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The impact of short-rotation hybrid aspen (*Populus tremula* L. × *P. tremuloides* Michx.) plantations on nutritional status of former arable soils

Reimo Lutter [a,*], Arvo Tullus [b], Arno Kanal [c], Tea Tullus [a], Hardi Tullus [a]

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

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ABSTRACT

The area of short-rotation forest (SRF) plantations with hybrid aspen (*Populus tremula* L. × *P. tremuloides* Michx.) for pulp and energy wood production in approximately 25-year rotation period has increased considerably during the last few decades in Northern Europe on previous agricultural lands. However, little is known about how this new land use will alter the chemical properties of soils in the long-term and how long nutrients from the land's previous use will sustain high productivity of trees. Little is also known about the dynamics of soil micronutrients and the plantations' influence on subsoil layers. Repeated soil monitoring was carried out in hybrid aspen plantations at the ages of 5 (young) and 15 years (midterm) to detect changes in soil chemical characteristics, including soil reaction (pH_{KCl}), and concentrations of nutrients and organic carbon (C_{org}) in A- and B-horizon on 51 permanent experimental plots. The main soil- and stand-related factors responsible for changes in soil chemical properties, were analyzed. Significant changes were observed both in soil A-horizon and B-horizon. In A-horizon, pH_{KCl} (−0.2 units), Ca (−19.4%) and B (−25.8%) had decreased while total N (+5.8%), Cu (+20.3%) and Mn (+21.3%) had increased. In B-horizon, Ca (−23.4%), Mg (−12.8%) and B (−45.0%) had decreased, while C_{org} (+17.2%) and Cu (+53.8%) had increased. The concentrations of available P, K and C_{org} in A-horizon had remained unchanged. Reduction of soil chemical characteristics mainly occurred in plantations where their initial level had been high (this relationship was observed in A-horizon for total N and B and in B-horizon for C_{org}, Mg and B). Several soil chemical characteristics decreased more (or increased less) in plantations where tree growth was more vigorous (in A-horizon: $pH_{KCl,}$ total N and B; in B-horizon: Mg and B). Soil cation exchange capacity, base saturation and moisture conditions also explained some of the observed variation in changes. Relatively high loss of B in faster growing plantations indicates possible future limitations of this essential micronutrient. To summarize, first generation hybrid aspen plantations planted on former agricultural fields had significantly altered soil reaction (pH_{KCl}) but did not show significant depletion of primary macronutrients (N, P, K) and soil organic carbon.

1. Introduction

The area planted with short-rotation forest (SRF) plantations has expanded rapidly in Northern Europe during recent decades (Weih, 2004; Tullus et al., 2013). Hybrid aspen (*Populus tremula* L. × *P. tremuloides* Michx.) has proven to be one of the most promising species for intensive pulp and biomass production in this region due to its fast growth, cold resistance, pathogen resistance and the existence of long-term breeding programs (Karacic et al., 2003; Rytter and Stener, 2005, 2014; Tullus et al., 2012; Johansson, 2013). In Estonia, a SRF pilot program with hybrid aspen for pulp and energy wood production was initiated in 1999 on former arable lands (Tullus et al., 2007).

SRF is recommended to reuse abandoned agricultural lands (Weih, 2004; Tullus et al., 2013), where soils have several distinctive features. Firstly, former arable soils have higher concentrations of nutrients from previous agricultural fertilization, which can persist at a high levels at least during the first few decades after afforestation (Hofmann-Schielle et al., 1999; Ritter et al., 2003; Wall and Hytönen, 2005; Lutter et al., 2015) or possibly for longer

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

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times (Falkengren-Grerup et al., 2006). Secondly, abandoned agricultural lands have fairly homogeneous properties in their topsoil layer, as a result of long-term ploughing and tilling practice (Messing et al., 1997; Wall and Heiskanen, 2003). Additionally, former arable soils are strongly affected by drainage (Baker et al., 2004) and they lack of the ectomycorrhizal fungi and microbial community typical to native forest soils (Baum et al., 2002; Yannikos et al., 2014). Little is known about how afforestation with fast-growing *Populus* spp. changes the soil properties of arable lands, how trees can alter internal nutrient cycling in the soil and what the general effects on the environmental conditions of the site are.

Sustainable management of nutrients is important in SRF plantations with fast-growing trees, which deplete nutrients quickly (Binkley et al., 2004; Vance et al., 2014) and continuous fertilization has been necessary to maintain high productivity in many cases (Ericsson, 1994; Berthrong et al., 2009; Liao et al., 2012). *Populus* spp. are well-known for their high demand for fertile conditions and their ability to accumulate relatively high amount of nutrients in their bark and stemwood, along with high biomass production (Stanturf et al., 2001; Pare et al., 2001; Stark et al., 2015). At the same time, *Populus* spp. leaf litter cycling can be efficient without significant losses from leaching or runoff (Meiresonne et al., 2006). In some cases, *Populus* spp. as deciduous trees can even improve indigenous forestland soil quality in the first 30 cm of depth within the first few decades (Stark et al., 2015). The impact of arable land afforestation with *Populus* spp. plantations on soil nutrient dynamics has mostly been studied in southern and central temperate conditions in short-rotation coppice plantations (*ca* 3–5 years rotation) with very high numbers of trees (>10,000 trees ha^{-1}) (Kahle et al., 2007, 2010) and often along with fertilization experiments (Hofmann-Schielle et al., 1999; Jug et al., 1999; Berthelot et al., 2000). Findings from these studies cannot be directly translated to longer rotation (20–30 years) hybrid aspen plantations in northern temperate and boreal conditions. Moreover, the effect of afforestation on soil macronutrients has been more frequently studied compared to micronutrients, but the importance of micronutrients should not be underestimated (Römkens and Salomons, 1998; Watmough et al., 2007; Lehto et al., 2010). Hence, understanding the changes and dynamics in concentrations of soil essential nutrients (N, P, K, Ca, Mg, Mn, Cu, B) in fast growing midterm hybrid aspen plantations in hemiboreal conditions is important for practical SRF plantation management, to determine how nutrients from previous agricultural land use will last and to predict a possible need for fertilization to retain productivity. Understanding the nutrients' dynamics is also important if the land will be reversed back to agricultural use.

The root system of hybrid aspen growing on former agricultural land is mainly distributed in the nutrient-rich A-horizon (Rosenvald et al., 2014), where trees probably have a more immediate effect on soil chemical properties compared to deeper B-horizon. However, trees with their extensive root systems, are able to access deeper soil layers (B-horizon) that are unreachable for annual agricultural crops. As such, trees are able to alter subsoil microbial activity and provide extra nutrients for cycling (Kahle et al., 2010; Stark et al., 2015). So far, little attention has been devoted to the dynamics of deeper soil layers after previous agricultural land has been planted with trees.

Afforestation of former agricultural land can significantly alter soil N and C cycling, as the amounts of root (Rytter, 1999; Block et al., 2006) and leaf litter are increasing (Van Cleve et al., 1993; Vervaet et al., 2002; Kahle et al., 2007) and soil cultivation has stopped (Makeschin, 1994). However, little is known about how afforestation with fast-growing hybrid aspen influences soil organic carbon (C_{org}) and total N at different soil depths on former agricultural lands comprised of different soil types. So far, results from different pedoclimatic conditions are quite contradicting. Several studies have shown a decrease in C_{org} during the first decades (<30 years) after agricultural land afforestation, followed by a recovery stage, during which such areas transform from C_{org} sources into C_{org} sinks (Paul et al., 2002; Laganiere et al., 2010; Bárcena et al., 2014). Other studies report that C_{org} concentration remains at the same level (Vesterdal et al., 2002; Lutter et al., 2015) or even increases (Kahle et al., 2007) during the first l5 years after afforestation.

pH is one of the fastest responding soil characteristics to indicate a return to a forest soil environment, as pH tends to change quickly due to the tree canopy. In Northern Europe nutritional conditions of previous arable lands were significantly altered through intensive liming to reduce topsoil acidity (Kõlli and Ellermäe, 2003; Ritter et al., 2003; Wall and Hytönen, 2005). Afforestation of arable lands with fast growing deciduous trees has often resulted in a decrease in topsoil pH during the first few decades after afforestation (Jug et al., 1999; Ritter et al., 2003; Berthrong et al., 2009; Uri et al., 2011; Lutter et al., 2015). Soil reaction is an important factor that determines solubility of organic and mineral compounds, overall biological activity and mobility of nutrients as well as their loss via leaching. Thus, for sustainable nutrient management, it is important to clarify pH dynamics in SRF plantations on previous agricultural lands.

Repeated soil monitoring was carried out in permanent sample plots in young (5-year-old) and midterm (15-year-old) hybrid aspen plantations to analyze the changes in the topsoil (A-horizon) and in the subsoil (B-horizon) on previous agricultural lands in hemiboreal Estonia. The measured and evaluated soil features were: soil reaction (pH_{KCl}), concentrations of nutrients (N, P, K, Ca, Mg, Cu, Mn, B), concentrations of organic carbon (C_{org}), and C:N ratio. We analyzed what the main drivers that are responsible for the changes are. Hypotheses were: (1) the concentrations of macronutrients and micronutrients have remained unchanged and C_{org} and pH_{KCl} have decreased in soil humus (A) and illuvial (B) horizons; (2) Changes are more eminent in A- than in B-horizon; (3) Growth of the trees is the main factor that explains changes in soil chemistry.

2. Materials and methods

2.1. Studied plantations

The study was carried out in Estonia (Fig. 1). Estonia is situated in the hemiboreal vegetation zone within a transition zone from maritime to continental climate (Ahti et al., 1968). The weather in Estonia is considerably milder than the continental climate that is characteristic for 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 to the studied plantations (The Estonian Environment Agency).

The hybrid aspen plantations studied were established in 1999 and 2000 with 1-year-old clonal micropropagated plants originating from Finland on previous mineral agricultural lands (Tullus et al., 2007). Trees belonging to 27 hybrid aspen clones were planted randomly in these plantations (Tullus et al., 2007). For site preparation, whole-area or strip ploughing was done before planting the trees to reduce competition between young seedlings and ground vegetation. The average planting density was 1300 trees per hectare (range: 1200–1600) and all the trees were protected with photodegradable plastic tubes against possible damage by rodents and hares (Tullus et al., 2007). None of the plantations were fenced to prevent game damage.