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Long-term effects on the nitrogen budget of a short-rotation grey alder (*Alnus incana* (L.) Moench) forest on abandoned agricultural land

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ABSTRACT

Short-rotation energy forestry is one of the potential ways for management of abandoned agricultural areas. It helps sequestrate carbon and mitigate human-induced climate changes. Owing to symbiotic dinitrogen (N_2) fixation by actinomycetes and the soil fertilizing capacity and fast biomass growth of grey alders, the latter can be suitable species for short-rotation forestry. In our study of a young grey alder stand (*Alnus incana* (L.) Moench) on abandoned arable land in Estonia we tested the following hypotheses: (1) afforestation of abandoned agricultural land by grey alder significantly affects the soil nitrogen (N) status already during the first rotation period; (2) input of symbiotic fixation covers an essential part of the plant annual N demand of the stand; (3) despite a considerable N input into the ecosystem of a young alder stand, there will occur no significant environmental hazards (N leaching or N_2O emissions). The first two hypotheses can be accepted: there was a significant increase in N and C content in the topsoil (from 0.11 to 0.14%, and from 1.4 to 1.7%, respectively), and N fixation (151.5 kg N ha^{-1} yr^{-1}) covered about 74% of the annual N demand of the stand. The third hypothesis met support as well: N_2O emissions (0.5 kg N ha^{-1} yr^{-1}) were low, while most of the annual gaseous N losses were in the form of N_2 (73.8 kg N ha^{-1} yr^{-1}). Annual average NO_3–N leaching was 15 kg N ha^{-1} yr^{-1} but the N that leached from topsoil accumulated in deeper soil layers. The soil acidifying effect of alders was clearly evident; during the 14-year period soil acidity increased 1.3 units in the upper 0–10 cm topsoil layer.

1. Introduction

Land use changes are one of the key factors of climate change (IPCC, 2007). Since 1850, about 35% of anthropogenic CO_2 emissions have resulted from altered land use (Foley et al., 2005). Owing to climate warming, both C sequestration (Schimel et al., 2001) and global terrestrial net primary production (Nemani et al., 2003) have increased. However, soil fertility limits C sequestration by forest ecosystems in a CO_2-enriched atmosphere (Oren et al., 2001; Heath et al., 2005). On the other hand, elevated atmospheric nitrogen (N) deposition makes a minor contribution to C sequestration in temperate forests (Nadelhoffer et al., 1999; Liu and Greaver, 2009). Thus, it is believed that fast growing energy crops and short-rotation forests can mitigate anthropogenic greenhouse gas (GHG) emissions (Foley et al., 2005; Bonan, 2008). The nearest goal in the European Union is to increase the share of the energy generated from renewable sources from 5% to 12% by 2010 (Kuiper et al., 1998; EU Commission, 1997). In 2007, renewable energy made up already 7.8% of gross inland consumption (Europe's energy. . ., 2010). Future land use scenarios for Europe foresee a significant increase in energy crop areas (Rounsevell et al., 2006). Accordingly, the investigation of tree species suitable for short-rotation energy forestry and different related problems has been intensified.

The most suitable areas for bioenergy production are abandoned agriculture lands, which cover globally 385–472 million ha (Campbell et al., 2008). Although the energy content of potential biomass grown on these abandoned lands accounts for <10% of the primary energy demand for most nations in North America and Europe, for some regions like Eastern and Northern Europe (Peterson and Aunap, 1998; Larsson and Nilsson, 2005) as well as for mountainous areas of Europe (MacDonald et al., 2000), this potential is significant. A considerable increase in the area of abandoned agricultural lands, due to changes in the political and economic situation, has occurred in Eastern Europe, including

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Estonia, during last decades (Mander and Palang, 1994). According to a recent estimation, about 300,000 ha of agricultural lands are abandoned in Estonia (Astover et al., 2006).

In the zone of temperate and boreal forests, abandoned agricultural areas are predominantly afforested with deciduous trees. Different alder species are among the most common trees in these secondary successions: their invading former arable lands and meadows has been reported from Sweden (Granhall and Verwijst, 1994), Finland (Saarsalmi, 1995), Russia (Shvidenko et al., 1997), Norway (Staaland et al., 1998), Estonia (Uri et al., 2009), Korea (Lee et al., 2002), France (Anthelem et al., 2001), Swiss Alps (Frelechoux et al., 2007), Latvia (Liepins et al., 2008), and other areas. As pioneer species alders are successfully used for restoration of mining areas (Helm and Carling, 1993; Kramer et al., 2000; Frouz et al., 2001; Lõhmus et al., 2006a).

The essential advantage of alders is the symbiotic N_2 fixation ability of the actinomycete *Frankia* (Benson, 1982). Red alders (*Alnus rubra* Bong.) are widely used for improvement of soil fertility and biomass production in mixed alder-conifer stands (Binkley et al., 1992; Hart et al., 1997; Rothe et al., 2002; Binkley, 2003). In addition to increasing soil N, C, and available P content, microbial biomass and activity, red alders significantly alter community-level microbial functions in mixed stands (Selmants et al., 2005). Most of N from decomposed red alder leaves has been incorporated into growing plants and the soil pool (Swanston and Myrold, 1997). Other alder species have been successfully used as a source of biological fertilizers in mixed stands with walnuts (*Juglans nigra* mixed with *Alnus glutinosa*; Bohanek and Groninger, 2005) and agricultural crops (alleys of *Alnus crispa* subsp. *sinuta* in between sweet corn (*Zea mays*) rows; Seiter and Horwath, 1999). Owing to enhanced microbial activity and tree growth in alder stands, carbon fluxes are somewhat larger there than in other temperate forests (Kutsch et al., 2005). In general, alder species have a favourable impact both on the diversity and activity of the microbial communities of the soil and the rhizosphere (Lõhmus et al., 2006b), which has also been reported in relation to increased soil phosphorus availability under alder species (Binkley, 1984; Giardina et al., 1995; Uri et al., 2002; Gökkaya et al., 2006).

Several studies demonstrate that grey alder (*Alnus incana* (L.) Moench) is a most promising fast-growing tree species for a short-rotation forestry in Estonia (Uri et al., 2002, 2003b, 2009). This species is highly productive both on mineral and organic soils (Granhall and Verwijst, 1994; Saarsalmi, 1995; Rytter, 1996; Telenius, 1999). Hence, grey alder as an actinorrhizal N_2-fixing tree species can be used effectively for biological fertilization of the soil with N (Granhall, 1994). Owing to its symbiotic nitrogen fixation capacity, grey alder is able to cover a large proportion of its annual nitrogen demand with nitrogen from the atmosphere and, compared with other short-rotation energy forest tree species the need for expensive nitrogen fertilization will be smaller or lacking altogether. Grey alder has also some essential silvicultural advantages, which makes it a promising species for short-rotation forestry. Grey alder seedlings withstand direct sunlight and frost; they have only a few pests and diseases (Granhall and Verwijst, 1994). After cutting, a new alder generation emerges both from root suckers and stump sprouts owing to which artificial reforestation of clearcuts is not needed. Rytter (1995) demonstrated that thinning of *A. incana* stands is not necessary as it does not increase the mean annual increment of stands. A comparative study by Johansson (2000) shows that mean annual total above-ground biomass in Swedish grey alder stands was about 64% higher than in common alder (*A. glutinosa*) stands.

However, owing to symbiotic N fixation, introduction of additional nitrogen in the alder forest ecosystem, and enhanced nitrification, the pH value in soils can decrease resulting in leaching of nitrate and base cations (Van Miegroet and Cole, 1984, 1985; Verburg et al., 2001). Leaching of nitrates from soils under alder stands has been reported in several studies (Binkley et al., 1992; Van Miegroet et al., 1992; Compton et al., 2003) and even a low alder cover in riparian zones has been found to be a source of elevated N exports (Cairns and Lajtha, 2005). In riparian buffer zones of agricultural landscapes, which receive a concentrated lateral inflow from adjacent intensively fertilized areas uphill, the decrease in N loading is significant. Nevertheless, the outflow is lower (13.2 kg N ha^{-1} yr^{-1}; Lõhmus et al., 2002; Mander et al., 2008) than that found in red alder stands (Binkley et al., 1992). Intensive denitrification in riparian zones transforms nitrates to dinitrogen (N_2) and nitrous oxide (N_2O), 51.7 and 0.5 kg N ha^{-1} yr^{-1}, respectively, as reported by Mander et al. (2008).

Replacement of set-aside agricultural field by forest brings about various changes at different levels of ecosystems, including N cycling. Land use type may have an essential effect on soil C and N content, quality of organic matter, microbial activity and mineralization of organic N (Compton et al., 1998).

Cultivation of temperate soils may reduce soil nitrogen about 8% from the initial value (Post and Mann, 1990), but changes in soil N level and processes occurring after agricultural abandonment are not well established and are likely to be highly site specific (Compton et al., 1998). The effect of trees on the soil N status depends essentially on the tree species forming a new forest ecosystem. In the case of alders, the respective effect on the nitrogen budget and the soil N status is particularly significant owing to their symbiotic N fixation ability (Binkley, 2005). How is N cycling affected during the transition of the ecosystem from field to forest and what kind of possible environmental risks may occur in this process, taking into account N input by symbiotic nitrogen fixation? Long-term investigations of N budget in alder forests are almost lacking. To our knowledge, there is only one long-term study dealing with an *Alnus japonica* stand on an abandoned rice field in Korea, which reports an increase in soil N concentration during the first 8 years and stabilization at a level of 1.8% during the following 42 years (Lee et al., 2002).

The working hypotheses of the present case study were: (1) afforestation of abandoned agricultural land by grey alder significantly affects the soil N status already during the first rotation period; (2) symbiotic fixation input covers an essential part of the plant annual N demand of the stand; (3) despite a considerable N input into the ecosystem of a young alder stand, there will occur no significant environmental risks (N leaching or N_2O emissions).

To test these hypotheses, the main objectives of our study were: (1) to compile an N budget for a young short-rotation grey alder stand growing on abandoned agricultural land and to assess the influence of alders on the soil N status (*i.e.*, the potential of N-related environmental hazards); (2) to estimate the flux of the symbiotic N fixation of this 10-year-old grey alder stand; (3) to analyse formation of a forest ecosystem and the dynamics of functioning of this young grey alder stand on abandoned agricultural land in relation to N cycling.

2. Materials and methods

2.1. Study area

A grey alder plantation (0.1 ha) was established on abandoned farmland in spring 1995, in the southeastern part of Estonia, 58°3′ N and 27°12′ E. According to the data of the closest meteorological station, mean annual temperature, amount of precipitation and length of the vegetation period are 6 °C, 653 mm and 191 days, respectively. The soil is classified as *Eutric Podzoluvisol* (according to the FAO classification). One-year-old transplants of natural origin