The pattern of change in the fertility of podzolic soils in the early stages of natural reforestation

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Abstract. The study identified the patterns of change in podzolic soils forming over different parent rocks at early stages of reforestation upon clear-cutting of pine stands. Soils of the first chronosequence, representing Albic Podzol, demonstrated an illuvial distribution of organic matter down the soil profile, with its maximum deposition in the forest litter. As more time passed since logging, mineral horizons gradually got enriched in organic matter, and a thin organo-mineral horizon with elevated carbon and nitrogen content formed under the forest litter by the age of 8 years. The second chronosequence, representing Entic Podzol, displayed a slight reduction in soil richness upon logging, due to intensive humification and mineralization of organic matter. The study found proof that logging using multifunctional machines helps preserve the living ground cover and the top organic horizons in a substantial part of the logging site. Natural reforestation in sites with soils relatively rich in organic matter proceeded through settlement of deciduous species, whereas sites on poor soils were naturally reforested by pine.

1. Introduction

Commercial timber harvesting, in particular clear-cutting, is one of the most destructive forms of exploitation of natural resources which has a significant impact on the biodiversity and productivity of forest ecosystems [1–3]. The loss of forested area to logging affects the economic and environmental situation in the country. In this context, the establishment of a knowledge-based system of forestry practices designed to enhance the efficiency of forest exploitation and restoration is becoming one of the most pressing tasks. The success of artificial and natural reforestation relies heavily on the physico-chemical properties and fertility of the soil, which in turn, are directly dependent on the ground vegetation composition. There is quite a number of Russian and foreign studies on the structural and functional relationships between boreal forest plant communities after logging and soils [4–8]. Yet, these studies deal with the forest and soil types most characteristic of the region. In the case of Northwest Russia these are pine stands growing on podzols over fluvioglacial sediments [9, 10]. Logging-disturbed soils forming on other types of parent rock have been poorly studied [11, 12]. Changes in soil properties upon logging done using modern harvesting techniques and in the process of natural reforestation also remain to be elucidated. In connection with the above, it is necessary to conduct parallel studies of forests and soil to identify the relationships between forest regeneration and soil formation processes occurring under various environmental conditions to predict how long the restoration of boreal ecosystems will take.
2. Methods and Materials

2.1. Study area
Surveys were carried out in boreal forests of the Republic of Karelia, Northwest Russia, which is situated between 66°39’ and 60°41’ N. Republic of Karelia lies in the eastern part of the Fennoscandian Shield and has no thick sedimentary rocks masses. The main parent rocks are Quaternary sediments: till; aqueo-glacial deposits in the form of esker ridges, kames and outwash plains; glaciolacustine deposits; varved clay and loams. Due to the prevalence of air masses of Atlantic and Arctic origin, proximity to the Baltic, White and Barents seas, as well as peculiarities of the local natural conditions (abundant lakes and wetlands, rugged terrain, etc.) the climate features of the region are the following: low average annual air temperature (3°C), long but mild winter (145–155 days with snow cover), short and cool summer (the period with average daily air temperature above 15°C lasts 40–45 days), high relative air humidity (60–90%), significant amount of precipitation (550–600 mm). Most of the territory of Karelia (14.8 hectares, or 85%) is occupied by the state forest fund, of which 10.4 million hectares is exploitable forests (71.7%). The forest fund of the Republic of Karelia has a total timber stock of 945.7 million m³, including 826.3 million m³ in coniferous stands [13].

2.2. Study design
To study the structural and functional relationships between vegetation and soil, an approach based on the study of chronosequences of cuttings was used, because chronosequences enable soil dynamics to be elucidated at the decadal to centurial scales [14]. Sample plots were selected taking into account the uniformity of forest site conditions, including terrain features, parent rocks, soil hydrological regime, etc. For the taxation description of the stands, trial areas of the tape form were laid. The living ground cover of forest plant communities was described using the standard geobotanical research technique in 10 × 10 m plots. Soil pits were made across the entire profile in typical sites in the sample plots, and their detailed morphological descriptions were produced. To identify the features of carbon and nitrogen transformations in soils disturbed by logging, two chronosequences of cuttings were investigated. The chronosequences are made up of a mature bilberry pine stand, a current-year cutting, and cuttings logged 3- and 8- years ago. Soils of the first chronosequence are represented by podzols forming on fluvioglacial sands (Albic Podzol), of the second one – by podzols forming on shale (Entic Podzol). The sample plots of the first chronosequence were designated SP1 – undisturbed stand, SP2 – fresh cutting, SP3 – 3-year cutting, SP4 – 8-year cutting, the second chronosequence – SP5, SP6, SP7, SP8, respectively.

Descriptions of forest types, types of clear-cuts and the living ground cover were made according to techniques generally accepted in Russia. The soils were diagnosed according to the WRB soil classification. Equipment of the KarRC RAS Core Facility was used to determine total carbon and nitrogen content (2400 Series II CHNS/O Elemental Analyzer (Perkin Elmer, USA)). The acidity of water and salt extracts was determined. Statistical processing was carried out using Microsoft Excel, Statistika software.

3. Results and discussion

3.1. Changes in soil properties after forest harvesting
Soils in the control plots are Albic Podzol, widespread in Karelia, and coarsely humified Entic Podzol, which has a limited distribution. Albic Podzol is characterized by a clear differentiation into sub-horizons: O-E-BF-C. Soil formation proceeds in a highly acidic environment, the lowest pH_CaCl of 2.9–3.1 observed in the forest litter and the podzolic horizon, whereas pH values in the mineral part of the root layer do not exceed 4.5. Forest litters have a high content of carbon and nitrogen (35.1% and 0.90%, respectively), while the content of these components in mineral horizons gradually decreases (1.45% and 0.08 in horizon E; 0.56% and 0.02 in BF). The soils are generally poor in macro- and microelements.
The division of the Entic Podzol soil profile into sub-horizons is impeded by high stoniness, but the following horizons are diagnosed in the profile: O-AE-BHF-C. The litter is underlain by an organo-mineral horizon, characterized by a high content of organic matter. Forest litters are of the coarse-humus type, acidic (4.5), with high carbon and nitrogen content (39.4% and 1.42%, respectively). The distribution of carbon and nitrogen across the soil profile has an illuvial pattern, since the content of these components in the organo-mineral horizon is 12.39% and 0.38%, and in the BHF horizon – 3.75% and 0.21%, respectively. The acidity of the organo-mineral and mineral horizons of the root zone ranges within 4.1–4.3.

The first post-logging chronosequence demonstrated the following trends (Figure 1). In the fresh cutting, there was no change in carbon and nitrogen content in the organic and mineral horizons compared to the control. As more time passed since logging, these parameters gradually declined in forest litters, indicating an accelerated transformation of organic residues. The lowest values of these parameters were observed in the forest litter in the 8-year-old clear-cutting, which had the best conditions for mineralization and humification of organic matter. These changes were most likely caused by an increase in microbiological activity, which is accompanied by intensive nitrogen consumption. The change in the hydrothermal regime upon the removal of woody vegetation causes organic matter to migrate and accumulate down the soil profile. As a result, mineral horizons of the root zone in the 3-year-old clear-cutting were slightly enriched in carbon and nitrogen. An organo-mineral horizon with high total nitrogen and carbon content is being formed in the 8-year-old cutting. This horizon is most likely formed due to the calcium released as a result of forest litter mineralization, which contributes to organic matter fixation. The formation of such horizons is characteristic of soils disturbed by human impact. Logging operations have contributed to a decrease in the acidity of the forest floor. Thus, pH in fresh clear-cutting is 4.0, and after 8 years it is 4.9. The migration of humus down the soil column is accompanied by an acidity decrease in the mineral horizons to 5.5.

![Figure 1](image-url)  
**Figure 1.** Changes in the chemical properties of Albic Podzol: (a) – total carbon content, %; (b) – total nitrogen content, %.

In the first three years after cutting, the content of carbon and nitrogen in the forest floor and organo-mineral horizons decreases, pointing to intensive humification and mineralization of organic matter. When the tree stands reach the age of 8 years, the organic matter content in these horizons increases somewhat compared to 3-year-old cuttings due to an increase in the litter input to the soil surface. As regards the mineral horizons, there is no significant enrichment at any stages of reforestation. The acidity of the forest litter, organo-mineral and mineral horizons is gradually reduced with time since logging.
Figure 2. Changes in the chemical properties of Entic Podzol: (a) – total carbon content, %; (b) – total nitrogen content, %.

3.2. Natural reforestation after clear-cutting

Albic Podzol, which is relatively poor in organic matter, maintains pine (Pinus sylvestris L.) stands mixed with birch (Betula Pendula Roth.), which have the following inventory characteristics of the main species. The composition of the stand is 9P1B, quality class I, mean tree height 28.2 m, quadratic mean diameter 31.6 cm, stocking rate 0.6, timber stock 296 m$^3$ per 1 ha, stand density 400 trees per hectare. The underwood is poor, consisting of occasional spruce (Picea abies (L.) Karst), rowan (Sorbus aucuparia L.), aspen (Populus tremula L), willow (Salix caprea L.) and juniper (Junipirus communis L.). The dominants in the living ground cover are bilberry (Vaccinium myrtillus L.), lingonberry (Vaccinium vitis-ideae L.), red-stemmed feathermoss (Pleurozium schreberi (Brid.) Mitt) and glittering woodmoss (Hylocomium splendens (Hedw.) Schim.). Quite abundant are common heather (Calluna vulgaris (L.) Hull), hairy wood-rush (Luzula pilosa (L.) Willd.), arctic starflower (Trientalis europaea L.), cow-wheat (Melampyrum pratense L.) and broom fork moss (Dicranum scoparium Hedw.).

The stands growing on Entic Podzol are less productive. The composition of the stand is 10P, quality class III, mean tree height is 19.7 m, quadratic mean diameter is 18.1 cm, stocking rate is 0.9, timber stock is 322 m$^3$ per 1 ha, stand density is 1300 trees per ha. The underwood is made up of rowan, aspen, willow, juniper and rose hip (Rosa acicularis Lindl). The herbs sinusia includes, in addition to the species characteristic of Albic Podzols, some quite rare species: field scabious (Knautia arvensis (L.) Coult.), twinflower (Linnaea borealis L.) and interrupted club-moss (Lycopodium annotinum L.).

Plant communities in the fresh clear-cutting of the first chronosequence show a prevalence of species characteristic of undisturbed areas, but the number of moss-lichen species is considerably reduced. There is also a large number of emerging pine, birch and willow undergrowth (Table 1). After a 3-year period, the territory gets overgrown with herbaceous vegetation dominated by wavy hair-grass (Deschampsia flexuosa (L.) Trin.) and roseybay willowherb (Chamaenerion angustifolium (L.) Scop.). However, the surface does not get thoroughly sodded, and light-loving dwarf shrubs, lingonberry and common heather, still prevail in the ground cover. Owing to augmented illumination and nutrition area the growth of young pine is activated, and the amount of pine undergrowth significantly increases compared to a recent cutting. There is an intensive growth of hardwood species, especially birch and aspen. Reed grass (Calamagrostis arundinacea Roth.) and roseybay willow-herb prevail in the living ground cover on the 8-year-old clear-cutting. Large numbers of herbs appear: yarrow (Achillea millefolium L.), common bent (Agrostis tenuis Sibth.), wild angelica (Angelica sylvestris L.), sweet vernal grass (Anthoxanthum odoratum L.), cow parsley (Anthriscus sylvestris (L.) Hoffm.), bearberry (Arctostaphylos uva-ursi (L.) Spreng.), common speedwell (Veronica officinalis L.). The share of reindeer lichen (Cladonia arbuscula (Wallr.) Flot.) and broom fork moss is significantly reduced, but a new species, pohlia moss (Pohlia
nutans (Hedw.) Lindb.), arrives and becomes abundant. At this stage, new pine growth is sufficient for a stand of commercially valuable species to form.

Table 1. Taxation descriptions of the felling of the first chronosequence.

| Years since logging | Site type / stand composition | Tree species | Stocking (thousand pc/ha) | Prevalence (%) | Mean tree height (m) |
|---------------------|-------------------------------|--------------|--------------------------|----------------|---------------------|
| 0                   | Dwarf shrub-true moss         | Pine         | 1.2                      | 52             | 0.29±0.02           |
|                     |                               | Birch        | 0.3                      | 12             | 0.30±0.04           |
|                     |                               | Willow       | 1.7                      | 10             | 0.54±0.08           |
| 3                   | Dwarf shrub-true moss         | Pine         | 5.3                      | 77             | 0.49±0.22           |
|                     |                               | Birch        | 3.7                      | 83             | 1.26±0.16           |
|                     |                               | Aspen        | 0.8                      | 53             | 0.98±0.30           |
|                     |                               | Willow       | 1.1                      | 30             | 0.69±0.18           |
|                     |                               | Alder        | 0.5                      | 7              | 0.91±0.06           |
| 8                   | Dwarf shrub-forbs pine stand  (7P3B+As) | Pine      | 5.7                      | 88             | 2.1±0.06            |
|                     |                               | Birch        | 1.9                      | 39             | 3.0±0.18            |
|                     |                               | Aspen        | 0.3                      | 28             | 1.6±0.40            |
|                     |                               | Willow       | 0.9                      | 28             | 2.5±0.21            |
|                     |                               | Alder        | 0.2                      | 4              | 3.4±0.06            |

The living ground cover in logged sites with Entic Podzol is the most often dominated by reed grass, with the presence of wavy hair-grass and rosebay willowherb. Reforestation begins primarily with deciduous species, birch and aspen, while pine seedlings are much fewer (Table 2). After a 3-year period, there is no change in the species composition of herbaceous vegetation since the fresh cutting, but its percent cover increases. The share of dwarf shrubs and mosses drops markedly, since the only remaining mosses are red-stemmed feathermoss and glittering woodmoss.

The amount of young pine growth is significantly reduced, not only because part of it is destroyed during logging, but also due to intensive growth of the herbaceous cover, which prevents seeds from germinating and suppresses the growth of the existing understorey. By this time, the area is overgrown with deciduous seedlings, mainly aspen. In the 8-year-old clear-cutting, the heterogeneity of the tree layer is reflected in the mosaic pattern of the ground cover, whose species composition is highly variable. Compared to the living ground cover of an undisturbed stand, this layer is highly productive and has diverse herbaceous vegetation: yarrow, wild angelica, wavy hair-grass, cow-wheat, may lily (Maianthemum bifolium (L.) F.W. Schmidt.), bush grass (Calamagrostis epigeios (L.) Roth), lily of the valley (Convallaria majalis L.). The moss cover recovers slowly, the regeneration of conifers is hampered. Birch and aspen impose heavy competition on new pine growth. The increased density of aspen regrowth is primarily associated with sprouting from the roots of maternal trees, where soil characteristics, herbaceous cover and underwood abundance have little effect on the conditions of aspen regeneration. A constraint on aspen growth and development is the zoogenic factor, i.e., moose browsing on branches of saplings. The amount of new pine growth is insufficient for valuable tree stands to form.

The different directions of forest regeneration in the chrosequences are due to a significant decline in soil richness of the Albic Podzol compared to Entic Podzol, which is associated with a lower water capacity of sands compared to soils with a finer texture, and a smaller active surface of soil particles in sands.
Table 2. Taxation descriptions of the felling of the second chronosequence.

| Years since logging | Site type / stand composition | Tree species | Stocking (thousand pc/ha) | Prevalence (%) | Mean tree height (m) |
|---------------------|-------------------------------|--------------|---------------------------|----------------|---------------------|
| 0                   | Potentially reed-grass-hair grass | Pine 0.3    | 12                        | 0.42±0.22      |
|                     |                               | Birch 0.8   | 8                         | 0.34±0.05      |
|                     |                               | Willow 1.7  | 24                        | 0.66±0.20      |
| 3                   | Potentially reed-grass-hair grass | Pine 3.0    | 35                        | 0.22±0.03      |
|                     |                               | Birch 1.0   | 15                        | 0.65±0.31      |
|                     |                               | Aspen 1.6   | 25                        | 0.49±0.06      |
|                     |                               | Willow 1.3  | 15                        | 0.89±0.38      |
| 8                   | Herb-grass aspen stand (5As2P2B1Al, few S, W) | Pine 1.8    | 36                        | 2.12±0.40      |
|                     |                               | Spruce 0.4  | 16                        | 0.77±0.14      |
|                     |                               | Birch 2.5   | 44                        | 3.67±0.43      |
|                     |                               | Aspen 5.2   | 52                        | 3.34±0.19      |
|                     |                               | Willow 0.2  | 4                         | 1.25±0.25      |
|                     |                               | Alder 1      | 16                        | 3.20±0.33      |

4. Summary
The productivity of undisturbed forest stands and the success of restoration sylviculture depend on a set of factors, where soil fertility is a decisive one. The level of fertility can be judged from the patterns of organic matter deposition and decomposition in the forest floor and the root zone of the soil. The first chronosequence, representing Albic Podzol, is characterized by an illuvial distribution of organic matter down the soil profile, with maximum accumulation of organic matter in the forest floor. The same pattern of organic matter distribution across the soil profile is retained after clear cutting. As more time passes since the felling, the mineral horizons gradually get enriched with organic matter, and by the age of 8 years a thin organo-mineral horizon with an elevated carbon and nitrogen content is formed underneath the forest floor. In contrast to the first chronosequence, the second one, representing Entic Podzol, demonstrates a slight decline of soil richness upon logging, caused by intensive humification and mineralization of organic matter.

The study found evidence that the application of multifunctional logging machines helps better preserve the living ground cover and the forest floor in a significant part of the logging area. Natural reforestation proceeds following 2 different scenarios. Albic Podzol, which is relatively poor in organic matter, support the formation of mixed pine stands with a large contribution of birch, where the moss cover regenerates rapidly in the living ground cover, and the most common dominants in the herb-dwarf shrub layer are cowberry, heather and may lily. In the early stages of natural reforestation on Entic Podzol there mainly form deciduous stands made up of aspen and birch. The most frequent dominants in the living ground cover are feather reed grass and raspberry, the moss cover recovers slowly, and regeneration of coniferous species is hampered.

The study has led to the conclusion that there happens no major change in carbon and nitrogen content in the soil profile of podzolic soils with different degrees of fertility in the early stages of reforestation upon clear-cutting done using modern logging technologies. It can therefore be assumed that soil properties in such sites will recover sooner than where traditional logging methods are employed. The site conditions of the original forest type, which predetermines the effective fertility of the soil, and the composition of the stand to be logged are reliable indicators for predicting the success of the subsequent natural regeneration of stand-forming species in the clearings.
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References

[1] Grigor’ev I and Zhukova A 2004 Technological possibilities of raising efficiency of utter choppings of main use by wood Izvest. Sankt-Peter. Lesotehn.akad. 171 (Saint-Petersburg: LTA Publ.) 18-24
[2] Grigor’eva I, Zhukova A, Grigor’eva O and Ivanov A 2008 Eco efficient technologies of wood harvesting in the North-West region of the Russian Federation (Saint-Petersburg: LTA Publ.) p 176
[3] Ulanova N 2015 Proceedings of the anniversary scientific-practical conference dedicated to the 80th of the Oka state biosphere reserve “The role of the Russian scientific reserves in the conservation and study of nature” 34 207-212
[4] Clarke N, Gundersen P, Jönsson-Belyazid U, Kjenaas O J, Persson T, Sigurdsson B D, Stupak I and Vesterdal L 2015 Influence of different tree-harvesting intensities on forest soil carbon stocks in boreal and northern temperate forest ecosystems For. Ecol. and Manag. 351 9-19
[5] Piirainen S, Finer L and Starr M 2015 Changes in forest floor and mineral soil carbon and nitrogen stocks in a boreal forest after clear-cutting and mechanical site preparation. Eur. J.1 of S. Sc.66 735–743
[6] Smolander A and Heiskanen J 2007 Soil N and C transformations in two forest clear-cuts during three years after mounding and inverting. Can. Jour. of Soil Sc. 87 251-258
[7] Dymov A, Milanovskii E and Lapteva E 2012 Soil and soil organic matter changes during natural reforestation after felled Forest. Bull. 2 67-72
[8] Il’intsev A, Tretyakov S, Nakvasina E, Amosova I, Aleinikov A and Bogdanov A 2017 The effect of long-term, gradual felling in mixed pine stands for natural regeneration, living ground cover and some properties of the upper soil Forest.Jour. vol 7 3 (27) 85-99
[9] Bakhmet O and Medvedeva M 2013 Changes in Soil Properties at Different Stages of Artificial Reforestation in Karelia Pochvoved. 3 38-45
[10] Zyabchenko Z, Zagural’skaya L and Lazareva I 1988 Dynamics of ecological processes in large-scale clear-cuts in northern Karelia Lesoved. 3 3-10
[11] Vdovichenko V, Bakhmet O and Yu Tkachenko 2016 Early stages of soil recovery on rock formations after pine stands clear-cuttings Proc. of Petroz. St. Univ. 3(159) 37–41
[12] Vdovichenko V and Bakhmet O 2017 Impact of forest cuttings on transformation of soil organic matter in Karelia Izvest. ufim. nauch. tsent. RAN 3(1) 41–44.
[13] Nazarova L 2003 Climate. The diversity of biota of Karelia: conditions of formation, cenosis, species (Petrozavodsk: KarRC RAS Publ.) 6–8
[14] Walker R L, Wardle D A, Bardgett R D and Clarkson B D 2010 The use of chronosequences in studies of ecological succession and soil development Jour.of Ecol. 98 725-736