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CARBON STOCK OF DECIDUOUS FORESTS ON ORGANIC SOILS IN LATVIA

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Abstract
Forests play a significant role in the mitigation of climate change through carbon storage and sequestration. However, a forest's capacity to absorb carbon is influenced by a number of factors, such as soil characteristics, the selection of tree species, and the application of silvicultural practices. A study in Latvia was conducted to evaluate the carbon stock and sequestration potential of birch, common aspen, black alder and grey alder growing on periodically waterlogged and drained organic soils. Empirical data of forest resources were obtained from the National Forest Inventory (NFI) from 2016 to 2020. The findings indicate that black alder may thrive in both soil types, as it showed the best increase in carbon stock in periodically waterlogged soils, reaching a maximum of 129 t C ha^{-1} at the age of 61–70 years. Greater carbon sequestration in tree biomass occurs on drained soils compared to periodically waterlogged. Birch, aspen, and black alder stands may store between 106 and 119 t C ha^{-1} at age of 61 and 70 years, which is similar to grey alder stands at ages of 31–40 (114 ± 0.73 t C ha^{-1}). Therefore, a short rotation for grey alder growing on drained organic soils could maximize carbon accumulation and add substitution value. These results suggest that different types of deciduous trees have varying capacities for carbon storage and sequestration, and that it's important to consider site-specific factors, rotation age and silvicultural practices when aiming to maximize carbon sequestration in tree biomass.
Key words hemiboreal forests, peat soils, carbon storage, climate-smart-forestry.

Introduction

The mitigation of climate change has become a vital commitment for many nations, particularly for those with large forested areas that are capable of storing and sequestering carbon in tree biomass, vegetation, and soil (especially organic soil). The efficient use of land resources to optimize carbon storage is becoming increasingly important in the pursuit of climate neutrality objectives (Chen, 2021).

The ability of a forest to absorb carbon is significantly affected by several factors, including soil characteristics, tree species selection, and silvicultural practices. Silvicultural methods, such as drainage, thinning, and fertilization can be used to enhance the carbon sequestration potential of forest stands (Dixon, 2009).

In Latvia, approximately 11% the total forest area is situated on periodically waterlogged organic soils with an organic (peat) layer exceeding 30 cm. These forests typically have low productivity, with an average stock ranging from 110–180 m^3 ha^{-1}, depending on the soil fertility and water regime as well as selected tree species (Zālītis & Jansons, 2013). The productivity of these stands is generally limited due to excessive soil moisture with some exceptions such as black alder and grey alder stands. Drainage with open-type ditches has been identified as the most effective measure to enhance the productivity and above-ground carbon storage of these forests (Zālītis *et al.*, 2013). Currently, approximately 12% of the total forest area in Latvia consists of drained forests with organic soils (peat layer >20 cm), with a growth potential ranging from 220–400 m^3 ha^{-1} (Zālītis & Jansons, 2013).

The most common deciduous tree species found in Latvia are birch (*Betula spp.*), common aspen (*Populus tremula*), black alder (*Alnus incana*), and grey alder (*Alnus glutinosa*). Furthermore, they exhibit different growth rates and biological ages at which they begin to degrade. As a result, forest policy has established to define felling ages for different tree species. Fast-growing tree species, such as grey alder, does not have a felling age, whereas aspen can be harvested at the age of 40 years. Black alder (71 years) and birch (71 or 51 years at poor site types) have longer rotation cycles (Meža likums, 2000).

Fast growing deciduous trees with shorter rotation cycle can be advantageous for carbon sequestration purposes as well to provide substitution effect for fossil energy sources (Binkley *et al.*, 1997; Rytter & Rytter, 2016; Tullus *et al.*, 2013). While energetic wood has a lower substitution factor than other wood assortments, there has been a growing demand for energetic biomass, thus increasing its value (*Material Economics*, 2021). Birch and black alder have more valuable timber assortments with a longer life span and higher substitution potential (Claessens *et al.*, 2010; Dubois *et al.*, 2020).

The economic efficiency of forest land use is primarily influenced by the selection of tree species suitable for soil conditions. However, in order to comply with aspects of climate change mitigation targets, it is necessary to promote the replacement of low-productive stands with the most suitable tree species to develop more productive stands in terms of carbon sequestration. Climate-Smart Forestry is a focused strategy that aims to maximize the potential advantages of forest ecosystems and the forest industry to capture CO_2 in tree biomass as well as through material and energy substitution (Weatherall *et al*., 2022). Information in the scientific literature about carbon stock of deciduous trees growing on organic soils is scarce; however, it is necessary for management purposes. Therefore, it is crucial to conduct research on tree species growth and carbon storage potential on a national scale. The aim of this study is to evaluate the carbon stock and sequestration potential in tree biomass of deciduous forests growing on periodically waterlogged and drained organic soils.

Materials and Methods

Information about forest resources in Latvia has been gathered through the National Forest Inventory (NFI) since 2003. The NFI uses four permanent sample plots (500 m^2) in each 4x4 m grid network across the territory of Latvia, totaling 16157 sample plots. Each sample plot is remeasured every five years. In the current study, data from the NFI (from 2016 to 2020) were used to obtain stand-level growing stock. This study focused on deciduous forests in Latvia, specifically the four most common native tree species: birch, common aspen, black alder and grey alder, growing on organic soils. The research analyzed empirical data of deciduous forest stands growing on drained and periodically waterlogged (undrained) organic soils (Table 1). The forest stands were grouped based on the soil type: drained – forest stands are improved with an established ditch system that regulates the groundwater level and others lacking drainage systems and thus are periodically waterlogged. Forest stand growing stock was estimated using locally developed models for each tree species by Liepa (Liepa, 1996). Study stands were divided by 10-year age classes up to 90 years. Biomass-weighted means were calculated based on the proportional distribution of the whole tree biomass of different species in forest stands, taking into account the proportional distribution of admixed tree species (Liepiņš *et al*., 2018, 2021). Data on weighted average C content in wood (g kg^{-1}) were used to calculate average carbon stock and mean annual rate of carbon accumulation in tree biomass for each tree species and 10-year age class (Bārdule *et al*., 2021). Annual carbon sequestration (accumulation) was calculated by dividing carbon stock with stand age. Normal distribution of data was checked with the Shapiro-Wilk normality test. A t-test was used to evaluate the statistical significance of average carbon sequestration differences observed between two distinct soil type groups for each species. A linear model was used to test the effect of tree species, soil type, and stand age on the dependent variable – carbon stock. Significant effects ($p \leq 0.05$) were examined with ANOVA type III test (sum of squares). All data analyses were performed at level α=0.05 with R Studio (R Core Team, 2021).

Table 1

Number of observations (plots) for each species and soil type

Age	Drained soils				Periodically waterlogged soils			
	Birch	Black alder	Aspen	Grey alder	Birch	Black alder	Aspen	Grey alder
1-10	50	13	6	7	14	15	-	2
11-20	33	11	2	3	14	15	-	3
21-30	16	4	1	2	16	7	2	4
31-40	34	4	-	2	16	13	2	3
41-50	35	9	1	5	43	16	-	4
51-60	60	14	3	-	45	21	-	2
61-70	46	11	2	-	30	18	-	-
71-80	28	8	2	-	18	13	-	-
81-90	13	2	1	-	6	4	-	-

Results and Discussion

Carbon stock

The evaluated tree species exhibit differences in their carbon sequestration capacity (Table 2), as well as the required length of their rotation cycle. Carbon stock of all analyzed deciduous tree species have similar trend: carbon stock increases with increasing stand age (Figure 1). In some cases, high data variation of carbon stock for some tree species can be observed. This could be explained with small sample size in certain decade and differences in specific growing conditions, site index and management history.

Table 2

Average carbon stock (t C ha^{-1}) by decades

Age	Drained soils				Periodically waterlogged soils			
	Birch	Black alder	Aspen	Grey alder	Birch	Black alder	Aspen	Grey alder
1-10	1.09	2.69	1.72	0.28	0.53	2.83	-	2.02
11-20	18.45	16.66	6.72	21.36	13.18	16.68	-	3.22
21-30	36.10	24.90	-	57.19	31.56	42.23	46.06	31.55
31-40	69.63*	68.86	34.13	114.30	45.91*	48.11	50.11	53.50
41-50	80.72	86.26	102.46	56.21	69.63	73.48	-	59.14
51-60	87.49	105.77	127.58	-	69.58	98.12	-	20.33
61-70	106.47*	114.24	119.05	-	84.99*	129.41	-	-
71-80	106.57*	133.21	168.82	-	67.89*	116.49	-	-
81-90	94.10	139.80	199.95	-	68.19	126.70	-	-

* significant differences ($p<0.05$).

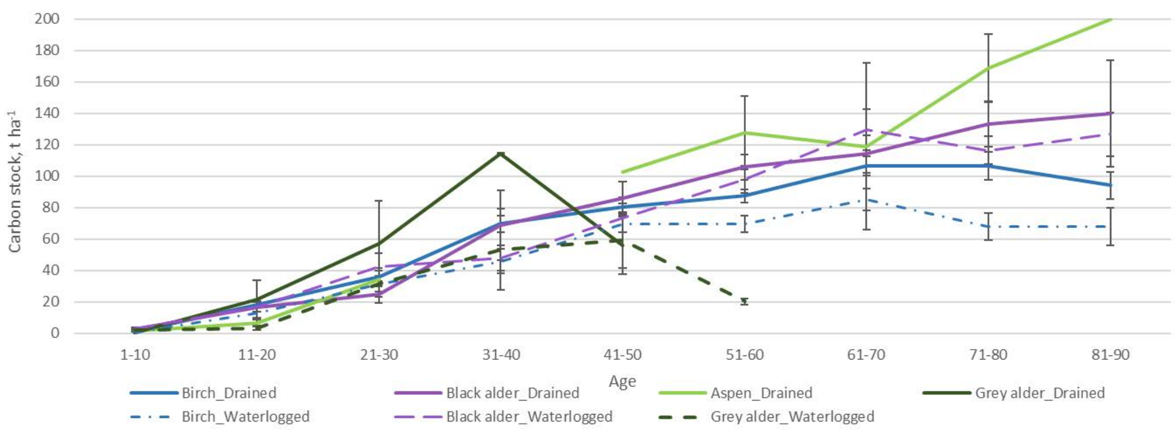

Figure 1. Average carbon stock of deciduous forest stands per decade in both soil types (whiskers denote ± standard error).

Drained soils

On drained organic soils, the carbon stock of grey alder forest stands reached its maximum by the age of 31–40 years, thus grey alder can potentially reach 114 ± 0.73 t C ha^{-1} (average ± standard error) in a 40-year rotation. However, after the fourth decade, carbon accumulation in grey alder stands significantly decreases as the trees begin to decay due to biological factors (Arhipova *et al.*, 2011), leading to emissions from dead wood (Köster *et al.*, 2015). Indeed, to maximize carbon sequestration, it is advisable to cultivate grey alder stands for a period of up to four decades, subsequently harvesting them and initiating re-growth. This approach allows for efficient utilization of the grey alder resources while ensuring continuous and sustainable carbon sequestration over multiple growth cycles. (Rytter & Rytter, 2016). Hence, the carbon accumulation over two successive rotations is projected to reach 228 t C ha^{-1} by the eighth decade (Figure 2), aligning with the felling age of the other species, namely birch and black alder. At an age class of 61–70 years, the carbon storage capacity in stands of birch, aspen and black alder exhibit comparable levels, with birch accumulating 106 ± 6.18 t C ha^{-1}, followed by black alder at 114 ± 12.02 t C ha^{-1}, and then aspen at 119 ± 53.22 t C ha^{-1}. Notably, the carbon sequestration achieved by these tree species within the age of 61–70 years is comparable to that attained by grey alder within the age range of 31–40 years. Aspen and black alder continues to increase carbon stock even until the age of 81–90 years, achieving carbon stocks of 200 t C ha^{-1} and 140 ± 33.40 t C ha^{-1}, respectively. However, it is crucial to interpret aspen carbon stock estimates with caution due to potential overestimation caused by unregistered or unaccounted internal stem decay. This concern is particularly relevant for older stands, as internal decay becomes more common and its proportion often increases over time (Ķēniņa *et al.*, 2022). Hence, an effective management strategy for aspen stands involves implementing shorter 40–50-year rotation cycles to optimize carbon sequestration and promote the substitution of fossil materials (Figure 2). Additionally, younger aspen trees are less prone to decay-related damage, reducing the risk of timber loss. Birch, however, displays a distinct pattern, with its maximum carbon stock (107 t C ha^{-1}) attained within the age range of 71–80 years, which goes along with the legislated age of final felling for birch. Furthermore, it is noteworthy that only birch stands exhibited a significant difference between the two soil types. Specifically, within the 4th, 7th, and 8th decades, significant variations were observed in the average carbon stock. This indicates that the soil type plays a significant role in influencing the carbon storage potential of birch stands during this specific time period.

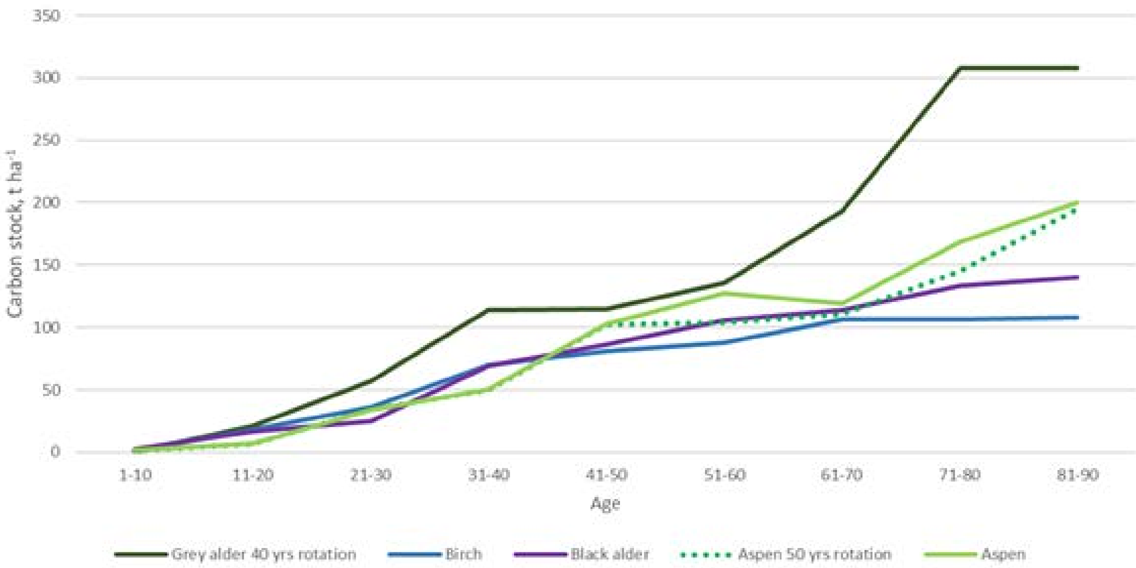

Figure 2. Total carbon stock of deciduous forest stands on drained organic soils within 90 years period. Comparison of two rotation cycles for grey alder and aspen with one rotation for birch and black alder.

Periodically waterlogged soils

The carbon stock of deciduous forest stands in periodically waterlogged organic soils exhibits a trend similar to that in drained organic soils. Black alder shows better growth and carbon accumulation potential in periodically waterlogged organic soils than in drained, and this could be explained with tree species biological traits to favour growth in wet conditions (Claessens *et al.*, 2010). Among the tree species studied, black alder displays the best increase in carbon stock, reaching a maximum of 129 ± 13.10 t C ha^{-1} at the age of 61–70 years, followed by birch with a maximum carbon stock of 85 ± 6.95 t C ha^{-1} at the same age. Grey alder reaches a maximum carbon stock value of 59 ± 17.71 t C ha^{-1} at the age of 41–50 years. However, all tree species exhibit a decline in carbon stock after reaching their respective maximum values. Periodically waterlogged organic soils are known to have a reduced carbon stock potential compared to drained organic soils, hence forest drainage is often regarded as a useful management practice for trees growing in forest types with organic soils. Similar findings have been reported by previous studies (Laurén *et al*., 2021; Lupikis & Lazdins, 2017; Maki, 2015; Zālītis, 2006; Zālītis *et al*., 2013), which have demonstrated the positive effect of drainage on tree growth. However, black alder is an exception to this trend by exhibiting comparable carbon accumulation potential in both periodically waterlogged and drained organic soils. Moreover, black alder demonstrates a faster growth rate during the early growth stage in periodically waterlogged organic soils, which makes it better suited for growing in wet conditions when compared to other deciduous tree species found in the region. Furthermore, it is worth noting that available data from the National Forest Inventory (NFI) regarding aspen stands growing on periodically waterlogged organic soils provides estimates specifically for the third and fourth decades. This pattern may be partially attributed to the fact that during the initial two decades, aspen often coexist with other species. However, as time progresses, aspen gradually outcompetes slower-growing trees, leading to its dominance in the subsequent decade.

Annual carbon sequestration

Average annual carbon sequestration was evaluated for the whole analyzed time period for both soil type groups (Figure 3). On average, the largest average annual carbon sequestration potential (1.43 ± 0.09 t C ha^{-1} yr^{-1}) can be observed for black alder in both soil types, followed by aspen in drained soils (1.34 ± 0.25 t C ha^{-1} yr^{-1}). Birch shows better carbon sequestration potential in drained soils compared to periodically waterlogged, 1.34 ± 0.05 t C ha^{-1} yr^{-1} and 1.16 ± 0.05 t C ha^{-1} yr^{-1}, respectively, and the difference is statistically significant ($p<0.05$). Grey alder shows the lowest carbon sequestration potential in drained soils and periodically waterlogged soils, 1.20 ± 0.31 t C ha^{-1} yr^{-1} and 0.94 ± 0.18 t C ha^{-1} yr^{-1}, respectively; however, the difference is insignificant. Lower average annual carbon sequestration for grey alder compared to other species could be explained with rapid decrease of carbon stock after the reached maximum due to wood decaying (Arhipova *et al*., 2011; Ryan *et al*., 1997).

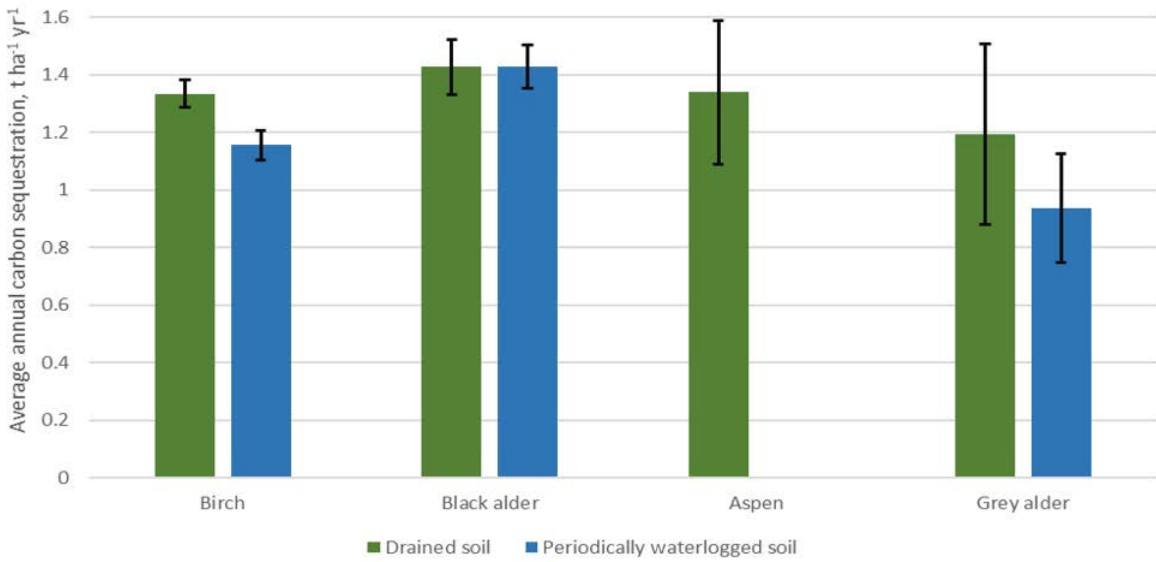

Figure 3. Average annual carbon sequestration for deciduous stands growing in drained and periodically waterlogged organic soils (whiskers denote ± standard error).

Linear model

A linear model was constructed to investigate the variables that influence carbon stock. The analysis of variance of the model revealed that several factors significantly affect carbon stock in the stands under investigation (Table 3). Specifically, soil type, dominant tree species, and stand age were identified as major determinants of carbon stock. The findings suggest that these factors play a crucial role in the ability of forest stands to store carbon, and thus, should be taken into consideration when developing forest management strategies aimed at maximizing carbon storage.

Conclusions

1. Carbon accumulation capacity in tree biomass

Table 3

Results of analysis of variance

Variable	Sum of squares	F-value	p-value
(Intercept)	1230	1.002	0.3124
Soil type	30611	25.427	<0.001
Tree species	29346	12.188	<0.001
Stand age	496497	412.410	<0.001

during one rotation cycle in deciduous stands is strongly influenced by soil conditions, selected tree species and rotation age.

2. Forest drainage is a useful silvicultural technique for boosting carbon sequestration in deciduous stands growing on organic soils, as evidenced by the higher average annual carbon sequestration in drained soils.
3. Regardless of the soil moisture regime, black alder is a viable tree species for growing on organic soils since it has an equivalent average yearly sequestration potential in both drained and periodically waterlogged soils.
4. Grey alder and aspen are fast growing tree species that can be managed in short rotation cycles on drained organic soils to maximize carbon sequestration and possibly substitution effect for fossil fuels.

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