Forest Fertilization: Economic Effect and Impact on GHG Emissions in Latvia

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Abstract

The research objective was to estimate how the application of nitrogen fertilizer and wood ash in state forests can influence the additional volume increment and to determine the economic impact and national level climate change mitigation potential of the forest fertilization practice. National forest inventory data was used to select stands that are suitable for fertilization with ammonium nitrate and wood ash. Forest management restrictions are not considered; therefore, the study represents theoretical values of the additional income and the national climate change mitigation potential. According to the study, applying 436 kg ha^{-1} ammonium nitrate (30% of nitrogen) at 2.0 thous. ha of forests annually increases the additional volume increment by 28 thous. m^3 in the 10th year, but cumulative increment is 142 thous. m^3. Application of 5 tons of wood ash per ha at 4.3 thous. ha of forests annually increases the additional volume increment in the 10th year by 58 thous. m^3, but cumulative increment during the period of 10 years is 290 thous. m^3. Internal rate of return (IRR) for the nitrogen application in 20 years from the project start-up is 11 %, but for ash application is 13 %. The impact on gross domestic product reaches its maximum (3.2 million € per year) 11 years after project start. Cumulative reduction of greenhouse gas emissions in national inventory due to forest fertilization can reach 635 thous. CO_2 eq. in 10 years. Forest fertilization would contribute to CO_2 sequestration equivalent of 12.7 million € in 10 years. The value of additional CO_2 removal is equal to 156 € ha^{-1}.

Keywords: forest fertilization, wood ash, nitrogen, volume increment, CO_2 removals, internal rate of return.

Introduction

The economic effect of forest fertilization is determined by costs of the fertilizer and its spreading, additional volume increment as well as the time interval between applying fertilizers and logging. Forest fertilization with nitrogen fertilizers is a common practice in the Nordic countries, especially in Sweden and Finland. Mineral soils in pre-mature coniferous stands are commonly fertilized with ammonium nitrate and the typical nitrogen (N) dosage is 100...150 kg ha^{-1} (Nohrstedt 2001, Mäkinen and Hynynen 2014). The growth response to this dose is 20...25 m^{3}ha^{-1} of the additional volume increment, most of which is obtained during 5 years after fertilization. The effect of N application lasts about 10...12 years (Pukkala 2017). There are two kinds of forest fertilization practices: 1) extensive forest fertilization, which requires application of fertilizer 10 years before thinning or regenerative felling and repeating of the application up to 3 times per rotation, and 2) optimized fertilization, when soil amendments are first applied, when trees are 2...4 m tall, then repeated every second year until tree canopies close and afterwards each 7...10 years. Smaller dosages of the fertilizer are used in the optimized forest fertilization practice. The former method is characterized by a relatively small additional increment (10...20 m^3 ha^{-1} in 10 years), but the IRR exceeds 15%; whereas the latter method results in significantly lower IRR of investment but creates considerably higher climate change mitigation effect (Hedwall et al. 2014). Fertilization of pre-mature forest stands 10...15 years before regenerative felling was carried out in Latvia from early 1970s to late 1980s (Kāposts and Sacenieks 1977). The utility aircraft (Antonsov An-2 airplanes) were used to spread fertilizer, and fertilization costs amounted 50 rubles ha^{-1}. After 1989 forest fertilization was officially terminated due to increase in aviation service costs (Špalte 1991). In Norway, financial analyses of N application in Norway spruce (*Picea abies* (L.) Karst) and Scots pine (*Pinus sylvestris* L.) stands have typically showed a high IRR. About 0.015 % (0.7 thous. ha in 2015) of the productive forest area has been fertilized with N in Norway (Karstad and Asbjørn 2012).

Economic effect of wood ash application in forest is mainly studied in the context of recycling and utilization of biofuel combustion waste, for instance, comparing costs of ash application in forest and disposition in landfills. The type of wood ash processing has a significant influence on the economic effect of the wood ash application. In their research, Rasmusson et al. (2013) evaluated which type of wood ash treatment is the top-grossing one. According to the study, the use of granulated ash was considerably cheaper in comparison with self-hardened ash due to smaller transportation costs. However self-hardening is still more common because it is simple and easy to organise and does not require special equipment. Studies on utilization and economics of wood ash application in the south-eastern part of Finland demonstrated that the use of fly ash and bottom ash in forest is the most advantageous ash utilization method, which increases net present value (NPV) of predicted forest management by 58%. The large increase is related to decline of demand of fertilizers by 21%, replacing them with wood ash, as well as by the reduced use of fertilizers and liming material in forests (Deviatkin et al. 2016).

According to Tuovinen (2015), in 2015 large majority of ash producers in Finland pay to forest owners in order to avoid deposition costs. A part of interviewees criticized wood ash application as fertilizer because it has to be applied in larger doses than commercial fertilizers, it is heterogeneous and has low nutrient content. Wood ash dosage in forest is 3...5 tons ha^{-1}, therefore transportation costs more in comparison with chemical fertilizers. The expenses for wood ash transportation in Finland were justified within a radius of 50-200 km around the boiler house and a part of interviewees considered the costs of wood ash fertilization too high. To defend the use of wood ash as fertilizer, representatives of various stakeholders implied that wood ash is local, renewable and easy to apply (Tuovinen 2015). Results from Finland and Sweden indicate that wood ash application in forests can be encouraged by mutual benefit: an ash producer does not increase costs for the ash management, and the forest owner receives ash material for free or is at least partly compensated by the manufacturer.

According to expert judgment, in Finland and Sweden 30% of wood ash is applied as fertilizer. In Sweden wood ash is mainly applied on mineral soils, specifically during the forest regeneration, whereas in Finland wood ash is applied on nutrient-poor drained mineral and organic soils to increase potassium and phosphorus stock. Accordingly, in Finland wood ash is applied in middle-aged and mature stands. Results of a study carried out in southern Sweden in drained and forested peatlands show that over the first 5 years after the wood ash application (at doses of 3.1, 3.3 and 6.6 tons dry weight ha^{-1}) the mean annual increment of a stand basal area was significantly larger in the plots, where the biggest dose was applied, in comparison with the control plots (0.64 m^2 ha^{-1} year^{-1} and 0.52 m^2 ha^{-1} year^{-1}, respectively) (Ernfors et al. 2010). In boreal pine stands in Finland wood ash application on an N-poor peatland site increased tree growth by 17% during 25 years, whereas in an N-poor upland site tree growth was increased by 11% during 20 years (Saarsalmi et al. 2014).

In Latvia, more information can be found about wood ash application before 1940, when farmers and forest managers were encouraged to substitute chemical fertilizers and liming material with wood ash (Lauksaimnieks 1937). After 1940 this topic was set aside and wood ash usage was taken into consideration again only after regaining independence, when biomass became widely used in district heating. In Latvia, wood ash is used to a limited extent in drained forests or on organic or mineral soils, where potassium and phosphorus deficiency periodically emerges and wood ash can significantly increase the volume increment (Bārdule 2012, Lazdiņš et al. 2012, Okmanis et al. 2015). Results of a study conducted in central Latvia in a mixed Scots pine and Norway spruce stand on drained organic soil show a significant positive growth response in the volume increment of spruce after application of wood ash (the average dosage was 1 ton ha^{-1}). During the 12-year period after fertilization the additional volume increment was 8.3 m^3 ha^{-1}, or 0.7 m^3 ha^{-1} annually (Libiete et al. 2016). According to studies in Latvia the application of wood ash can be an efficient measure to minimize forest damages in coniferous forests on organic soils, which is another great benefit requiring more attention in future research (Klavina et al. 2015, 2016).

Forest sector has a significant impact on climate change mitigation. The Intergovernmental Panel on Climate Change (IPCC) defines climate change mitigation as the implementation of policies to reduce greenhouse gas (GHG) emissions and to increase sinks (IPCC 2006). Forest-related activities towards this target include reduction of deforestation, increase of carbon stocks and substitution of energy demanding materials and fuels with wood. Biofuel production has indirect impact on the implementation of climate change mitigation targets through substitution effect in energy sectors. A study carried out in Sweden suggests that an additional one-time increase in average carbon stock in standing trees and wood products trees, corresponding to 149 and 197 million tons CO_2 eq., respectively, would occur if 10% of Swedish forest land is fertilized. Fertilizing 10% of Swedish forest land can result in annual GHG emission reduction of 11.9 million or 18.1 million tons CO_2 eq., if the reference fossil fuel is fossil gas or coal, respectively (Sathre et al. 2010). The aim of this study is to assess the theoretical impact of nitrogen fertilization and wood ash application on the wood volume increment in state forests as well as to determine the economic impact and climate change mitigation potential of this forest management practice.

Materials and Methods

In this study NFI data on state forests was used. The NFI plots and sectors suitable for nitrogen fertilizer application were selected regardless of age and position. The total area of selected monitoring plots corresponded to 211 thous. ha. The selection criteria were based on dominant species (Norway spruce, Scots pine and Silver birch) and stand type, forests on poor mineral soils with optimal water regime. By dividing the total area with the regenerative felling age (101 for pine, 81 for spruce and 71 for birch), the average annual area suitable for fertilization was obtained amounting 2.1 thous. ha. The stands suitable for wood ash application were selected with a similar approach, however only forest sites on drained organic soils were selected. The site index was not considered because potassium and phosphorus deficiency in drained areas most frequently become apparent in middle-aged or mature stands regardless of tree growth in early ages. Total area of stands suitable for wood ash application is 435 thous. ha. The annual average area of stands suitable for wood ash spreading is 4.3 thous. ha. The total annual average stand area suitable for fertilization in the state forests is 6.4 thous. ha (0.4% of forests managed by LVM). Environmental and other restrictions of forest management are not considered, however, following to distribution of forest areas with management restrictions, nature conservation and other restrictions can affect about 10% of forest stands. Characteristics of stands suitable for fertilization are summarized in Table 1.

Table 1. Characteristics of forest stands suitable for fertilization with nitrogen fertilizer and wood ash

		Nitrogen fertilizer	Wood ash
Site index		II...IV	N/A
Forest type according to Latvian forest classification (Latin name)		*Vacciniosa, Myrtillosa, Hylocomiosa, Vaccinioso-sphagnosa, Myrtilloso-sphagnosa*	*Vacciniosa mel.*[1], *Myrtillosa mel. Mercurialosa mel., Vacciniosa turf. mel., Myrtillosa turf. mel., Oxalidosa turf. mel.*
Stand area, thous. ha	Pine	145	148
	Spruce	44	153
	Birch	22	134

[1] *mel.* - drained

It is assumed that ammonium nitrate is applied in forests on mineral soils. In order to spread nitrogen fertilizer, it is intended to use the agricultural tractor with attachable fertilizer spreader with load capacity of at least 500 kg, and for application of wood ash the spreader with moving floor mounted on the forwarder and the average load of 9 tons.

Productivity of spreading the nitrogen fertilizer was assumed according to the modeled data of speed, width of treated area and time consumed for preparatory works. The productivity of ash spreading was assumed according to results of earlier studies (Okmanis et al. 2015). Full time equivalent in calculations is assumed to be 1584 hours a year. Additional time consumption for wood ash delivery was not considered because the wood ash should be delivered either to landfill or forest regardless of destination. The socioeconomic impact of the project is assessed using the added value method. Calculations include depreciation, wages and profit. Tax burden is assumed to be 30% according to the average indicator in Latvia. Increase in national GDP is assumed according to estimates of the Ministry of Finance. The year of 2017 is assumed to be the starting point of the project. Assumptions on ammonium nitrate and wood ash are shown in Table 2.

Table 2. Assumptions on ammonium nitrate and wood ash fertilizer

	Ammonium nitrate (Nitrogen content 34%)	Wood ash
Amount applied	436 kg ha^{-1}	5 t ha^{-1}(dry mass 2 t ha^{-1})
Price of fertilizer	289 € t^{-1}	N/A
Spreading costs	38 € ha^{-1}	120 € t^{-1}
Spreading productivity	1.1 h ha^{-1}	1.6 h ha^{-1}
Delivery costs	N/A	0.75 € km^{-1}
Application time before final felling	10 years	10 years
Duration of impact	10 years	10 years
Expected timber yield, ha^{-1}	15 m^3	15 m^3

In order to calculate yield of wood products and average prices, data from 2013 provided by Joint Stock Company "*Latvia's State Forests*" (LVM) experts were used (Table 3). Price of biofuel (wood chips) was assumed to be 9 € loose volume m^3. Additional revenue due to production of solid biofuel from logging residues was calculated for areas, where nitrogen fertilizer has been applied. Delivery time of fertilizer is assumed according to average distances of wood delivery in different LVM regions.

Table 3. Wood yield from final felling according to dominant species (Lazdiņš et al. 2017)

Wood yield in final felling	Pine stands, %	Spruce stands, %	Birch stands, %	Average wood price, € m^{-3}
Coniferous sawlogs	75	51	23	61
Deciduous sawlogs	-	4	9	41
Birch veneer sheets	2	8	20	55
Pulpwood	18	29	39	35
Firewood	4	8	10	24

Delivery time of fertilizer is calculated according to average distances of wood transport in the specified LVM regions. Financial analysis was done for a 20-year investment project as well as for a 50-year project, assessing long-term cumulative effect, which is caused by soil improvement measures. Value of the CO_2 removals was assumed to be 20 € CO_2 ton ha^{-1} in average during the period (European Commission 2016). Potential revenues due to additional removals of CO_2 are not considered in economic analysis.

Reference harvesting stock was assumed in accordance with average values at final felling age according to the NFI. Default emission factors of direct and indirect N_2O emissions due to nitrogen fertilizer application from the guidelines of the Intergovernmental Panel on Climate Change were used to calculate N_2O emissions (IPCC 2006). In order to characterize carbon stock changes in soil and dead wood, the Yasso model was applied (Lazdiņš et al. 2014). In order to characterize CO_2 sequestration in harvested wood products the methodology from GHG inventory report was used (Gancone et al. 2016).

In order to estimate the substitution effect of biofuel, it was compared with natural gas (Lazdiņš 2013). Coefficients applied are provided in Table 4. Firewood and logging residues from nitrogen-fertilized areas are included in calculations of substitution effect. Crown and residue fraction is assumed as 30 % of stem volume, production losses (the biomass of the residues left in forest) are 40% of the available material.

Table 4. GHG emission factors for substitution effect assessment (Lazdiņš 2013)

Indicator	Unit	Natural gas	Biomass
Biomass carbon content	kg $tonne^{-1}$	-	527
Thermal input	MWh m^{-3}	0.01	4.90
Boiler efficiency	-	0.85	0.80
CO_2 emission factor	tonnes CO_2 MWh^{-1}	0.19844701	-
N_2O emission factor	tonnes N_2O MWh^{-1}	0.00000036	0.00001440
CH_4 emission factor	tonnes CH_4 MWh^{-1}	0.00000360	0.00010800

Results

In areas, where nitrogen fertilizer can be applied, estimated additional increment in 10 years will reach its maximum, 28 thous. m^3 per year, but the cumulative volume increment (accumulated over period of 10 years) is expected to be 142 thous. m^3. Additional 31 thous. m^3 of wood can be obtained annually on average as well as 14 thous. m^3 loose volume of biofuel from logging residues. In areas, where wood ash is applied, the estimated additional increment in 10 years can reach 58 thous. m^3 annually, but cumulative increment during the 10 years period can reach 290 thous. m^3. Logging is planned 10 years after spreading wood ash. On average it is expected to harvest additional 64 thous. m^3 annually from ash fertilized stands. The total additional increment in areas fertilized with nitrogen and wood ash in 10 years is expected to be 86 thous. m^3 per year, and the cumulative additional increment is expected to be 431 thous. m^3. Annually produced biofuel would correspond to 70 GWh as primary energy.

Average annual costs of nitrogen application would be 349 thous. € (165 € ha^{-1}). Each year 0.9 thous. tons of ammonium nitrate would be applied in forest (0.6 % from the amount of mineral fertilizers used in agriculture). Average annual costs for wood ash spreading would be 517 thous. € (120 € ha^{-1}). Each year up to 22 thous. tons of wood ash are required to fertilize all available stands.

The average additional logging costs in areas, where nitrogen fertilize would reach 1,785 thous. € per year. In areas, where wood ash can be applied, additional logging costs would be 1,447 thous. € per year, but revenue from selling of roundwood would be 3,216 thous. € per year. The total additional logging costs, wood and biofuel delivery from areas, where soil has been improved, are 2,588 thous. € per year. In average, the estimated gross revenue by selling wood and biofuel at current prices would reach 5,001 thous. € per year.

In the event of implementation of the forest fertilization investment project, considering application of fertilizers during the 10 years period and regenerative felling in the fertilized stands during the following 10 years, the internal rate of return (IRR) would reach a positive value (3 %) in 14 years after starting the project, but 6 years later the IRR would reach 11 %, when the nitrogen fertilizer is applied. In case of wood ash application, the IRR reaches a positive value 13 year after the beginning of the project and in 20 years it will be 13 %. Applying 4.24 % discount rate on a 10-year long investment project in 15 years it would result in the net present value (NPV) of 301 thous. € and 1,805 thous. € after 20 years when using nitrogen fertilizer, but in case of wood ash application the respective values would be 1,360 thous. € and 4,785 thous. €. Project influence on GDP in 10 years after startup would be 322 thous. € per year in average, but from the 11th year it would increase to 4.9 million € per year. Public gain (tax revenue) would increase by 97 thous. € per year during the first 10 years and by 1.5 million € annually from the 11th year.

Forest fertilization would create new jobs for processing and spreading wood ash and nitrogen fertilizer as well as for logging and processing the additional volume increment. Nitrogen spreading would generate at least 1 full-time equivalent job position, and logging in nitrogen-fertilized areas would generate 4 full-time equivalents. Wood ash application in forests at the planned level would produce 4 full-time equivalent job positions and harvesting in fertilized areas would produce 8 full-time equivalents. In total fertilization in state forests would provide at least 18 full-time job positions.

Application of nitrogen fertilizer and wood ash would provide the maximum effect of GHG emission reduction after 10 years, when the cumulative reduction of net greenhouse gas emissions would reach 133 thous. tons CO_2 eq per year (Figure 1), including biofuel substitution effect. If substitution effect (16 thous. tons CO_2 eq. per year in average) is not taken into account, the net GHG emission reduction in the years of 11...50 would gradually drop from 38 thous. tons CO_2 eq. to 26 thous. tons CO_2 eq. per year.

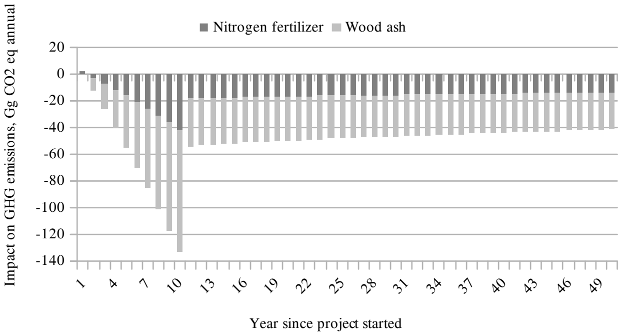

Figure 1. GHG emission projections due to forest fertilization

CO_2 removals can be also expressed in monetary terms. In the climate policy assessment document on land use, land-use change and forestry influence, prepared by European Commission (EC), the assumed value of the removal unit over the period 2021...2030 will be 20 € CO_2 per ton in average. According to this assumption, in 10 years forest fertilization would result in net CO_2 removals equal to 2.7 million € annually (Figure 2); however, in further years it would gradually decrease from 1.1 million € to 0.8 million € per year. If a full-scale forest fertilization project would be started in 2017, the potential value of sequestration units, which is accumulated over a period of 2021...2030 would reach 9.6 million €. Reduction of GHG emissions due to forest fertilization in 2030 would correspond to about 15 % of net CO_2 removals in forest, in accordance with the recent GHG projections for Latvia.

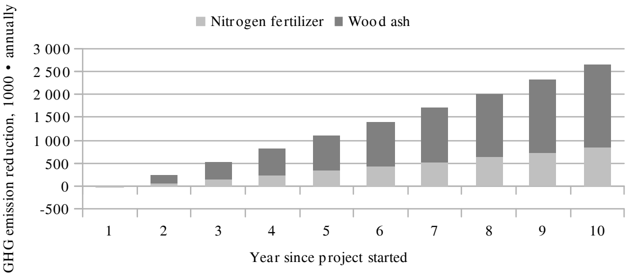

Figure 2. Reduction of GHG emissions caused by soil improvement measures expressed as CO_2 sequestration units 10 years after starting the project

Discussion and Conclusions

The financial rate of return of the fertilization depends on additional increment, quality of roundwood, time between fertilization and harvest, wood prices and the cost of fertilization. Logging costs were assumed to be 45 % from the revenue of selling wood, according to calculations of experts from the LVM (Lazdiņš et al. 2017). According to previous studies, productivity of wood ash spreading is 1.6 h ha^{-1}, but delivery of 1 m^3 of roundwood consumes 0.2 h of working time (Adamovičs et al. 2009).

Forest fertilization has an effect on GHG emissions directly after implementation of the fertilization project and secure a long-lasting cumulative effect in all carbon pools. Results from a research carried out in 2011...2015 were used for conversion of additional increment into biomass and carbon units (Muiznieks et al. 2015, Gancone et al. 2016, Liepiņš et al. 2016). In the following years the mitigation effect would gradually decrease because CO_2 removals in living biomass are partially compensated by logging in previously fertilized areas. When assessing how logging influences climate change mitigation (drop in CO_2 sequestration after the 11th year of the project), it has to be taken into account that logging provides the financial resources necessary for continuation of the soil improvement measures, therefore without logging the additional wood volume increment would gradually decrease and approach zero. In order to provide continually increasing effect of the GHG emissions reduction in areas, where forest fertilization measures have been applied, optimized soil improvement systems have to be introduced after reforestation, providing a significantly higher CO_2 sequestration in young, middle-aged and pre-mature stands. Significantly higher climate change mitigation effect can be reached by application of fertilizers repeatedly and shortening of rotation length. In order to introduce this practice, forest management guidelines should be reviewed and measures reducing natural mortality (loss of additional increment) and providing conditions (sufficient light and moisture) for continuous formation of the additional volume increment should be introduced.

Several studies indicate that wood ash and nitrogen fertilization are financially feasible methods of forest management. Long-term effect of wood ash fertilization on financial performance of a Scots pine (*Pinus sylvestris* L.) stand in a nitrogen-rich drained peatland forest in central Finland was examined and the financial analysis approved that fertilization with wood ash resulted in significantly better financial performance than control sites for the period between fertilization and thinning. When the discount rate was 3%, the discounted equivalent annual income (EAI) of wood ash fertilization was about three times higher than that of the control treatment (76.1 and 28.4 € ha^{-1} year^{-1}, respectively) (Moilanen et al. 2015). Another study suggests that N fertilization improves the profitability of management of the boreal upland conifer forest in Finland. If 10 years after fertilization 25% of the additional volume increment is harvested as pulpwood and 75% as sawlogs, the IRR would be around 8% (Pukkala 2017). Also, in Sweden N fertilization on mineral soils is profitable. Application of standard fertilizer amount (150 kg N ha^{-1}) may produce an IRR of 15% (Jacobson and Pettersson 2010).

Environmental issues, such as potential pollution with heavy metals, nutrient leaching, impact on biodiversity and human health effects should be considered, when mineral fertilizers or wood ash are applied in forest. Although fertilization increases carbon sequestration in living biomass and carbon stock may increase in forest soil because of additional litter production, it should be taken into account that manufacturing, transport and application of mineral fertilizers cause additional GHG emissions. Majority of CO_2 emissions (85...97%) from combustion of biomass are indirect emissions, which occur because carbon is released to the atmosphere at once, not by slow decomposition of logging residues at the harvest site (Repo et al. 2011). Negative effects of wood ash on vegetation, soil microorganisms and GHG emissions are reduced, when hardened wood ash is applied instead of loose ash and the applied doses correspond to the removal of biomass (Jacobson 2017). Application of granulated wood ash does not influence nitrous oxide (N_2O) emissions in boreal peat forests but in laboratory reduction of N_2O emissions from soil was observed due to reduction of pH (Liimatainen et al. 2014). No significant changes in fluxes of carbon dioxide (CO_2), methane (CH_4) and N_2O from the forest floor were observed during a study carried out in Sweden in nutrient poor drained peatland forests (Ernfors 2009). Whereas in Finland, in peatlands drained for forestry, fertilization with granulated wood ash significantly increased CO_2 emissions, especially in the nitrogen poor sites (Liimatainen et al. 2017). Application of nitrogen reduces autotrophic and heterotrophic respiration of soil. Nitrogen availability also has a large impact on species composition and diversity of ground vegetation. In a study carried out in boreal forest in Sweden abundance of grasses and several nitrophilous herbs increased by more than 100%, while dwarf shrubs were reduced by more than 40% (Strengbom and Nordin 2008). In order to reduce negative effects, nitrogen dose and application time should be adjusted.

It is reasonable to extend research on forest fertilization measures to evaluate the “start-up” fertilization method, which has been already successfully applied in Nordic countries and Latvia on an experimental scale. “Start-up” fertilization means spreading of wood ash on fertile forest soils (*Oxalidosa, Aegipodiosa, Myrtillosoi-polytrichosa* and *Drypteriosa* forest types) after final felling and thinning as well as simultaneous application of ash and nitrogen fertilizer. This solution would significantly increase the area available for the forest fertilization measures at the same time providing larger economic effects. Wood ash is available for free and it is cheaper to apply this material in forest after final felling because the machines do not need to manoeuver between trees or consider other safety requirements applicable in forest stands. Further research plans include the evaluation of the impact of forest management restrictions, analysis of influence of growing conditions and logistics as well as analysis of stand topography characteristics.

Conclusions

1. Application of ammonium nitrate with predictable positive impact on the additional volume increment in the state forests theoretically can be done on 2.1 thous. ha (0.14% of the state forests) resulting in the maximum additional increment in the 10th year. The area for potentially efficient application of wood ash is considerably bigger (4.3 thous. ha or 0.26% of the state forests annually).

2. The average annual costs of spreading mineral fertilizer in an area of 2.1 thous. ha is 349 thous. € (167 € ha^{-1}), but the costs of spreading wood ash are 517 thous. € (120 € ha^{-1}). Average additional logging costs from the 11th year of soil improvement practice are 2,250 thous. € annually. The average gross revenue from selling of additional volume increment considerably exceeds forecast of the expenses (5,001 thous. € per year).

3. The IRR value of the nitrogen fertilizer application in the 20th year of the hypothetical fertilization project is 11 %, whereas the IRR of wood ash application at the same time is 13 %. In spite of more expensive spreading the application of wood ash in forest results in better economic effect. Project influence on gross domestic product (GDP) would reach maximum (4.9 million € per year, if the measures are implemented in 6.4 thous. ha annually) in the 11th year. The public benefit of project implementation from tax revenues in this time increases up to 1.5 million € per year.

4. Besides the economic effect, the forest fertilization is among the most effective measures, which can be utilized to reduce GHG emissions in forest lands. By applying nitrogen fertilizer and wood ash each year in an area of 6.4 thous. ha, cumulative reduction of GHG emissions in the 10th year would reach 635 thous. tons CO_2 eq.

Biofuel substitution effect in average equals to 16 tons CO$_2$ ha^{-1} annually.

5. Monetary value of CO$_2$ removal units gained due to forest fertilization in area of 6.4 thous. ha annually in the 10th year would equal to 2.7 million €. In the following 40 years the annual net CO$_2$ removals would gradually decrease from 1.1 to 0.8 million € due to decomposition of deadwood and harvested wood products. Additional net CO$_2$ removals due to forest fertilization equals to 156 € ha^{-1}.

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