Dissertationes Forestales 296

Essays on optimal forest management and water protection

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Academic dissertation
To be presented, with the permission of the Faculty of Agriculture and Forestry of the University of Helsinki, for public examination in Lecture Hall 1 of the Forest House (Metsätalo), Unioninkatu 40, Helsinki, on 25th June 2020, at 12 o'clock.

Title of dissertation: Essays on optimal forest management and water protection

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Dissertationes Forestales 296

https://doi.org/10.14214/df.296

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ISSN 1795-7389 (online)
ISBN 978-951-651-682-3 (pdf)

ISSN 2323-9220 (print)
ISBN 978-951-651-683-0 (paperback)

Publishers:
Finnish Society of Forest Science
Faculty of Agriculture and Forestry at the University of Helsinki
School of Forest Sciences at the University of Eastern Finland

Editorial Office:
Finnish Society of Forest Science
Viikinkaari 6, FI-00790 Helsinki, Finland
http://www.dissertationesforestales.fi

Miettinen, J. (2020). Essays on optimal forest management and water protection.
Dissertationes Forestales 296. 38 p. https://doi.org/10.14214/df.296

ABSTRACT

This dissertation develops a framework to examine socially optimal forest management when nutrient and sediment loads from forestry are considered as a negative externality. The Faustmann rotation model is extended to include the runoff function to describe the water quality impacts of nutrient and sediment loads from forestry.

This thesis consists of an introductory section and four articles that analyze the different forest management practices and associated water protection. Examined practices include final harvesting in both mineral soils and peatlands, stem-only harvesting and whole-tree harvesting in peatlands, and ditch network maintenance. The water protection measures included are buffer zones in mineral soil forestry and overland flow fields and sedimentation ponds in drained peatlands.

The main contribution of this thesis is the developed framework for analyzing socially optimal forest management when water quality is taken into account. The analysis shows that the nutrient and sediment load damages associated with forest management depends highly on management practices. The nitrogen load caused by final harvesting in mineral soils results in relatively low nitrogen load damages. In contrast, the sediment load damages due to ditch network maintenance in the sensitive headwater catchment are very high. Furthermore, the cost-effectiveness of water protection measures differs significantly. From society´s viewpoint, the buffer zones used in mineral soil forest management are not a cost-effective water protection measure but when biodiversity benefits are taken into account, in addition to water quality, they become socially desirable. Overland flow fields are very cost-effective water protection measures for peatland forestry. Finally, the water protection costs in forestry and agriculture are compared in a river basin model. A cost-effective solution requires the highest nutrient reductions in agriculture, though it also implements water protection measures, especially in drained peatland forestry.

Keywords: rotation model, even-aged forest management, ditch network maintenance, nutrient load, sediment load, cost-effectiveness

ACKNOWLEDGEMENTS

I would like to thank all the people who have supported my work during the years. First and foremost, I am indebted to my supervisors for their support throughout the dissertation process. I would like to express my deepest gratitude to Markku Ollikainen for excellent teaching and guidance through my master´s and doctoral studies in environmental economics. I highly appreciate the opportunity to combine my interest in forest economics and environmental economics. This thesis would not have been possible without your invaluable contributions. I am also grateful to my other supervisor Lauri Valsta for guidance and helpful advice throughout these years. My warm thanks to the personnel and both current and previous fellow doctoral students in the environmental economics discipline at the University of Helsinki for all your support.

This thesis is a result of multidisciplinary work, and I would like to acknowledge a long list of coauthors. My sincere thanks to Jukka Aroviita, Leena Finér, Soili Haikarainen, Jari Hynynen, Harri Koivusalo, Ari Laurén, Mika Lehtonen, Mika Nieminen, Tiina Nieminen, Jarno Turunen and Liisa Ukonmaanaho for providing hydrological and ecological data and sharing your knowledge on different aspects related to water protection in forestry. In particular, my warmest appreciation to Mika Nieminen for your contribution to the last two articles of this thesis.

I am grateful for the pre-examiners Olli-Pekka Kuusela and Jussi Uusivuori for their thorough examination of my thesis and valuable comments. Sincere thanks to Tommi Ekholm for agreeing to be my opponent. I acknowledge funding from the University of Helsinki, Academy of Finland, Finnish Cultural Foundation, Kyösti Haataja Foundation, Alfred Kordelin Foundation, Yrjö Jahnsson Foundation and Niemi Foundation.

Finally, I wish to thank my family and friends for always being there for me in both joys and sorrows. In particular, my heartfelt thanks to my parents, my sister and brother, and my parents-in-law for helping us with the children and even more significantly for being a close part of their lives. Above all, I am sincerely thankful for Antti, Emma and Oona for all the love and happiness you have brought to my life.

LIST OF ORIGINAL ARTICLES

I Miettinen, J., Ollikainen, M., Finér, L., Koivusalo, H., Laurén, A., Valsta, L. (2012). Diffuse load abatement with biodiversity co-benefits: the optimal rotation age and buffer zone size. Forest Science 58(4): 342-352. https://doi.org/10.5849/forsci.10-070

II Miettinen, J., Ollikainen, M., Nieminen, T.M., Ukonmaanaho, L., Laurén, A., Hynynen, J., Lehtonen, M., Valsta, L. (2014). Whole-tree harvesting with stump removal versus stem-only harvesting in peatlands when water quality, biodiversity conservation and climate change mitigation matter. Forest Policy and Economics 47: 25-35. https://doi.org/10.1016/j.forpol.2013.08.005

III Miettinen, J., Ollikainen, M., Aroviita, J., Haikarainen, S., Nieminen, M., Turunen, J., Valsta, L. (2019). Boreal peatland forests: ditch network maintenance effort and water protection in a forest rotation framework. Manuscript accepted for publication in Canadian Journal of Forest Research.

IV Miettinen, J., Ollikainen, M., Nieminen, M., Valsta, L. (2019). Cost function approach to water protection in forestry. Water Resources and Economics. In press. https://doi.org/10.1016/j.wre.2019.100150

AUTHOR´S CONTRIBUTION

Summary: Jenni Miettinen wrote the summary.
Article I: "Diffuse load abatement with biodiversity co-benefits: the optimal rotation age and buffer zone size". Jenni Miettinen and Markku Ollikainen jointly planned the study and analyzed the theoretical model. Jenni Miettinen carried out the numerical analysis. Leena Finér, Harri Koivusalo and Ari Laurén provided the hydrological data. Jenni Miettinen was primarily responsible for writing the article, except for Leena Finér, Harri Koivusalo and Ari Laurén, who wrote the description of the hydrologic and nitrogen models.
Article II: "Whole-tree harvesting with stump removal versus stem-only harvesting in peatlands when water quality, biodiversity conservation and climate change mitigation matter". Jenni Miettinen, Markku Ollikainen, Tiina Nieminen and Liisa Ukonmaanaho jointly planned the study and conducted the numerical analysis. Jenni Miettinen and Markku Ollikainen analyzed the theoretical model. Tiina Nieminen, Liisa Ukonmaanaho and Ari Laurén provided the hydrological data. Mika Lehtonen and Jari Hynynen provided the Motti simulation data. Jenni Miettinen was primarily responsible for writing the article, except for Tiina Nieminen and Liisa Ukonmaanaho, who wrote the description of the hydrological data and Motti simulations and data.
Article III: "Boreal peatland forests: ditch network maintenance effort and water protection in a forest rotation framework". Jenni Miettinen and Markku Ollikainen jointly planned the study and analyzed the theoretical model. Jenni Miettinen carried out the numerical analysis. Jukka Aroviita and Jarno Turunen provided the data on a threshold of ecological harm for stream ecosystems. Mika Nieminen provided the data on the retention capacities of overland flow fields. Soili Haikarainen provided the data for the Motti simulations. Jenni Miettinen conducted the Motti simulations. Jenni Miettinen was primarily responsible for writing the article, except for Jukka Aroviita, Jarno Turunen and Mika Nieminen, who wrote the descriptions of the data they provided.
Article IV: "Cost function approach to water protection in forestry". Jenni Miettinen and Markku Ollikainen jointly planned the study and analyzed the theoretical model. Jenni Miettinen carried out the numerical analysis. Mika Nieminen provided the data on the retention capacities of overland flow fields and sedimentation ponds. Jenni Miettinen was primarily responsible for writing the article, except for Mika Nieminen, who wrote the description of the data on the retention capacities of overland flow fields and sedimentation ponds.

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1 INTRODUCTION

1.1 Background and motivation

Forests provide several ecosystem services, such as timber, biodiversity conservation, climate regulation, flood prevention and water quality, to society. However, forest management also causes negative impacts on several ecosystem services, for instance by increasing nutrient and sediment loads to watercourses; accelerating biodiversity loss and creating climate impacts through harvesting. These impacts are economically considered as negative externalities. This thesis focuses on the negative externalities caused by different forest management practices, especially with respect to water quality.

Even-aged forest management practices causing nutrient and sediment loads include final harvesting, regeneration, ditch network maintenance and fertilization (e.g., Grip 1982; Ahtiainen and Huttunen 1999; Joensuu 2002; Laurén et al. 2005; Palviainen et al. 2014, 2015; Nieminen et al. 2018a). In Finland, the share of the forestry-induced nutrient load covers 5% of the total nitrogen load and 8% of the total phosphorus load (Finér et al. 2010). However, regionally, forestry may account for a significantly higher share of the total nutrient loads. Furthermore, the main adverse effect of forestry as a polluting sector comes especially in the form of high sediment loads from drained peatlands.

Several water protection measures are available to decrease nutrient and sediment loads to watercourses, including buffer zones along watercourses, sedimentation ponds, overland flow fields and other defensive measures (e.g., Ahtiainen and Huttunen 1999; Joensuu 2002; Laurén et al. 2005; Haahti et al. 2018; Nieminen et al. 2018b). While these water protection measures decrease the nutrient and sediment loads, there are costs associated with the measures; thus, there is a trade-off between reducing damages and increasing costs.

The traditional Faustmann rotation model (1849) describes the optimal framework for decision-making at the stand level when only harvest revenue is taken into account. To consider the negative water externalities caused by forestry to the recreationalists and other users of aquatic resources, the basic Faustmann model must be extended to include water quality aspects via nutrient runoff function and valuation of the damages they cause. The extended model allows the social planner to trade-off harvest revenue against negative externalities to maximize social welfare. The model can be interpreted as a version of the Hartman model (1976), which extends the Faustmann rotation model to include amenity values.

There are few studies linking forest economics and water protection in the social welfare framework (an exception is Matero 1996; 2002; 2004). This thesis fills this gap in research and provides a full analysis of forest management when negative externalities from nutrient and sediment loads are included.

1.2 Research objectives

Forest management practices and their impacts on nutrient and sediment loads differ depending on, among other things, whether forestry is based on even-aged or uneven-aged harvesting. In this thesis, the focus is on even-aged forestry, which entails clear-cutting. Even-aged forestry may take place in mineral soils or in drained peatlands. Nutrient and sediment loads and means of reducing the loads differ greatly between these land types.

In mineral soils, buffer zones can be applied as a water protection measure to reduce the nutrient load. The land area allocated to an unharvested buffer zone reduces the harvest revenue from the specific harvest area, inducing costs. Additionally, prolonging the rotation age postpones the nutrient load damage following the clear-cut. Hence, the question to examine is how the social planner simultaneously chooses the optimal rotation age and the size of the buffer zone when water quality is included in the analysis?

In drained boreal peatlands, forest management practices consist of clear-cuts accompanied by ditch network maintenance to increase forest growth. Clear-cuts and ditch network maintenance induce nutrient and sediment loads, which can be reduced by overland flow fields. Both ditch network maintenance and the overland flow field have costs. The research question is as follows: how does the optimal rotation age and ditch network maintenance effort change due to nutrient and sediment loads, and what is the size of the overland flow field to best serve as a water protection measure?

Once the optimal forest management is known, a question arises regarding how great the required reduction in nutrient loads from forestry should be relative to that in other polluting sectors. Economic theory suggests that to reach cost-effectiveness in water protection, the marginal abatement costs of different polluting sectors must be equalized for any target level of nutrient reductions. For this reason, the marginal abatement costs must be defined for all polluting sectors, including forestry. The analysis of the nutrient loads and the measures to reduce them provide a starting point for this analysis.

At a general level, the two main research questions of this thesis are as follows:

1) How does optimal forest management look like when nutrient and sediment loads and measures to reduce them are simultaneously taken into account?

2) How great are the marginal abatement costs of reducing nutrient and sediment loads, and what is the forestry's cost-efficient share in overall nutrient abatement in a river basin scale?

The thesis consists of four studies employing both analytical and numerical approaches:

Study I: Diffuse load abatement with biodiversity co-benefits: the optimal rotation age and buffer zone size

Study II: Whole-tree harvesting with stump removal versus stem-only harvesting in peatlands when water quality, biodiversity conservation and climate change mitigation matter

Study III: Boreal peatland forests: ditch network maintenance effort and water protection in forest rotation framework

Study IV: Cost function approach to water protection in forestry

Table 1 summarizes the key components of the studies. Study I examines the water quality impacts of final harvesting in mineral soil forests when nutrient loads can be reduced by a buffer zone. Study II compares two different forest harvesting practices used in peatland forestry. Study III focuses on the overland flow field and abstaining from ditch network maintenance as the means of reducing nutrient and sediment loads from harvesting and ditch network maintenance in drained peatlands. Study IV covers both final harvesting in mineral soils and drained peatlands and ditch network maintenance in peatland forestry to estimate the marginal abatement costs in forestry drawing on studies I and III.

Even though this thesis focuses mainly on the water quality impacts of forest management, studies I and II also include impacts on other related ecosystem services. In addition to nutrient load damage, the biodiversity benefits provided by the buffer zone are analyzed in Study I. Study II includes both several water quality damages (nitrogen, phosphorus and mercury load damages) and climate impacts (substitution of fossil fuels, CO_2 emitted by harvesting vehicles and lost woody biomass as a carbon sink).

Table 1. Summary of the key components of the studies.

	Forest management practices	Water protection measures	Externalities caused by forest management	Numerical approach
I	Final harvesting	Buffer zone	Nitrogen load damage Biodiversity benefits	Numerical model and optimization
II	Stem-only harvesting Whole-tree harvesting	No water protection methods included	Nitrogen load damage Phosphorus load damage Mercury load damage Substitution of fossil fuels CO_2 emitted by harvesting vehicles Lost woody biomass as a carbon sink	Numerical evaluation of net social benefits
III	Final harvesting Ditch network maintenance	Overland flow field Abstaining from ditch network maintenance	Nitrogen load damage Phosphorus load damage Sediment load damage	Numerical model and optimization
IV	Final harvesting Ditch network maintenance	Buffer zone Overland flow field Sedimentation pond	Nitrogen load damage Phosphorus load damage Sediment load damage	Numerical evaluation of marginal abatement costs and optimization

1.3 Literature review

Previous analytical literature on socially optimal forest management and water quality is scarce. Closest to this thesis is the study by Matero (2004), who presented a two-period model to analyze cost-effective measures for water protection in Finnish forestry. The study included both harvesting and drainage maintenance as forest management practices and buffer strips, sedimentation pools and sedimentation fields as water protection measures. Matta et al. (2009) employed the Faustmann rotation model to examine biodiversity protection in Florida (USA), and among other practices, the study included buffer zones and prolonged rotation ages. However, Matta et al. (2009) did not include water quality impacts. Analytical studies that apply the Faustmann rotation model to examine water aspects typically include water yield (e.g., Clarke 1994; Creedy and Wurzbacher 2001), not water quality management.

For the most part, the previous economic literature on forest management and associated water protection includes studies that empirically estimate the costs of water protection in forestry, especially the costs of buffer zones. The majority of studies examine forest management and water protection in the USA and Scandinavia. Earlier economic studies related to buffer zones and their costs in forestry include Ellefson and Miles (1985); Yoshimoto and Brodie (1994); Matero (1996, 2002, 2004); Laurén et al. (2007); Zobrist and Lippke (2007); Trenholm et al. (2013); Tiwari et al. (2016); and Lundström et al. (2018). Ellefson and Miles (1985) analyzed the costs of six different water protection measures, including bugger strips, used to reduce the water quality impacts of harvesting in the Midwest (USA). Yoshimoto and Brodie (1994) studied spatial restrictions on harvest areas located in riparian areas and their effects on the total present net worth from harvesting in Oregon (USA). Laurén et al. (2007) studied the water protection costs and benefits in mineral soil forestry in Finland. They simulated nitrogen export levels for different combinations of buffer zone sizes and cutting intensities to determine the costs of nitrogen reductions. Zobrist and Lippke (2007) compared the costs of riparian regulations in two states, western Washington and Oregon, in the Pacific Northwest (USA). Trenholm et al. (2013) combined contingent valuation and wood supply modeling methods in a cost-benefit analysis of riparian buffers in eastern Canada. Tiwari et al. (2016) compared the costs of fixed-width buffer zones to variable-width buffer zones in the Kryclan catchment in northern Sweden. A trade-off between ecological and economic values related to alternative management of buffer zones was studied by Lundström et al. (2018). They developed a decision support system Heureka applied to Swedish forest management.

Large part of the studies from the USA are related to forestry best management practices (BMPs) used to prevent non-point pollution related to forest management, e.g., Ellefson and Miles (1985); Henly et al. (1988); Shaffer et al. (1998); Kluender et al. (2000); Cubbage (2004); and Sun (2006). As in most of these studies, Ellefson and Miles (1985), Henly et al. (1988), Shaffer et al. (1998) and Kluender et al. (2000) estimated the costs of these practices. Cubbage (2004) provided a review of these studies related to the costs of forestry BMPs. Sun (2006) analyzed the welfare impacts of forestry BMPs, including stream management zones, on different stakeholders.

In addition to buffer zones and BMPs, alternative forest management intensities may be used to mitigate water impacts in forestry. Miller and Everett (1975) analyzed different forest management practices and alternative harvesting intensities and their effects on sediment loss in Indiana (USA). Eriksson et al. (2011) analyzed the impacts of the EU Water Framework Directive on the net present value of forestry under given requirements on water quality. They used a linear programming model describing forest management that included requirements on concentrations of nitrogen, phosphorus, methyl mercury and dissolved organic carbon in northern Sweden. Duncker et al. (2012) studied the impacts of forest management alternatives on several ecosystem services by simulating a virtual normal forest located in Central Europe. The estimated ecosystem services and impacts included merchantable timber production, land expectation value, biodiversity, water quality and quantity, soil fertility, carbon sequestration and carbon stock. Hökkä et al. (2017) analyzed how varying ditch network maintenance intensity impacts timber production, profitability and nutrient and sediment loading in Finland.

There are also some catchment-scale studies that have included forestry in the model frameworks. Ovando and Brouwer (2019) review studies that examine the interactions between forest management and watershed services in economic frameworks. The reviewed literature covered various watershed services, including studies on water quality aspects. A study by Hjerppe and Väisänen (2015) included forestry as one polluting sector and analyzed the cost-effective reduction of phosphorus in 8 different Finnish catchments. They developed a KUTOVA tool with 19 different measures to reduce phosphorus loads, of which five were used in the forestry sector: buffer zones, overland flow, peak runoff control, drowned weir for runoff control and constructed wetlands. Xu et al. (2018) provided an integrated modeling framework for Lake Erie's Sandusky River watershed (Ohio, USA) to analyze both phosphorus reduction and economic performance. The model included the conversion of cropland to forestry as one option.

2 FORESTRY AND WATER PROTECTION IN FINLAND

Currently, forestry is estimated to cause a nitrogen load of 1600 Mg year^{-1} and a phosphorus load of 130 Mg year^{-1} (Finér et al. 2010). The share of forestry as a polluting sector is only approximately 5% of the total nitrogen load and 8% of the total phosphorus load in Finland (Finér et al. 2010). However, locally, in northern headwater catchments, forestry can be the only significant anthropogenic source of nutrient and sediment loads, and its contribution may be significantly larger (15% of the total nitrogen load and 20% of the total phosphorus load) (Markkanen et al. 2001, Finér et al. 2010). Furthermore, based on recent studies (Nieminen et al. 2017a; Nieminen et al. 2018c) suggesting that the nutrient exports caused by peatland drainage are not short-term, but rather, there is a permanent legacy effect, drained peatlands may contribute to nutrient and sediment loads much more than previously estimated. The nutrient and sediment loads from forestry are forms of nonpoint pollution, which poses challenges for designing water protection. The loads are generally high during the first few years after forest management but may last ten years or even longer. (Finér et al. 2010).[1]

[1] It should be noted that in January 2020, after this introductory article was written, new results concerning nutrient and organic carbon export from forests to watercourses in Finland were published. According to the new results, forestry causes 12% of the total nitrogen load and 14% of the total phosphorus load in Finland. The main reason for the increased significance of forestry as a polluting sector is forest drainage. (Finér et al. 2020.) In Studies III and IV of this thesis, the nutrient and sediment load figures used are based on previous official estimates of the specific load values, i.e., those reported in Finér et al. (2010).

2.1 Forest management and water quality in mineral soil and drained peatland forests

Even-aged forest management is a source of nitrogen, phosphorus and sediment loads to brooks, rivers and lakes. Currently, the main sources of loading are clear-cutting, site preparation, fertilization, burn-clearing and ditch network maintenance (Finér et al. 2010). The annual clear-cut area in Finland was between 109,126 ha and 144,818 ha in 2010-2014 (Natural Resources Institute Finland 2015). Clear-cuts in mineral soil forests and drained peatlands are significant sources of nutrient loads. Clear-cutting in mineral soils has been observed to enhance both nitrogen and phosphorus loads (Vitousek et al. 1979; Grip 1982; Rosén et al. 1996; Ahtiainen and Huttunen 1999; Laurén et al. 2005; Palviainen et al. 2014, 2015). As the trees are removed, the mineralization of nutrients from soil and harvest residues increase, and the nutrient uptake decreases, which increases leaching (Rosén et al. 1996).

In drained peatlands, ditch network maintenance and clear-cutting have been shown to increase sediment and nutrient loads to watercourses (e.g., Manninen 1998; Ahtiainen and Huttunen 1999; Lundin 1999; Joensuu 2002; Nieminen 2003, 2004; Nieminen et al. 2010; Nieminen et al. 2017b; Nieminen et al. 2018a). Peatlands are wetlands where the high groundwater level limits tree growth (Päivänen and Hånell 2012; Sikström and Hökkä 2016). As drainage lowers the groundwater level, it increases tree growth (Sikström and Hökkä 2016). Currently, pristine peatlands are not drained in Nordic countries, but because of ditch deterioration over time since drainage, ditches require maintenance every 15-30 years (Päivänen and Hånell 2012; Sikström and Hökkä 2016). Ditch network maintenance means either clearing the old ditches (ditch cleaning), excavating new ditches between the old ditches (supplementary ditching), or executing both practices. When ditch network maintenance is implemented, erosion in the ditch network increases, inducing sediment loads (Stenberg 2016). Ditch network maintenance is regarded as the most harmful forest management measure in Finland, particularly because of high sediment loads but also because of the nutrients that adhere to sediments (Finér et al. 2010; Joensuu et al. 2002; Nieminen et al. 2017a).

Nutrient loads from clear-cut areas located in drained peatlands are clearly higher than those from clear-cuts in mineral soil forests (Finér et al. 2010). Drained peatland forests comprise approximately 25% of forestland in Finland, and a considerable share of them will reach maturity within the next 10-30 years. Thus, clear-cuts in drained peatland forests will undergo a significant increase in the future. After clear-cutting in peatland forests, the groundwater level rises, and both runoff and nutrient loads increase (Lundin 1999; Kaila et al. 2014; Sikström and Hökkä 2016).

While stem-only harvest removes only tree stems, whole-tree harvesting also removes harvest residues, such as tree tops, branches and foliage. Additionally, tree stumps have been harvested in recent years. Studies from Finnish conditions (Kaila et al. 2014, 2015) suggest that the effects of these two harvesting practices on nutrient loads may not differ significantly, but the effects of clear-cuts may differ significantly depending on the site characteristics (Lundin 1999; Nieminen 2003, 2004). The studies related to the impacts of harvesting on mercury (Hg) and methylmercury (MeHg) concentrations show mixed results. Increased levels of Hg and MeHg caused by harvesting were found by Porvari et al. (2003), Desrosiers et al. (2006) and Skyllberg et al. (2009), but de Wit et al. (2014) found no impact on MeHg levels. Furthermore, the study by Eklöf et al. (2013) did not indicate increased total mercury (THg) and MeHg concentrations after stump harvesting. When comparing stem-only harvesting and whole-tree harvesting with stump harvesting, no clear differences in Hg and MeHg concentrations were found by Ukonmaanaho et al. (2016).

In Study I, the nitrogen export data following clear-cutting in mineral soil were from the Finnish Forest Research Institute based on load figures used in the FEMMA model (a more detailed description of the data is found in Study I). In Study II, the numerical data on loads were based on a catchment experiment conducted in Sotkamo, eastern Finland. The data included analysis of total nitrogen, phosphorus and mercury from five drained catchments, including both low- and high-fertility sites (a more detailed description of the data is found in Study II). In Studies III and IV, the nutrient and sediment load figures used were based on the specific load values reported in Finér et al. (2010). They expressed how much the loads increased above non-managed levels due to forest management. The figures were estimated per managed area separately for each forest management practice. (Finér et al. 2010.)

2.2 Water protection measures in forestry

Water protection measures applied in Finnish forestry differ depending on the associated forest management practice and whether the target is to reduce the nutrient and sediment loads from mineral soil forests or from drained peatland forests. A buffer zone is a strip between a clear-cut site and a watercourse, and it is used as a water protection measure to reduce the increased nutrient load after clear-cutting in mineral soils (Norris 1993; Ahtiainen and Huttunen 1999; Laurén et al. 2005). It can be left uncut or selective cuttings may be conducted. The nutrient retention capacity of the buffer zone depends on its soil type, topography, hydrological pathways, vegetative cover, microbial activity and the area of the buffer zone relative to the treated upslope area (Gundersen et al. 2010). Requirements concerning buffer zone widths in Finland are provided in forest management guidelines and forest certification systems, and they vary from 5 to 30 meters (Finnish FSC Association 2010; PEFC Finland 2014; Äijälä et al. 2019).

In drained peatland forestry, various water protection measures to reduce both nutrient and sediment loads to watercourses are used, such as overland flow fields, sedimentation ponds, peak runoff control dams, sedimentation pits and ditch breaks (Joensuu et al. 1999; Liljaniemi et al. 2003; Nieminen et al. 2005; Väänänen et al. 2008; Marttila et al. 2010; Marttila and Kløve 2010; Vikman et al. 2010; Hynninen et al. 2011; Haahti et al. 2018; Nieminen et al. 2018b). In this thesis (studies III and IV), we concentrated on two water protection measures most often used in peatland forestry, namely, overland flow fields and sedimentation ponds.

Overland flow fields are constructed between the drained area and a watercourse by directing drainage waters from the drained peatland area to a pristine or restored mire. The efficiency of overland flow fields to reduce nutrient and sediment loads depends on their size, ground vegetation, slope and type of surface soil. (Nieminen et al. 2005.) Overland flow fields are efficient, especially when the size of the overland flow field is at least 0.5-1% of the upstream catchment area and the nutrient and sediment loads are high (Sallantaus et al. 1998; Nieminen et al. 2005; Silvan et al. 2005; Väänänen et al. 2008; Vikman et al. 2010). The Finnish forest management guidelines for water protection recommend that the minimum size of the overland flow field be 1% of the catchment area (Joensuu et al. 2012).

Sedimentation ponds are excavated in the main outlet ditch to slow water flow from the drained area and enable sedimentation (Joensuu et al. 1999; Nieminen et al. 2018b). In drained peatlands, the size of the sedimentation pond usually varies from 40 m^3 to 500 m^3 (Joensuu et al. 1999). Sedimentation ponds are used to reduce the sediment load, and their efficiency mostly depends on their volume, the amount of the annual sediment load entering the pond, and the characteristics of inflowing sediment (Nieminen et al. 2018b). The recommended size of the sedimentation pond is given in the Finnish forest management guidelines for water protection (Joensuu et al. 2012). Sedimentation ponds are the most common water protection measure used in drained peatlands, but their efficiency varies significantly (Joensuu et al. 1999; Nieminen et al. 2018b). Overland flow fields are used infrequently in practical forestry even though they may be very efficient, and unlike sedimentation ponds, they are able to reduce both dissolved nutrient and sediment loads. The use of overland flow fields is restricted to sloping areas, as the blocking of ditches in flat areas to create an overland flow field may cause the water table to rise in the upstream forest area, impairing tree vitality and growth there. (Nieminen et al. 2018b.)

Finally, in addition to the technical water protection measures presented above, it might sometimes be reasonable to reduce the nutrient and sediment loads by not implementing ditch network maintenance. This is particularly true at sites where the financial profitability of ditch network maintenance is low (Ahtikoski et al. 2008, 2012).

2.3 Co-benefits of forest management and water protection

Forest management and associated water protection offer several co-benefits. This thesis covers the biodiversity benefits provided by the buffer zone (Study I) and the climate impacts of stem-only harvesting compared to whole-tree harvesting (Study II).

Buffer zones used in mineral soils in conjunction with final harvesting provide various terrestrial and aquatic biodiversity benefits (Kuglerová et al. 2014), such as maintaining microclimatic environments (Brosofske et al. 1997), protecting bird communities (Spackman and Hughes 1995; Hagar 1999; Pearson and Manuval 2001) and riparian plant communities (Hylander et al. 2002; Selonen and Kotiaho 2013; Elliott et al. 2016; Oldén et al. 2019), controlling stream temperature (Sweeney and Newbold 2014) and protecting macroinvertebrates (Newbold et al. 1980; Sweeney and Newbold 2014) and fish (Horwitz et al. 2008; Sweeney and Newbold 2014). Furthermore, buffer zones act as riparian corridors between terrestrial and aquatic environments (Naiman et al. 1993). Most often, regulations and guidelines are provided to protect the aquatic environment and are less focused on terrestrial biodiversity (Gundersen et al. 2010; Phoebus et al. 2017). In addition to the width of the buffer zone, the structure of the vegetation, species composition and forest management activities in the buffer zone area affect the impacts that a buffer zone has on the stream (Broadmeadow and Nisbet 2004).

All harvesting has climate impacts, as carbon is released to the atmosphere, but harvesting practices matter. Climate impacts of stem-only harvesting and whole-tree harvesting with stump removal differ due to the use of forest residues and stumps in the latter alternative. Forest biomass has been previously regarded as a carbon neutral or low-carbon energy source, as carbon dioxide emissions from biomass combustion are compensated by the growth of new tree generation (e.g., Stupak et al., 2007). However, the climate impacts of forest bioenergy have been found to depend on various aspects, such as the regulator´s time horizon and preference and the social cost of carbon as a measure of damage (Repo et al. 2011; Repo et al. 2012; Rautiainen et al. 2018). Furthermore, the climate impacts of forest biomass depend highly on the type of biomass considered. Climate impacts of burning stumps are much higher than, for example, the impacts of burning small branches and foliage (Repo et al. 2012; Rautiainen et al. 2018). The study by Repo et al. (2015) showed that forest bioenergy may have significant climate impacts because the time lag between carbon loss in combustion and carbon sequestration of the new tree generation takes decades. Finally, as concluded by Rautiainen et al. (2018), in addition to time preference and the social cost of carbon, the climate impact of forest residues also depends on the type of energy source that the forest bioenergy is compared with, such as coal or natural gas, as the carbon contents differ. According to the Intergovernmental Panel on Climate Change (IPCC) guidelines, carbon dioxide emissions from biomass combustion can be counted as zero in the energy sector if these emissions are taken into account in the land use, land use change and forestry sector (LULUCF) (IPCC 2006).

3 THEORETICAL FRAMEWORK

This section outlines how the Faustmann rotation model can be extended to cover nutrient and sediment loads caused by forest management practices and associated water protection measures. The model describes socially optimal forest management in both mineral soil and peatland forests.

3.1 Socially optimal forest management and water protection in mineral soil forests

Consider a social planner maximizing harvest revenue while also considering the nutrient load to watercourses caused by final harvesting. The planner uses buffer zones as a measure to decrease the nutrient load. The buffer zone is a permanently unharvested share of land between a harvest area and a watercourse. The planner operates on a mineral soil forest stand next to a watercourse. Nutrient loading starts after the final harvesting of the stand and is expected to last x years. The share of the buffer zone from the area of the forest stand is m, and for a forest stand of a given size and shape, m, uniquely defines the width of the buffer zone. Thus, m refers to the size of the buffer zone. The nutrient load from the forest stand area after final harvesting, $g(s,m)$, is expressed as a function of the size of the buffer zone and the time since the clear-cut, s. If the size of the buffer zone increases, the nutrient load is reduced, and the first derivative is negative, $g_m < 0$. However, the rate of reduction decreases as the size of the buffer zone increases ($g_{mm} > 0$). The size of the forest stand is normalized to unity. For any share of the buffer zone, the nutrient load from the area of the stand is $z = (1-m)g(s,m)$. Then, adding a monetary value to describe the damage from the decreased water quality caused by the nutrient load after final harvesting, $D(z)$ describes the nutrient load damage as a function of the periodic nutrient loads, z:

$$D(z) = D\left[\int_0^x (1-m)g(s,m)e^{-rs}ds\right]. \quad (1)$$

From equation (1), the nutrient load is reduced via two channels: the harvested area decreases and the buffer zone fixes released nutrients. A positive linear damage function is assumed. The regeneration cost is C, the timber price is p and the real interest rate is *r*; these variables are assumed to be constant.

Different approaches can be considered to model social welfare in a rotation framework that combines a choice of optimal harvesting and a buffer zone reducing water quality damage. We focus on cases where bare land is either planted or naturally regenerated. Timber volume is a function of rotation age and is denoted by $f(T)$ with conventional concavity properties. Consider first the case where bare land is planted. The steady state cycle of net harvest revenues and water quality damages from final harvest follows (P denotes regeneration by planting):

$$SW^P = \{(1-m)[pf(T)-c] - D(z)\}e^{-rT}(1-e^{-rT})^{-1} - c. \quad (2)$$

The social planner chooses the optimal rotation period, T, and the size of the buffer zone, m, to maximize social welfare. The first-order conditions are as follows:

$$SW_T^P = (1-m)[pf_T(T) - rpf(T)] + rD(z) - rS\widehat{W}^P = 0 \quad (3)$$

$$SW_m^P = -[pf(T)-c] - D'(z)\left[\int_0^x z_m(s,m)e^{-rs}ds\right] = 0 \quad (4)$$

where $S\widehat{W}^P = SW^P + mc$. Equations (3) and (4) describe the choices of the optimal rotation age and the size of the buffer zone, respectively.

Assuming alternatively a natural regeneration of the stand leads to the model presented in Study I. In this case, the social welfare is as follows (N denotes natural regeneration):

$$SW^N = \{(1-m)[pf(T)e^{-rT} - c] - D(z)e^{-rT}\}(1-e^{-rT})^{-1}. \quad (5)$$

The social welfare described in equation (5) differs from the social welfare defined in equation (2) due the different timing of actions, replacement of planting costs by costs associated with natural regeneration in (5) and consequent difference discounting net harvest revenue. The first-order conditions are as follows:

$$SW_T^N = (1-m)[pf_T(T) - rpf(T)] + rD(z) - rSW = 0 \quad (6)$$

$$SW_m^N = -[pf(T)e^{-rT} - c] - D'(z)e^{-rT}\left[\int_0^x z_m(s,m)e^{-rs}ds\right] = 0 \quad (7)$$

The first-order condition describing the choice of the optimal rotation age in equation (6) differs from the respective condition in equation (3) in terms of bare land value. Comparing equation (7) to equation (4) shows that in equation (4), the social benefits from the nutrient load reduction by the buffer zone are lower as well as the net harvest revenue lost due to differences in how the harvest revenue and nutrient load damage terms are discounted. However, the main findings with respect to first-order conditions are similar in both alternative formulations of the model. As shown in Study I, including the nutrient load damage in the Faustmann rotation model tends to lengthen the optimal rotation age. Furthermore, the optimal size of the buffer zone is determined so that the marginal net harvest revenue is equal to the marginal damage from the reduced nutrient load.

Theoretical results are new in the forest economics literature and can be used to describe water policies in forestry. Furthermore, the model can be used to examine other forest management practices, water protection measures and in addition to nutrient loads, also other water pollutants can be taken into account in optimizing water protection in forestry. Finally, to analyze social welfare, it is useful to include in the framework also other ecosystem services provided by forestry, such as biodiversity conservation (Study I) and climate regulation (Study II), and simultaneously analyze socially optimal forest management with several ecosystems taken into account as externalities.

This basic description of the theoretical model was modified in the following articles of the thesis. First, in Study II, the model was used to examine the two alternative harvesting practices in peatlands: whole-tree harvesting and stem-only harvesting. Second, in Study IV, the marginal abatement cost functions in mineral soil forestry were derived based on this theoretical framework developed in Study I. However, in Study IV, the model was modified such that the initial stand was assumed instead of starting with bare land. Furthermore, the framework can be added with investment in forest management, such as ditch network maintenance, which is presented in the next section.

3.2 Socially optimal forest management and water protection in drained peatland forests

Defining the socially optimal forest management and water protection in drained peatlands follows the analytical framework developed for mineral soils in Study I. In drained peatlands, however, one does not start with bare land. Instead, in previously drained peatlands, the starting point is an initial stand, as there are trees in the stand that have been born before and after the first-time drainage of pristine peatland.

Suppose that the drained peatland stand is located next to a watercourse. Let the initial stand age be A and the time of final harvesting be T. Thus, the time until final harvesting is $T - A$. We assume the first commercial thinning has been made. Given that time has elapsed since the first-time drainage, ditches are in poor condition and need improvement. Ditch network maintenance is needed to recover forest growth. The forest growth of the stand depends both on the age of the stand, T, and on the ditch network maintenance effort, n, and can be denoted as $f(T - A; n)$ (Chang 1983; Amacher et al. 1991). The properties of the growth function (as the relevant range of the rotation age is assumed) are $\frac{\partial f}{\partial T} = f_T > 0$, but $\frac{\partial^2 f}{\partial T^2} = f_{TT} < 0$; and $\frac{\partial f}{\partial n} = f_n > 0$, but $\frac{\partial^2 f}{\partial n^2} = f_{nn} < 0$; and $\frac{\partial^2 f}{\partial T n} = f_{Tn} > 0$ as the impact of marginal change in the ditch network maintenance effort on the current annual increment is positive (Chang 1983). The unit cost of the ditch network maintenance effort is w, the timber price is p, and the real interest rate is r (all assumed to be constant). The net harvest revenue function, V, is described as:

$$V = pf(T - A; n)e^{-r(T-A)} - wn. \qquad (8)$$

Modeling of the nutrient and sediment load damages from ditch network maintenance and final harvesting follows a similar description as that in Section 3.1 for nutrient load damages in mineral soil forestry. Nutrient and sediment load caused by ditch network maintenance starts at stand age A when ditch network maintenance is implemented. Let g^1 denote nutrient loading, g^2 denote sediment loading and k denote the number of years that the nutrient and sediment load are assumed to last after ditch network maintenance has been implemented. The marginal damage from nutrient and sediment loads (assumed to be constant) are d_1 and d_2, respectively. Hence, the nutrient load damage from ditch network maintenance is $d_1 \int_0^k g^1(s, n, B)e^{-rs}ds$, and the sediment load damage from ditch network maintenance is $d_2 \int_0^k g^2(s, n, B)e^{-rs}ds$, where s denotes time and B denotes the size of the overland flow field.

Increasing the ditch network maintenance effort increases the nutrient and sediment loads in an increasing or linear fashion, i.e., $g_n^i > 0$ and $g_{nn}^i \geq 0$ for $i = 1, 2$. The properties of the load function with respect to the size of the overland flow field are similar to those presented previously for the buffer zone, $g_B^i < 0$, but $g_{BB}^i > 0$ for $i = 1, 2$. The size of the overland flow field has no impact on how the ditch network maintenance effort increases the nutrient and sediment load, as the overland flow field is located outside the area where ditch network maintenance is implemented. Thus, the cross derivative is zero, $g_{nB}^i = 0$ for $i = 1, 2$. The nutrient and sediment load damage from ditch network maintenance is:

$$D(z_D) = d_1 \int_0^k g^1(s, n, B)e^{-rs}ds + d_2 \int_0^k g^2(s, n, B)e^{-rs}ds \quad (9)$$

In addition to ditch network maintenance, final harvesting causes nutrient loading. The number of years that the nutrient load takes place after final felling is denoted by h. The nutrient load function is g^3, and we assume that $g_B^3 < 0$ and $g_{BB}^3 > 0$. Thus, the damage function can be expressed as:

$$\widehat{D}(z_H) = d_1 \int_0^h g^3(s, B)e^{-rs}ds \quad (10)$$

The unit cost of the overland flow field is denoted by γ, and the social welfare in the steady state is denoted by W, where the latter is exogenous based on Chang (1998). Equations (8), (9) and (10) are combined to describe social welfare, which the social planner maximizes:

$$SW = pf(T - A; n)e^{-r(T-A)} - wn - \gamma B - D(z_D) - e^{-r(T-A)}\widehat{D}(z_H) + e^{-r(T-A)}W. \quad (11)$$

The social planner chooses the optimal rotation period, T, the ditch network maintenance effort, n, and the size of the overland flow field, B. The first-order conditions are as follows:

$$SW_T = pf_T - rpf + r\widehat{D}(z_H) - rW = 0 \quad (12)$$

$$SW_n = pf_n e^{-r(T-A)} - w - D'(z_D)\frac{\partial z_D}{\partial n} \leq 0 \quad (13)$$

$$SW_B = -\gamma - D'(z_D)\frac{\partial z_D}{\partial B} - e^{-r(T-A)}D'(z_H)\frac{\partial z_H}{\partial B} = 0. \quad (14)$$

The optimal rotation age is chosen based on equation (12): adding nutrient load damage to the Faustmann rotation model tends to lengthen the optimal rotation period. According to equation (14), the optimal choice of ditch network maintenance effort requires that the increased marginal harvest revenues due to ditch network maintenance should equal the sum of the unit costs of ditch network maintenance and the marginal nutrient and sediment load damages caused by ditch network maintenance. The optimal size of the overland flow field should be expanded to a point where the overland flow field unit costs are equal to the social benefits of the decreased nutrient and sediment loads.

Later, in Study IV, the model is modified to describe an initial stand with one rotation to derive the marginal abatement costs of nutrients and sediments in peatland forestry. Additionally, in Study III, the overland flow field is the assumed water protection measure but other water protection measures can be included in the model as well, and in Study IV, it is also used for sedimentation ponds.

4 SUMMARIES OF THE ESSAYS

4.1 Diffuse load abatement with biodiversity co-benefits: the optimal rotation age and buffer zone size

This study analyzed the socially optimal rotation age and the optimal size of the buffer zone when harvest revenue, water quality and biodiversity benefits were considered as the ecosystem services provided by the forests. The theoretical model was developed based on the classical Faustmann rotation model (1849), which was extended to include the impacts of clear-cutting on water quality. New theoretical findings on how including water quality in the optimization problem affects optimal forest management were found. First, the prolonged rotation ages postpone the stream of nutrient load damage in the infinite series of rotation ages. Second, the size of the buffer zone is increased until the harvest revenue lost from the buffer zone equals the marginal benefits from reduced nutrient load damage.

Based on the numerical model applied to Finnish conditions, it may not be optimal for a social planner to implement a buffer zone if the decreased nitrogen load is included as the only ecosystem benefit provided by the buffer zone. The lost harvest revenue from the buffer zone is high and, on the contrary, the nitrogen damage is low as the amount of nitrogen leaching from the clear-cut area remains low. As the biodiversity benefits provided by the buffer zone area were also taken into account, the socially optimal size of the buffer zone was 4% of the total managed area. Thus, it was concluded that the biodiversity benefits provided by the buffer zone may be higher than the benefits provided by the decreased nitrogen load damage.

4.2 Whole-tree harvesting with stump removal versus stem-only harvesting in peatlands when water quality, biodiversity conservation and climate change mitigation matter

The second article examined the social net benefits of stem-only and whole-tree harvesting regimes when water quality, biodiversity benefits and climate impacts were evaluated in peatland forestry. As the estimated climate impacts of forest management alternatives clearly depend on how society views the climate impacts of wood use, we examined two different alternative climate policies: the carbon neutral bioenergy policy and a carbon non-neutral bioenergy policy. The Faustmann rotation model was extended to include the nutrient (nitrogen and phosphorus) and mercury load damage, biodiversity benefits and climate impacts in the theoretical framework. A new theoretical finding is that for stem-only harvesting under a carbon neutral bioenergy policy, adding climate damage lengthens the rotation age. This result reinforces the findings regarding the biodiversity benefits and nutrient load damages and their effects on the optimal rotation age from earlier studies (Amacher et al. 2009; Study I). Under a non-neutral bioenergy policy, the impact of climate damage is ambiguous for stem-only harvesting. For whole-tree harvesting with stump removal, the effect of climate impacts on the optimal rotation age remains ambiguous in both harvesting regimes.

In the numerical application to Finnish forestry, we compared the social net benefits for a given rotation length under alternative climate policies. The numerical results showed that under the carbon neutral bioenergy policy, whole-tree harvesting with stump removal provided the highest social net benefits. If society chooses to follow the carbon non-neutral bioenergy policy, stem-only harvesting will produce the highest social net benefits. In this latter case, it should be noted that the social net benefits were negative for the three studied catchments and positive for only one catchment for stem-only harvesting. We can conclude that how society views bioenergy policies clearly defines which harvesting practice is optimal. Furthermore, as already shown in previous studies (Ahtikoski et al. 2012, Sikström and Hökkä 2016), peatland forestry with ditch network maintenance may have low financial profitability in some peatland sites.

4.3 Boreal peatland forests: ditch network maintenance effort and water protection in a forest rotation framework

In drained peatlands, ditch network maintenance maintains the increased forest growth achieved by first-time ditching (Päivänen and Hånell 2012). However, at the same time, ditch network maintenance and final harvesting in peatlands increase nutrient and sediment exports to watercourses (e.g., Joensuu 2002; Nieminen 2003, 2004; Nieminen et al. 2010). Ditch network maintenance is considered the most harmful forest management measure, particularly due to significantly increased sediment exports (Joensuu et al. 2002). In the social optimum, ditch network maintenance provides benefits as it increases harvest revenues. However, the negative externalities caused by water quality impacts of ditch network maintenance and final harvesting induce damages. Overland flow fields and abstaining from ditch network maintenance were the options to reduce both the nutrient and the sediment loads caused by forest management practices. This study contributes to the earlier economic literature of forestry and water protection by analytically and numerically describing a damage value for sediment load caused by ditch network maintenance when an overland flow field is used as a water protection measure.

The first key theoretical finding is that in optimizing the ditch network maintenance effort, the marginal harvest revenues from increased forest growth due to ditch network maintenance should be equal to the unit costs of ditch network maintenance and water quality damages caused by ditch network maintenance (see also Matero 2004 for a similar result). A new theoretical finding is that the size of the overland flow field is increased until the unit costs of the overland flow field equals the marginal benefits from reduced nutrient and sediment load damages caused by final harvesting and ditch network maintenance.

A numerical case study is applied in northeastern Finland, concentrating on the water quality impacts of final harvesting and ditch network maintenance on ecologically sensitive headwater streams. We use extensive field data collected from 33 forest streams to determine the sediment load damage value and data on nutrient and sediment loads from drained peatland sites to find the socially optimal solution with a numerical model. Depending on the parameters used, it may not be socially optimal to implement ditch network maintenance in all drained forest sites. The reason behind this result is the low increase in harvest revenue due to ditch network maintenance compared to the high nutrient and sediment damages caused by forest management and the costs of water protection.

If ditch network maintenance is nevertheless implemented, the optimal size of the overland flow field varies greatly (from 0.28% to 4.32% of the catchment) depending highly on its costs and the determined sediment load damage value. The current recommendation according to the Finnish forest management guidelines for water protection is that the overland flow field should be at least 1% of the catchment (Joensuu et al. 2012). According to the numerical results, especially if the high sediment load damage value is assumed, the optimal size of the overland flow field is higher than the current recommendation.

4.4 Cost function approach to water protection in forestry

This study describes the marginal abatement cost functions for nutrients and sediment in forestry, which have not been analyzed in previous literature. Furthermore, as the European Water Framework Directive (WFD) emphasizes cost-effectiveness when aiming to reach a good environmental status in all water bodies by 2027, defining the marginal abatement costs of nutrients in forestry is highly needed to compare these costs to other polluting sectors, such as agriculture and wastewater treatment plants. Additionally, the marginal abatement costs of sediment were calculated.

The marginal abatement costs are defined for three water protection measures used in Finnish forest management: buffer zones, overland flow fields and sedimentation ponds. First, the analytical marginal abatement cost of nutrients in both mineral soil with final harvesting and peatland forestry with ditch network maintenance and final harvesting were developed. Second, the marginal abatement costs of sediment in peatland forestry with ditch network maintenance were described. Then, the marginal abatement costs were numerically calculated using data from Finnish forestry.

Study IV shows that marginal abatement costs of nutrients are high (from 470 € kg^{-1} Ne and 2472 € kg^{-1} Ne, when the nutrient reduction target was 10% and 30%, respectively) when using buffer zones as a water protection measure in mineral soils. This result is due to the high costs of establishing the buffer zone with uncut trees located in the buffer zone area and the low nutrient exports caused by final harvesting in mineral soil forests. On the other hand, it was found that marginal abatement costs of nutrients using overland flow fields in peatlands when ditch network maintenance and final harvesting is implemented are low (0.02 € kg^{-1} Ne at the 10% abatement level and 0.04 € kg^{-1} Ne at the 30% abatement level).

Furthermore, in the study, the marginal abatement costs of sediments in peatlands were calculated using either overland flow fields or sedimentation ponds as a water protection measure in ditch network maintenance. It was shown that the marginal abatement costs of sediments might be lower when using an overland flow field as a water protection measure instead of a sedimentation pond.

Finally, the calculated marginal abatement costs of nutrients were used in a river basin model to analyze the cost-effective abatement solution when, in addition to forestry, agriculture is included as a polluting sector in the model. The river basin model included four different water protection measures: buffer strips and restrictions on nitrogen fertilizer in agriculture, buffer zones in mineral soil forestry and overland flow fields in peatland forestry. In a cost-effective solution, 3% (1%) of the total nutrient reduction is made in forestry and 97% (99%) is made in agriculture when the reduction target is set as 10% (30%).

5 DISCUSSION AND CONCLUSIONS

The main contribution of this thesis is to extend the Faustmann rotation model to include water quality. The inclusion of nutrient and sediment load damage functions offers a social optimum framework to examine different forest management practices and associated water protection measures. The model can be conveniently applied to other ecosystem services, such as biodiversity conservation and climate change mitigation, as co-benefits.

5.1 Main findings

Buffer zones have received much attention in the literature. This study suggests that in the social optimum, the buffer zone may be more reasonable for biodiversity reasons than reducing the water quality impacts of final harvesting in mineral soil forests (Study I). This result is simply because the nitrogen loads caused by final harvesting are quite low and there are high-value trees that cannot be cut in the buffer zone area. The result that a buffer zone implies high costs is also supported by earlier studies (Laurén et al. 2007; Trenholm et al. 2013). However, the study by Hjerppe and Väisänen (2015) finds buffer zones in forestry a cost-efficient water protection measure in the catchment-scale study.

Ditch network maintenance has been a significant part of forest management in peatlands. While ditch network maintenance is privately optimal in most but not all sites, it is socially optimal even in fewer cases due to the high sediment load damage and overland flow field costs following the implementation of ditch network maintenance (Study III). This result was also supported by a previous study by Matero (2004).

From a cost-efficiency point of view, the marginal abatement costs of nutrients in forestry relative to those from other sectors are important. The developed cost estimates for buffer zones are very high, considerably higher than those in agriculture (Helin et al. 2006; Helin 2014; Lötjönen and Ollikainen 2019) or in wastewater treatment plants (Hautakangas et al. 2014). In contrast, the marginal abatement costs of nutrients using overland flow fields in peatlands are very low compared to other polluting sectors. As the water protection costs in forestry and agriculture are compared in a river basin scale, a cost-effective solution requires the highest nutrient reductions in agriculture, though it also implements water protection measures, especially in drained peatland forestry.

Finally, it can be concluded that the impact of different forest management practices on water quality and the associated nutrient and sediment load damages differs highly. Final harvesting in mineral soil forestry causes very low levels of nitrogen loads to watercourses (Finér et al. 2010) and thereby relatively low nitrogen load damages (Study I). In contrast, ditch network maintenance in drained peatlands causes very high water quality impacts due to high sediment loads (Joensuu et al. 2002; Finér et al. 2010) and high sediment load damages, especially in headwater streams (Study III). Furthermore, the effectiveness and costs of different water protection measures in forestry differ. In Studies I and IV, it was concluded that from society´s viewpoint, the buffer zones used in mineral soil forestry are very expensive water protection measures. On the other hand, overland flow fields are very effective in reducing nutrient and sediment loads with relatively low costs, as Studies III and IV show.

Detailed practical recommendations can be presented based on this thesis. First, the buffer zones used in mineral soil forestry following final harvesting might not be a cost-efficient water protection measure. However, as their importance on biodiversity is high (e.g., Gundersen et al. 2010; Tolkkinen 2020), from a social viewpoint, buffer zones should be used in practical forest management because they provide biodiversity and other co-benefits. Furthermore, in drained peatlands, overland flow fields are recommended as a cost-efficient water protection measure. The results show that overland flow fields have very low marginal abatement costs of nutrients. Thus, it would be worthwhile to consider whether overland flow fields could be used as permanent water protection measures in drained peatland forests, as recent studies also show that nutrient loads are high from drained peatlands even when there are no recent forest management practices implemented (Nieminen et al. 2017a, 2018a). It should be noted, however, that the use of overland flow fields is limited to sloping areas (Nieminen et al. 2018b). Finally, as ditch network maintenance is not a socially optimal choice in all drained peatland sites, the subsidy on ditch network maintenance paid to private landowners based on the Act of the Financing of Sustainable Forestry in Finland should be redesigned. The subsidy should focus more clearly on water protection measures and the society should consider to what extent it is desirable to promote ditch network maintenance in peatland forestry in the future.

5.2 Further research needs

Additional data on several aspects of water protection in forestry are needed to improve the numerical analysis of water protection in forestry. In particular, more knowledge on the costs of water protection measures, their effectiveness in reducing nutrient and sediment loads and valuation of nutrient and sediment load damages are highly needed.

Water protection measures used in forestry may potentially provide other co-benefits, such as biodiversity conservation or climate change mitigation. To analyze the overall social optimum related to water protection measures used in forest management, further research on co-benefits provided by these measures would be beneficial. As Study I shows, co-benefits, such as biodiversity, might even have higher social benefits than the water quality aspect. Additionally, it could be important to analyze the carbon storage and greenhouse gas dynamics related to buffer zones (Gundersen et al. 2010) in the social optimum framework. Furthermore, as ditching has significant negative biodiversity impacts (Lõhmus et al. 2015; Saarimaa et al. 2019) while the overland flow field could potentially provide significant biodiversity benefits, further research is needed on the biodiversity impacts of ditch network maintenance and overland flow fields. The rotation framework presented in this thesis could also be applied to assess the biodiversity impacts of ditch network maintenance in addition to water quality impacts. Furthermore, the climate impacts from peatland forestry would be highly valuable to include in the analysis due to high greenhouse gas emissions from drained peatlands (Nieminen et al. 2018d).

Economic studies on water policy instruments targeted at forest management are missing (Ollikainen 2016) and are needed to redesign the policy instruments used in forestry. For example, based on the Act on the Financing of Sustainable Forestry in Finland, financing may be granted for private forest owners implementing ditch network maintenance and the associated water protection measures in peatlands. As Study III concludes, further research on whether the subsidies should be more than currently targeted on water protection measures in peatlands instead of also subsidizing the ditch network maintenance effort is needed. Additionally, more regionally targeted policies and their effects should be analyzed, as the water quality impacts of forest management highly differ regionally (e.g., Markkanen et al. 2001; Hökkä et al. 2017).

Finally, as the social costs associated with ditch network maintenance in peatlands are high, further research is needed on forest management alternatives without ditch network maintenance relying on continuous cover forestry and fertilization. The reasoning behind these both options is that studies show that if the forest stock is high enough, the need for ditch network maintenance decreases (Sarkkola et al. 2010, 2013).

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