

REVIEW

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Influence of trees and associated variables on soil organic carbon: a review



Angom Sarjubala Devi

Abstract

The level of soil organic carbon (SOC) fluctuates in different types of forest stands: this variation can be attributed to differences in tree species, and the variables associated with soil, climate, and topographical features. The present review evaluates the level of SOC in different types of forest stands to determine the factors responsible for the observed variation. Mixed stands have the highest amount of SOC, while coniferous (both deciduous-coniferous and evergreen-coniferous) stands have greater SOC concentrations than deciduous (broadleaved) and evergreen (broadleaved) tree stands. There was a significant negative correlation between SOC and mean annual temperature (MAT) and sand composition, in all types of forest stands. In contrast, the silt fraction has a positive correlation with SOC, in all types of tree stands. Variation in SOC under different types of forest stands in different landscapes can be due to differences in MAT, and the sand and silt fraction of soil apart from the type of forests.

Keywords: Coniferous, Deciduous, Evergreen, Sand, Silt

Introduction

Soil organic carbon (SOC) is an essential component of environmental quality assessment. Atmospheric CO₂ is transferred into long-lasting pools, such as soil organic matter (SOM), thus reducing the atmospheric concentration of CO₂ (McBratney et al. 2014). SOC is vital for soil fertility, plant growth, and production (Janzen 2006). The total amount of carbon (C) stored in soil globally is estimated to be 1500 Pg C, with soil containing more C than the atmosphere (800 Pg C) and vegetation (500 Pg C) combined (FAO & ITPS 2015). A small variation in SOC concentrations can significantly affect the global carbon cycle (Walter et al. 2016).

Climate, land cover, soil texture, and soil order all affect SOC storage (Batjes 2016): Entisols and Aridisols store low amounts of SOC, whereas Histosols naturally store high amounts. When CaCO₃ is present in the soil, typically at pH 6.5 or higher, soil inorganic carbon (SIC) is formed (Lal et al. 1995). Histosols, Andisols, Spodosols, Oxisols, and Ultisols do not contain SIC, but Aridisols may store high amounts of SIC. On average,

Inceptisols store the lowest amount of total C (SOC and SIC) and Histosols store the highest amount of total C (mostly SOC) (Eswaran et al. 2000). Global SOC concentrations range from low to high in soils of arid and temperate regions, respectively, and extremely high in organic or peat soils (Lal 2004).

Vegetation community structure may also affect the size of the SOC pool by altering both the microenvironment and soil characteristics (You et al. 2014). Globally, forest soil is a much more important C sink than live forest biomass, with concentrations two to four times higher in the upper 30 cm, and three to six times higher in the upper 50 cm (Calvode et al. 2020). Worldwide, forests cover 4.03 billion ha, approximately 30% of the earth's surface: of the total C stock in forest biomes, 37% occurs in low latitude forests, 14% in mid latitudes and 49% in high latitudes. A large part of the total SOC occurs in soils of tundra, pre-tundra, and taiga regions (Wyse 2012). Forests with different tree species vary in litter quality and root exudates, generating a divergence in soil properties, which may influence the soil microbial community (Chandra et al. 2016). SOC dynamics also differ due to variations in local vegetation types (Saiz et al. 2012; Gruba et al. 2015).

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Research into the effect of tree species on SOC is crucial for mitigating the effects of greenhouse gases (Jandl et al. 2007). Tree species are one of several factors that influence soil C and nitrogen (N) inputs and outputs. Comparative studies of tree species grown under different conditions are beneficial in determining their effect (Binkley 1995), and the influence of tree species depends on the differences in soil conditions, such as parent material or land use (Vesterdal et al. 2008). Zhou et al. (2020) observed mixed forest stands of *Cunninghamia lanceolata* and *Phyllostachys heterocyclus* have 3.33% of SOM compared with pure stands of *C. lanceolata* (1.77%) indicating mixed forest stands are better for storing SOM. Marler et al. (2016) have also indicated mixed deciduous tree stands can store more SOC (130.0 mg g^{-1}) than pure forest stands of *Leucaena leucophela* (73.7 mg g^{-1}). Mixing of Acacia tree species in *Eucalyptus* plantations in sandy and nutrient-poor soils involved soil C and N accretion after 7 years in the Republic of Congo (Koutika et al. 2019). Similar observations of mixed forest stands recording more SOC than pure stands were also reported by Yao et al. (2019). While, deciduous forests, with large C pools in the forest floor, store less carbon in soil (Oostru et al. 2006), and more C has been found in soils under mixed spruce forest in central western Europe (Berger et al. 2002). According to Guedes et al. (2016), coniferous tree stands of *Pinus taeda* recorded 135 Mg/ha of SOC compared with deciduous tree stands of Miombo (87 Mg/ha). Adivia et al. (2016) have provided consistent evidence of greater buildup of forest floor humus leading to more SOC in coniferous forest soils. Therefore, vegetation type is the most important variable driving the spatial pattern of SOC (Shi et al. 2012). Trees may influence the properties of soils beneath them, with a number of species affecting factors such as pH (Finzi et al. 1998), C and N levels, and the composition of the microbial community (Mitchell et al. 2010).

In this review, the author sought to determine whether variation in tree species is the only factor regulating the amount of SOC, or if other variables are involved. The effect of mean annual temperature (MAT), mean annual precipitation (MAP), tree age, elevation, soil pH, and the relative composition of sand, silt, and clay were selected for analysis as these have been commonly reported in the literature. The aim of this review is to determine what effect these variables have on SOC.

Methodology

For this review, a literature survey was carried out using the following search engines and academic platforms: ResearchGate (<https://www.researchgate.net>), Google Scholar (www.google.com), Science Direct (<https://www.sciencedirect.com>), Springer (www.springer.com), and Taylor and Francis (<https://www.taylorandfrancis.com>). Research published prior to January 2020 was considered for the present study. The keywords used were “SOC in different tree stands” and “influence of trees on SOC.” Numerous studies have reported SOC from different forest types; however, the specific tree species and the level of SOC in the forests are less reported. Therefore, literature on “litter decomposition,” where soil characteristics have been reported, were also collected. In numerous studies, SOC has been given in the form of C-storage. This is difficult to convert into SOC without knowing the bulk density value and weight of soil particles ≥ 2 mm, therefore these studies were not included.

The most widely reported procedure for SOC estimation is the wet digestion method of the Walkley-Black technique (Walkley 1947), which uses the heat from a sulfuric acid reaction to oxidize SOC by hot chromic acid. In recent studies, a CHN-elemental analyzer is used for SOC estimation. In many studies, a conversion factor of 1.2 has been applied for the SOC levels determined by the Walkley-Black method; in the present review, however, no conversion factor was applied as DeVos et al. (2007) have pointed out sandy soils with conifers showed 6% higher recoveries than broadleaved species on heavier textured soils. For each laboratory and type of soil, they recommended that specific recovery factors need to be determined in order to standardize the results. Studies that reported only SOM were converted to SOC by dividing by 1.72 as SOM contains 58% SOC. In most of the studies, SOC levels were given in g kg^{-1} , which was converted into percentage by dividing by a factor of 10.

The composition of sand, silt, and clay were determined either by the micro-pipette method (Miller and Miller 1987), the sieve method, or the hydrometer method (Day 1965). Studies that measured soil pH using a 1:1 or a 1:2.5 soil to water ratio were selected, as many studies have also reported the pH as the soil to KCl ratio. The soil sampling depths were variable (Adekunle et al. 2011; Guedes et al. 2016; Zhou et al. 2020); however, the most common depth was 0–20 cm, therefore, the present review was limited to reports from this depth. In all the selected studies, soil sampling was done by removal of the organic layer prior to sampling. As many as 60 tree species were recorded. Among the coniferous trees, the number of deciduous-conifer was very less compared with evergreen-conifers; therefore, they were grouped together as coniferous trees. The broadleaved-deciduous and broadleaved-evergreen trees were simply classified as deciduous and evergreen trees. Altogether the trees were broadly classified into four categories: coniferous, deciduous, evergreen, and mixed types.

Table 1 Soil organic carbon (SOC) and associated variables (age, mean annual temperature [MAT], mean annual precipitation [MAP], soil type, altitude, depth, % sand, % silt, % clay, and pH) in different types of tree stands, C: coniferous; D: deciduous; E: evergreen; and M: mixed. Results are shown in chronological order; (“do” indicates the same as above)

Sl. no.	Species name	Age (years)	MAT (°C)	MAP (mm)	Soil type	Altitude (m asl)	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	pH	SOC (%)	Reference
1.	<i>Acer saccharum</i> (D)	44			Fragiocept		0–10				4.00	5.9	Riha et al. (1986)
	<i>Pinus resinosa</i> (C)	44			do						3.83	5.1	do
	<i>Picea abies</i> (C)	44			Dystrochrept						3.76	4.9	do
2.	<i>Dipterocarpus tuberculatus</i> (D)		22.0	1245		300–360		70.00	18.00	12.00	6.20	0.2	Yadava and Devi (2007)
3.	<i>Fagus sylvatica</i> (D)						0–10	82.00			3.70	5.0	Kooijman et al. (2009)
	do							47.00			4.00	3.7	do
	do							5.00			6.70	8.4	do
4.	<i>Quercus leucotrichophora</i> (D)					1566	0–20					2.3	Sheikh et al. (2009)
	<i>Pinus roxburghii</i> (C)					900	do					1.8	
5.	<i>Fagus sylvatica</i> and <i>Fraxinus excelsior</i> (M)	60	7.8	750–800	Eutric cambisol	440	0–10	2.60	46.2	51.10		5.3	Kutsch et al. (2010)
6.	<i>Castanopsis carlesii</i> and <i>Litsea acuminata</i> (M)		18.2	2342–2743	Inseptisol and Ultisol	670–1000	0–20	23.00	42.00	35.00	4.50	3.9	Owen et al. (2010)
7.	<i>Gmelina arborea</i> (D)	20					0–30	34.71	29.76	20.53	7.30	2.7	Adekunle et al. (2011)
	do	10						21.04	21.76	27.20	7.33	1.9	do
	<i>Tectona grandis</i> (D)	15						68.73	19.23	12.04	8.33	1.1	do
	do	8						64.00	22.75	13.45	6.93	0.5	
8.	<i>Shorea siamensis</i> and <i>Vitex peduncularis</i> (M)		25.0	1650	Alfisol	150–350	0–13	49.50	37.40	13.20	6.40	2.3	Takahashi et al. (2011)
9.	<i>Pinus densiflora</i> (C)	25	10.6	1245		400	0–10				5.2–5.70	3.3	Yang et al. (2011)
10.	<i>Quercus mongolica</i> (D)		4.6	600–1000	Cryumbreps	251	0–20				4.50	3.3	Sun et al. (2012)
	do		7.3	do	Haplocryolls	201	do				5.6	4.4	do
11.	<i>Cinnamomum chekiangense</i> (E)	600	19.4	1731	Red soil/hapludult	390–430	0–20				4.08	2.9	Yu et al. (2012)
	<i>Castanopsis fargesii</i> (E)										4.65	2.9	do
	<i>Altingia gracilipes</i> (E)										4.12	6.3	do
	<i>Tsoongiodendron odorum</i> (D)										4.00	3.33	do
	<i>Cunninghamia lanceolata</i> (C)										4.60	2.2	do
12.	<i>Pseudotsuga menziesii</i> , <i>Pinus lambertiana</i> and <i>Pinus ponderosa</i> (M)	50				495–1199	0–15					8.3	Heckman et al. (2013)
13.	<i>Populus davidiana</i> (D)		2.0	400		1250–1300	0–10				6.14	10.6	Miao et al. (2013)
	<i>Populus davidiana</i> and <i>Betula platyphylla</i> (M)					1370–1550					5.89	8.4	do
	<i>Betula platyphylla</i> (D)					1550–1720					5.93	6.8	do
	<i>Larix principis-rupprechtii</i> (C)					1840–1890					5.83	6.2	do
14.	<i>Calocedrus formosana</i> (C)	> 40	21.0	>	Dystrudept	500	0–10	5.10	45.30	49.70	3.80	6.1	Lin et al.

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Sl. no.	Species name	Age (years)	MAT (°C)	MAP (mm)	Soil type	Altitude (m asl)	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	pH	SOC (%)	Reference
				4000									(2014)
	<i>Cryptomeria japonica</i> (C)	do	do	do	do	do	do	6.6	45.00	48.40	3.90	5.3	do
15.	<i>Pinus tabulaeformis</i> and <i>Robinia pseudoacacia</i> (M)	20	10.8	602		900–1300	0–20	30–55	20–45	15–25		1.9	Liu et al. (2014)
16.	<i>Shorea robusta</i> (D)		27.0	2021		450	0–15	66.01	14.12	19.87	6.21	1.8	Mandal and Joshi (2014)
	do					600		69.87	10.12	20.01	5.89	1.8	do
	do					850		55.44	26.11	18.45	5.69	1.6	do
17.	<i>Albizia zygia</i> and <i>Myrianthus arboreus</i> (M)		23.5	1350–1550	Oxisol	650–700	0–10			58.30	4.60	1.9	Sugihara et al. (2014)
18.	<i>Larix kaempferi</i> (C)	17					0–20				5.39	4.2	Chen et al. (2015)
	do	23									4.96	3.9	do
	<i>Pinus armandii</i> (C)	25									5.35	4.4	do
19.	<i>Pinus pinaster</i> (C)	67	15.35	883	Regosil	6	0–10	93.00	3.00	4.00	4.40	1.0	Matteucci et al. (2015)
20.	<i>Picea abies</i> (C)	81–100	7.4	550–700	Leptic cambisols	502–530	0–10	12.30	72.10	15.50	3.80	2.6	Andivia et al. (2016)
	<i>Fagus sylvatica</i> (D)	do	do	do	do	do	do	20.8	65.6	13.6	4	2.8	do
	<i>Picea abies</i> and <i>Fagus sylvatica</i> (M)	do	do	do	do	do	do	28.10	55.40	16.50	3.70	3.7	do
21.	<i>Quercus mongolica</i> (D)		10.8	1170		1424	0–20	27.80	19.40	52.80	4.60	6.9	Chae et al. (2016)
22.	<i>Shorea robusta</i> (D)		26.0	73.1		265	0–10	66.70	6.00	27.33	6.36	0.4	Chandra et al. (2016)
	Sal mixed		26.0	do		258		60.00	20.67	19.33	6.33	0.9	do
	<i>Pinus roxburghii</i> (C)		16.5	151.9		1822		73.33	9.33	17.33	6.48	4.5	do
	<i>Quercus leucotrichophor</i> (D)		16.5	do		1333		48.67	16.67	34.67	6.88	2.8	do
	Oak mixed		16.5	do		1305		52.67	8.00	39.33	6.61	4.2	do
23.	<i>Brachystegia boehmii</i> (E)	34	21.2	1300	Ferrasol and cambisol		0–10				5.1–5.3	1.8	Guedes et al. (2016)
	<i>Pinus taeda</i> (C)	do	do	do	do		do				5.1–5.3	3.8	do
	<i>Eucalyptus grandis</i> (E)	do	do	do	do		do				5.9–6.0	3.7	do
24.	<i>Leucaena leucocephala</i> (E)										7.15	7.4	Marler et al. (2016)
25.	<i>Picea smithiana</i> (C)		< 1.0	254–400		2860						3.3	Shedayi et al. (2016)
	do		do	do		3260						6.8	do
	<i>Pinus wallichiana</i> (C)		do	do		2890						2.2	do
	do		do	do		3350						2.4	do
	<i>Juniperus excelsa</i> (C)		do	do		3080						1.7	do
	do		do	do		3170						0.7	do
	<i>Betula utilis</i> (D)		do	do		3290						2.1	do
			do	do		3440						7.5	
26.	<i>Abies alba</i> (C)	70–90			Dystric cambisol	388–407	0–10	32.8	60.7	6.49	4.28	4.6	Ewa Blonska

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Sl. no.	Species name	Age (years)	MAT (°C)	MAP (mm)	Soil type	Altitude (m asl)	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	pH	SOC (%)	Reference
													et al. (2017)
	<i>Fagus sylvatica</i> (D)	do			do	do	do	38.98	55.23	5.29	4.56	3.0	do
27.	<i>Acacia confusa</i> (E)		23.0	1347		110	0–10				3.8–3.9	4.5–4.9	Huang et al. (2017)
	<i>Cryptomeria japonica</i> (C)	60	16.6	2635		1250	do				5.80	3.4	do
28.	<i>Pinus massoniana</i> and <i>Lithocarpus glaber</i> (M)		17.3	1416	Acrisol	55–260	0–10					1.6	Ouyang et al. (2017)
	<i>Lithocarpus glaber</i> and <i>Cyclobalanopsis glauca</i> (M)		17.3	1416	Acrisol	55–260	0–10					2.4	do
29.	<i>Pinus pinaster</i> (C)						0–15	94.7	2.6	2.7	4.1–4.8	3.1	Suaze et al. (2017)
30.	<i>Albizia zygia</i> (D)	20–30	23.5	1350–1550	Oxisol	650–700	0–10			54.90	4.80	2.5	Sugihara et al. (2017)
	do	50	do	do	do	do	do			60.60	4.70	1.9	do
31.	<i>Araucaria angustifolia</i> (C)		17.0	1600–1800	Humic Cambisol	820	0–5	21.00	29.00	50.00	3.80	4.6	Thomaz (2017)
32.	<i>Fagus sylvatica</i> (D)			800	Sandy						3.40	5.6	Weemstra et al. (2017)
	do				Clayey						6.80	3.8	do
	<i>Picea abies</i> (C)				Sandy						3.40	6.0	do
	do				Clayey						6.60	4.8	do
33.	<i>Picea abies</i> and <i>Larix decidua</i> (M)	110	7.8	1645	Lithic to rendzic leptosols and chromic cambisols	950	0–10					9.4	Zehetgruber et al. (2017)
34.	<i>Pinus jeffreyi</i> (C)			1800–3500			5–8	74.28	18.04	7.65	5.41	1.8	Fry et al. (2018)
35.	<i>Picea abies</i> and <i>Pinus cembra</i> (M)		11.0	1000	Haplic podsol	1737					3.30	11.0	Margesin et al. (2016)
	<i>Pinus sylvestris</i> and <i>Quercus pubescens</i> (M)		do	900	Drystic cambisol	570					4.10	4.1	do
36.	<i>Castanopsis carlesii</i> (E)		19.0	1749	Ferralic cambisols		0–10	60.5	13.82	25.69	4.33	2.8	Si et al. (2018)
	<i>Castanopsis fargesii</i> (E)		do	1688	Humic alfisol		do	37.29	43.55	19.17	4.64	6.8	
37.	<i>Albizia zygia</i> (D)		23.5	1350–1550		600–650	0–10			55.20	4.40	1.8	Sugihara et al. (2018)
	do												do
38.	<i>Podocarpus falcatus</i> (C)		21.0	1700–2824	Oxisols	900–1500	0–15	34.33	49	16.42	5.82	4.7	Tellen and Yerima (2018)
	<i>Eucalyptus salinga</i> and <i>Eucalyptus grandis</i> (M)		do	do	do	do	do	36	49.2	14.5	5.61	4.3	do
39.	<i>Quercus ilex</i> (D)		17			1600–2200						3.2	Ali et al. (2019)
	<i>Pinus wallichiana</i> and <i>Cedrus deodara</i> (M)					1600–3100						4.1	do
	<i>Pinus roxburghii</i> (C)					800–1600						2.4	do
40.	<i>Acacia mangium</i> (E)	7	25.0	1200	Ferralic arenosol	100	0–5	> 90	2.00	6.00	4.20	2.2	Koutika et al. (2019)

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Sl. no.	Species name	Age (years)	MAT (°C)	MAP (mm)	Soil type	Altitude (m asl)	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	pH	SOC (%)	Reference
	<i>Eucalyptus urophylla</i> and <i>Eucalyptus grandis</i> (M)	do	25.0	do								2.2	do
	Acacia and Eucalyptus 50: 50 (M)				do							2.3	do
41.	<i>Pinus densiflora</i> (C)		25.0	1437		170	0–10					4.3	Lee et al. (2019)
42.	<i>Pinus koraiens</i> (C)		< 1	800–1800	Dark brown	699	0–20	23.25	45.10	31.60	6.12	5.9	Liu et al. (2019)
	do					937		18	47.2	34.7	6.00	5.4	do
	do					1177		16.3	40.2	43.4	5.50	3.7	do
43.	<i>Fagus orientalis</i> and <i>Carpinus betulus</i> (M)		15.4	528–817	Umbric fluvisol Chromic cambisol	210–995	0–9	10.5	57	32		4.0	Moslehi et al. (2019)
44.	<i>Machilus calcicola</i> and <i>Styrax suberifolius</i> (M)		12.7	1067			0–10				6.58	5.3	Sheng et al. (2019)
	<i>Quercus aliena</i> and <i>Carpinus viminea</i> (M)		9.5	1234			do				5.35	2.8	do
45.	<i>Castanopsis chinensis</i> and <i>Schima superba</i> (M)	400	20.7	1996	Ferralic cambisol	250–350	0–20	27.60	58.60	13.70	4.20	5.6	Sun et al. (2019)
	<i>Pinus massoniana</i> (C)	60	20.9	1990	Ferralic cambisol	50–150	0–20	44.70	46.80	8.40	4.00	5.5	do
	<i>Quercus aliena</i> (D)		15.1	855	Drystic cambisol	1380–1400	0–20	24.00	62.90	3.50	4.60	5.9	do
	<i>Quercus aliena</i> and <i>Pinus armandi</i> (M)	64	15.1	855	do	1330–1360	0–20	6.00	83.10	10.90	4.60	7.0	do
	<i>Betula platyphylla</i> and <i>Populus davidiana</i> (M)		3.6	689	Eutric cambisol	729–781		7.40	86.20	6.40	5.50	9.0	do
46.	<i>Acacia mangium</i> (E)	6	27.0	950	Grayish agrisol		0–10	92.44	1.87	5.69	5.40	1.0	Weber et al. (2019)
	<i>Anadenanthera colubrina</i> (E)	do	do	do	do	do	do	do	do	do	do	1.2	do
	<i>Casuarina equisetifolia</i> (E)											1.2	do
	<i>Eucalyptus urophylla</i> (E)											0.88	do
	<i>Astronium fraxinifolium</i> (D)											0.8	do
47.	<i>Michelia champaca</i> and <i>Castanopsis</i> sp. (M)					2300–3000	0–10	71.40	22.82	5.78	4.88	5.0	Yam et al. (2019)
	<i>Cryptomeria japonica</i> (C)	60	16.6	2635		1250	do				5.80	3.4	do
48.	<i>Pinus massoniana</i> (C)		19.0	1621	Red soil		0–20					1.9	Yao et al. (2019)
49.	<i>Pinus massoniana</i> (C)	11	18.1	1022	Yellow	453	0–10				3.98	1.6	Zhang et al. (2019)
50.	Oak field (D)			1300–1500	Alluvial sediment		0–10	10.00	77.00	13.00	5.60	1.9	Zhou et al. (2019)
51.	<i>Ficus ovate</i> and <i>Sapium ellipticum</i> (M)		20.0	1272–1397	Vertisol and lithosol		0–15				6.54	3.8	Kasa et al. (2019)
	<i>Eucalyptus</i> sp. (E)		do	do	do		do				6.31	2.1	do
52.	<i>Prosopis juliflora</i> (E)						0–10					3.9	Meena et al. (2020)
53.	<i>Tectona grandis</i> SOC Within 1.5 m (D)	9					0–10					0.8	Ikhajeagbe et al. (2020)
	<i>Tectona grandis</i> SOC											0.4	do

Table 1 Soil organic carbon (SOC) and associated variables (age, mean annual temperature [MAT], mean annual precipitation [MAP], soil type, altitude, depth, % sand, % silt, % clay, and pH) in different types of tree stands, C: coniferous; D: deciduous; E: evergreen; and M: mixed. Results are shown in chronological order; (“do” indicates the same as above) (Continued)

Sl. no.	Species name	Age (years)	MAT (°C)	MAP (mm)	Soil type	Altitude (m asl)	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	pH	SOC (%)	Reference
	outside 1.5 m												
54.	<i>Casuarina equisetifolia</i> (E)	6–8	25.0	1300		6–8	0–5	Sandy			7.10	0.3	Panda (2020)
55.	<i>Quercus rubra</i> (D)		8.0	700–800			0–15				3.70	1.1	Stanek et al. (2020)

Data were summarized by the mean, maximum, minimum, and standard deviation. The Pearson’s correlation coefficient was used to find associations between SOC and the following variables: MAT; MAP; sand, silt, and clay composition; age; elevation, and soil pH. A Student’s *t* test was performed to determine the significance level ($p < 0.05$) for these correlations. A one-way analysis of variance was performed on the SOC levels in the different categories of trees using SPSS (IBM, version 16.0).

Results and discussion

SOC under different tree stands

SOC was found in very high concentrations under specific tree stands. Table 1 shows that the maximum level of SOC (11.02%) was found in mixed stands of the coniferous trees *Picea abies* and *Pinus cembra* (Margesin et al. 2016), followed by mixed coniferous stands of *Picea abies* and *Larix decidua* (9.44%) (Zehetgruber et al. 2017). Mixed deciduous stands of *Betula platyphylla* and *Populus davidiana* (Sun et al. 2019), deciduous stands of *Fagus sylvatica* (Kooijman et al. 2009), mixed coniferous stands of *Pseudotsuga menzeisii*, *Pinus lambertiana* and *Pinus ponderosa* (Heckman et al. 2013), deciduous stands of *Betula utilis* (Shedayi et al. 2016), and evergreen stands of *Leuceana leucocephala* (Marler et al. 2016) had SOC concentrations of 9.03%, 8.4%, 8.3%, 7.57%, and 7.37%, respectively. The lowest concentration among the higher group was found in coniferous and deciduous mixed stands of *Quercus aliena* and *Pinus armandi* (7.01%) (Sun et al. 2019).

Table 2 Mean and standard deviation of soil organic carbon (SOC) for all recorded tree species and different categories of tree stands ($p < 0.058$, one-way ANOVA)

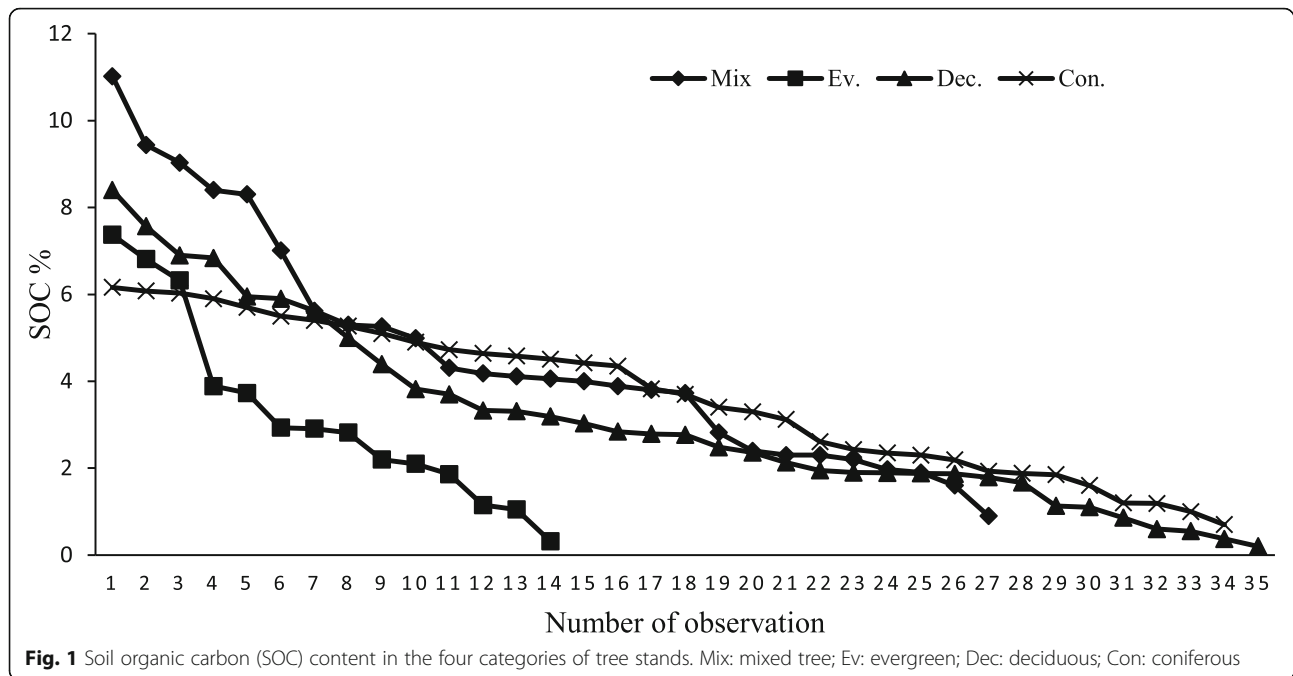
SOC(%)	Max	Min	Mean	SD	N
All tree species	11.02	0.2	3.70	1.80	119
Coniferous	6.16	0.32	3.63	1.49	34
Deciduous	8.4	0.2	3.14	1.7	35
Evergreen	7.37	0.88	3.28	1.66	14
Mixed	11.02	0.9	4.62	2.08	27

The results show that, out of the top eight tree stands that recorded the highest SOC level, three were from mixed coniferous tree stands: one from mixed deciduous trees, one from mixed coniferous and deciduous tree stands. The mixed stands recorded an average SOC of $4.62\% \pm 2.08\%$, with a range of 0.9% to 11.02% ($p < 0.058$). The average SOC of mixed tree stands was higher than the overall average of all trees (3.70%) (Table 2). These results indicate that mixed tree stands are common and can store the most SOC.

Within the coniferous tree stands, an average SOC of $3.63\% \pm 1.49\%$ was recorded: *Larix principallis* from Northeast China had the maximum (6.16%) (Miao et al. 2013) and *Junepurus excelsa* from Northern Pakistan, had the least (0.70%) (Shedayi et al. 2016). In deciduous tree stands, which had an average SOC of $3.14\% \pm 1.70\%$, *Fagus sylvatica* had the maximum (8.4%) (Kooijman et al. 2009) followed by *Betula utilis* (7.57%) (Shedayi et al. 2016), *Quercus mongolica* (6.9%) (Chae et al. 2016), *Betula platyphylla* (6.8%) (Miao et al. 2013) and *Dipterocarpaceae tuberculatus* had the least (0.2%) (Yadava and Devi 2007). In evergreen tree stands, the maximum SOC level was 7.37% in *Leuceana leucocephalla* (Marler et al. 2016), followed by 6.8% in *Castanopsis fargesii* (Si et al. 2018), and the minimum level was 0.32% in *Casuarina equisetifolia* (Panda 2020); the average was $3.28\% \pm 1.66\%$.

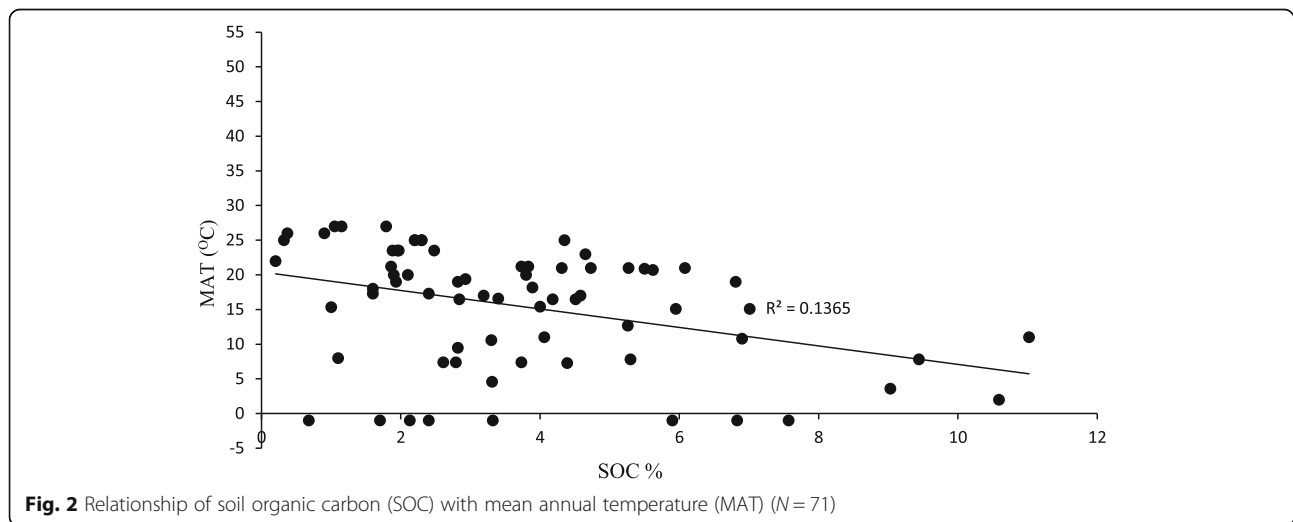
The analysis of variance showed variation of SOC among the four types of stands ($F_{3,106} = 2.56$; $P < 0.058$). SOC levels were most commonly reported from deciduous tree stands, with 35 concentrations recorded from different locations, followed by 34 recordings from coniferous tree stands. SOC levels from mixed tree stands were reported from 27 different locations, and only 14 evergreen tree stands had SOC levels recorded. As shown in Fig. 1, mixed tree stands can store the highest concentrations of SOC. Coniferous tree stands recorded higher amounts of SOC than deciduous trees, while evergreen tree stands recorded the lowest SOC level; however, this could also be due to fewer observations.

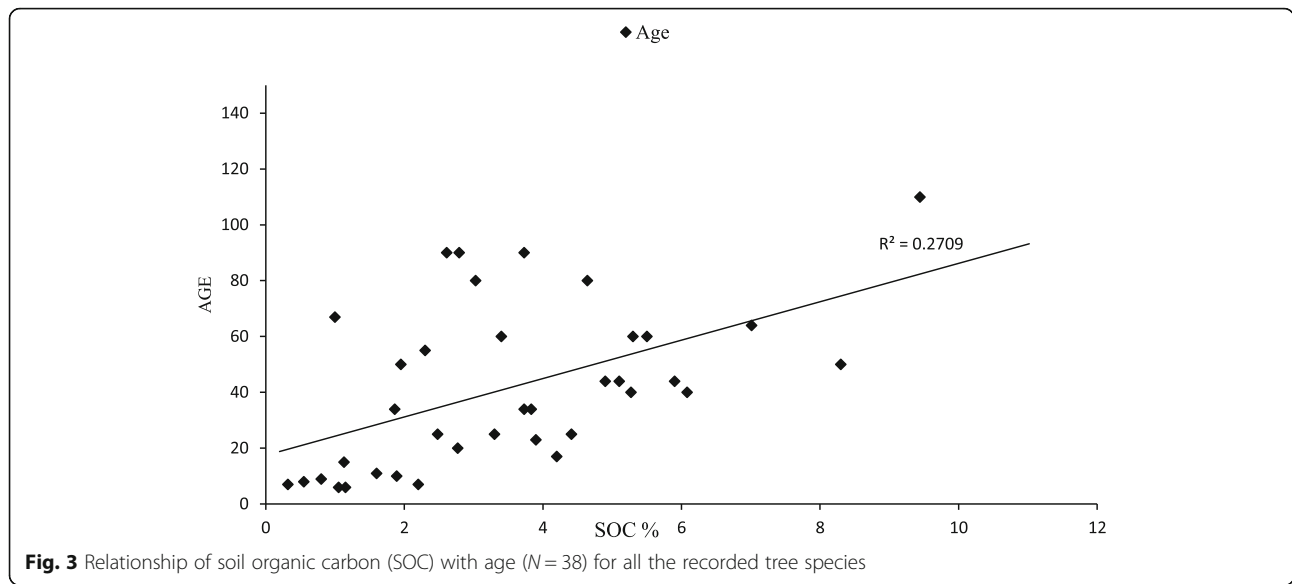
Coniferous species generally accumulate greater SOC concentrations in the forest floor layer than deciduous



species (Augusto et al. 2015). Soil C reserves in the forest floor are generally greater under conifers than under broadleaved species (Vesterdal et al. 2013). As the needles of conifers take more time to decompose subsequent buildup of the litter can lead to more SOC, moreover conifers commonly occur in colder regions contributing to the delayed rate of decomposition. Disturbance due to human activities leading to erosion of soil is also an important factor in lowering SOC, which can be relatively lower in cold regions compared with warmer regions. Another factor can be attributed to the low amount of precipitation passing through a dense and low canopy in coniferous forests that prevented

nutrient loss from the soil organic horizons (Lukina et al. 2019). Combining different tree species can have a profound effect on C accumulation ratios and SOC distribution within the soil profile (Chapin 2003), and compared with monospecific stands, the establishment of mixed forests promotes soil C sequestration. In mixed Norway spruce and European beech tree stands, the Norway spruce favored SOC accumulation in the forest floor whereas C incorporation into the uppermost mineral soil was promoted by root turnover of European beech. Therefore, conversion of monospecific plantations into mixed stands enhance SOM accumulation and stabilization in the mineral layers and, hence, the long-





term storage of C (Andivia et al. 2016). The mixed type of tree stands provides a different composition in the input litter, regulating growth and survival of different types of soil macro- and microorganisms.

2001). Oxisols occur in the hot and humid conditions of tropical regions, where the B horizon is enriched with iron, aluminum oxides, and kaolinite (Beinroth et al. 1996).

Soil type

The main soil type was found to be Cambisol, along with different subcategories, followed by Oxisol. Cambisols have a number of important characteristics that enable them to occur in widely differing environments: they contain weatherable minerals in the silt and sand fractions, have good water holding capacity, and have a neutral to weakly acidic soil reaction that promotes chemical fertility and an active soil fauna (Driessen

Role of MAT and MAP

For all the tree types, SOC was significantly correlated with MAT ($p < 0.05$) (Table 3), with a lower air temperature resulting in a higher SOC content (Fig. 2). This correlation was also significant in deciduous and mixed tree stands. Sun et al. (2019) observed an average rate of reduction in SOC was 1.87% with 1 °C increase in MAT in monospecific stands and mixed tree stands. However, annual litter fall (input) and soil microbial

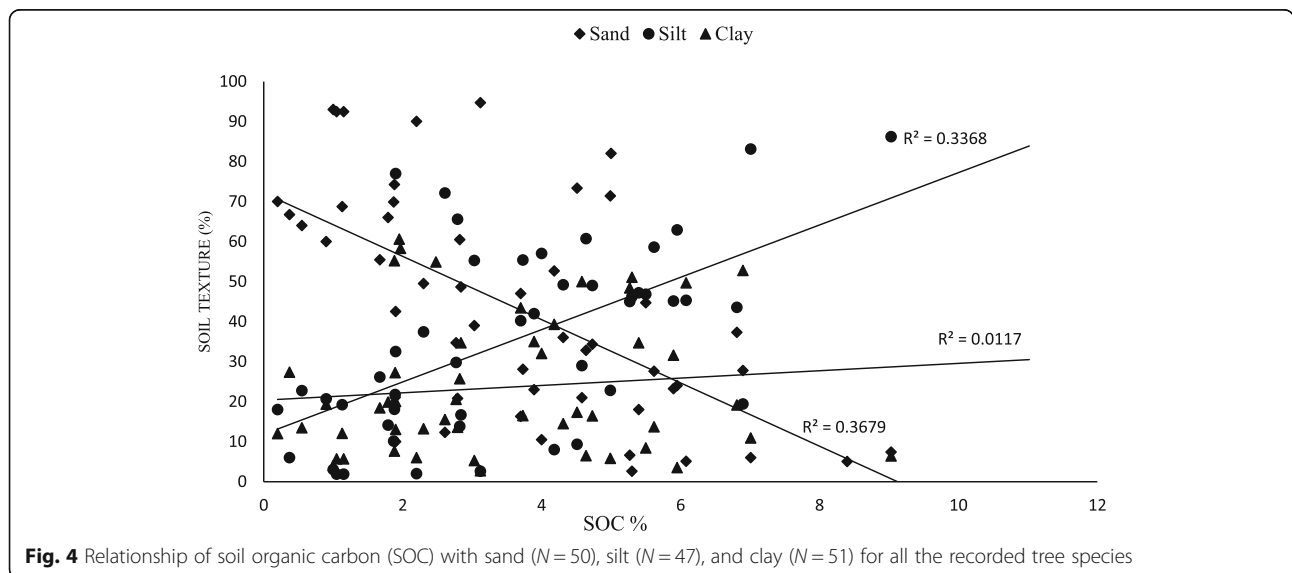


Table 3 Correlation coefficient between soil organic carbon (SOC) and mean annual precipitation (MAP), mean annual temperature (MAT), sand, silt, clay, age, altitude, and pH for all tree species and the four categories of tree stands

	All tree species		Coniferous		Deciduous		Evergreen		Mixed	
	R ² (%)	r	R ² (%)	r	R ² (%)	r	R ² (%)	r	R ² (%)	r
MAP	0.9	0.09	13.0	0.36	3.3	- 0.18	48.6	0.69	0.1	0.03
MAT	13.6	- 0.37*	0.4	- 0.06	27.2	- 0.52*	1.7	- 0.13	21.4	- 0.45*
Sand	36.7	- 0.61*	40.8	- 0.63*	27.7	- 0.52*	88.0	- 0.93*	35.7	- 0.59*
Silt	33.6	0.58*	22.1	0.47	11.3	0.33	96.0	0.97*	52.6	0.72*
Clay	1.2	0.11	31.2	0.56*	2.4	0.15	37.0	0.60	4.8	- 0.21
Age	27.0	0.52*	3.3	0.18	23.5	0.48	1.6	0.13	2.6	- 0.16
Altitude	2.0	0.14	0.1	0.04	25.0	0.50*	100	1.0	14.0	0.37
pH	3.7	- 0.20	6.2	- 0.25	8.2	- 0.28	1.7	0.13	10.8	- 0.32

*Significant at $p < 0.05$ (using t test)

respiration (output) increased with MAT, indicating that a decrease in SOC concentration did not result from changes in either organic matter input or output, but from the balance between them. Chandra et al. (2016) had recorded a significant higher concentration of microbial biomass C in temperate forests having a maximum MAT range of 18–30 °C than dry deciduous forests having 28–42 °C. Liu et al. (2016) also recorded a negative correlation of SOC and MAT in different forests at separate provinces, citing lower temperatures slow down decomposition and respiration allowing SOC to accumulate.

The correlation between SOC and MAP was not significant for all tree types, as well as for different tree stands ($P > 0.05$). This result was in contrast to the results of Yost and Hartemink (2019) who reported that SOC generally increased with increasing rainfall. They found that, on average, SOC exceeded 2% in soils from cold and temperate zones, and increased to 4% when MAP was between 500 and 750 mm, and 11% when MAP was between 800 and 1000 mm. In the tropics, SOC was < 0.5% when MAP was between 500 and 700 mm, and increased to 2% when MAP was between 800

and 1000 mm. Calvode et al. (2020) also stated that MAP was the variable most predictive of SOC, followed by lithology, land use, and soil pH.

Age and altitude

Tree age showed a significant and positive correlation with SOC for all tree types ($p < 0.05$): C storage in the soil increased with tree age. Singh and Sharma (2007) reported greater SOC and available macronutrients in older plantations of *Populus deltoides* compared with younger plantations. In *Gmelina arborea* stand, the highest percentage of SOM with 4.78% was recorded in the oldest stand of 20 years while the least 0.7% was recorded in the youngest stand of 10 years (Adekunle et al. 2011). However, it was not significant for the different types of tree stands ($p > 0.05$). Edmondson et al. (2014) reported there was no effect of tree size on soil C storage, especially for oaks where the largest individuals were 1.6 to 2.0 m dbh. The correlation of SOC with altitude was not significant overall ($p > 0.05$); however, it was significant in the deciduous tree stands ($p < 0.05$). Shedayi et al. (2016) demonstrated that organic C has a

Table 4 Mean and standard deviation for the mean annual precipitation (MAP), mean annual temperature (MAT), sand, silt, clay, age, altitude, and pH in evergreen and mixed tree stands

	Evergreen					Mixed				
	Max	Min	Mean	SD	N	Max	Min	Mean	SD	N
MAP (mm)	1749	950.0	1366	305.0	6	2542	73	1159.76	509.24	21
MAT (°C)	27.00	19.0	19.65	0.77	5	25.00	7.4	15.57	5.38	22
Sand (%)	92.44	37.29	74.53	20.51	5	71.40	2.6	32.09	18.38	14
Silt (%)	43.55	1.87	12.62	12.84	5	86.20	8.0	46.08	17.40	14
Clay (%)	25.69	5.69	12.44	7.98	5	58.30	5.78	24.31	14.48	15
Age (yrs.)	600.00	6.0	161.75	219.12	4	400.0	20.0	81.87	113.42	7
Altitude (m asl)	410	100	255	155	2	2650	157.0	931.18	519.66	22
pH	7.15	4.08	5.11	0.77	12	6.58	3.3	5.21	0.93	17

Table 5 Mean and standard deviation for the mean annual precipitation (MAP), mean annual temperature (MAT), sand, silt, clay, age, altitude, and pH in all types of tree species

	Max	Min	Mean	SD	N
MAP(mm)	4000.00	73.00	1210.00	588.00	74
MAT(°C)	27.00	- 1.00	15.49	7.10	71
Sand (%)	94.70	2.60	43.20	23.74	50
Silt (%)	86.20	1.87	34.89	19.91	47
Clay (%)	60.60	3.50	23.51	14.31	51
Age (yrs.)	110.00	6.00	41.46	23.41	37
Altitude (m asl)	3440.00	6.00	1065.00	700.00	71
pH	8.33	3.30	5.23	1.02	89

strong positive correlation with elevation in different types of tree stands.

Texture

The sand fraction showed a significant negative correlation with SOC for all trees (Fig. 4), as well as for the different types of tree stands (Table 3). The silt fraction demonstrated a significant positive correlation for all trees and for evergreen and mixed types of tree stands: the average silt fraction was highest in mixed tree stands (46.08%) (Table 4). The clay fraction did not show a significant correlation with SOC, except for in coniferous tree stands ($p < 0.05$). The negative correlation of SOC with the sand fraction has been reported previously (Tiessen & Stewart 1983; Liu et al. 2016; Zhong et al. 2018), however, a positive correlation with the silt fraction is less well documented, although Riestra et al. (2012) reported a positive correlation of SOC content with clay plus silt content in forest soils. Loam soils are 40% sand, 40% silt, and 20% clay, which is ideal for plant growth due to the desirable characteristics of these mineral particles (Sun et al. 2019). Therefore, silt composition of

up to 40% is beneficial for maintaining a stable SOC level in forest ecosystems.

Sand content is affected by soil erosion; therefore, it can be used as an indicator for evaluating soil degradation under different land-use systems (Ayele et al. 2013). There is only limited information on how physical fractions and the chemical structures of SOC relate to climate and vegetation types, especially for forest soil (Watson et al. 2000). C storage is affected by soil texture and aggregation: the highest amount of soil C is found in the silt- and clay-sized fractions, while the sand-sized fraction is low in soil C (Galeote et al. 2015). Vegetation characteristics may be a local modifier of clay content under similar climatic conditions. Therefore, the correlation between SOC concentrations and clay content may be localized and climate-dependent, and regulated by the large moisture difference that plays an essential role in driving the significant positive correlation of SOC and the clay fraction (Zhong et al. 2018).

pH

The average pH of all the tree stands was 5.23 (Table 5), with the lowest pH found in coniferous trees (4.84) (Table 6). The correlation of SOC with pH was not significant; however, a negative trend was observed (Table 3). Negative relationships between SOC and soil pH have been found in all soil groups, except the soil group, which has the highest SOC level (Zhang et al. 2020). In general, pH values in the topsoil were lower because topsoil is rich in organic matter, which decomposes, leading to the production of more organic acids and thus lowering the pH (Hong et al. 2019).

Conclusions

This review demonstrates that variation in tree species is an important factor in the amount of SOC: mixed forest stands store more SOC than simple pure forest stands. Processes associated with individual trees, such as stem

Table 6 Mean and standard deviation for the mean annual precipitation (MAP), mean annual temperature (MAT), sand, silt, clay, age, altitude, and pH in coniferous and deciduous tree stands. N = number of tree species

Variables	Coniferous					Deciduous				
	Max	Min	Mean	SD	N	Max	Min	Mean	SD	N
MAP (mm)	4000	327	1550	805	21	1450	73.0	916.0	419.0	18
MAT (°C)	21.00	- 1.0	12.42	8.73	20	27.00	- 1.0	14.38	8.07	16
Sand (%)	94.70	5.1	39.26	26.24	14	69.87	5.0	45.59	20.27	19
Silt (%)	72.10	2.6	36.66	17.33	14	77.00	6.0	30.97	18.24	15
Clay (%)	48.40	2.7	24.02	16.23	14	60.60	3.5	25.80	14.67	18
Age (yrs.)	91.00	7.0	46.35	19.26	14	90.00	8.0	35.10	24.72	10
Altitude (m asl)	3125	7.0	1038.78	705.78	25	3440	201	1085.6	729.3	21
pH	7.10	3.4	4.84	0.87	25	8.33	3.4	5.40	1.15	28

flow and litter accumulation, can have significant effects on soil chemical properties, as well as on chemical components of litter composition (Riha et al. 1986). Coniferous tree stands have a greater SOC storage capacity than deciduous tree stands. A common variable that regulates or reduces the level of SOC could not be established for the different categories of forest stands except the sand fraction. However, the silt fraction and MAT were found to have positive and inverse relationships respectively, in all forest stands, as well as in the category of mixed forest stands. As highlighted by Mayer et al. (2020), further research is necessary to tease apart the influence of species and sites. Combining a network of common garden experiments, at greater spatial scales, could identify where and how certain tree species could be beneficial to C soil sequestration, and in which forms and soil layers. The important influencing factors of spatial variations in SOC concentration in different forest stands are MAT, sand, and silt fractions of soil.

Abbreviations

C: Carbon; SOC: Soil organic carbon; SIC: Soil inorganic carbon; SOM: Soil organic matter; MAT: Mean annual temperature; MAP: Mean annual precipitation; C: Coniferous; D: Deciduous; E: Evergreen; M: Mixed

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Author's contributions

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