The impact of former land-use type to above- and below-ground C and N pools in short-rotation hybrid aspen (Populus tremula L. \textit{x} P. tremuloides Michx.) plantations in hemiboreal conditions

Reimo Lutter \textsuperscript{a,*}, Arvo Tullus \textsuperscript{b}, Arno Kanal\textsuperscript{c}, Tea Tullusa \textsuperscript{a}, Hardi Tullusa \textsuperscript{a}

\textsuperscript{a}Institute of Forestry and Rural Engineering, Estonian University of Life Sciences, Kreutzwaldi 5, Tartu 51014, Estonia
\textsuperscript{b}Department of Botany, Institute of Ecology and Earth Sciences, University of Tartu, Lai 40, Tartu 51005, Estonia
\textsuperscript{c}Department of Geography, Institute of Ecology and Earth Sciences, University of Tartu, Vanemuise 46, Tartu 51014, Estonia

\textbf{Abstract}
Short-rotation forestry with fast-growing hybrid aspen (Populus tremula L. \textit{x} P. tremuloides Michx.) on former arable lands is a novel land-use system in northern Europe that has substantially increased in the region during the last few decades. The objective of this study was to assess the potential of hybrid aspen plantations to sequestrate C and N to above- and below-ground pools from the age of 5 (young) to 15 years (midterm) depending on former land-use type. Data were collected from permanent experimental plots on former croplands (n = 28) and grasslands (n = 23). Based on repeated soil monitoring and destructive model tree sampling, the following C and N pools were estimated: above-ground biomass of trees, soil uppermost layer (A-horizon), coarse roots and subsoil (below A-horizon up to a depth of 75 cm). On average, A-horizon SOC and N\textsubscript{tot} pools had decreased significantly on former grasslands, while no change was observed on croplands. Unexpectedly, considerable changes had occurred in subsoil, where SOC and N\textsubscript{tot} pools increased significantly on both former land-use types. Therefore, grasslands’ A-horizon C loss was compensated for by increased coarse-root fraction and subsoil gains. About one-third of below-ground C pool was stored in subsoil. In above-ground leafless part of 15-year-old hybrid aspen model trees the weighted average C concentration was 45.8% and the N concentration was 0.309%. From the age of 5–15, hybrid aspen plantations acted as C sinks because total ecosystem C pool increased significantly by 3.17 Mg C ha\textsuperscript{-1}/yr\textsuperscript{-1} on former croplands and by 2.56 Mg C ha\textsuperscript{-1}/yr\textsuperscript{-1} on former grasslands. The main C sequestration had taken place in the above-ground pool (for croplands 73.8% and for grasslands 94.9%). To conclude, hybrid aspen plantations already showed during the first 15 years a great potential to sequestrate C and N at the ecosystem level, whereas former SOC-exhausted croplands have a higher ability to sequestrate new C to the below-ground pool than already SOC-rich grasslands. Deeper subsoil should definitely be taken into account in SOC estimations.

\textsuperscript{*} Corresponding author.
\textsuperscript{E-mail address: reimo.lutter@emu.ee (R. Lutter).}

\section{Introduction}
One of the most important challenges in nowadays is the need to replace fossil fuel-based energy sources with renewable energy, such as woody biomass, in order to sequestrate atmospheric CO\textsubscript{2} (Petersen Raymer, 2006; Haus et al., 2014). One way to satisfy the increasing demand for woody biomass and mitigate the impact of climate change is through the establishment of short-rotation forest (SRF) plantations (Paquette and Messier, 2010). In northern Europe, this is still a relatively novel forest management approach on former arable lands (Weih, 2004; Tullus et al., 2013). SRF plantations have a great potential to sequestrate high amounts of atmospheric CO\textsubscript{2} to above-ground woody biomass over a short period of time because of faster tree growth than with conventional forestry in the Nordic region (Eriksson and Johansson, 2006; Lutter et al., 2015). Hybrid aspen (Populus tremula L. \textit{x} P. tremuloides Michx.) is considered to be one of the most suitable tree species for SRF on former fertile arable lands in northern Europe, aimed at pulp and energy wood production with a 25-year rotation period due to high productivity, cold resistance and an active breeding programmes (Tullus et al., 2012).

Aforestation of former arable lands brings about a drastic land-use change, which could have a significant impact on ecosystem C allocation (Litton et al., 2007), including alterations in the storage of soil organic carbon (SOC) (Post and Kwon, 2000; Guo and
Gifford, 2002; Poeplau and Don, 2013). According to global meta-
analyses, the former land-use type is considered to be one of the
most important factors, along with the time since afforestation,
that determines the dynamics of SOC storage after arable land
is taken under forest (Paul et al., 2002; Guo and Gifford, 2002;
Laganiere et al., 2010; Poeplau et al., 2011; Bárcena et al., 2014a).
As a broad generalization for boreal and northern temperate condi-
tions, previous studies have found that afforestation has a rather
positive or neutral impact on the SOC pool on former C-
exhausted croplands and a rather negative or neutral impact on
former C-saturated grasslands (Li et al., 2012; Poeplau et al.,
2011; Poeplau and Don, 2013; Bárcena et al., 2014a).
The ability of different land-use systems to sequestrate SOC
after afforestation depends mostly on the period of time that has
passed since afforestation and SOC pools are expected to increase
slowly until C input and mineralization equilibrates (Thuille and
Schulze, 2006). During the early development after afforestation,
the net primary production of young trees is low and C input to soil
from above- and below-ground litter does not exceed the decom-
position of C inherited from agriculture (Vesterdal et al., 2002;
Paul et al., 2003). The initial SOC depletion from the uppermost soil
layer (0–30 cm) could be replaced by a new C accumulation not
earlier than after about a decade in SRF poplar plantations
(Hansen, 1993; Grigal and Bergson, 1998; Sartori et al., 2007;
Arevalo et al., 2011) or more than 30 years with different longer-
rotation tree species (Paul et al., 2002; Cerli et al., 2006;
Laganiere et al., 2010; Nave et al., 2013; Bárcena et al., 2014a,b;
Wellock et al., 2014) or by a still unknown period later (Guidi
et al., 2014). Therefore, the main sequestration of C at ecosystem
level after arable land afforestation takes place in above-ground
biomass of trees (Vesterdal et al., 2002; Dowell et al., 2009; Yang
et al., 2011; Verlinden et al., 2013; Bárcena et al., 2014b). The rota-
tion period for several deciduous tree species managed under the
principles of SRF is usually less than or around 30 years in northern
Europe (Weih, 2004; Tullus et al., 2013), which raises several
uncertainties about the ability of intensively managed SRF planta-
tions to sequestrate and retain C in soil after afforestation on for-
mer arable soils. Studies about soil C changes after arable lands
afforestation in northern Europe cover conventional long-rotation
forest management tree species with a chronosequence approach
(e.g. Vesterdal et al., 2002; Cerli et al., 2006), while studies using
long-term repeated soil sampling approach are scarce (Bárcena
et al., 2014b; Rytter, 2016). To the best of our knowledge, there
are no long-term empirical studies about the former land-use type
effect on C dynamics in SRF plantations with fast-growing decidu-
ous trees in northern Europe.
The majority of studies of SOC changes after arable land
afforestation focus on the uppermost (0–30 cm) soil layers (e.g.
Paul et al., 2002; Vesterdal et al., 2002; Kahle et al., 2007;
Bárcena et al., 2014a; Rytter, 2016), where changes are more
apparent than in deeper soil layers (Nave et al., 2013). However,
a significant amount of SOC is also stored in deeper soil layers
(Jobbágy and Jackson, 2000; Hooker and Compton, 2003;
Fontaine et al., 2007; Rumpel and Kögel-Knabner, 2011; Poeplau
and Don, 2013), the inclusion of which is rare due to sampling
complexity. The deeper subsoil is a more static environment,
where soil chemical and physical processes are not as instant as in
the uppermost soil (Hooker and Compton, 2003; Mao et al.,
2010; Nave et al., 2013). However, a deeper SOC balance should
also be included more in long-term C estimations after land-use
change (Trumbore and Czimczik, 2008; Salomé et al., 2010) as less
disturbed deeper soil C might have a greater potential to store C in
the long term than the uppermost (0–30 cm) soil, where tree nutri-
tion and management activities have a more instant effect on C
pools (Jandl et al., 2007; Clarke et al., 2015). The impact of former
land-use type (crop- or grassland) on deeper SOC pools after
afforestation is not well understood and so far it has shown a sim-
ilar trend to the uppermost soil dynamics (Poeplau and Don, 2013).
So far the changes in deeper SOC after arable land afforestation
have shown a positive trend of SOC concentration increase even
after a first decade in temperate coppice plantations (Kahle et al.,
2010; Dimitriou et al., 2012) or a weak accumulation over a longer
period in more northern conditions with conventional forest tree
species (Bárcena et al., 2014b).
The N and C cycles in soil are strongly interrelated (van Cleve
et al., 1993; Vervaet et al., 2002). However, changes in mineral soil
total nitrogen (Ntot) pools are less studied than SOC after arable
land is taken under forest, where a decrease of Ntot is reported
on former grasslands (Berthrong et al., 2009; Li et al., 2012).
So far, there are no empirical studies about the ability of first-
generation commercial hybrid aspen plantations to sequesterate C
in above-ground biomass whereas C concentration in dry biomass
could significantly vary between different tree species (Lamliom
and Savidge, 2003; Zhang et al., 2009; Thomas and Martin,
2012). A few studies have found that the concentration of C in
wood for parental species of hybrid aspen varies from 44% to 49%
(Lamliom and Savidge, 2003; Zhang et al., 2009). This means that
the general recommendation to use 50% as the C concentration
in wood (Matthews, 1993) from total dry biomass might overesti-
mate the C bind into biomass of Populus spp.
Forest management activities that support sustainable N supply
and cycling in the ecosystem are essential as significant amounts of
N could be removed from the ecosystem during whole-tree harvest
(Rytter, 2002; Rytter and Stener, 2003; Ge et al., 2015). However,
the largest proportion of the total forest ecosystem N in boreal condi-
tions is located in soil (Finér et al., 2003) and N cycling from leaf
litter is very efficient in poplar plantations (Meirsonne et al.,
2006). There are only a few studies about first-generation hybrid
aspen plantations’ above-ground N accumulation in the early
development (Rytter, 2002; Tullus et al., 2009) and midterm period
(Rytter and Stener, 2003). So far, the ability of hybrid aspen plan-
tations to sequestrate N at the whole ecosystem level in the long
term has not been evaluated yet.
The network of 51 permanent experimental plots was estab-
lished in SRF hybrid aspen plantations on abandoned agricultural
lands in hemiboreal Estonia for long-term monitoring of tree
growth and environmental impacts of this novel land use (Tullus
et al., 2007, 2009, 2015; Soo et al., 2009; Lutter et al., 2016).
The aim of this study was to estimate the potential of former
crop- and grasslands to sequestrate C and N to above- and
below-ground pools after afforestation with first-generation hybrid
aspen plantations from young (5-year) to midterm (15-
year) age. The study relies on repeated measurements in the
above-mentioned network of experimental plots. The hypotheses
were: (1) hybrid aspen plantations’ SOC and Ntot pools in the A-
horizon (0–30 cm) have already decreased on former C-rich
grasslands and increased on former C-poor croplands from the
young to midterm period; (2) SOC and Ntot pools in subsoil (below
A-horizon up to a depth of 75 cm) are more stable and changes
have not yet occurred from the young to midterm period; (3) the
average C concentration in hybrid aspen dry above-ground bio-
mass is less than the generally suggested 50% for woody plants
(4) at an ecosystem level the major increase of C and N storage
between 5 and 15 years since afforestation has taken place in
above-ground C and N pools.

2. Materials and methods

2.1. Studied plantations

The study was conducted in commercial hybrid aspen (Populus
tremula L. × P. tremuloides Michx.) plantations in Estonia (Fig. 1).
The study area lies in a hemiboreal vegetation zone within a transition zone from a maritime to a continental climate (Ahti et al., 1968). The weather in Estonia is considerably milder than the continental climate characteristic of the same latitude. The mean annual temperature from 2000 to 2014 was 5.8 °C and the mean annual precipitation was 694 mm according to data from the nearest weather stations (The Estonian Environment Agency: http://www.ilmateenistus.ee/) to the studied plantations.

The studied plantations were established on former mineral arable lands in 1999 and 2000 with one-year-old clonal micropropagated plants originating from Finland. Altogether 27 different hybrid aspen clones were planted randomly in a mixture, on average 15 clones per plantation (Tullus et al., 2007), thus the exact mixture as well as proportion of different clones varies between the plantations. Whole-area or strip ploughing was used as site preparation before planting to reduce weed competition (Tullus et al., 2007). The average planting density was 1300 trees per hectare (range: 1200–1600) (Tullus et al., 2007), which decreased to 963 trees per ha⁻¹ (range: 540–1450) in 15-year-old plantations (Lutter et al., 2016). None of the studied plantations was fenced to prevent game damage, nor were they fertilized or herbicides applied after establishment.

The long-term network of 51 permanent experimental plots, each with a size of 0.1 ha, was established in 2003 and 2004 in 24 hybrid aspen plantations (we define plantation as a land property) to monitor the above-ground tree growth development and dynamics of soil physico-chemical properties (Tullus et al., 2007) (Fig. 1). The sizes of hybrid aspen plantations varied from 0.7 to 32 ha and 15 plantations consisted of smaller scattered parts with varied edaphic conditions (different soil types). In plantations with homogeneous soil conditions, one experimental plot was established. In plantations with varied soil types (usually larger land properties, where afforested areas were scattered), two to five experimental plots were established in typical parts of micro-relief of the respective plantation area. Thus, in spatial sense in this network of long-term experimental plots, each ‘experimental plot’ is regarded as one independent experimental unit.

The studied sample plots were divided into former croplands (n = 28) and grasslands (n = 23) according to Soo et al.’s (2009) classification. Former croplands are characterized by intensive ploughing and tilling practice in the uppermost ~30 cm soil layer, where also fertilization and liming were applied to improve nutrients availability and increase crop yields. Former grasslands were mainly used for annual grass removal.

2.2. Above-ground biomass estimations and allometric equations in 15-year-old plantations

Hybrid aspen above-ground leafless biomass sampling was carried out during the wintertime at the end of the 15th growing season. Model trees were taken from a plantation lying on the prevailing soil type - Retisol (Lutter et al., 2016). Ten model trees were selected randomly from the plantation so that their DBH distribution would be in accordance with the DBH distribution of all trees growing in sample plots. Model trees were felled and measured (Supplementary Material, Table S1) and sampled for further analysis.

The stem of each model tree was divided into subsections. The first section was from the beginning of the stem from ground level to a height of 1.3 m. Next the stem was cut into 2 m-long sections until the beginning of the top shoot (current-year top of the stem), which was sampled separately. All the stem sections were freshly weighted in the field and a sample disc from the centre of each section was taken with two parallel cross-sectional cuts for further laboratory analysis.

The living crown of the model trees was divided into three equal-length sections and all the branches were freshly weighted in each section. One or two typical sample branches were taken from each crown section for further laboratory analysis. All the dead branches below the living crown were freshly weighted and one general dead branch sample from each model tree was taken for further laboratory analysis as well. In the laboratory, stem bark of the sample discs was carefully removed to estimate the proportion of the stemwood and stem bark based on their dry weights (Supplementary Material, Table S2). All the sample branches from living crown were divided into current-year branches, older living branches and dead branches. All the different model tree compartments (stemwood, stem bark, top shoot, current-year branches, older living branches and dead branches) were freshly weighted and then dried to constant weight at 70 °C. The obtained dry matter content was then multiplied by a given tree compartment’s fresh weight to estimate its dry weight. The dry weights of all compartments were summed to calculate the total dry weight. Based on model tree data, an allometric Eq. (1) was parameterized

![Fig. 1. Locations of the studied hybrid aspen plantations (n = 24), marked as black circles. The number of experimental plots (n = 51) is shown besides the circle when more than one plot is present within the given plantation (land property).](http://www.ilmateenistus.ee/)
to predict the above-ground biomass of all hybrid aspens growing in the sample plots based on their DBH:

\[ AGB = b_0 \times DBH^{b_1} \]  

(1)

where AGB is the above-ground leafless biomass (kg) of a given tree compartment, \(b_0\) and \(b_1\) are parameters (Table 1) and DBH (cm) is the stem diameter at breast height over bark.

The constructed power equations were used to calculate the above-ground leafless dry biomass for all studied hybrid aspen plantations according to the individual tree’s DBH measurement on the studied sample plots at the age of 15. The total dry biomass of all the trees growing in each sample plot with a size of 0.1 ha was multiplied by 10 to obtain the results on a hectare basis (Table 2).

### 2.3. Determination of C and N concentrations in woody biomass

All the subsamples of oven-dried stemwood, stembark, top shoot, current-year branches, older living branches and dead branches were milled with a Retsch SM 300 cutting mill (Retsch GmbH, Haan, Germany) and then sent to the Laboratory of the Department of Soil Sciences and Agrochemistry (Estonian University of Life Sciences), where nitrogen (N, %) and carbon (C, %) concentration was determined with a varioMAX CNS (Elementar Analysensysteme GmbH, Hanau, Germany) elemental analyser using the dry combustion method. The mean concentrations of C and N in different tree compartments were weighted average concentrations of C and N (%) in different compartments of 15-year-old hybrid aspen model trees. The letters denote significant differences between tree compartments according to Tukey’s LSD test (Table 3).

### 2.4. Soil sampling

A 1-metre-deep soil pit was dug in the centre of each experimental plot, where the soil type was determined and samples were collected from each revealed soil horizon at the ages of 5 (Tullus et al., 2007) and 15 (Lutter et al., 2016) up to a depth of 75 cm (Supplementary Material, Table S3). Soil sampling was carried out at the end of the growing season at both monitoring times.

### 2.5. Total ecosystem C and N pools estimation

The above-ground leafless dry biomass for five-year-old hybrid aspen plantations was calculated according to growth measurements by Tullus et al. (2007) and with allometric equations constructed for young hybrid aspen plantations in Estonia (Tullus et al., 2009). The weighted average C and N concentration of the whole tree from 15-year-old plantations (Table 3) was used to estimate above-ground C and N pools for 5-year-old plantations.

Table 2
15-year-old hybrid aspen plantations above-ground leafless dry biomass (Mg ha\(^{-1}\)) according to tree compartments on different former land-use types.

<table>
<thead>
<tr>
<th>Tree compartment</th>
<th>Croplands Mean</th>
<th>Grasslands Mean</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stem</td>
<td>40.2 ± 3.2</td>
<td>41.6 ± 4.1</td>
<td>40.8 ± 2.5</td>
</tr>
<tr>
<td>Dead branches</td>
<td>3.3 ± 0.3</td>
<td>3.5 ± 0.3</td>
<td>3.4 ± 0.2</td>
</tr>
<tr>
<td>Older living branches</td>
<td>7.2 ± 0.6</td>
<td>7.4 ± 0.8</td>
<td>7.3 ± 0.5</td>
</tr>
<tr>
<td>Current-year branches</td>
<td>1.1 ± 0.1</td>
<td>1.1 ± 0.1</td>
<td>1.1 ± 0.1</td>
</tr>
<tr>
<td>Whole tree</td>
<td>51.7 ± 4.1</td>
<td>53.6 ± 5.4</td>
<td>52.6 ± 3.3</td>
</tr>
</tbody>
</table>

According to soil monitoring in 15-year-old plantations, the following soil types are present among the 51 experimental plots: Cambisols (n = 9), Gleysols (n = 5), Histosols (n = 1), Leptosols (n = 1), Luvisols (n = 3), Retisols (n = 20) and Umbriisols (n = 12) (Lutter et al., 2016). During the soil monitoring in 5-year-old plantations, only a general soil sample was collected from the entire A-horizon (Tullus et al., 2007). In 15-year-old plantations, the A-horizon was divided into sub-layers (0–10; 10–20; 20–30 cm) to estimate the detailed distribution of C (Fig. 4) and N and (Fig. 5), therefore the changes in the uppermost soil (0–30 cm) are estimable only at the total A-horizon level (Lutter et al., 2016). One general sample from the deeper subsoil B-horizon and E-horizon (if present) was taken during both soil monitorings, therefore “subsoil” in this study is the soil layer beneath the A-horizon up to a depth of 75 cm. During both soil monitoring times, the total nitrogen (N\(_{tot}\)) was determined according to Kjeldahl (ISO 11261:1995) and the concentration of organic matter was determined by wet oxidation (Tyrin, 1935), which was converted to soil organic carbon (SOC) by multiplying organic matter content by 0.58 (Kononova and Belchikova, 1960).

Undisturbed core samples using a steel cylinder (50 cm\(^3\)) were used to determine soil bulk density (BD, g cm\(^{-3}\)) during both soil surveys. The samples for BD in the A-horizon were taken from sub-layers (0–10; 10–20; 20–30 cm) in three replications. The samples for deeper soil horizons BD were taken from the centre of each revealed horizon in three replications. Collected samples were oven-dried at 105°C to constant weight and soil BD was calculated as an arithmetic mean of the samples for a given horizon.

Table 3
Weighted average concentration of N (%) and C (%) in different compartments of 15-year-old hybrid aspen model trees. The letters denote significant differences between tree compartments according to Tukey’s LSD test.

<table>
<thead>
<tr>
<th>Tree compartment</th>
<th>N Mean</th>
<th>Range</th>
<th>C Mean</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stemwood</td>
<td>0.179 ± 0.008 (^{b})</td>
<td>0.144–0.223</td>
<td>45.5 ± 0.10 (^{d})</td>
<td>45.0–46.0</td>
</tr>
<tr>
<td>Stembark</td>
<td>0.617 ± 0.033 (^{a})</td>
<td>0.464–0.750</td>
<td>46.5 ± 0.27 (^{ab})</td>
<td>45.0–47.7</td>
</tr>
<tr>
<td>Current-year branches</td>
<td>1.055 ± 0.061 (^{a})</td>
<td>0.644–1.273</td>
<td>47.0 ± 0.12 (^{a})</td>
<td>46.5–47.7</td>
</tr>
<tr>
<td>Older living branches</td>
<td>0.638 ± 0.040 (^{b})</td>
<td>0.387–0.842</td>
<td>46.5 ± 0.13 (^{c})</td>
<td>46.0–47.1</td>
</tr>
<tr>
<td>Dead branches</td>
<td>0.335 ± 0.031 (^{a})</td>
<td>0.260–0.584</td>
<td>46.5 ± 0.22 (^{ab})</td>
<td>45.8–47.8</td>
</tr>
<tr>
<td>Stem with bark</td>
<td>0.233 ± 0.000 (^{a})</td>
<td>0.206–0.274</td>
<td>45.6 ± 0.09 (^{a})</td>
<td>45.2–46.1</td>
</tr>
<tr>
<td>Total living branches</td>
<td>0.690 ± 0.044 (^{a})</td>
<td>0.408–0.899</td>
<td>46.6 ± 0.12 (^{a})</td>
<td>46.1–47.1</td>
</tr>
<tr>
<td>Whole tree</td>
<td>0.309 ± 0.009 (^{a})</td>
<td>0.263–0.364</td>
<td>45.8 ± 0.08 (^{a})</td>
<td>45.3–46.3</td>
</tr>
</tbody>
</table>

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of the coarse roots based on their allometric relation with DBH. For five-year-old plantations, coarse-root dry biomass was calculated according to Rosenvald et al.’s (2014) equation ($R^2 = 0.94; p < 0.01$) for a seven-year-old hybrid aspen plantation on previous agricultural land. For 15-year-old plantations, a general equation ($R^2 = 0.78; p < 0.001$) for mature hybrid poplar plantations’ coarse roots on abandoned farmland was used (Fortier et al., 2015).

The coarse-root C and N pool for both study periods was calculated by multiplying the total dry coarse-root mass per hectare by the weighted mean C and N concentration for the whole tree (Table 3).

In this study we did not include the production of leaves and fine roots in the total ecosystem estimation as they are labile and describe mainly the annual flux of C and N in the ecosystem (Meiresonne et al., 2006; Litton et al., 2007; Finér et al., 2011; Hu et al., 2016), which was not the focal point of our study. We did not include the forest floor in the total ecosystem C and N storage either as the permanent forest floor had not formed yet or was

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**Fig. 2.** Comparison of above-ground C and N pools between 5- and 15-year-old hybrid aspen plantations representing different types of former land-use (the differences between the ages of 5 and 15 were in all cases significant at $p < 0.001$; error bars denote standard error).

**Fig. 3.** Comparison of five-year-old hybrid aspen plantations’ SOC (a) and Ntot (b) pools according to former land-use type (ns: not significant, $p < 0.05$, $p < 0.01$, error bars denote standard error).

**Fig. 4.** SOC pools and distribution in different soil layers up to a depth of 75 cm and a comparison between different former land-use types in 15-year-old plantations. The letters denote significant differences between soil layers inside land-use groups; while the difference between land-use types was not significant (ns). Error bars denote standard error.
sporadic on the studied fertile mineral soils (Tullus et al., 2015; Lutter et al., 2016). The share of herbaceous understory vegetation from the total ecosystem C storage also appeared to be negligible in other Estonian studies (e.g. Uri et al., 2012) and was therefore left out of the calculations.

The total ecosystem C and N storage was calculated by summing up the ecosystem stable pools, i.e. pools where C and N are more constantly stored: (1) below-ground pool (A-horizon + sub-soil + coarse tree roots); (2) above-ground pool (woody biomass). Below-ground and above-ground C and N changes were calculated for each sample plot as the pairwise differences between data from young (5-year) and midterm (15-year) hybrid aspen plantations. Total above-ground C and N pools were calculated by multiplying the obtained weighted average C and N concentrations (Table 3) by the given tree compartment’s dry biomass (Table 2).

2.6. Statistical analyses

The normality of the variables was tested with the Shapiro-Wilk test. Homoscedasticity of normally distributed variables was checked with the F test. Accordingly, the use of parametric or non-parametric tests was decided. The significance of C and N changes between young and midterm plantations within former land-use groups (crop- or grassland) was tested with a pairwise Student’s t-test or non-parametric Wilcoxon test. The difference in C and N concentrations in different tree compartments and the impact of former land-use type on soil C and N pools and soil properties were tested with one-way ANOVA followed by the Tukey LSD test or with the Kruskal-Wallis test. In case of parametric tests, the observation of residuals distributions and Q-Q plots revealed that five sample plots caused extreme outliers in residuals and they were excluded from final calculations.

A level of significance of \( \alpha = 0.05 \) was used to reject the null hypothesis after statistical tests. All statistical analyses were carried out using R Statistics software (R Core Team, 2015).

3. Results

3.1. C and N concentrations and pools in above-ground biomass

The mean weighted average concentration of C in above-ground leafless parts of 15-year-old hybrid aspen trees was 45.8 ± 0.08%.

The concentration of C differed significantly between the tree compartments with the highest in current-year branches (47.0 ± 0.12%) and the lowest in stemwood (45.5 ± 0.10%) (Table 3).

The mean weighted average concentration of N in whole tree was 3.09 ± 0.09% with the highest in current-year shoots (1.056 ± 0.061%) and the lowest in stemwood (0.179 ± 0.008%). The concentration of N differed significantly between different tree compartments (Table 3), except between stem bark and older living branches.

Above-ground C and N pools were similar in 15-year-old plantations growing on former crop- and grasslands (Fig. 2a and b) as the total above-ground leafless biomass did not differ either between the studied land-use types (Table 2). The total above-ground C and N pools increased significantly from the age of 5–15 (Fig. 2a and b), with the 10-year average increase being +2.38 Mg C ha\(^{-1}\) yr\(^{-1}\) (\(p < 0.001\)) and +13.5 kg N ha\(^{-1}\) yr\(^{-1}\) (\(p < 0.001\)) when analysing all sample plots together.

3.2. Below-ground SOC and N\(_{\text{tot}}\) pools in five-year-old plantations

The pools of SOC and N\(_{\text{tot}}\) up to a soil depth of 75 cm differed significantly between former crop- and grasslands (\(p = 0.042\) and \(p = 0.002\), respectively) in five-year-old plantations (Fig. 3a and b). This was caused by significant difference in the A-horizon SOC and N\(_{\text{tot}}\) pools (\(p = 0.030\) and \(p = 0.004\), respectively) as there were no differences in subsoil pools between crop- and grasslands (Fig. 3a and b).

3.3. Below-ground SOC and N\(_{\text{tot}}\) pools in 15-year-old plantations

The significant difference between crop- and grasslands’ SOC pools in the A-horizon and total 75 cm soil layer disappeared in 15-year-old plantations (Fig. 4). In 15-year-old plantations, SOC pools did not differ between former crop- and grasslands in the uppermost soil layers (Fig. 4); in 5-year-old plantations, sampling from the A-horizon was not done on a sub-layer basis. Fifteen years after afforestation, the mean SOC pool up to a depth of 75 cm was 71.5 ± 5.7 Mg ha\(^{-1}\) as an average for both land-use types (Fig. 4).

The majority of SOC pool were located in the A-horizon, being as an average 54.8 ± 4.9 Mg ha\(^{-1}\) for both land-use types (Fig. 4). A soil depth of 30–75 cm stored about 30% of the total soil SOC pool

![Fig. 5. N\(_{\text{tot}}\) pools and distribution in different soil layers up to a depth of 75 cm and a comparison between different former land-use types in 15-year-old plantations. The letters denote significant differences between soil layers inside land-use groups; the significance of the difference between land-use types is shown as follows: ns – not significant, \(p < 0.05\), \(p < 0.01\). Error bars denote standard error.](image-url)
In the uppermost 0–30 cm soil layer, SOC pools decreased gradually significantly in 10 cm-thick soil layers both on crop- and grasslands (Fig. 4).

The N\textsubscript{tot} pool in a total depth of 75 cm was significantly \((p = 0.014)\) higher on grasslands \((7.3 \pm 0.7 \text{ Mg ha}^{-1})\) than on croplands \((5.5 \pm 0.4 \text{ Mg ha}^{-1})\) in 15-year-old plantations (Fig. 5). This was mainly initiated by the difference in the A-horizon \((p = 0.026)\), where significant differences were also found in 0–10 cm \((p = 0.006)\), 10–20 cm \((p = 0.005)\) and 20–30 cm \((p = 0.015)\) soil layers between crop- and grasslands. Similarly to SOC pools, the majority of N\textsubscript{tot} pool were located in the A-horizon, where N\textsubscript{tot} pools decreased significantly with 10 cm-thick soil layers in the uppermost 0–30 cm (Fig. 5).

### 3.4. The changes in SOC and N\textsubscript{tot} pools between 5- and 15-year-old plantations

During the development of hybrid aspen plantations from the age of 5–15 years, former grasslands significantly lost their A-horizon SOC pool, on average by \(-0.85 \text{ Mg C ha}^{-1} \text{ yr}^{-1}\) \((p = 0.025)\) (Fig. 6), and N\textsubscript{tot} by \(-0.07 \text{ Mg N ha}^{-1} \text{ yr}^{-1}\) \((p = 0.020)\) (Fig. 7). Former croplands’ SOC and N\textsubscript{tot} pools remained unchanged in the A-horizon (Figs. 6 and 7).

SOC pools increased significantly in deeper subsoil both on former grasslands, by \(+0.66 \text{ Mg C ha}^{-1} \text{ yr}^{-1}\) \((p = 0.002)\), and on former croplands, by \(+0.42 \text{ Mg C ha}^{-1} \text{ yr}^{-1}\) \((p = 0.007)\) (Fig. 6). The subsoil N\textsubscript{tot} increase of \(+0.03 \text{ Mg N ha}^{-1} \text{ yr}^{-1}\) was significant for croplands \((p = 0.024)\), and also for grasslands \((p = 0.045)\) at \(+0.05 \text{ Mg N ha}^{-1} \text{ yr}^{-1}\) (Fig. 7).

The total below-ground C change from the age of 5–15 was insignificant for former grasslands as the A-horizon C loss was compensated for by coarse-root and subsoil C increase (Fig. 6). Former croplands’ total below-ground C pool increase with the inclusion of coarse roots \((+0.83 \text{ Mg C ha}^{-1} \text{ yr}^{-1})\) was marginally significant \((p = 0.051)\).

Similarly to SOC changes, former grasslands’ N pool significant decrease in the A-horizon was compensated for by increases in subsoil and coarse-root pools (Fig. 7). As a result of that, the total 75 cm below-ground N pool on grasslands \((p = 0.453)\) and croplands \((p = 0.442)\) remained unchanged (Fig. 7).
3.5. Total ecosystem C and N distribution in 15-year-old plantations

As an average of all studied 15-year-old hybrid aspen plantations, the main storage of the total ecosystem C was located in the below-ground pool (75.6%) (Table 4). The share of C stored in above-ground biomass had increased from 1.4% (5-year-old plantations) to 24.4%. About half of the total ecosystem C storage was located in the uppermost 0–30 cm soil layer (50.8%), followed by 21.5% in subsoil (30–75 cm) and 18.8% in tree stems. The share of subsoil from below-ground SOC pools was 30.4%. The average total ecosystem C pool in 15-year-old hybrid aspen plantations was 98.8 ± 6.2 Mg ha\(^{-1}\), which did not differ between former land-use types (\(p = 0.216\)), being 105.0 ± 5.9 Mg ha\(^{-1}\) for grasslands and 94.1 ± 6.2 Mg ha\(^{-1}\) for croplands (Table 4).

Compared to C pool distribution, only a marginal amount (2.4%) of N was stored in above-ground pools in 15-year-old plantations (Table 4). About 68% of total ecosystem N was located in the 0–30 cm soil layer. The uppermost 0–10 cm soil layer stored about a quarter of the total ecosystem N pool (Table 4). The total ecosystem N storage of 15-year-old hybrid aspen plantations on former grasslands (7.5 ± 0.7 Mg ha\(^{-1}\)) was significantly (\(p = 0.004\)) higher than for plantations on former croplands (5.6 ± 0.3 Mg ha\(^{-1}\)) (Table 4).

3.6. Total ecosystem C and N changes between 5- and 15-year-old plantations

During a decade-long growth period, former cropland plantations increased total ecosystem C pools by 3.17 Mg C ha\(^{-1}\) yr\(^{-1}\) (Fig. 8b) and former grassland plantations by 2.56 Mg C ha\(^{-1}\) yr\(^{-1}\) (Fig. 8a). There were remarkable differences between the ability of former land-use types to sequestrate C and N at the total ecosystem level. On former grasslands, only 5.1% from the total C increase had taken place in below-ground pool (Fig. 8a), while the respective number for croplands was 26.2% during the studied 10-year period (Fig. 8b). Former grasslands' above-ground N gain was levelled out by below-ground N loss and reduction of N occurred also in the total ecosystem level (Fig. 9a). At the same time, both above- and below-ground N pools increased in former croplands (Fig. 9b).

### Table 4: Total ecosystem C and N storage and distribution between above- and below-ground pools in 15-year-old hybrid aspen plantations representing different former land-use types. The letters denote differences between former crop- and grasslands.

<table>
<thead>
<tr>
<th>Soil layer/tree compartment</th>
<th>Croplands</th>
<th>Grasslands</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pool %</td>
<td>Pool %</td>
<td>Pool %</td>
</tr>
<tr>
<td>C, Mg ha(^{-1})</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0–10 cm</td>
<td>18.9</td>
<td>20.1</td>
<td>19.6</td>
</tr>
<tr>
<td>10–20 cm</td>
<td>15.9</td>
<td>16.9</td>
<td>17.3</td>
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<tr>
<td>20–30 cm</td>
<td>12.6</td>
<td>13.4</td>
<td>15.2</td>
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<tr>
<td>30–75 cm</td>
<td>19.8</td>
<td>21.1</td>
<td>23.1</td>
</tr>
<tr>
<td>Coarse roots</td>
<td>3.1</td>
<td>3.3</td>
<td>3.3</td>
</tr>
<tr>
<td>Total below-ground</td>
<td>70.4 ± 5.7</td>
<td>80.4 ± 5.9</td>
<td>76.6</td>
</tr>
<tr>
<td>Stem</td>
<td>18.3</td>
<td>19.5</td>
<td>18.6</td>
</tr>
<tr>
<td>Dead branches</td>
<td>1.6</td>
<td>1.7</td>
<td>1.6</td>
</tr>
<tr>
<td>Older branches</td>
<td>3.3</td>
<td>3.5</td>
<td>3.4</td>
</tr>
<tr>
<td>Current-year branches</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Total above-ground</td>
<td>23.7 ± 1.9</td>
<td>24.6 ± 2.5</td>
<td>24.1</td>
</tr>
<tr>
<td>Total ecosystem C</td>
<td>94.1 ± 6.2</td>
<td>100</td>
<td>98.8</td>
</tr>
<tr>
<td>N, Mg ha(^{-1})</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0–10 cm</td>
<td>1.5</td>
<td>26.9</td>
<td>25.4</td>
</tr>
<tr>
<td>10–20 cm</td>
<td>1.2</td>
<td>21.5</td>
<td>24.1</td>
</tr>
<tr>
<td>20–30 cm</td>
<td>1.0</td>
<td>17.9</td>
<td>20.1</td>
</tr>
<tr>
<td>30–75 cm</td>
<td>1.7</td>
<td>30.5</td>
<td>28.1</td>
</tr>
<tr>
<td>Coarse roots</td>
<td>0.02</td>
<td>0.4</td>
<td>0.3</td>
</tr>
<tr>
<td>Total below-ground</td>
<td>5.5 ± 0.4</td>
<td>7.3 ± 0.7</td>
<td>6.3</td>
</tr>
<tr>
<td>Stem</td>
<td>0.094</td>
<td>1.7</td>
<td>1.3</td>
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<tr>
<td>Dead branches</td>
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<tr>
<td>Older branches</td>
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<tr>
<td>Current-year branches</td>
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<td>0.04</td>
</tr>
<tr>
<td>Total above-ground</td>
<td>0.152</td>
<td>2.7</td>
<td>2.1</td>
</tr>
<tr>
<td>Total ecosystem N</td>
<td>5.6 ± 0.4</td>
<td>7.5 ± 0.7</td>
<td>6.4</td>
</tr>
</tbody>
</table>

Fig. 8. The total ecosystem C change between 5 and 15-year-old hybrid aspen plantations representing different former land-use types in above-ground (AG) and below-ground (BG) pools, where arrows show the direction of the change (ns – not significant, \(p < 0.05\), \(p < 0.01\), \(p < 0.001\)) and values next to curly brackets indicate how the total change is partitioned between AG and BG.
amounts of root litter (Rytter, 1999; Block et al., 2006) and leaf litter inputs to soil after afforestation. Despite that, on average we observed A-horizon SOC pool stabilization, but not significant sequestration on former croplands during the first 15 years, thereby rejecting the first part of our first hypothesis.

In contrast to former croplands, former grasslands were less influenced by soil cultivation and were probably consistently supplied with root residues of herbaceous vegetation in the uppermost soil layer during the previous land-use history (Meyer et al., 2012). Therefore, grassland soils have higher SOC (Franzluebbers et al., 2000; Wiesmeier et al., 2012) and N\textsubscript{tot} (Franzluebbers et al., 2000) pools than croplands. However, grasslands are very vulnerable to land-use disturbances, such as afforestation, in terms of SOC and N\textsubscript{tot} (e.g. Paul et al., 2002; Guo and Gifford, 2002; Li et al., 2012), which was also observed in our study: within ten years SOC and N\textsubscript{tot} pools had decreased in the A-horizon, confirming the second part of our first hypothesis about the response of grasslands. The establishment of plantations on more moist grasslands could cause an immediate SOC decrease (Hillbrunner et al., 2013; Wellock et al., 2014; Guidi et al., 2014) as enhanced soil respiration (Sun et al., 2015) and microbial activity promote rapid organic material decomposition rates (Richter et al., 1999) and increased N mineralization (Uri et al., 2008). Populus spp. are also well-known for their high transpiration rates (Zhang et al., 1999; Petzold et al., 2011) in order to maintain high productivity (Stanturf et al., 2001), which means that trees could have a drying effect on more moist soils (Gleysols), thereby promoting mineralization.

The dynamics of SOC and N\textsubscript{tot} pools in the A-horizon depend in turn on soil horizon depths (Vesterdal et al., 2002; Ritter et al., 2003). In our studied 15-year-old hybrid plantations, SOC and N\textsubscript{tot} pools were significantly higher in the uppermost 0–10 cm soil layer than in the following 10–20 cm and 20–30 cm in spite of land-use. Similar tendencies have been reported in several other studies after arable land afforestation in the uppermost 0–10 cm soil layer in relation to SOC (Jug et al., 1999; Vesterdal et al., 2002; Bárcena et al., 2014b) even during a century (Cerli et al., 2006).

The effect of former arable lands' afforestation on N\textsubscript{tot} pools in mineral soil has so far been less studied than SOC; however, the pattern is considered to be similar to SOC changes (Jug et al., 1999; Berthrong et al., 2009; Li et al., 2012). Similarly to our studied croplands, Mao et al. (2010) report that soil N\textsubscript{tot} pool in a depth of 0–30 cm did not change significantly between the ages of 5 and 15 on former agricultural land in semi-arid temperate zone afforested with poplars. Similarly to our grasslands, Jug et al. (1999) report a significant decrease in N\textsubscript{tot} and SOC pools in a depth of 0–30 cm on former grassland during a decade after afforestation with SRC poplars in temperate conditions.

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Our results are different from several studies reporting initial C recovery and expected sequestration already a decade after afforestation of former agricultural land with fast-growing poplars in North America (Hansen, 1993; Grigal and Berguson, 1998; Sartori et al., 2007; Arevalo et al., 2011). Studies of the impact of poplar species on SOC in Europe are mainly carried out in temperate conditions in short-rotation coppice (SRC) plantations, where the afforestation of arable lands can result in an increase (Kahle et al., 2007) or, similarly to our study, in a decrease of SOC in a soil depth of 0–30 cm on former grasslands (Jug et al., 1999) during the first decade. However, probably due to lower planting density, the results from our study are more similar to studies with a longer observation time (ca 30–50 years) in northern Europe that cover conventional forest management tree species with a chronosequence approach and report no SOC accumulation in 0–30 cm of mineral soil after arable lands afforestation (Vesterdal et al., 2002; Armolaitis et al., 2007; Bárcena et al., 2014b) even during a century (Cerli et al., 2006).

4. Discussion

4.1. A-horizon SOC and N\textsubscript{tot} changes and storage

This study showed that former land-use type had a significant impact on changes of soil A-horizon SOC and N\textsubscript{tot} pools during the 10-year period (from the age of 5–15 years) under hybrid aspen plantations. Generally former cropland soils are C-exhausted from former intensive ploughing and tilling practice (Arevalo et al., 2011), which was replaced against increasing decomposition rates (Richter et al., 1999) and increased N mineralization (Uri et al., 2008).
Higher SOC and N tot pools in the upper soil layer (0–10 cm) can be explained by a more direct impact of litter fall to the forest floor (Vesterdal et al., 2002), a higher amount of fine roots (Rosenvald et al., 2014), the presence of N₂ fixing herbaceous understory vegetation (Tullus et al., 2015) and a more direct impact of atmospheric N deposition.

### 4.2. Subsoil SOC and N tot changes and storage

Our study shows the importance of deeper subsoil for SOC and N tot pools in total estimations (Rumpel and Kögel-Knabner, 2011) as about one-third of SOC and N tot pools were located in the soil layer beneath the A-horizon (~30 cm thick) up to the studied soil depth of 75 cm. We did not find any impact of former land-use type on subsoil SOC, which has been reported by Poeplau and Don (2013), and for N tot which has been reported by Clark and Johnson (2011), where former croplands improved subsoil SOC and N tot pools. Unexpectedly and in contrast to the A-horizon, subsoil SOC and N tot pools increased significantly both on former crop- and grasslands from the age of 5–15 years, and therefore we rejected the second hypothesis. Subsoil organic material accumulation is mainly influenced by increased amounts of root-derived residues (Hansen, 1993; Hooker and Compton, 2003; Kahle et al., 2010), especially from fine root decomposition (Finér et al., 2011; Hu et al., 2016), as we observed an increase of SOC and N tot concentration in the B-horizon in the studied hybrid aspen plantations (Lutter et al., 2016). Humus adsorbing capacity in subsoils of our soil selection is supported by higher clay content in the B-horizon (Supplementary Material, Table S3), i.e. they have a better capacity to store C and N (Laganiere et al., 2010; Chang et al., 2014). A similar pattern to our study is reported by Mao et al. (2010) from semi-arid temperate conditions after agricultural lands afforestation with poplars, where subsoil (depth from 30 to 60 cm) SOC as well as N tot pools tended to increase in the chronosequence from 5 to 15 years after afforestation.

Generally, deeper soil layers’ microbial activity in terms of SOC and N tot mineralization is more stable than in the uppermost soil layers (Hansen, 1993; Hooker and Compton, 2003; Powolson et al., 2011) and therefore subsoil is considered to be a potential sustainable C sink in the long term (Poeplau and Don, 2013; Hu et al., 2016; Wang et al., 2016). Deeper soil SOC accumulation might be especially important in the long term in intensively managed SRF plantations, where the upper soil layer (0–30 cm) is more directly influenced by plantation management activity. However, longer empirical observations are needed regarding subsoil SOC and N tot dynamics as deeper soil SOC mineralization might be stimulated by soil structural disturbances (Salomé et al., 2010) caused by older trees root penetration into deeper soil (Strong and La Roi, 1985) as well as by increasing microbial activity (Mobley et al., 2015).

### 4.3. Above-ground C and N concentration

In this study we found that the 15-year-old hybrid aspen weighted average C concentration in above-ground dry woody biomass was 45.8%, varying a little between tree compartments from 45.5% to 47.0%. This supports our third hypothesis and suggests that the frequently used 50% of C in dry above-ground woody biomass for estimating C storage (e.g. Kurz et al., 2009; Rytter, 2012b; Bárcena et al., 2014b; Wellock et al., 2014) might cause about an 8% overestimation for hybrid aspen above-ground C storage. The obtained average C concentration of hybrid aspen is quite close to 46–47% which has been estimated for similar-aged hybrid poplar plantations in British Columbia (Zabek and Prescott, 2006), and a little less than 47.05%, which is reported for older Populus tremuloides Michx. in North America (Lampl and Savidge, 2003). The somewhat lower C concentration of hybrid aspen biomass is in agreement with a high cellulose: lignin ratio in its wood (Tullus et al., 2012) as cellulose has a much lower C content than lignin (Pettersen, 1984). The weighted average concentration of N in stem (0.233%) and branches (0.690%) are comparable with the results reported by Rytter and Stener (2003) (0.215% and 0.602%, respectively) for 14-year-old hybrid aspen in southern Sweden.

### 4.4. Total ecosystem C and N dynamics and implications for further management of hybrid aspen plantations

In 15-year-old hybrid aspen plantations, the main C pool was located in the below-ground pool. About half of the ecosystem C was located in the soil A-horizon, similarly to 13-year-old silver birch stand on former agricultural land (Uri et al., 2012). The relative share of above-ground C pools compared to below-ground pools increases significantly with stand age after afforestation (Vesterdal et al., 2002; Sartori et al., 2007; Dowell et al., 2009; Mao et al., 2010; Wellock et al., 2014; Bárcena et al., 2014b). This hold true also in our study, confirming the fourth hypothesis. During our 10-year study period, this was most apparent on former grasslands where 94.9% of the total ecosystem C change occurred in above-ground pool, while the respective number for former croplands was 73.8%. The main below-ground C pool improvement on both land-use types was caused by subsoil and coarse-root gains. The significant increase of subsoil SOC pools means that grasslands’ A-horizon SOC and N tot loss was compensated by subsoil gains in the total 75 cm soil profile.

Based on studies covering the whole rotation period of short-rotation forests (Strukelj et al., 2015; Clarke et al., 2015), thinnings will become the major C output from total ecosystem storage during the second half of the rotation period in our studied plantations being the most important factor that could further alter total ecosystem C storage and allocation before clear-cut (Litton et al., 2007; Bárcena et al., 2014b). A common practice in midterm hybrid aspen plantation is to remove a quarter to a third of above-ground standing biomass during thinnings (Tullus et al., 2012). In light of the results obtained from the current study, even after a thinning hybrid aspen plantations are C-sequestering systems at the total ecosystem level.

When there were no significant differences in the total ecosystem C pools between different land-use types, then total ecosystem N storage was still higher on former grasslands in 15-year-old plantations. The majority of the total ecosystem N in forest in dormant season is located in below-ground pool (Buchmann et al., 1996; Finér et al., 2003), whose share in our study was 97.6%. Commercial thinnings will cause, similarly to C, the output of N from the ecosystem. Rytter (2002) reported that whole tree thinning (22% of total stand volume) removed 41.2 kg ha⁻¹ of N from 15-year-old hybrid aspen plantations. Using the same thinning rate in our studied plantations, the removal of N will be 34.1 kg ha⁻¹. However, N tot in soil does not show the direct availability of N to plants (Stanford, 1982) large N pools in our studied soil range should compensate N removals from the ecosystem well.

### 5. Conclusions

For a decade (5–15 years after conversion into fast-growing hybrid aspen plantations), former crop- and grasslands’ A-horizon SOC and N tot pools showed different patterns of change. In terms of A-horizon SOC and N tot pools, hybrid aspen plantations soil conditions had become more similar in two completely different former land-use types (crop- and grasslands). At ecosystem level, former croplands showed a higher capacity to sequesterate new SOC to below-ground pools; meanwhile both former land-
use types significantly increased the total ecosystem C pool. Our study confirmed the importance of the inclusion of deeper (>30 cm) soil layers in total C estimations under deep-rooted perennial plants as subsoil SOC storage constituted about a third of the total SOC pool of the 75 cm soil profile. The total soil SOC pool increased significantly during the last decade in 15-year-old plantations on both former agricultural land-use types. As expected, the main C sequestration in fast-growing hybrid aspen plantations took place in above-ground woody biomass whereas there were no significant differences in biomass increment between the two land-use types. We also found that the average C content in dry above-ground leafless biomass of hybrid aspen in hemiboreal plantations is 46%, which means that the widely recommended 50% for C content should cautiously be used in C storage calculations.

To conclude, first-generation SRF hybrid aspen plantations on former arable lands had acted as C sinks by their midterm period and therefore have a great potential for climate change mitigation despite the relatively short rotation period. However, research needs to be continued and final conclusions should be drawn after the end of the whole rotation period.

Acknowledgement

This work was supported by Institutional Research Funding IUT (grants IUT21-4 and IUT34-9) of the Estonian Ministry of Education and Research.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.foreco.2016.07.021.

References


