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

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ABSTRACT

Short-rotation forestry with fast-growing hybrid aspen (*Populus tremula* L. × *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_{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_{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^{-1} yr^{-1} on former croplands and by 2.56 Mg C ha^{-1} yr^{-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.

1. 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_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_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. × *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).

Afforestation 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

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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 conditions, 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 decomposition 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 Berguson, 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 rotation 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 plantations to sequestrate and retain C in soil after afforestation on former 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 deciduous 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 nutrition 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 similar 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 (N_{tot}) pools are less studied than SOC after arable land is taken under forest, where a decrease of N_{tot} 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 sequestrate C in above-ground biomass whereas C concentration in dry biomass could significantly vary between different tree species (Lamlom 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% (Lamlom 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 overestimate 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 conditions is located in soil (Finér et al., 2003) and N cycling from leaf litter is very efficient in poplar plantations (Meiresonne 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 plantations 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 established 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 N_{tot} 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 N_{tot} 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 biomass 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).