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Soil respiration and nitrogen leaching decreased in grey alder (\textit{Alnus incana} (L.) Moench) coppice after clear-cut

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**ABSTRACT**
Grey alder (\textit{Alnus incana}) is a highly productive indigenous tree species, potential for short-rotation forestry in the Baltic and Nordic countries. The aim of the study was to investigate the development of a new forest generation, as well as the nitrogen (N) and carbon (C) storages and fluxes in a grey alder regenerating coppice (COP) after clear-cut and in an adjacent unharvested 21-year-old stand (MAT), which had reached its bulk maturity. The regeneration of COP was rapid and 5 years after clear-cut, stem mass was 6.4 t ha\(^{-1}\). The nitrogen demand of the aboveground part of the 5-year-old COP trees was estimated to be roughly half of the corresponding value for MAT, depending mostly on leaf production. The annual N leaching flux in MAT was in the range of 16–29 kg ha\(^{-1}\), the corresponding values for COP were roughly half of that. Net nitrogen mineralization did not differ significantly between MAT (117 kg ha\(^{-1}\)) and COP (129 kg ha\(^{-1}\)). For the soil respiration study, a 32-year-old grey alder stand growing at a similar site was included; soil respiration was significantly higher in MAT compared to COP in all study years in both studied stands.

**Introduction**
Grey alder (\textit{Alnus incana} (L.) Moench) is one of the most productive forest tree species in the Northern and Baltic countries. Several publications have reported the high biomass production of grey alder both on mineral and organic soils (e.g. Granhall et al. 1994; Rytter 1996; Uri et al. 2003a, 2009, 2017; Aosaar et al. 2013; Hytönen and Saarasma 2015; Rytter and Rytter 2016, etc.). Recently, the role of grey alder stands in carbon (C) accumulation in the Nordic countries was analyzed (Rytter and Rytter 2016) and a new yield-table for Estonian grey alder stands was published (Uri et al. 2014). Grey alder is a suitable tree species for short-rotation forestry with an optimal rotation length of about 20–25 years (Aosaar et al. 2012; Uri et al. 2014). However, because of its low economic value, only very few publications have considered the impact of management on functioning and development of grey alder stands (Rytter 1995; Daugavietis et al. 2009; Becker et al. 2015). However, in the light of the Paris Agreement (2016), an increasing demand for renewable energy is predictable, which may also lead to more intensive management of grey alder stands for biomass.

In Estonia, the principal management method for grey alder stands is clear-cut (Estonian Environmental Information Centre 2017). Clear-cut causes drastic changes in the forest ecosystem’s functioning due to changed light, microclimate, and soil physical and chemical conditions. All these aspects affect the growth of the next forest generation and soil processes (\(\text{CO}_2\) emissions, nitrogen (N) leaching, net nitrogen mineralization (NNM)). In the current paper, the N and C storages and fluxes in a 21-year-old grey alder stand and in an adjacent developing coppice after clear-cut are studied (Voopste study site). For estimating the effect of clear-cut to soil respiration fluxes, measurements were carried out in the above mentioned Voopste as well as in the 32-year-old Agali study site.

N is the main growth-limiting nutrient in a boreal forest ecosystem (Näsholm et al. 1998), affecting biomass production of trees and hence C sequestration in the forest ecosystem. However, because of the \(\text{N}_2\) fixing ability, the presence of alder stands increases total soil N (Bormann and DeBell 1981; Uri et al. 2011) and may induce higher annual NNM (Van Miegroet and Cole 1989) and substantial NO\(_3^-\) leaching (Binkley et al. 1982). In a clear-cut area, soil moisture and temperature presumably increase, which should intensify NNM. Some studies report an increase in NNM intensity after clear felling (Morris and Boerner 1998) whereas others report lowered NNM intensity (Thibodeau et al. 2000) and still others do not report any significant change (Lapointe et al. 2005).

Another crucial issue in regard to the environmental impacts of forest management is the reaction of soil respiration (Rs), which comprises autotrophic (root) respiration and heterotrophic (decomposing organic matter) respiration (Rh). In a forest ecosystem, Rs is the largest C efflux to the atmosphere (Janssens et al. 2001). Loss of respiring root biomass and a decrease in the litter input and root exudates as a consequence of biomass removal through harvesting can cause a decrease in Rh, resulting in an overall decrease in total Rs (Kowalski et al. 2004). On the other hand, recent clear cutting can increase C substrate availability (slash
residues, decomposing roots) as well as soil temperature and soil moisture content, which can favour decomposition of organic matter (Peng and Thomas 2006; Kukumägi et al. 2011; Kurth et al. 2014) and enhance Rh. The harvesting method, forest type, speed of regeneration and climatic conditions play an important role in the response of post-harvest Rs. The combined effect of these factors can lead to high variation in the results: clear cutting can have a stimulating (Wiseman and Seiler 2004), suppressing (Payeur-Poirier et al. 2012) or zero effect (Toland and Zak 1994) on Rs. Although a number of studies have quantified post-harvest Rs responses, most of them focus on coniferous tree species.

We hypothesize that compared to unharvested mature grey alder stands, the NMN, N leaching, and soil CO2 emission increase in developing coppices after clear-cut. The aims of the study were:

1. To estimate the production dynamics of natural regeneration of grey alder coppice after clear-cut.
2. To estimate the dynamics of the nitrogen pools and fluxes in the developing grey alder coppice after clear-cut.
3. To estimate the effect of clear-cut and development of natural regeneration on soil respiration in young grey alder coppice.

**Material and methods**

**Study areas**

The Voopste grey alder study site, located in Eastern Estonia (Table 1), was established in May 2012. Two adjacent plots (both 25 × 30 m) were marked in a homogeneous 21-year-old natural grey alder stand. One of the plots was clear-cut, where vigorous natural regeneration from stump sprouts and root suckers emerged, which is treated as a coppice (COP) in this study. The other one was left for monitoring as a mature stand (MAT). From clear-cut area, only the stems were removed while cutting residues, including leaves, were left on site. The clear-cut was carried out with chainsaws and the timber was extracted manually to avoid soil disturbances.

The site is highly fertile and, according to the Estonian classification (Lõhmus 1984), belongs to the Aegopodium site type. All the trees growing in sample plots were measured for breast height diameter (D1.3) and the length of 15 felled trees were measured for height by sampling across the diameter range of the stand (Table 1). Part of the data from the Voopste study has been utilized in our earlier studies, which focused on the growth dynamics (Uri et al. 2014) and carbon budget of the site (Uri et al. 2017). This paper will deal with the N storages and fluxes as well as the CO2 emissions after clear-cut and during the coppice regeneration. For a better understanding of the soil respiration a similar study site was established in spring 2011 in a 32-year-old grey alder stand in Agali, using identical sampling and measurement methods.

**Soil**

At the Voopste and Agali study sites, 10 randomly located soil pits were dug in both the MAT and COP to a depth of 1.0 m. The soil profile was described and the soil type was determined according to the “The World Reference Base for Soil Resources, 2006” (Table 2). The soil texture was evaluated in the field using the texture-by-feel method. For calculating soil C and nutrient storages, the soil bulk density before clear-cut was determined from MAT and COP. From each of the ten soil pits on both plots three bulk density samples from each 10 cm soil layer were taken to a depth of 30 cm in Agali and to a depth of 50 cm in Voopste with a stainless steel cylinder (d = 40 mm, volume 50 cm³), avoiding compression of the soil. The samples were dried at 105°C to constant weight and weighed to 0.01 g. Soil nutrient contents were estimated from the samples taken from 15 random points in both plots at depths of 0–10, 10–20 and 20–30 cm in Agali whereas in Voopste also 30–40 and 40–50 cm layers were included with a soil corer (d = 40 mm). Altogether three composite samples from each depth layer, consisting of five samples each, were pooled and taken to laboratory for chemical analyses (Uri et al. 2014).

**Aboveground biomass and production**

**Trees**

At the Voopste site, the mean breast height diameter (D1.3) and mean height of the stand were determined in May 2012 before clear-cut (in both MAT and COP) and thereafter in MAT every October from 2012 to 2016. Aboveground biomass (AGB) was estimated, by using the model tree method (Bormann and Gordon 1984; Aosaar et al. 2016) in May 2012. Five model trees were selected according to the distribution of D1.3 of trees so that the range of D1.3 was covered. The model trees were divided into sections and in each section, the mass and proportion of the stemwood, stem bark and branches were determined. The process is thoroughly described in Uri et al. (2009, 2014). Since it was the beginning of the growing period and the biomass of leaves was not yet at year’s maximum, the leaf mass of the stand was not estimated.

We used allometric Equation (1) for estimating AGB (y) of the stand.

\[
y = ax^b
\]

where y is the AGB of tree (g), x is the tree diameter at breast height (cm) or height of the tree (m) and a and b are the parameters of the equation. For estimation of the biomass of the

<table>
<thead>
<tr>
<th>Study site</th>
<th>Location</th>
<th>Age, yr</th>
<th>Stand density, trees ha⁻¹</th>
<th>Stem volume, m³ ha⁻¹</th>
<th>D1.3, cm</th>
<th>H, m</th>
<th>Basal area, m² ha⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voopste</td>
<td>58°21'N; 27°16'E</td>
<td>21</td>
<td>3,280</td>
<td>177.3</td>
<td>9.5</td>
<td>14.3</td>
<td>23.1</td>
</tr>
<tr>
<td>Agali</td>
<td>58°17'N; 27°17'E</td>
<td>32</td>
<td>1,528</td>
<td>124.7</td>
<td>9.1</td>
<td>13.7</td>
<td>18.7</td>
</tr>
</tbody>
</table>

*The Agali stand was included only in the soil respiration experiment.
different compartments of trees at the stand level, the percentage distribution of the different fractions based on the model trees was used.

The current annual increment of the stemwood, bark and branches of the MAT was calculated as the difference between the masses of the respective fractions for the study year and for the previous year, measured annually in October. Leaf mass and production for 2012–2015 was found on the basis of the annual leaf litter flux, which was estimated using 10 litter traps with a collecting area of 0.36 m² each. Leaf litter was gathered every fortnight and weekly during intensive litter fall. The leaf litter data of MAT for 2012–2014 is partly published in Uri et al. (2017) where the annual C input into the soil via leaf litter is estimated. In the current paper, the corresponding N flux is presented.

In COP, the growth of natural regeneration of alders was estimated in five circular subplots (S=25 m²). In 2013–2016, the height and later also the D₁₃ of all trees in the subplots were measured. For estimating the AGB of COP, 7 model trees were taken and allometric Equation (1) was applied; the function of height was used for 2013 and D₁₃ for 2014–2016.

**Herbaceous understorey**

The AGB of the herbs was estimated in both MAT and COP plots at the end of June 2012–2014 when the biomass of the current year was at maximum. The aboveground part of all herbaceous plants was collected from a 0.5 m² quadrat at 10 random points over the whole plot. The samples were dried at 70°C to constant weight and weighed to an accuracy of 0.1 g. As the aboveground part of herbs is annual, their aboveground biomass was considered equal to the annual production. For 2016 the above- and belowground biomass of herbs were predicted based on samplings of 2013 and 2014.

**Belowground biomass and production**

The coarse root biomass (CRB) (d>2 mm) and stump core of the alder trees for MAT was calculated on the basis of earlier studies where the total root systems of trees were excavated in 5-, 10- and 40-year-old stands (Löhmus et al. 1996; Uri et al. 2009) and the proportion of coarse roots was found to be 19% of leafless AGB. Further, it was assumed that AGB and CRB develop proportionally and therefore the coarse root production is proportional to the aboveground biomass production. Thus, CRB and coarse root production were calculated according to Equations (2) and (3), respectively (Aosaar et al. 2013).

\[
\text{CRB} \text{ (t ha}^{-1}\text{)} = (\text{AGB}_{\text{leafless}}) \times 0.19
\]

(2)

\[
\text{Coarse root production (\%)} = \frac{\text{AGB}_{\text{prod}}}{\text{AGB}}
\]

(3)

Fine root (d<2 mm) biomass for both MAT and COP and the belowground biomass of the herbaceous understorey for COP were estimated in October 2013 (Uri et al. 2017). Twenty soil cores were taken from COP and MAT with a soil auger (d=48 mm) and divided into four 10 cm layers. Next, the root material was carefully washed out of the soil and the fractions of tree fine roots and herb roots were separated and washed to remove soil particles under a microscope. The root samples were dried until constant weight and weighed thereafter to 0.001 g. Based on the samples, the root biomass of the trees and herbs per hectare were calculated. The biomass of the nodules was not estimated since their proportion of total belowground biomass is modest (roughly 0.2–0.3 t ha⁻¹ by Saarsalmi et al. 1985; Uri et al. 2002; Aosaar et al. 2013).

The fine root production of MAT was estimated using the root mesh method (Hirano et al. 2009; Lukac and Godbold 2010; Uri et al. 2017). Nylon meshes (20 × 7 cm) were installed in autumn 2012 and the first sampling was done one year later when 25 root meshes with the surrounding soil block were dug out in order to avoid loss of fine roots. In the laboratory, the fine roots were carefully washed and removed from the mesh. The fine roots of grey alder were separated, dried and weighed to 0.001 g and the fine root production per hectare was calculated. For estimating the annual N flux into the soil through fine root litter, we assumed that it was equal with the fine root annual production (Uri et al. 2017). The belowground biomass of herbs for 2014 was calculated on the basis of the aboveground/belowground biomass ratio for 2013 and the turnover rate was assumed to be 1 year (Uri et al. 2011; Varik et al. 2015) and hence the root biomass of the herbs was considered to be equal to their belowground production.

**Nitrogen fluxes**

**Nitrogen demand**

The nitrogen demand (ND) of the stand is considered as the amount of N bound in the annual production of the above- and belowground biomass of trees and herbs. The N concentration was determined for the different fractions of the trees (leaves, twigs, branches, stemwood and stembark) and for the

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**Table 2.** The soil characteristics of the Voopste and Agali study sites (Uri et al. 2014, 2017; Becker et al. 2015).

<table>
<thead>
<tr>
<th>Study site</th>
<th>Soil layer</th>
<th>Soil type</th>
<th>N</th>
<th>P</th>
<th>K</th>
<th>Mg</th>
<th>pH₀₂</th>
<th>Bulk density, g cm⁻¹</th>
<th>N pool, t ha⁻¹</th>
<th>C pool, t ha⁻¹</th>
<th>CN ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voopste</td>
<td>0–10 cm</td>
<td>Endogleyic Arenosol</td>
<td>0.36</td>
<td>8.3</td>
<td>55.0</td>
<td>166.3</td>
<td>4.5</td>
<td>0.73</td>
<td>2.63</td>
<td>35.7</td>
<td>14.0</td>
</tr>
<tr>
<td></td>
<td>10–20 cm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.84</td>
<td>2.36</td>
<td>34.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>20–30 cm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.21</td>
<td>2.29</td>
<td>34.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>30–40 cm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.54</td>
<td>1.23</td>
<td>20.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>40–50 cm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.50</td>
<td>1.35</td>
<td>22.1</td>
<td></td>
</tr>
<tr>
<td>Agali</td>
<td>0–10 cm</td>
<td>Umbric Planosol</td>
<td>0.36</td>
<td>9.4</td>
<td>59.1</td>
<td>325.7</td>
<td>5.9</td>
<td>0.98</td>
<td>3.40</td>
<td>36.5</td>
<td>11.9</td>
</tr>
<tr>
<td></td>
<td>10–20 cm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.14</td>
<td>3.10</td>
<td>33.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>20–30 cm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.92</td>
<td>2.10</td>
<td>22.8</td>
<td></td>
</tr>
</tbody>
</table>

N-nitrogen concentration (%), P- available (AL) phosphorus, K- available (AL) potassium, Mg – available magnesium concentration, (mg kg⁻¹).

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herbs. For analysing N concentration in trees of MAT, three model trees were sampled in 2012. For analysing N status of COP, four trees were sampled annually in 2013–2015. In the different fractions of the sample trees, the N concentrations were calculated as weighted averages. Both the N pool and the annual ND in the biomass of the plants were calculated by multiplying the biomass or the annual production of a compartment by the corresponding N concentration. The ND of the coarse roots was calculated based on earlier studies (Lõhmus et al. 1996; Uri et al. 2009) assuming that AGB and coarse root biomass develop proportionally (Aosaar et al. 2013).

Nitrogen leaching
For estimating the effect of clear-cut on N and C leaching, 10 stainless steel plate lysimeters with a collecting area of 627 cm² each were installed into the soil to a depth of 40 cm before clear-cut in May 2012 in both plots. The lysimeters were connected to 5,000 ml polyethylene canisters, which were deposited at a depth of 100 cm. Beginning in 2012, the water from the canisters was sampled monthly from June to October through a plastic pipe, using a vacuum pump, up to April 2015.

Nitrogen transformations
To estimate N retranslocation from the senescing leaves in MAT, the difference between the amount of N in the fresh leaves and in the leaf litter was calculated, considering the N% in the leaves during the time of their highest concentration in June, and the N% in the leaf litter when collected from the litter traps. The return of N from the senescing leaves was estimated in 2012 and 2015.

For estimating net nitrogen mineralization (NNM) the well-known widely used method of incubated polyethylene bags was implemented (Eno 1960), which was used also in our earlier studies (Uri et al. 2003b, 2008, 2011; Becker et al. 2016, 2018). The annual NNM dynamics in MAT and COP was studied in the 0–10 cm soil layer from May 2012 to May 2013 and in the 0–20 cm soil layer from May to June 2013. For estimating NNM in the 0–20 cm soil layer, soil cores from the upper 20 cm layer were separated into two layers (0–10 cm and 10–20 cm). A soil corer (d = 48 mm) was used for soil sampling; altogether 24 samples were taken with a monthly interval. Assessment of NNM was based on the comparison of the nitrate and ammonium forms of N in the initial and incubated samples. The experiment of NNM is thoroughly described in Uri et al. (2003b, 2008) and in Becker et al. (2015, 2016, 2018). Atmospheric deposition of N for this region has been estimated with the method of polyethylene gutter described in Uri et al. (2003b, 2008) and in Becker et al. (2015, 2016, 2018). To distinguish heterotrophic respiration (Rh) from total soil respiration (Rs), the trenching method (Luo and Zhou 2006) with the insertion of 8 deep PVC cylinders (diameter 20 cm, height 50 cm) to a depth of 40 cm was applied to each treatment at least one month before launching soil respiration measurements. At approximately 50 cm from each deep PVC cylinder (trenched), collars (diameter 10 cm, height 5 cm) for Rs measurement were installed at a depth of 2–3 cm. To measure only the soil CO₂ efflux, the herbaceous vegetation was carefully removed from the inside of the trench and collar with minimum soil disturbance and the measurement points were kept free from living vegetation throughout the study.

Soil temperature (°C) was measured both discretely and continuously. Discrete temperature measurements were made simultaneously with Rs and Rh measurements using an attached soil temperature probe STP-1 (PP Systems International, Inc., USA) inserted at a depth of 5 cm. Soil temperature (model 1425, Technologies, Inc, USA) was measured continuously every hour during the snow-free period (May–November) and the data was stored with a data logger (one in the COP and one in the MAT) (WatchDog 1425, Spectrum Technologies, Inc, USA). Volumetric soil moisture (%) was measured after each soil respiration measurement at a depth of 5 cm using a HH2 Moisture Meter Version 2 (Delta-T Devices Ltd, UK).

Chemical analyses
The block digestion and steam distillation methods were used for analysing the plant material for Kjeldahl nitrogen concentration (Tecator AN 300). Soil pH and the content of organic matter (as loss on ignition at 360°C) were determined as well. Soil pH in 1 M KCl suspensions was measured at a ratio of 10 g:25 ml. The Tecator ASN 3313 was employed for testing the soil samples for nitrogen according to Kjeldahl. For determination of NH₄⁺–N, NO₃⁻–N, and NO₂⁻–N in the soil, flow injection analysis was employed using the Tecator ASN 65-32/84 and the Tecator ASN 65-31/84. Available phosphorus in the soil was determined by means of flow injection analysis (ammonium lactate extractable) with the use of the Tecator ASTN 9/84. The content of available potassium was determined from the same solution by the flame photometric method. Soil magnesium content was determined by means of flow injection analysis with the Tecator ASTN 90/92. Calcium was determined from the same solution by the flame photometric method. Water samples were analyzed for NH₄⁺, NO₃⁻, NO₂⁻ and dissolved organic nitrogen in the lab of the Estonian Environmental Research Ltd, using standard methods for water research (APHA 1989).

Statistical analysis
The normality of the variables was checked with Shapiro-Wilk’s, Lilliefors and Kolmogorov–Smirnov tests. Allometric regression models were employed for estimating model
The quality of the fit of the models was evaluated by the coefficient of determination ($R^2$) and the level of probability (P). The statistical significance of differences in NNM and leaching between the MAT and COP was checked with the t-test (two-sample assuming unequal variances). Regression analysis was used to estimate the dynamics of nitrogen leaching in MAT and COP. The soil respiration data was converted from μmol CO₂ m⁻² s⁻¹ to kg CO₂ ha⁻¹ h⁻¹ in figures and tables to be consistent with the other measured variables. The soil respiration data were normalized by log-transformation. The effect of clear-cut on Rs (or Rh), soil temperature and soil moisture was tested by repeated measures analysis of variance (ANOVA), including treatment, temperature and soil moisture as the repeated variables. The soil respiration data was normalized and partial correlation analysis was used to examine the relationships between Rs (or Rh), temperature in the trench and the control plots. A multilinear regression analysis was used to examine the relationships between Rs (or Rh), soil temperature and soil moisture. Furthermore, Pearson’s coefficient of correlation for Rs and soil temperature was calculated. To eliminate the confounding effect of soil temperature, partial correlation analysis was used to find out the effect of soil moisture on Rs (or Rh). An exponential model (4) was used to describe the relationship between Rs (or Rh) and soil temperature for each site, treatment and growing season:

$$Rs(or\ Rh) = ae^{bTs}$$

(4)

where a and b are fitted parameters, and Ts is soil temperature (°C). Daily temperature values from data loggers were used to calculate cumulative Rs and Rh fluxes for the snow free period (May-November).

The software packages STATISTICA 7.1 and R were used and the significance level $a = 0.05$ was accepted in all cases.

### Results

**Nitrogen storages and demand**

In the mature stand (MAT) N was mainly bound in the stemwood, despite its low average concentration (0.24%). The storage increased with the increasing growing stock of the stand, up to 174 kg ha⁻¹ in 2016 (Table 3). Also a considerable amount of N was bound in the stembark because of its high N concentration (1.28%). The N storage in the belowground part of the trees was significantly lower and N was mostly bound in the coarse roots.

The annual nitrogen demand (ND) of the aboveground part of the trees and herbs in MAT in 2013 and 2016 was 179 and 189 kg ha⁻¹ yr⁻¹, respectively, of which the ND of the trees made up approximately 80% in both years. The ND of the trees depended mainly on the leaf production, which varied from 3.4 to 4.2 t ha⁻¹ yr⁻¹ in 2011–2016. For the leaf production, the proportion of ND in the total aboveground ND of the trees was approximately 82% in 2012–2016 and as high as 89% in 2015. For woody aboveground biomass, the highest proportion of N was utilized by the twigs, which was 2–4 times as high as the corresponding proportion for the other fractions. Because of their low production (∼0.5 t ha⁻¹ yr⁻¹), the ND of the coarse roots and stumps was only about 4–5 kg ha⁻¹. The fine root production was 1.78 in 2013 and 2.35 t ha⁻¹ yr⁻¹ in 2014 (Uri et al., 2017), which made up roughly 85% of the total belowground biomass production and the corresponding ND varied between 20 and 30 kg ha⁻¹ yr⁻¹.

The ND of the herbaceous understorey in MAT accounted roughly for 20% of the ecosystem’s total aboveground annual ND in 2013 and 2016. The aboveground production of the herbs increased from 0.8 t ha⁻¹ yr⁻¹ in 2012 to 1.6 t ha⁻¹ yr⁻¹ in 2014 and the respective ND from 25 to 50 kg ha⁻¹ yr⁻¹. The ND of the belowground part of the herbs in 2013 was 8 kg ha⁻¹; and the corresponding ND for 2016 was 10 kg ha⁻¹.

After the clear-cut, the pattern of the regeneration characteristics was typical for grey alder coppice stands: many trees emerged from the root sprouts and stem suckers with intensive self-thinning and rapid mean height growth (Table 4). At the age of 5 years, the stand density was 25,000 trees ha⁻¹, the mean height was 4 m and the stem mass was 6.4 t ha⁻¹. Because of the low biomass of young trees during the first 3–4 growing years, the N storage of the stems and branches was also very low. The stemwood production in the 2-year-old stand was 0.6 t ha⁻¹; in the following years it was around 2 t ha⁻¹ (Table 4). The leaf production increased year by year from 0.2 t ha⁻¹ in 2013 to 1.6 t ha⁻¹ in 2016. A similar pattern was evident for the branches and twigs. The leaf production was the main factor influencing the ND of the aboveground part of the trees, amounting to 77 kg ha⁻¹ yr⁻¹ in 2016 while 74% of N was bound in the leaves (Table 3).
In 2013, the annual aboveground and belowground production of herbs in COP was 1.8 and 0.7 t ha\(^{-1}\), respectively. The respective ND values 49.1 and 12.3 kg ha\(^{-1}\). One year later the production of the aboveground part of the herbs was 2.8 t ha\(^{-1}\) and the respective ND 77 kg ha\(^{-1}\). The respective values for the belowground parts were 1.1 t ha\(^{-1}\) and 19 kg ha\(^{-1}\) (values not shown in Table 3).

Nitrogen fluxes

The difference in the total annual nitrogen net mineralization (NNM) flux in the upper 0–20 cm soil layer between MAT and COP was statistically non-significant (\(P<0.05\); \(t\)-test), being 116.7 and 129.1 kg ha\(^{-1}\), respectively. The proportion of NNM in the 0–10 cm soil layer out of the total annual flux in the 0–20 cm soil layer was 58% in MAT and 84% in COP. The intensity of NNM was well correlated with soil temperature (Figure 1). Nitrification was a complete process, the proportion of nitrification in total NNM was 100% in both plots, and the process was more intensive during the growing period, from June to August (Figure 1). The intensity of NNM was similar for the studied plots, except for June 2012 when it was significantly higher in MAT.

Total annual N leaching was significantly higher (\(P=0.04\)) in MAT compared to COP in all study years. It was the highest in 2012, being roughly twice as high as in 2013 and 2014 (Table 5). In MAT, N leached mostly in the form of NO\(_3\) and the proportion of organic N was 6–11%. In COP, the proportion of NO\(_3\) varied between 55 and 81% and the proportion of organic N varied between 16 and 39%.

In MAT, the N flux into the soil via leaf litter in 2012 and 2015 was 90 and 111 kg ha\(^{-1}\) yr\(^{-1}\), respectively and in COP it was 32 kg ha\(^{-1}\) yr\(^{-1}\) in 2015. In 2013, the N flux into the soil through fine root litter in MAT was 22 kg ha\(^{-1}\). The total amount of retranslocated N in MAT was 25 and 29 kg ha\(^{-1}\) in 2012 and 2015, which constituted 22 and 21% of total leaf N, respectively. In 2015, the amount of retranslocated N in COP was 7.4 kg ha\(^{-1}\) yr\(^{-1}\) and the C/N ratio for leaf litter in MAT was 17.8. The annual N deposition flux is approximately 6 kg ha\(^{-1}\) yr\(^{-1}\) as estimated for the same region by Mander et al. (1997).

Soil nitrogen

The total soil N pool in the upper 0–50 cm layer at the Voopste study area was 9.9 t ha\(^{-1}\), and in the upper 0–30 cm layer it was distributed in relatively equal proportions in the three 10 cm layers (Table 2). The amount of N removed by stemwood and stembark during clear-cut in spring 2012 was 254 kg ha\(^{-1}\), which was equivalent to 2.6% of the soil N pool in the 0–50 cm soil layer.

![Figure 1. Dynamics of NNM and soil temperature in the mature stand and in the coppice in the upper 10 cm soil layer from May 2012 to May 2013.](image-url)
The annual dynamics of the soil nitrate N concentration in the uppermost 0–10 cm layer differed between MAT and COP (Figure 2). The nitrate N concentration in MAT peaked in August while the corresponding concentrations in COP were smaller and fluctuated less. Compared with COP, the values of the soil mineral N concentration for MAT were significantly higher (P < 0.001) in August, September and October. In both plots, soil mineral N occurred mainly in the form of NO₃, fluctuating from 5.8 to 22.4 mg kg⁻¹ in MAT and from 4.5 to 11.4 mg kg⁻¹ in COP. The concentrations of NH₄ were lower and more stable, peaking at 2.7 and 3.5 mg kg⁻¹ in MAT and COP, respectively.

**Soil respiration**

Mean soil temperature was similar in MAT and COP at both the Agali and Voopste study sites (Appendix 1, P > 0.05). Trenching did not affect soil temperature neither in the COP nor in MAT (P > 0.05). In general, soil moisture was higher in COP than in MAT (Figure 3, Appendix 1). A clear difference in soil moisture between MAT and COP was found in all growing seasons in Voopste (P < 0.05). In Agali, the soil moisture was significantly higher in the fresh COP (P < 0.05), however, in the following years, especially during the most active growing period in spring and summer, soil moisture did not differ significantly between COP and MAT. Although, significant difference in soil moisture was found between trenched and control plots it was caused by differences in June, July and September 2013 and in June, August and September 2014 in Voopste. In Agali the difference between trenched and control plots was found in September only in MAT in both years, 2013 and 2014.

In general, the soil CO₂ effluxes (Rs and Rh) were higher in MAT compared with COP (Figure 4, Table 6, Appendix 1, P < 0.05), however, there was no significant difference in the Rs measurements between COP and MAT in the last two study years in Agali (Appendix 1).

The cumulative Rs and Rh fluxes for the snow-free period were similar between the study years. Soil temperature was the main factor explaining 74–93% of the temporal variation in Rs and Rh (Figure 5). There was no significant effect of soil moisture on Rs either in COP or in MAT (partial correlation, P > 0.05). A weak negative effect of soil moisture on Rh was found in the Agali COP only (partial correlation, r = −0.21, P = 0.004).

**Discussion**

**Stand development and nitrogen demand**

The development of natural regeneration in COP was abundant: vigorous emergence of numerous young stems with intensive height growth and rapid self-thinning, which is inherent for grey alder. However, stem mass in the studied 5-year-old naturally regenerated stand (6.4 t ha⁻¹) was quite

![Figure 2](image-url)
low. In 3-year-old stands in Sweden, a stem mass of 10.1–13.7 t ha$^{-1}$ was reported (Rytter et al. 2000), and in 5-7-year-old stands in Estonia 15–33 t ha$^{-1}$ (Uri et al. 2014).

In the studied 5-year-old stand, the annual leaf production was 1.6 t ha$^{-1}$ and N demand (ND) 57 kg ha$^{-1}$. The leaf production is expected to reach a stable level of 3–4 t ha$^{-1}$ at a stand age less than 10 years (Uri et al. 2009; Aosaar et al. 2013). The leaf mass values reported for older grey alder stands from Sweden are 2.7–6.2 t ha$^{-1}$ (Johansson 1999). In 2015, leaf mass and the ND of the leaves in Voopste MAT was 4.2 t ha$^{-1}$ and 141 kg ha$^{-1}$, respectively.

Besides the foliage, the ND of herbaceous understorey in such grey alder ecosystems may constitute a significant proportion of stands total (Uri et al. 2004, 2011). However, its production fluctuates in different years, depending on stand age or density but rather on weather conditions (Uri et al. 2014). Thus, when the goal is an exact N budget on the stand level, then reliable estimation of the annual production of herbs of the current year is needed.

**Nitrogen fluxes**

Intensified NNM is an expected outcome after clear-cut, which is due to higher soil temperature and an increased amount of decomposing organic material, including dying roots (Tietema and Verstraten 1992). However, there occurred no significant changes in annual NNM after clear-cut in current study. On the other hand, similar NNM rates in MAT and COP were somewhat expected in the light of comparable results from our earlier studies with a similar concept (Becker et al. 2015). The annual NNM flux in our study is of the same magnitude as other published NNM values for grey alder (Uri et al. 2003b, 2011; Becker et al. 2015) and for a silver birch (*Betula pendula*) stand in Estonia (Uri et al. 2008). Since grey alder shoots emerged vigorously from stumps and from the root systems of old trees, there apparently occurred no mass dying of N rich fine roots, which may also be one reason for the unchanged NNM.

In our study, NNM was studied only to a soil depth of 20 cm, indicating that our results underestimate total soil NNM. However, since the substantial majority of the fine roots of herbaceous plants and trees growing at fertile sites in Estonia are located in the upper 0–20 cm soil layer (Aosaar et al. 2013; Varik et al. 2013; Rosenvald et al. 2014), the amount of mineral N located deeper than 20 cm in the soil is modest regarding the plants’ mineral nutrition.

The total amounts of the N leaching in 2012 in MAT and COP may be considered average, being in the range reported for grey alder stands in earlier studies, (Kuusemets 1999; Uri et al. 2011; Becker et al. 2015). In MAT the proportion of leached NO$_3^-$ was around 90% in all study years while in COP it was somewhat fluctuating (Table 5). In COP the proportion of dissolved organic nitrogen was notable, amounting to 16–38% of total leached N, which was probably caused by the increased organic matter input into the soil due to decomposing residues. During all the study years the leaching peaks occurred in late autumn or spring, mostly because of the missing plant uptake of N and by the melting of snow in spring. During the growing period, N leaching was practically missing. However, considering higher N leaching in MAT during all study years (Table 5), it is evident that no elevated N leaching rates were initiated by the clear-cut, which does not support the general paradigm (Brown et al. 1973; Gundersen et al. 2006). Yet, results similar to ours were reported from the northwestern USA from red alder stand (Bigger and Cole 1983). There may be several explanations for such results: missing of the N-rich leaf litter input into the soil; higher denitrification rate due to higher soil moisture in COP; ammonium immobilization in soil organic matter and logging residues or...
nutrient uptake by the ground vegetation (Vitousek and Matson 1984; Gundersen et al. 2006).

Through leaf litter, the largest nutrient and carbon flux input reached the soil. Because of the high N concentration of alder leaves, the annual N flux into the soil via leaf litter in alder stands is significantly higher compared to other common deciduous tree species of the hemiboreal forests. In COP, the amount of leaf litter increases annually with increasing leaf mass and stabilizes thereafter with canopy closure (Berg and McLaugherty 2003). High N% and a

![Graph showing seasonal dynamics of soil and heterotrophic respiration](image)

**Figure 4.** Seasonal dynamics of (a) soil and (b) heterotrophic respiration (kg CO₂ ha⁻¹ h⁻¹) in the coppice (COP) and in the mature stand (MAT) at the Agali and Voopste study sites for 2011–2014. The data represent mean (±SE).

<table>
<thead>
<tr>
<th>Year</th>
<th>Agali – MAT</th>
<th>Rs</th>
<th>Rh</th>
<th>Voopste – COP</th>
<th>Rs</th>
<th>Rh</th>
</tr>
</thead>
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<tr>
<td>2011</td>
<td>6,198</td>
<td>2,799</td>
<td>3,534</td>
<td>1,658</td>
<td>5,372</td>
<td>3,493</td>
</tr>
<tr>
<td>2012</td>
<td>5,179</td>
<td>2,720</td>
<td>3,438</td>
<td>1,905</td>
<td>8,909</td>
<td>4,382</td>
</tr>
<tr>
<td>2013</td>
<td>4,750</td>
<td>2,351</td>
<td>4,134</td>
<td>1,721</td>
<td>8,042</td>
<td>4,245</td>
</tr>
<tr>
<td>2014</td>
<td>5,829</td>
<td>2,614</td>
<td>4,362</td>
<td>1,687</td>
<td>8,042</td>
<td>4,245</td>
</tr>
</tbody>
</table>

*In Agali the flux is calculated for period June-November, in Voopste the flux is calculated for period July-October.

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**Table 6.** Cumulative soil (Rs) and heterotrophic (Rh) fluxes (kg C ha⁻¹) in the coppice (COP) and mature stand (MAT) for snow-free period (May-November).
favourable C/N ratio ensure fast decomposition of alder leaf litter and hence the rapid return of nutrients to the soil, which is also one reason for high productivity not only on the tree level but also on the stand level (Morozov et al. 2019). Besides the high N concentration of the leaf and leaf litter, N retranslocation from the senescent leaves of alders is modest compared with other deciduous tree species. The retranslocation values of 55 and 60% are reported for silver birch (Uri et al. 2007; Aosaar et al. 2016), in the Voopste stand, N retranslocation was around 20% in both study years, which is somewhat higher than 3 and 14% reported by Lõhmus et al. (2002) and Uri et al. (2011) for grey alder stands. However, annual N retranslocation depends on weather conditions, in droughty years it may increase significantly (Uri et al. 2011). The N flux into the soil via leaf litter covered 64 and 71% of the annual ND of the aboveground biomass production of trees in 2012 and 2015, respectively.

**Soil nitrogen**

Another important issue related to forest management is potential site depletion due to nutrient removal with biomass. In cases where a large amount of biomass is removed from the site, an appreciable quantity of nutrients may be removed. In our study area, the soil N pool in the upper 0–50 cm soil layer was very high, amounting to 9.9 t ha⁻¹, which exceeds the upper limit of a soil N content of 1–8 t ha⁻¹ for boreal forest ecosystems (Gundersen 1995). Mostly grey alder stands grow at fertile sites where high soil N content is typical (Uri et al. 2014, 2017). Moreover, due to its N₂ fixing ability grey alder is known to increase the soil N content during stand development (Uri et al. 2011, 2014; Aosaar et al. 2013). In the Voopste stand, the total N stock removed with the stems made up only a few percentages of the total soil N.

**Soil respiration**

In our study, both the Rs and Rh fluxes decreased after clearcut which is in accordance with studies both in coniferous forest (Wiseman and Seiler 2004; Payeur-Poinier et al. 2012) and deciduous forests (Weber 1990; Kurth et al. 2014). This indicates that the decomposition of logging residues and dying tree roots did not compensate for the loss of root and rhizosphere respiration (Peng and Thomas 2006), despite the fast recovery of the herbaceous vegetation and regeneration of grey alder. In general, this pattern persists for up to 3–4 years following harvest. In Voopste, Rs was significantly lower in COP than in MAT throughout the three growing seasons, however, in Agali, the difference in Rs between the treatments was insignificant after the second growing season. A similar result has been found for an aspen forest by Weber (1990) and Kurth et al. (2014). The inconsistency of the results of harvesting studies can be explained by the different lengths of time following harvest. In our study, the measurements of the respiration fluxes started 2 months after harvest. Peng and Thomas (2006) found that immediately after harvest, Rs increased ~55%, whereafter, it decreased below the pre-harvest level for 1–3 years and recovered to pre-harvest level 5–6 years after harvest.

Several studies conducted in boreal and temperate forests report that soil temperature is the main environmental driver of the seasonal soil CO₂ effluxes and soil moisture plays rather a minor role (Pypker and Fredeen 2003; Moroni et al. 2009; Kukumägi et al. 2017; Uri et al. 2017, 2019), which explains the variability of Rs, as was also found in this study. After clear-cut, an increase in soil temperature and soil moisture, which stimulate the decomposition processes, can be expected (Kurth et al. 2014). However, we did not find a significant effect of harvest on soil temperature, most probably because of shading by the recovered herbaceous vegetation and grey alder sprouts. The soil moisture increased significantly in three subsequent growing seasons in Voopste COP and in the first growing season in Agali COP. A high soil moisture content may inhibit decomposition (Prescott et al. 2000) and thus reduce Rh. Moreover, approximately 50% lower microbial biomass and 27% lower microbial activity were found in the Agali COP compared to the MAT (Becker et al. 2015).

Variation in soil respiration can also be related to tree species composition. Regenerating aspen suckers have been found to expend more resources to aboveground structures

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**Figure 5.** Relationship between (a) total soil (Rs) and (b) heterotrophic respiration (Rh) and soil temperature (Ts) in the coppice (COP) and in the mature stand (MAT) at the Agali and Voopste study sites. An exponential function was applied to the whole dataset; points mark the mean value of 4 collars, *P < 0.01* in all cases. The equations and adjusted determination coefficients are given.
logical properties can be more prominent as an influence on soil respiration than changes in the conditions of the physical environment. Practical forest management guidelines should consider that variation in soil C responses to harvest can be very complex, being species-, practice- as well as site-specific (Nave et al. 2011).

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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References


Appendix 1. Mean (±SE) of discrete measurements: soil (Rs) and heterotrophic (Rh) respiration (kg CO₂ ha⁻¹ h⁻¹), soil temperature (°C) and soil moisture (%) in the mature stand (MAT) and coppice (COP) in Agali and Voopste study site.

<table>
<thead>
<tr>
<th>Year</th>
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<th>Soil temperature</th>
<th>Soil moisture</th>
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<tr>
<td></td>
<td>MAT</td>
<td>COP</td>
<td>MAT</td>
<td>COP</td>
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<tr>
<td>2011</td>
<td>5.00 ± 0.46</td>
<td>2.91 ± 0.32</td>
<td>2.25 ± 0.14</td>
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<td>2012</td>
<td>5.22 ± 0.42</td>
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<td>2013</td>
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<td>4.09 ± 0.32</td>
<td>2.06 ± 0.11</td>
<td>1.62 ± 0.11</td>
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<td>2014</td>
<td>4.60 ± 0.48</td>
<td>3.69 ± 0.35</td>
<td>1.83 ± 0.13</td>
<td>1.37 ± 0.13</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Year</th>
<th>Rs</th>
<th>Rh</th>
<th>Soil temperature</th>
<th>Soil moisture</th>
</tr>
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<td></td>
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<td>COP</td>
<td>MAT</td>
<td>COP</td>
</tr>
<tr>
<td>2012</td>
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<td>4.43 ± 0.31</td>
<td>2.10 ± 0.18</td>
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<tr>
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<td>4.43 ± 0.30</td>
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<tr>
<td>2014</td>
<td>6.30 ± 0.60</td>
<td>4.27 ± 0.49</td>
<td>3.29 ± 0.31</td>
<td>1.78 ± 0.15</td>
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