2002), and soils with greater amounts of clay and silt tend to have higher amount of recalcitrant organic material with long residence time compared to coarse-textured soils. Dornburg soils with high amount of clay + silt, and therefore high surface area for retention, have higher potential to stabilize C compared to other study sites. In addition to having the highest amount of clay + silt particles, Dornburg soils also had high macro- and micro-aggregates formation, enabling C protection within soil aggregates. Similar to Dornburg, OC in Allendorf was also mostly stored in macro- and micro-aggregates, which also indicates a potential of Allendorf for OC sequestration. On contrast, in Forst despite lower amount of clay + silt (42 %) compared to Dornburg (95 %) and Allendorf (52 %), OC was mostly stored in clay + silt-sized aggregates. This can be attributed to the younger age of trees in Forst site, and therefore lower aggregates formation.

Contrary to findings of some studies (Haile et al. 2008; Howlett et al. 2011), who suggested that SRC should have higher SOC stocks in deep soil layers, due

Table 4 Spearman correlation coefficients* for the relationships between OC fractions at Allendorf, Dornburg, and Forst sites

		HWC stock	C stock in particle-size soil fractions		
			<53	53–250	250–2000
OC stock	Allendorf	0.810	0.768	0.763	0.796
	Dornburg	0.854	0.479	0.683	0.598
	Forst	0.888	0.769	0.733	0.59
HWC stock	Allendorf		0.634	0.656	0.711
	Dornburg		0.416	0.549	0.660
	Forst		0.806	0.697	0.471

* All values show significant correlation at $P < 0.01$

to the root decomposition, our study found no significant differences between SRCs and crops at 30–60 cm soil depth. This contradictory finding may be related to the comparatively young age of SRCs in our study (up to 5 years-old), compared to 8–40 years-old silvopastural systems studied by Haile at el. (2008).

Distribution of HWC showed a similar trend to total OC and OC at macro-aggregates, exhibiting vertical gradient with higher HWC in topsoils of SRCs (Fig. 5). This is a reflection of the greater amounts of rapidly decomposable litter material in topsoil of SRCs, as HWC indicates a labile, easily extractable C fraction, associated with short-term changes in OC stocks, related to land-use or management (Böhm et al. 2009). The lower HWC values at SRCs in Forst can be related to the youngest age of SRC at this site, and therefore lower litter returns compared to the older sites at Dornburg and Allendorf. A lack of difference in easily extractable labile HWC between black locust and crops could have resulted from a great amount of straw left on soil after maize harvesting in October. Soil tillage mixes straw into the soil, as well as increases soil aeration and moisture availability, which may enhance microbial decomposition, and therefore amount of labile HWC in crop strips. A positive correlations between HWC and all three particle-size aggregates (macro-, micro- and clay + silt), may indicate that HWC may be extracted from all three particle-size fractions. It may include easily leached hydrocarbons from macro-aggregates, and microbial C from clay + silt-sized aggregates. Though, a correlation between HWC and OC at different particle-size aggregates may be a coincidence due to the inter-correlation between OC fractions and total OC. A further investigation is needed to validate this pattern.

Compared to the other SRCs, poplar in Forst had lower amount of TOC, HWC, OC in macro-aggregates, and the amount of macro-aggregates. This could be related to the youngest age of polar SRC in our study. As poplar trees died after planting in 2010, and were replanted in 2011, there was no litter production in 2010. At a sampling time, in 2011, poplar trees were only 1 year old, and therefore had lower litter returns, compared to black locust. Soil disturbance during re-planting of poplar trees could have damage soil aggregates, resulting in lower macro-aggregates formation compared to black locust. Probably in a long run, due to the lower soil disturbance, the amount of macro-aggregates and C inclusion within aggregates will increase in poplar stands similar to the other SRCs.

Conclusion

Although no differences in the total OC stocks in 0–60 cm soil depth were observed between SRCs and adjacent crops, greater amounts in labile OC fractions (HWC and OC in macro-aggregates) were observed in topsoils of SRCs compared to adjacent crops, already few years after planting trees. A greater inclusion of OC in macro- and micro-aggregates related to lower soil disturbance in SRCs compared to the tilled crop strips, may preserve OC from the decomposition, and in a long run may enhance soil C sequestration. Longer-time investigations are needed to confirm this pattern.

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