

Carbon stock in the aboveground vegetation of remediated land quarries in Northwest Russia

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SILVICULTURE

ABSTRACT

Background: Forest recultivation can accelerate the formation of tree stand and increase carbon dioxide absorption. This study investigated the growth rates, biomass accumulation and carbon stock in stands of native Scots pine (*Pinus sylvestris* L.) (SP) and introduced lodgepole pine (*Pinus contorta* Dougl.) (LP) planted on remediated land quarries. A comparative analysis of the parameters is performed 1) in cultures using same planting material (bare-root SP seedlings) but developing on different parent materials (ancient alluvial sands, fluvioglacial sandy loams, and moraine loams) and 2) in pine cultures on the same deposits (fluvioglacial sandy loams), but using different planting materials: bare-root SP seedlings, container SP seedlings and container LP seedlings. Allometric equations were used to calculate stand biomass. The ground cover biomass was determined by the mowing method.

Results: Biometric parameters, biomass and carbon reserves, and the share of wood in the total biomass reserves increase along with the soil texture transformation from sands to silty loams. The aboveground biomass is dominated by mosses and lichens on sands to sandy loams and by herbaceous plants on loams. The LP cultures have better growth, survival, biomass and carbon stock values compared with those of the SP. In the quarries of the middle taiga subzone of Russia, 20-year-old experimental LP cultures accumulated 38% more carbon in the aboveground phytomass than SP cultures.

Conclusion: The soil conditions of quarries affect the growth and survival, biomass and carbon stock of pine crops. LP cultures outperformed SP cultures related to carbon storage on sandy loam substrates, highlighting its potential for recultivation in Northwest Russia.

Key words: biomass; forest recultivation; lodgepole pine; Scots pine; taiga.

HIGHLIGHTS

Carbon stock by the Scots pine planted trees increases in a series from sands to loams. The Quaternary sediments of quarries are favorable for the creation of forest cultures. Planting pine trees on ancient alluvial sands requires improvement of the soil substrate. The use of the lodgepole pine is promising for recultivation in Northwest Russia.

LIKHANOVA, I. A.; PRISTOVA, T. A.; FEDORKOV, A. L.; SHAKHTAROVA, O. V. Carbon stock in the aboveground vegetation of remediated land quarries in northwest Russia. CERNE, v. 32, e103573, 2026. DOI: 10.1590/01047760202632013573

INTRODUCTION

About 2 billion hectares of land worldwide are currently degraded to varying degrees, including through mining activities (FAO, 2022). Restoration of degraded land is critical for achieving a host of international environmental goals (Stanturf and Mansourian, 2020; di Sacco *et al.* 2021), mitigating climate change particularly (UN Framework Convention on Climate Change). Afforestation of degraded lands could take 0.9-1.5 Gt of CO₂ eq per year out the atmosphere between 2020 and 2050 (FAO, 2022). Species of the pine genus are frequently utilized for reforesting degraded lands. Beyond their role in carbon storage, pine plantations are vital tools in restoring biodiversity, protecting land from erosion, and participating in the conservation of water resources (Tudor *et al.*, 2025).

Between 2013 and 2021, the Russian Federation experienced an annual land disturbance of 130 to 445 thousand hectares due to activities like mineral extraction, construction industry, survey works and forest harvesting (Gorokhova and Arkhipova 2023). The Komi Republic is one of the regions of the Russian Federation with a significant area of technogenic disturbed lands (46 thousand ha at the end of 2021). Taiga forests occupy 94% of the republic territory, which aboveground phytomass contains from 25 to 74 Mg C ha⁻¹ (Osipov and Bobkova, 2020; Osipov *et al.*, 2021; Bobkova and Kuznetsov, 2023). Anthropogenic deforestation establishes the forest recultivation (planting forest crops) as the main trend of recultivation of disturbed lands in the Komi Republic as in the rest of the Russian Federation.

Quarrying of building materials, including sand, is one of the common types of anthropogenic disturbances characterized by significant environmental impact (Vacek *et al.*, 2021). There are about 100 quarries near the chief cities of the Komi Republic, while the area of each can reach several tens of hectares. Quarried sedimentary rock outcrops may have unfavorable physical and chemical properties, including high density, contrasting water and thermal regime, erodibility, low organic matter content, low biological activity, etc. (Jozefowska *et al.*, 2019; Likhanova *et al.*, 2022; Stanturf, 2024). Consequently, forest recultivation beyond planting native tree species, also usually involves the creation of conditions for their successful growth: liming, fertilization, seeding of herbaceous plants to stabilize soils, etc. (Macdonald *et al.*, 2015; Stanturf, 2024). But on the territory of the Russian Federation, common reforestation practices are typically limited to planting 1–3-year-old conifer seedlings without additional agricultural practices (Danilov *et al.*, 2019). Based on the above, the success of forest recultivation significantly depends on the properties of anthropogenic substrates. The most successful growth of forest crops is observed on fine-grained substrates provided a large range of nutrient elements. On coarse-grained substrates crops grow slower (Merlin *et al.*, 2019).

Pioneer and non-native species are often used for forest recultivation, which are able to quickly consolidate the substrate and create conditions for the introduction of tree species that are typical of indigenous forests (Löf *et al.*, 2019; Stanturf, 2024). Pioneer species (SP) are actively used

for afforestation on disturbed lands, which are extremely unpretentious with respect to substrate conditions (Danilov *et al.*, 2019; Vacek *et al.*, 2021; Osipenko *et al.* 2022). It is possible to activate the forest stand growth on disturbed lands by using the introduced species (LP) characterized by rapid growth in the northern European boreal zone (Elfving, 2017; Fedorkov and Gutiy, 2017; Zhigunov and Butenko, 2019). The reasons why the LP species grow faster under boreal conditions may be associated with an earlier onset of growth in spring and cold tolerance (Fedorkov, 2010). Species (LP) are undemanding to soil fertility (Padda *et al.*, 2020). According to Jacobsen and Hannerz (2020), understanding the degree of invasiveness of species in northern Europe requires further study. On disturbed lands, where the soil carbon pool and the carbon pool stored in above- and belowground biomass are completely destroyed (Misebo *et al.*, 2022; Gençay and Durkaya, 2023), newly-planted forest stand is actively involved in the process of carbon dioxide storage (Tudor *et al.*, 2025). However, estimates of carbon stocks in the biomass of artificial plantings (SP and LP) on disturbed lands in Russia currently have high uncertainties, which is mainly due to the small number of works on this topic (Fedorets *et al.*, 2011; Danilov *et al.*, 2019; Kostina *et al.*, 2022). The influence of anthropogenic substrates and natural rocks on the carbon storage process is insufficiently studied (Babich and Merzlenko, 1998).

This study aims to estimate the carbon stock on aboveground phytomass of artificial pine plantings at the pioneer stage of succession after forest recultivation on quarries in the northwestern Russia, depending on soil parent materials and the species used (SP or LP). To achieve research goal, we determined 1) survival, growth rates, biomass and carbon content in ground cover of artificial plantings (SP) on different parent materials of quarry areas 2) survival, growth rates, biomass and carbon content in plantings (SP and LP) on fluvio-glacial deposits, 3) biomass and carbon content in ground cover depending on soil parent materials of quarry areas.

The hypotheses tested were: The application of additional techniques to improve the substrate on ancient alluvial sands and the use of an introduced species (LP) will accelerate the process of carbon accumulation during forest recultivation practices.

MATERIAL AND METHODS

Study area

The study was carried out on the territory of the Komi Republic (north-west Russia) (Figure 1). The climate of the study area is temperate continental with long cold winters with a stable snow cover and short cool summers. The average annual air temperature is +0.4°C. The annual precipitation amount is 560 mm. The territory is a hilly-undulating plain with dominating heights of 140–160 m above sea level (Novakovskiy and Elsakov, 2014). Quaternary sediments represented by moraine loams, fluvio-glacial and ancient alluvial deposits usually crop

out during quarrying on territories of the RK. Moraine and fluvioglacial deposits have a similar mineralogical composition dominated by quartz and feldspars. Ancient alluvial sands have experienced multiple episodes of water transfer are characterized by a poor mineral composition (quartz content reaches 95%) and very low proportion of silty fraction (Likhanova et al., 2021; Likhanova et al., 2022).

The research plan was to determine the influence of Quaternary deposits (Experiment 1) and planting material (Experiment 2) on the stand parameters of pine cultures. In Experiment 1, the same planting material was used across different Quaternary deposits. In Experiment 2, the different planting materials were used on the same parent deposits (chart 1).

The study material included pine plantations in four quarries (Table 1, figure 2) - Yazel (Y), Dasa (D), Vazhelyu (V), and Koigorodok (K). Three test plots were established on each plantation site, evenly distributed across its area.

Regular measurements of stand parameters of plantings were conducted on these plots. To understand the effect of soil parent materials on the growth of pine cultures (Experiment 1), the SP plantings were studied in the quarries Y, D, and V, which differ by genesis and texture of soil parent materials (ancient alluvial sands (Y), fluvioglacial sands and sandy loams (D), moraine loams (V). The detailed information on the soils of quarries can be found in previous studies (Likhanova et al., 2021; Likhanova et al., 2022). The measure of soil richness in these quarries was organic carbon content (C_{org}) and silt content (Table 1). The quarries Y, D, V after the ground surface levelling in 2000–2001 were planted with one and the same planting material as 2-year-old bare-root SP seedlings of local origin (SP_{BR}), grown at the Syktyvkar and Sysola tree nurseries (Table 1). The main data to elucidate the role of soil parent material on the growth of forest crops were obtained in 2022 by studying 23–24-year-old SP_{BR} in the quarries Y, D, and V (Y23, D24, V24).

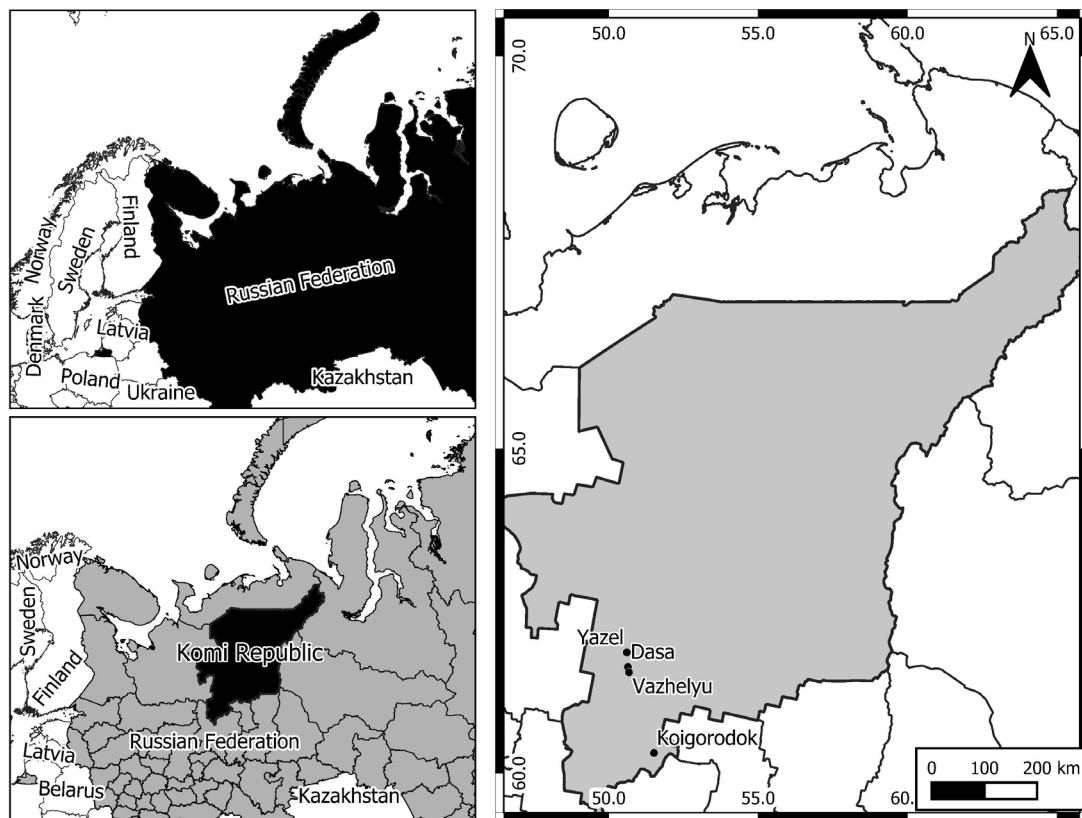


Figure 1: Location of the study region. Black points show the quarries planted by pine stands. The map was made in QGIS 3.16.3 software.

Chart. 1: Experimental design.

	Experiment 1			Experiment 2	
Planting material	Bare-root SP seedlings (SP_{BR})			Bare-root SP seedlings (SP_{BR})	Container SP seedlings (SPc) Container LP seedlings (LPc)
Parent material	Ancient alluvial sands	Fluvioglacial sandy loams	Moraine loams	Fluvioglacial sandy loams	

Table 1: Characteristics of pine plantations on the territory of the quarries.

Names of quarries, parameters	Quarries			
	Y	D	K	V
Latitude	61°57'36.11"	61°43'54.30"	60°20'21"	61°38'45.94"
Longitude	50°36'20.49"	50°38'31.09"	51°30'51"	50°40'41.27"
Year, planting season	2001, autumn	2000, spring	2004, spring	2001, spring
Area, ha	1.5	4.9	0.9	5.0
Planting density, thousand seedlings ha ⁻¹	5.5	4.8	3.1	5.1
Spacing, m	3×0.6	3×0.7	2×1.5	2.5×0.8
Planting material type	Two-yr-old bare-root SP seedlings (SP _{BR})	Two-yr-old bare-root SP seedlings (SP _{BR})	One-yr-old container SP (SP _C) and LP seedlings (LP _C)	Two-yr-old bare-root SP seedlings (SP _{BR})
Soil material	Ancient alluvial sands	Fluvioglacial sands and sandy loams	Fluvioglacial sands and sandy loams	Moraine loams
Silt content*, %	4	10	Not det.	25
Corg. content**, %	<0.1	0.2	0.2	0.3–0.4
Former stand	Lichen pine forest	Cowberry pine forest	Cowberry pine forest	Grass-blueberry spruce forest

Note. * To determine the particle size of the soils, the standard pipette method was used (soil treatment with 0.05 N HCl, dispersion with 1N NaOH) (Vanchikova *et al.*, 2024). ** Corg. in soil parent material was determined by the Tyurin method (Shamrikova *et al.*, 2022).

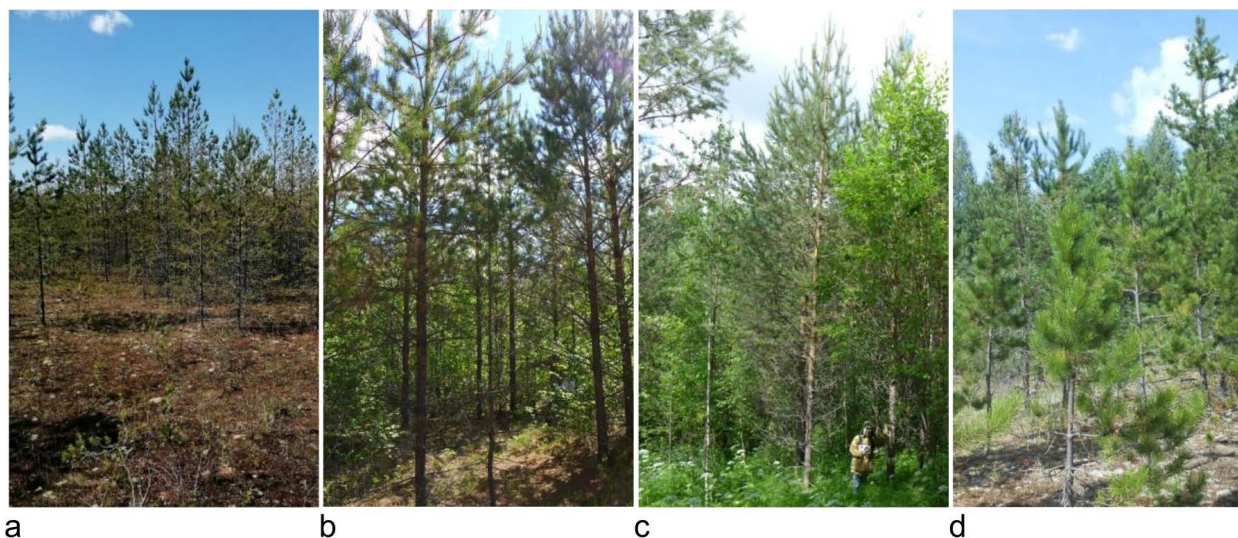


Figure 2: Plantations of the SP on the Yazel (a), the Dasa (b), the Vazhelyu (c) quarries differing in genesis and granulometric composition of soil parent materials. Plantation of the LP on the Koigorodok quarry (d).

The quarries D and K, characterized by one and the same soil parent material (fluvioglacial sediments), were used to study the efficiency of different planting materials for reclamation purposes: bare-root SP (SP_{BR}) and container SP (SP_C) seedlings, as well as container seedlings of the introduced LP species (LP_C) (Experiment 2). We analysed the study results obtained for a 21-year-old SP_{BR} in quarry D (D(SP_{BR})21) in 2019, as well as for 20-year-old SP_C and LP_C in quarry K (K(SP_C)20, K(LP_C)20) in 2022 (Table 1).

The conducted measurements of pine heights in the quarries at different years allowed for plotting pine heights in progress.

Measurements

Dominant trees without defects were callipered at breast height which was defined as 1.3 m (DBH, 1 mm accuracy) and tree height was recorded in meters (0.1 m accuracy) using a measuring stick. Tree survival was determined as the proportion of living trees at the time of assessment. Tree density was determined by the actual number of trees that survived per unit area (ha). The weight of aboveground organs of ground cover plants was estimated by the mowing method using a 625 cm² template in 10 repetitions (Manual..., 2002).

Data analysis

The biomass reserves of the studied SP cultures were calculated using the allometric equations of Babich and Merzlenko (1998). The main errors of the equations do not exceed 0.4, the residual variance is 0.2. To calculate the biomass reserves of the LP cultures the equations of Elfving *et al.* (2017) were applied (Table 2).

In the regression equations of the weight of individual biomass fractions on the stem diameter for the SP, we used the weight indices of the freshly-cut components (Babich and Merzlenko, 1998). To recalculate the weight of the SP trees from fresh-green to absolutely dry weight (a.d.w.), we determined the moisture content of individual aboveground biomass fractions of the cultures studied for 10 sample trees with three replicates (Usoltsev and Zalesov, 2005).

The carbon content in plant samples was evaluated at the Ecoanalytical Laboratory of the Institute of Biology Komi SC UB RAS according to the certified methodology by the gas chromatography method on the element analyzer EA 1110 (CHNS-O) (CE Instruments, Italy). We calculated the carbon reserves by multiplying the weight of structural components for every species by the carbon content in those tree structural components.

Statistical analysis

The statistical processing of the results was performed using the Statistica, MS Excel software packages.

The obtained tree measurement data were used to compile variation series and to calculate arithmetic mean (M), standard deviation (SD), asymmetry (A), excess (E) and other statistical parameters. The Shapiro–Wilk test was used to check the normality of tree height and diameter distribution of variational series in pine plantations. Since not all series followed a normal distribution, we used the Mann–Whitney U test to determine if significant differences exist between the series. The effect size (r) for the Mann–Whitney U test was calculated. The regression analysis was used.

RESULTS

Biometric tree parameters at SP and LP plantations

Towards the second succession decade, the number of trees in Y23 decreased from 5.5 to 2.1 thousand units ha⁻¹, in D24 from 4.9 to 3.4, and in V24 from 5 to 3.2 (Table 3). The tree survival rate of K(SP_c)20 and K(LP_c)20 is similar to that of D(SP_{BR})21 (Table 3).

By Figure 3 (A), the minimum growth rate among the forest crops created by planting SP_{BR} characterises SP_{BR} in sandy quarry Y. In sandy-sandy loam quarry D, the growth rate of SP_{BR} is higher than that in quarry Y and lower than that in loamy quarry V. Among the forest cultures grown from different planting material on same soil-forming rock, the growth rate of LP_c cultures is high, not as high of SP_c, and low of SP_{BR}. The differentiation of height becomes more pronounced with age (Figure 3 (B)).

Table 2: Regression equations used to calculate the biomass reserves.

Biomass component	SP*	LP**
Stem wood	$y=0.664-0.663D+0.294D^2$	$y=e^{-5.235 \times D} \times H^{1.729} \times H^{4.832} \times (H-1.3)^{-3.265}$
Stem bark	$y=-0.318+0.203D+0.017D^2$	
Living branches	$y=2.154-1.038D+0.128D^2$	$y=e^{-7.665 \times D} \times D^{3.601}$
Dead branches	$y=0.028-0.004D+0.006D^2$	$y=e^{-6.235 \times D} \times D^{2.797}$
Needles	$y=-0.839+0.290D+0.048D^2$	$y=e^{-1.708 \times D} \times D^{1.759} \times e^{-1.432(H/D)}$

Note. * – equation to calculate the mass of fractions in kg per fresh weight for the SP; ** – equation to calculate the mass of fractions in kg per absolutely dry weight for the LP, y – the mass of the corresponding biomass fraction, kg; D – stem diameter at a height of 1.3 m, cm; H – tree height, m.

Table 3: Performance of the SP and LP cultures in the quarries.

Cultures	Number of measured trees	Survival, %	Density, units ha ⁻¹	Height		DBH,	
				(M±SD), m	CV, %	(M±SD), cm	CV, %
Pine cultures on different soil parent materials (Experiment 1)							
Y23	59	38	2064	3.6±1.3	37	3.7±1.7	55
D24	98	71	3408	6.9±1.6	23	7.2±2.9	40
V24	91	62	3162	7.4±1.3	17	8.0±2.8	35
Pine cultures from different planting material (Experiment 2)							
D(SP _{BR})21	103	75	3600	5.2±2.3	25	6.1±1.3	39
K(SP _c)20	7	65	2050	5.9±1.1	22	9.4±1.9	27
K(LP _c)20	21	71	2201	6.9±0.8	16	10.0±1.3	17

Note. M – mean; SD – standard deviation; CV – coefficient of variation.

The tree growth rate in quarries is described by the polynomial regression equations (Table 4).

The Mann-Whitney U test showed (pairwise comparison of variational series of heights of Y23, D24, V24 cultures on different soil parent materials), the height of V24 trees is significantly higher than that of Y23 ($U=129$, $p<0.0001$, $r=0.95$) and D24 ($U=3487$, $p=0.0097$, $r=0.22$); the height of Y23 trees is significantly lower than that of D24 ($U=330$, $p<0.0001$, $r=0.89$) and B24 ($U=129$, $p<0.0001$, $r=0.95$). The diameter (DBH) of Y23 cultures is significantly lower than that of D24 ($U=921$, $p<0.0001$, $r=0.68$) and V24 ($U=558$, $p<0.0001$, $r=0.79$). The differences between DBH of B24 and D24 are not significant.

The variational series of height distribution of Y23 cultures is shifted towards low height steps (asymmetry index is positive $A=0.43$). As soil texture becomes fine, the distribution shifts towards higher height steps. Index A in the variational series of D24 tree heights is 0.29. The B24 height series is already dominated by trees which heights are greater than the average tree height (the asymmetry index is negative $A=-0.10$).

The kurtosis of variational series is minimal ($E=-0.80$) for D24 cultures, which is associated with the bimodality of the series due to the division of trees into dominant and suppressed samples following from better preservation of pine and, thus, greater competition between trees that accelerates the process of differentiation by growth and development. The low excess value of variation series, but this time because of flat-toppedness (extention), is characteristic of Y23 cultures ($E=-0.47$) and is related with the low competition between trees and dominant influence of rather extreme abiotic environmental factors. Natural thinning of B24 cultures due to rapid growth of SP_{BR} and relatively high crown density (the quarry is identified for rather abundant undergrowth of small-leaved species) causes narrowing of the variational series ($E=-0.17$). The height variation coefficient of the distribution series by height for Y23 cultures is 37%, D24 - 23%, V24 - 17%, which indicates a decrease in the variability degree by tree height in SP_{BR} stands as soon as soil texture becomes fine.

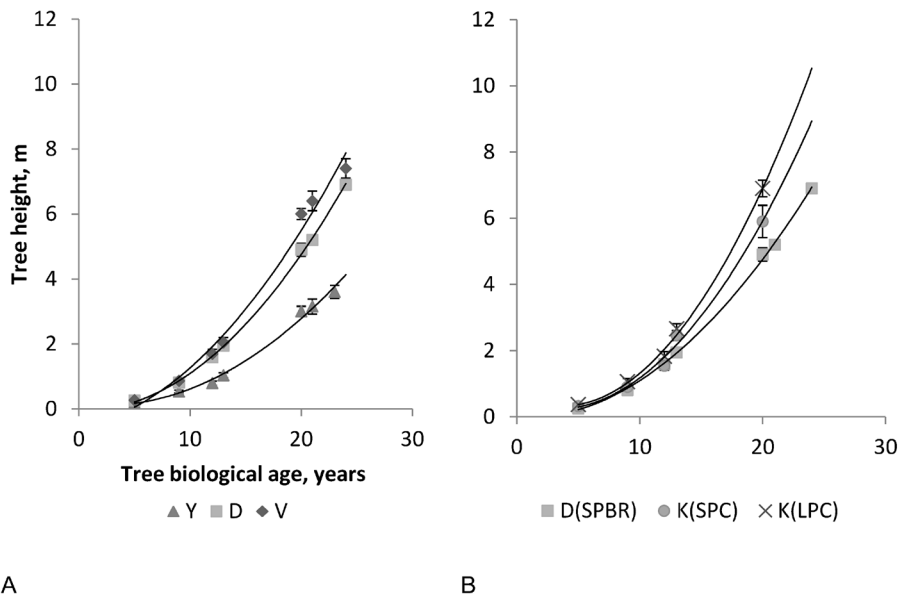


Figure 3: Growth rate of pine cultures: A - on different soil parent materials (Experiment 1); B - when using different planting material (Experiment 2). The boundaries of error indicate errors of the mean value.

Table 4: Regression equations of pine growth rate.

Quarry	Planting material	Equation	Approximation reliability value
Pine cultures on different soil parent materials (Experiment 1)			
Y	SP_{BR}	$H = 0.0085x^2 - 0.0389x + 0.1498$	$R^2 = 0.9920$
D	SP_{BR}	$H = 0.0127x^2 - 0.0141x - 0.0345$	$R^2 = 0.9992$
V	SP_{BR}	$H = 0.0121x^2 + 0.0595x - 0.5453$	$R^2 = 0.9857$
Pine cultures from different planting material (Experiment 2)			
D	SP_{BR}	$H = 0.0127x^2 - 0.0141x - 0.0345$	$R^2 = 0.9992$
K	SP_C	$H = 0.0199x^2 - 0.1229x + 0.4121$	$R^2 = 0.9923$
K	LP_C	$H = 0.0247x^2 - 0.1803x + 0.6531$	$R^2 = 0.9970$

Note. H - height, m; x - age, years.

By the results of pairwise comparison (Mann-Whitney U test) of variational series by heights of 21–20-year-old pine cultures grown from different planting material on fluvioglacial deposits, K(LP_c)₂₀ cultures are significantly higher than D(SP_{BR})₂₁ cultures (U=351, p<0.0001, r=0.68). The differences between heights of K(LP_c)₂₀ and K(SP_c)₂₀, as well as K(SP_c)₂₀ and D(SP_{BR})₂₁ cultures are not significant. The mean diameter of D(SP_{BR})₂₁ cultures is significantly lower than that of K(SP_c)₂₀ (U=129, p=0.0046, r=0.64) and K(LP_c)₂₀ (U=232, p<0.0001, r=0.79). The differences between DBH of K(LP_c)₂₀ and K(SP_c)₂₀ are not significant.

The variation distribution series by height for K(LP_c)₂₀ cultures is closer to normal distribution (A=0.12, E=0.20), in contrast to the variational series values of D(SP_{BR})₂₁ tree cultures (A=0.29, E=-0.88).

Biomass of cultures

The biomass of Y23, D24, V24 cultures on different soil parent materials varies from 4 (Y23) to 31 (V24) tonne or megagram (Mg) ha⁻¹. The stand biomass is dominated by stem wood (44–57%). The share of other fractions is much lower, e.g., needles take 20–25% of the total biomass, living branches and bark - about 10% each, dead branches - about 5% (Table 5).

The biomass of D(SP_{BR})₂₁, K(SP_c)₂₀ and K(LP_c)₂₀ cultures grown from different planting material on same soil parent materials ranged from 19 (D(SP_{BR})₂₁) to 43 (K(LP_c)₂₀) Mg ha⁻¹. The tree stand biomass is absolutely dominated by stem wood (Table 5).

Carbon storage in the stand

For SP, the carbon concentration in needles is 50.5%, living branches - 50.4, dead branches - 51.3, wood - 47.5, bark - 52.5; for lodgepole pine - 49.9, 49.6, 51.1, 47.8, 48.3,

respectively. The absolute error interval limits of carbon concentration determination (at the significance level P=0.95) are 1.7–1.8 %.

23–24-year-old cultures, grown on different soil parent materials, deposit from 2 (Y23) to 15 (V24) Mg C ha⁻¹ in the aboveground part of the stand (Figure 4). The carbon pool accumulated by biomass fractions is dominated by stem wood carbon - 43 (Y23) to 55% (V24). In other tree fractions, carbon accumulation is not as active: live branches concentrate 11–12%, dead branches - 3–6%, needles - 20–26%, bark - 10–15% of the total carbon stock in the aboveground part of trees.

The values of carbon stock by SP cultures and the content of Corg. in the soil parent materials are observed for the exponential regression $y = 0.0385e^{0.1353x}$ (R² = 0.9682), where y - amount of Corg., % in the soil parent material, x - C stock in the cultures. The regression between the values of carbon stock by SP cultures and the content of silt particles in the soil parent material takes the form: $y = 3.1178e^{0.1148x}$ (R² = 0.8338), where y - amount of silt, % in the soil parent material, x - C stock in Y23, D24, V24 cultures.

Among pine cultures planted on one and the same soil parent material but grown from different planting material, the maximum carbon stock is observed in K(LP_c)₂₀ cultures. Carbon stock by K(LP_c)₂₀ is by 1.5 higher than that by K(SP_c)₂₀ crops and by 2.2 times higher than that by D(SP_{BR})₂₁ (Figure 3).

Ground cover biomass

The soil ground cover biomass in the quarries varies considerably from 0.3 to 1.25 Mg ha⁻¹ depending on soil conditions (Table 6). Mosses and lichens (63–80%) dominate on sandy ancient-alluvial (Y quarry) and sandy-sandy loam fluvioglacial deposits (D, K quarries). Herbaceous plants (99%) are usual on moraine loams (V quarry).

Table 5: Aboveground biomass of fractions of SP and LP plantations, Mg ha⁻¹ a.d.w. and the proportions of tree fractions in total biomass, %.

Cultures	Needles	Living branches	Dead branches	Wood	Bark	Total
Pine cultures on different soil parent materials (Experiment 1)						
Y23	0.9±0.1	0.4±0.1	0.2±0.02	1.6±0.4	0.5±0.1	3.7±0.7
	25	11	6	44	14	100
D24	5.5±0.4	3.1±0.4	0.9±0.1	15.5±1.6	2.7±0.2	27.7±2.6
	20	11	3	56	10	100
V23	6.0±0.4	3.5±0.5	0.9±0.1	17.5±1.2	2.9±0.2	30.8±2.6
	19	11	3	57	9	100
Pine cultures from different planting material (Experiment 2)						
D(SP _{BR}) ₂₁	4.2±0.5	1.7±0.4	0.7±0.04	10.5±1.9	2.1±0.3	19.2±3.1
	22	9	4	55	11	100
K(SP _c) ₂₀	5.3±1.2	3.6±1.4	0.8±0.2	15.8±3.0	2.4±0.3	27.9±6.6
	19	13	3	57	9	100
K(LP _c) ₂₀	8.8±0.6	4.6±0.6	2.9±0.2	24.2±2.0	2.7±0.2	43.2±3.4
	20	11	7	56	6	100

In tables 5, 6 and in figure 3: ± error of the mean value.

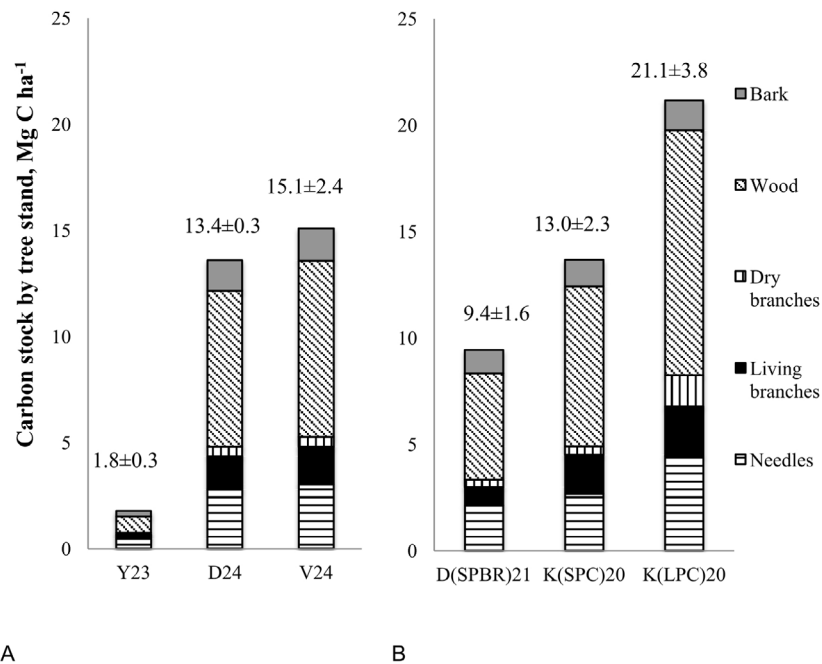


Figure 4: Carbon stock in aboveground tree biomass in pine cultures, Mg C ha⁻¹ dry matter: A - on different soil parent materials (Experiment 1); B – using different planting materials (Experiment 2).

Table 6: Biomass of ground cover plants, Mg ha⁻¹ a.d.w.

Stand	Dominating species		Dwarf shrubs	Herbaceous plants	Mosses	Lichens	Total
	Grass-dwarf shrub layer	Moss-lichen layer					
Y	–	<i>Pohlia nutans</i> , <i>Polytrichum piliferum</i> , <i>P. juniperinum</i> , <i>Cladonia mitis</i>	0.01 ± 0.002	0.16 ± 0.04	0.62 ± 0.22	0.08 ± 0.04	0.87 ± 0.30
D	<i>Calamagrostis epigeios</i> , <i>Chamaenerion angustifolium</i>	<i>Polytrichum juniperinum</i> , <i>P. piliferum</i> , <i>Cladonia sp.</i>	0.05 ± 0.02	0.04 ± 0.02	0.18 ± 0.07	0.07 ± 0.02	0.34 ± 0.13
K			0.01 ± 0.001	0.15 ± 0.02	0.12 ± 0.01	0.15 ± 0.02	0.42 ± 0.06
V	<i>Calamagrostis arundinacea</i> , <i>Chamaenerion angustifolium</i> , <i>Trifolium sp.</i>	–	–	1.24 ± 0.43	0.01 ± 0.001	–	1.25 ± 0.43

Carbon in ground cover plants

The carbon content in ground cover plants is 42.5–44.7% for mosses depending on species, 35–42 % for lichens, 48.9–50.8 for dwarf shrubs and 43.1–46.2% for herbaceous plants.

The ground cover plants in the studied quarries, in contrast to trees, accumulate a small amount of carbon from 0.2 to 0.6 Mg C ha⁻¹. Low values are characteristic of quarries D and K - about 0.2 Mg C ha⁻¹. High values are found for quarry Y and B - 0.4–0.6 Mg C ha⁻¹. The carbon distribution in the aboveground biomass of different groups of ground cover plants in the studied quarries is uneven. In quarry Y, 72% of carbon is concentrated in mosses, in quarry V 99% - in herbaceous plants. In quarries D and K, carbon stocks are distributed relatively evenly among plant groups.

DISCUSSION

The survival and growth rates of pine trees vary depending on the properties of soil parent materials. The high survival rate of Scots pine is noted for fluvio-glacial sands and sandy loams, which provide favorable forest conditions for this tree species as underlined in the works of other researchers (Babich and Merzlenko, 1998). The lower density of Scots pine in loamy quarry, compared to sandy-sandy loam quarry, is probably related not only to the death of stunted specimens in the course of natural thinning but also to the high soil density, competition with well-developed grass stand at the initial growth stages and then - with small-leaved species, which is also noted in the works of other authors (Fedorets et al., 2011). The Scots pine trees grow relatively fast on loams. The growth rates slightly decrease

on fluvioglacial sandy and sandy loams. The growth of pine cultures becomes largely slowed down on poor ancient alluvial sands with a contrasting hydrothermal regime, which agrees with the data of other researchers (Fedorets *et al.*, 2011; Danilov *et al.*, 2019; Kostina *et al.*, 2022). In general, the conclusion about the successful growth of Scots pine on fine-textured soil material is confirmed by the data of R. A. Osipenko *et al.* (2022) who underlines the high productivity and stability of artificial plantations of Scots pine on the territory of clay-extracting quarries. The earlier conducted studies have confirmed the viability of using the Scots pine trees for reclamation purposes due to its wide ecological amplitude, its stable growth in a variety of forest conditions (Danilov *et al.*, 2019; Vacek *et al.*, 2021; Osipenko *et al.*, 2022).

The biomass and carbon stock values of Scots pine in quarries after forest restoration are 1.5-3.5 times lower than those in felled areas of natural pine forests in the taiga zone of northern Russia (Ipatov, 1974; Babich *et al.*, 2010). For example, the biomass of 21–24-year-old stands planted instead of once felled lichen pine forest is 14 Mg ha⁻¹, cowberry pine forest - 36, bilberry pine forest - 46 Mg ha⁻¹. The carbon stocks in the stands vary from 6 to 23 Mg C ha⁻¹ (Babich *et al.*, 2010). Lower rates of biomass growth in recultivated quarries compared to same-age plantations of the original forest plots were reported by Vacek *et al.* (2021), which the authors attributed to the strong influence of unfavorable weather conditions on pine stand in recultivated plots.

The tree biomass and carbon stock values for cultures at quarries are by 4–12 times lower than those of natural taiga pine forests. For example, the stand biomass of 50–60-year-old lichen pine forests is 49 Mg ha⁻¹, lingonberry pine forests - 83 Mg ha⁻¹, bilberry pine forests - 110 Mg ha⁻¹ (Kazimirov *et al.*, 1977), whereas the carbon content of pine stands reaches 59–75 Mg ha⁻¹ (Osipov *et al.*, 2021). The biomass of ground cover plants at the studied quarries is 3–10 times lower than the biomass of grass-dwarf shrub layer and moss-lichen layer in natural pine forests (3–5 Mg ha⁻¹) (Kazimirov *et al.*, 1977).

The severe climate of the middle taiga zone accounts for low growth rates of stands and a slow tree biomass accumulation. According to M. Pietrzykowski (2019), technogenic landscapes of mixed and broad-leaved forests have the aboveground biomass reserves of 20–30-year-old SP cultures on fluvioglacial Quaternary sands and sandy loams reaching 81 Mg ha⁻¹, on a mixture of Tertiary clays and Quaternary sands - up to 130 Mg ha⁻¹.

The biomass increase in stands of tree cultures is accompanied by an increase in the proportion of stem wood and a decrease in the proportion of needles. The same regularities were observed by other researchers for Scots pine cultures at felling sites (Babich *et al.*, 2010) and in natural taiga pine forests (Kazimirov *et al.*, 1977).

Despite the fact that, in general, soil conditions at quarries for extraction of common minerals as sand, sandy loam, and loam are quite favourable for reforestation processes, the growth rate of pine cultures planted in quarries is lower than that at felled areas with preserved soil cover. Therefore, additional methods of soil material improvement are reasonable and especially important

when planting forest cultures on sandy sediments, as noted in the studies (Pietrzykowski *et al.*, 2017).

The process of tree layer formation on disturbed lands can be further accelerated using container seedlings, as well as fast-growing tree species. The introduced LP species is superior to SP in growth rate, which is also noted in a number of studies conducted in Fennoscandia and in the taiga zone in the north of European Russia (Fedorkov and Gutiy, 2017; Zhigunov and Butenko, 2019). The rapid growth of lodgepole pine is closely linked with specific structural features of its assimilation apparatus. Investigation showed that in the taiga zone of Russia, the introduced species has a higher needle density, lifespan, and longer needle length compared to the native species (Plyusnina *et al.*, 2024). The influence of forest conditions on these parameters appears to a lesser extent in lodgepole pine than in Scots pine (Plyusnina *et al.*, 2025). Lodgepole pine has longer growth period (Fedorkov, 2010) and exhibits greater resistance to fungal diseases (Elfving *et al.*, 2001), compared to Scots pine. The above gives the introduced species an advantage over the native species in terms of biomass accumulation and carbon storage on degraded lands.

Many researchers highlight the significant potential of lodgepole pine for reforestation on degraded lands in Europe, however, caution is recommended regarding its possible invasive behavior outside its native range (Vacek *et al.*, 2022; Riege *et al.*, 2025). It was previously believed that the risk of uncontrolled self-seeding of lodgepole pine was low under Northern European conditions. However, recent studies have begun to document its natural recruitment and invasion into native communities (Jacobson and Hannerz, 2020; Wasowicz *et al.*, 2025). It is necessary to investigate the natural regeneration of lodgepole pine in plantations within the Republic and to determine the impact of these cultures on native tree species.

CONCLUSIONS

Studies have shown that under the bioclimatic conditions of the taiga in the Northwest of Russia (the Komi Republic), the processes of forest stand formation in technogenic landscapes (quarries) are determined by substrate characteristics. In the series of increasing soil textural heaviness (ancient alluvial sands → fluvioglacial sands/loamy sands → moraine loams), the biometric indicators, biomass, and carbon content in Scots pine cultures increase. For establishment of planting on low-productive ancient alluvial deposits, intensive substrate enhancement is particularly important.

Increasing the rate of forest stand formation is possible through the proper selection of planting material. Investigation has shown the advantage of the introduced fast-growing species lodgepole pine over the native species Scots pine in terms of biomass accumulation and carbon storage. Further research on the growth of lodgepole pine and assessment of the degree of its invasiveness will provide recommendations on the use of this species for reclamation efforts.

FUNDING

The work was financially supported by the state tasks of the Institute of Biology Federal Research Center Komi Science Center of the Ural Branch of the Russian Academy of Sciences "Soils and soil resources of the European North-East of Russia in the context of modern climate change, anthropogenic pressure and socio-economic challenges" (№ 125021902454-1), "Microbial communities of the Northern ecosystems, their biotechnological potential and technologies for its realization" (№ 125021201993-3) and "The environment-forming role and productivity of forest and wetland ecosystems in the European Northeast of Russia" (№ 125020501547-8).

AUTHORSHIP CONTRIBUTION

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DATA AVAILABILITY

The datasets analyzed during the current study are available from the corresponding author upon reasonable request.

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