Master's Thesis

Impacts of fertilization on forest ecosystem services and biodiversity

Satu Kupari

University of Jyväskylä

Department of Biological and Environmental Science

Environmental Science

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UNIVERSITY OF JYVÄSKYLÄ, Faculty of Mathematics and Science
Department of Biological and Environmental Science
Environmental Science

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Finland's forestry industry is growing and demands for forest products are increasing, prompting an interest in forest fertilization. However, existing forest growth models do not fully account for the impacts that fertilizers have on forest ecosystem services and biodiversity. I examined different studies that were conducted in the Fennoscandian area to investigate the long-term effects of forest fertilization on ecosystem services and biodiversity for empirical data. I analyzed data from forest growth simulations which included information on various forest management strategies and ecosystem services, such as bilberry, cowberry, and carbon storage. The effects of fertilizers on boreal forests depend on several factors, including the type and amount of fertilizer used, the timing and rate of application, and the forest ecosystem's characteristics and management objectives. I also found that fertilization negatively affects bilberry yields and changes the species composition of plants, while heavy metal concentrations in berries and mushrooms are elevated due to ash fertilization. The study emphasizes the importance of developing models that consider both direct and indirect impacts of fertilizers on forest ecosystem services and biodiversity. Currently, there are limited research data on how forest fertilization affects ecosystem services and biodiversity. More research is needed to understand this. Forest fertilization is an important tool for boosting productivity and meeting demand, yet its long-term impacts on ecosystem services and biodiversity must be carefully evaluated.

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Suomen metsäteollisuus kasvaa ja metsätuotteiden kysyntä kasvaa, mikä herättää kiinnostuksen metsälannoitusta kohtaan. Nykyiset metsien kasvumallit eivät kuitenkaan täysin ota huomioon lannoitteiden vaikutuksia metsän ekosysteemipalveluihin ja luonnon monimuotoisuuteen. Tutkin erilaisia Fennoskandian alueella tehtyjä tutkimuksia metsien lannoituksen pitkäaikaisvaikutuksista ekosysteemipalveluihin ja luonnon monimuotoisuuteen empiiristä tietoa varten. Analysoin metsien kasvusimulaatioiden tietoja, jotka sisälsivät tietoa erilaisista metsänhoitomenetelmistä ja ekosysteemipalveluista, kuten mustikasta, puolukasta ja hiilinieluista. Lannoitteiden vaikutukset pohjoiseen havumetsävyöhykkeeseen riippuvat useista tekijöistä, kuten käytetyn lannoitteen tyypistä ja määrästä, levitysajoista ja -määrästä sekä metsäekosysteemin ominaisuuksista ja hoitotavoitteista. Sain myös selville, että lannoitus vaikuttaa negatiivisesti mustikan satoon ja muuttaa kasvien lajikoostumusta, kun taas marjojen ja sienten raskasmetallipitoisuudet nousevat tuhkalannoituksen seurauksena. Selvitys korostaa, että on tärkeää kehittää malleja, jotka huomioivat lannoitteiden suorat ja välilliset vaikutukset metsän ekosysteemipalveluihin ja luonnon monimuotoisuuteen. Tällä hetkellä on vähän tutkimustietoa siitä, miten metsälannoitus vaikuttaa ekosysteemipalveluihin ja luonnon monimuotoisuuteen. Lisää tutkimusta tarvitaan tämän selvittämiseksi. Metsien lannoitus on tärkeä väline tuottavuuden lisäämisessä ja kysynnän tyydyttämisessä, mutta sen pitkän aikavälin vaikutukset ekosysteemipalveluihin ja luonnon monimuotoisuuteen on arvioitava huolellisesti.

TABLE OF CONTENTS

1 INTRODUCTION

The European Commission (2020) outlined the EU Biodiversity Strategy for 2030, and they also published a communication regarding the New EU Forest Strategy for 2030 in July 2021 where it was stated that there are increasing requirements on forests to provide a variety of ecosystem services, such as the provision of collectable goods, recreational options, and effective biodiversity preservation, in addition to increasing production (the new policy set forward by the European Union aims to preserve at least 30 % of forested areas, although only about 7 % are now protected in Finland). As a result, there is a growing discussion about intensifying timber production in specific landscapes to be able to preserve larger areas and still obtain similar levels of timber production. Applying fertilization properly is one possible strategy for accomplishing this. One of the measures that promotes the growth of forests according to Finnish National Forest Strategy 2035, is to increase growth and carbon sequestration through responsible forest fertilization. However, it is crucial to take into account whether we have the knowledge necessary to develop effective approaches in fertilization and appropriately estimate the environmental impact of such managements.

This study assesses if we have sufficient understanding regarding the comprehensive syntheses of fertilization, ecosystem services, and biodiversity before introducing new techniques and findings, considering that there have been ecosystem services that were not as widely recognized in the past, and additionally, new fertilization products have emerged in the market. The main goal is to fill this gap in the current study. One of the central goals of this master's thesis is to conduct a comprehensive literature analysis on the influence of fertilization on various aspects of forest ecosystem services and biodiversity. The master thesis is literature-based thesis with quantitative analysis to assess whether future estimates of ecosystem services derived from structural forest properties after forest growth simulators are accurate. Different ecosystem services (ES) and biodiversity indicators, such as bilberry and cowberry, can be used in forest growth simulators, such as SIMO, for further evaluation and calculation. The outcome would be correcting the factors in the way the biodiversity and ecosystem services are calculated. Also, the aim is to assess the improvement of fertilization accounting in the decision-making. The outcome is to see how fertilization impacts on ecosystem services and biodiversity (Figure 1).

The study questions are:

1. What is the status-quo of the knowledge of the effects of fertilizers on non-wood forest ecosystem services and biodiversity?
2. How fertilizers affect the ecosystem services and biodiversity in boreal forests in Fennoscandia?
3. How well do the impacts of fertilizers on ecosystem services and biodiversity correspond with the simulated and empirical data?

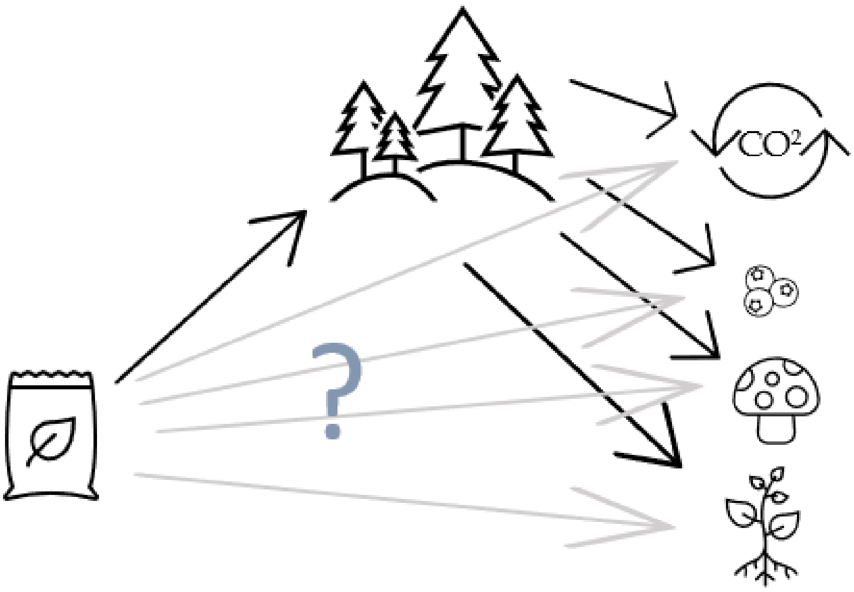

Figure 1. Conceptual scheme of the impacts of forest fertilizers. Most forest growth simulators used to do management plans and scenario analyses may include the impact of fertilizers on ecosystem services indirectly through affecting the growth of threes (black arrows). However, those are likely to disregard other effects of fertilizers on ecosystem services that are not correlated with tree growth (grey arrows).

2 BACKGROUND OF THE STUDY

2.1 Boreal forests in Nordic countries and ecosystem services

One of the largest terrestrial biomes is the boreal forest, and around two thirds of it is managed in some form (Jörgensen et al., 2021). The boreal biome is defined by a cold climate, great temperature changes between summer and winter, and a permanent snow cover in the winter. Precipitation may fall mostly as snow in some boreal areas. (Mönkkönen et al., 2018.) Finnish boreal forests are composed of approximately 50% Scots pine (*Pinus sylvestris*), 30 % Norway spruce (*Picea abies*), 17 % birch (*Betula pendula* and *Betula pubescens*) and 3 % other broadleaved trees (Vaahtera et al., 2018). In commercially maintained stands, these species also predominate. Exotic tree species are rarely grown. (Ministry of Agriculture and Forestry, n.d.a.)

Ecosystem services are the benefits supplied to humans by natural ecosystems. Many of the ecosystem services are vital for humans and to other organisms. Biodiversity is the foundation for ecosystem services because it helps nature to adapt and regenerate. Ecosystem services are divided into provisioning, regulating, cultural and supporting services. (Millennium Ecosystem Assessment, 2005.) In boreal forests, timber production is the most commercially valuable provisioning service (Peura et al., 2016). Other provisioning services are, for example, berries, game, and mushrooms. Regulating services are, for example, climate regulation through carbon sequestration and storage and maintaining soil productivity. Cultural services include the landscape as well as outdoor activities and recreation, and supporting services include photosynthesis and nutrition cycle. Supporting services form the basis for other ecosystem services. (Ministry of Agriculture and Forestry, 2014.)

Bilberry (*Vaccinium myrtillus* L.) and cowberry (*Vaccinium vitis-idaea* L.) are the most collected wild berries in Finland, with an annual harvest value of up to 100 million euros (Peura et al., 2016). It is estimated that in the average harvest year, the total yield of bilberries is 184 million kilograms and the total yield of cowberries 257 million kilograms (Turtiainen, 2021). Picking wild berries and mushrooms has a long history, and it provides recreational as well as economic values. Everyman's rights in many Nordic countries, allow anyone to have access to forests and collect berries and mushrooms. (Peura et al., 2016.) Berry picking is practiced by about 60 % of Finns, and mushroom picking by 40 %. However, due to increased forest management for timber production in recent decades, yields of several collectible goods, such as bilberries, have decreased. (Peura et al., 2016.) Given the long tradition of picking berries in many Nordic countries, the berry production by the dominant boreal dwarf shrubs in the *Vaccinium* genus, such as bilberry and cowberry, is an important ecosystem service with high economic value in addition to high cultural and recreational value (Granath & Strengbom, 2017).

2.1.1 Regulating

The most significant regulating service provided by boreal forests on a global scale is climate regulation. For reducing global climate change, boreal forests play a critical role in carbon storage and sequestration. (Mönkkönen et al., 2018.) The organic horizon, also known as the "mor layer," is a characteristic of boreal forests and is an important source of carbon. It is formed of both carbon (C) produced from litter-and root-derived. (Jörgensen et al., 2021.) More than 20 % of the world's carbon sinks are found in boreal forests, which store more than 30 % of the world's carbon. Several locally and regionally significant regulating services provided by forests that are also regarded as public goods relate to water and soil. Boreal forests regulate water flows, participate in hydrological cycles, filter groundwater, and act as nutrient-retentive buffer zones for nearby waters. One of the world's largest supplies of freshwater is found in the boreal regions. Furthermore, boreal forests conserve nutrients, preserve soil productivity, and resist natural disturbances as fires, floods, wind, diseases, and pests. If climate change causes more disturbances in the future, these benefits could become even more crucial. Moreover, they serve as habitat for a variety of useful organisms, including decomposers and pollinators. For instance, honeybees that live in forests pollinate a variety of commercially useful crop species. (Mönkkönen et al., 2018.)

2.1.2 Provisioning

In boreal forests, the most significant economic provisioning service is timber production. Around 45 % of the world's stock of growing timber is found in boreal forests, which also provide around 25 % of the world's exports from the forestry sector. Furthermore, non-timber forest products including berries and mushrooms provide essential provisioning services in boreal forests. For rural and indigenous communities in particular, these products are crucial culturally and economically. Annual harvests of berry and mushroom crops in Fennoscandia range from 5 % to 10 %. Since the sale of collectibles is tax-free, locals benefit financially. (Mönkkönen et al., 2018.)

In Fennoscandia, the financial value of game meat ranges from 44 to 125 million euros per year, and hunting game animals as moose (*Alces alces*) generates income for the local residents. The Nordic countries have a significant industry in nature tourism on both a regional and national level. For instance, 25,000 people work in forestry and 32,000 people are employed by nature tourism in Finland. Nature tourism is the most significant component of the local economy in Finnish Lapland. Reindeer herding and harvesting Christmas trees are two additional locally and regionally significant provisioning services that are unique to the boreal region. (Mönkkönen et al., 2018.)

2.1.3 Cultural

Because of their importance for recreation and culture, various non-timber forest products are also considered as cultural ecosystem services. Hunting and collecting berries and mushrooms for recreation are popular pastimes for local people. Other outdoor recreational activities, such hiking, camping, and bird watching, are also practiced out in boreal forests. Additionally, the scenic beauty of native species and forest landscapes carries its own recreational and cultural values. Moreover, forests offer opportunities for improving human health. (Mönkkönen et al., 2018.)

2.2 Biodiversity and sustainable forest management

Protecting biodiversity and the elements that influence ecosystem functioning improves ecological sustainability. Forests that are diverse and healthy provide the ecological framework for all forest management and use. As a result, biodiversity conservation is a critical component of sustainable forest management and use. As the usage of wood grows in Finland, are so efforts to secure and conserve forest biodiversity. (Ministry of Agriculture and Forestry, n.d.b.)

A substantial proportion of Finnish species depend directly or indirectly on forests. Mineral soil forests are habitat to about 36 % of all threatened species. However, previous studies have shown that only around 10 % of mineral soil species are threatened, suggesting that most species normally occurring in Finnish woods are still there. Aside from mineral forest soils, forested peatlands are home to a small percentage of all threatened species. (Ministry of Agriculture and Forestry, n.d.b.)

The majority of the forests in Fennoscandia are intensively managed for the production of biomass, and thinning is an often-used method to enhance the quality of the timber and enhance the economic output during a forestry rotation period (Jörgensen et al., 2021). Intensive forest management has altered different types of forest environments over time, for example, by changing the quantity of dead, old-grown, or deciduous trees. The alterations are frequently the result of historical events, which reflect the changing needs of society and the uses of wood. (Ministry of Agriculture and Forestry, n.d.b.) The management of forests outside of protected areas is critical for both biodiversity and ecosystem services. Forest exploitation in the Nordic countries has a long history reaching back to the 1600s. (Mönkkönen et al., 2018.) In terms of forest biodiversity, the most significant structural features are decaying wood. Forestry has had a significant impact to the quantity and quality of decaying wood in commercial forests. There is up to 95 % less decayed wood in commercial forests than in natural forests. (Päivinen et al., 2017.)

By the 1980s' end, there was widespread opposition to intense forest management techniques, and the environmental benefits of forests and forestry, as well as their connection to biodiversity, were being emphasized more and more (Mielikäinen & Hynynen, 2003). Protection of biodiversity has been a concern since the 1990s, and steps taken since then have resulted in some species no longer being classified as threatened. Nonetheless, the reduction in biodiversity has not yet been reversed, requiring additional actions. (Ministry of Agriculture and Forestry, n.d.b.)

The management of native tree species is the foundation of Finnish forestry. Forest management aims to emulate the natural cycle of boreal forests while respecting their natural growth. The aim is to ensure the production of high-quality timber while also preserving forest biological variety to establish the conditions for forest multi-use. (Ministry of Agriculture and Forestry, n.d.b.)

Economic, ecological, social, and cultural sustainability are all aspects of sustainable forest management. Economic sustainability refers to the ability of forests to maintain their viability, productivity, and profitability over time. Protecting forest biodiversity and keeping the rivers clean are examples of actions that can be taken to ensure ecological sustainability. People and diverse stakeholders continue to have access to the benefits derived from forests, which is referred to as social sustainability. Cultural sustainability requires a great comprehension of natural environments and human behavior, as well as considerations of the forest, economy, and culture. (Ministry of Agriculture and Forestry, n.d.c.)

The goal of forest legislation is to support environmentally, economically, socially, and culturally sustainable forest management and use so that they can create a great output while preserving biodiversity (Ministry of Agriculture and Forestry, n.d.c). This new strategy was outlined in the 1997 comprehensive reform of

Finnish forestry law (Mielikäinen & Hynynen, 2003). Forest Management Recommendations (national guideline) define the methods for managing and using forests in a way that also meets the goals of forest owners. The PEFC (the Programme for the Endorsement of Forest Certification) and FSC (the Forest Stewardship Council) certification systems are in use in Finland. Around 90 % of Finland's commercial forest area is certified under Finland's PEFC system, with the remaining 10 % certified under the FSC standard. (Ministry of Agriculture and Forestry, n.d.c.)

The profitability of Finnish forestry is based on the capacity of forests to produce wood products and the demand for Finnish wood. The main goal of forest management is to enhance the growth of valuable stands and increase roundwood quality. Forest management today focuses on the protection of natural assets, landscape management, and recreational purposes in addition to wood production. (Ministry of Agriculture and Forestry, n.d.a.) Forests supply timber, and a variety of other goods and services that are vital to human societies (Mönkkönen et al., 2018).

In Finland, forestry often includes the management of small forest stands with similar-aged trees. Such stands are managed according to a regeneration cycle that includes everything from planting to natural regeneration to harvesting. Forests can be renewed both naturally and artificially, by sowing seeds or planting seedlings cultivated in tree nurseries, or by leaving a few selected seed trees after final harvesting. The goal is to ensure that a productive stand of a suitable tree species for the given site regenerates in a reasonable amount of time. Depending on the tree type and the location of a forest stand, the regeneration cycle might last anywhere from 50 to 120 years. Special strategies for managing forest stands with trees of ages ranging have been developed in several regions, especially in recreational and landscape forests. (Ministry of Agriculture and Forestry, n.d.a.)

Younger commercially managed forests are often thinned out on a regular basis, with 25–30 % of the trees being removed. The growing demand for bioenergy wood has created new markets for trees cut down during thinnings, as well as logging residue including branches and stumps that were previously left in the forest. (Ministry of Agriculture and Forestry, n.d.a.) Bioeconomy is highly important sector for Finland. It generated 26 billion euros in value added in 2019, equivalent for 13 % of the total value created in the national economy. In the summer of 2020, the Ministry of Economic Affairs and Employment initiated a project to update the Bioeconomy Strategy and it was finished in 2022. By 2035, the strategy intends to increase the value added of the bioeconomy while being environmentally, socially, and economically sustainable. (Ministry of the Environment, 2022.)

Uneven-aged forestry is an alternative to even-aged forestry in which no final felling is conducted. From seedlings to timber trees, the trees in such a forest are of varying ages. Light selection felling or a small-scale group selection approach are used to regenerate forests. After logging, the forest regenerates naturally. Forest biodiversity is promoted in both strategies by preserving the characteristics of important ecosystems. (Ministry of Agriculture and Forestry, n.d.a.)

2.3 Impacts of forest management on ecosystem services and biodiversity

Many Finnish forests are intensively managed to enhance timber production while forgetting the significance of biodiversity and other ecosystem services. Intensive timber production can have a negative impact on biodiversity and other ecosystem services as recreation, water and soil quality, climate regulation through carbon sequestration and storage, and game and bilberry production. (Peura et al., 2016.) Current efforts to prevent historical deforestation have emphasized global afforestation as a potential strategy, while silvicultural practices can also be altered to reduce climate change. Since soil fertility and stand dynamics, both of which can be affected by directed management, are related to a forest's ability to bind carbon, optimizing forest management in order to maximize carbon sequestration may be a significant approach for achieving net zero emissions over the next few decades. (Jörgensen et al., 2021.)

Measures used in forestry affect wild berries in different ways. The coverage and abundance of bilberries have been reduced, for instance, by clear-felling, tillage, and the increase in the proportion of young forests. Bilberry suffers from direct sunlight and soil drying in clear-felled areas, and its coverage is lowest in young forests and in regeneration areas. Tillage destroys the rootstock of the bilberry and reduces its growth potential. Cowberry tolerates clear-cutting better than bilberry, even benefits from it, yet it also suffers from tillage. In peatland thinnings, bilberry and cowberry tend to become abundant when increases the amount of light. Ditch network maintenance (DNM) revives dwarf shrubs typical of mineral soils, such as bilberry. (Päivinen et al., 2017.)

2.4 Forest fertilization in Finland

In the early 1930s, regeneration of felling areas became prevalent, first through sowing and then through planting. The first mires were drained in the 1910s to expand the area of profitable forestland, and mires were drained at a faster rate after the introduction of mechanical ditching methods in the 1960s and 1970s. World War II marked a change in the use of state forest property. As foreign energy supplies ceased, wood was needed immediately and in large quantities, so intermediate fellings were replaced by extensive clear fellings. (Metsähallitus, n.d.) The Finnish forest industry was threatened by a shortage of raw materials in the 1960s after several years of total drain being higher than the growth. Several programs were set up to increase forest production (MERA-programs, Teho program). Fertilization and drainage of peatlands played a significant role in them. (Martikainen et al., 1994.)

The use of forest fertilization began in the mid-1960s. Fertilization areas increased rapidly together with the increase in drainage areas as the drainage was almost always associated with fertilization in state and forest product company lands. The rapid growth of fertilization areas in private forests began in 1968, when it was possible to receive a loan and / or grant from the forest improvement funds for fertilization. (Martikainen et al., 1994.) During the 1970’s, the annual fertilization areas could reach 150,000 ha in Finland (Pukkala, 2017). The peak of forest fertilization was reached in 1975, when 244,000 ha of forest were fertilized. After the shortage of wood, the requirements for fertilization targets were tightened and less funds were allocated for fertilization. Due to this, as well as fertilizer taxes, the economic depression in forestry and the environmental risks, the fertilization areas were decreased. In 1992, the forests were fertilized only a few hundred hectares. (Martikainen et al., 1994.)

Forest fertilization can be divided into growth fertilization, that used to improve growth and remedial fertilization, which is used to improve nutrient balance of soil (Heinonen et al., 2017). Remedial fertilization means ash fertilization of bog forests and fertilization on a site with a boron (B) deficiency in the soil (Finnish Forest Centre, 2022). Fertilization is a technique for increasing forest biomass. For decades, it has been used in boreal forest management. Long-term studies evaluating the impacts of site, growing stock, and fertilizer amount and type have been set and monitored at regular intervals. These studies provided data that may be used to model the influence of fertilization on volume growth in Finland. (Pukkala, 2017.) During the fertilization, nitrogen (N) and mineral nutrients are added to the soil to increase the growth of trees. The effect of fertilization lasts 6-8 years on mineral soils and slightly longer on peatlands. Fertilization studies have measured an average additional growth of 1.5-3 m^3 per hectare per year for heathlands and for peatlands 0.5-2 m^3 per hectare per year. Due to the additional growth, the forest stand becomes robust faster, and fellings can begin earlier. Fertilization increases the width of the annual growth ring and reduces the density of the wood. (Päivinen et al., 2017.)

Trees need at least 16 different types of nutrients. For example, nitrogen, phosphorus (P), and potassium (K) are required in a ratio of approximately 10:1:3.5. Peatlands are generally deficient in phosphorus, potassium, and boron. Fertile bogs are often rich in nitrogen compared to other nutrients, which easily leads to growth disturbances. The nutrients needed by trees are usually divided into main nutrients and micronutrients. The main nutrients are nitrogen, phosphorus, potassium, calcium (Ca), magnesium (Mg), and sulfur (S). Micronutrients include iron (Fe), manganese (Mn), copper (Cu), zinc (Zn), boron, molybdenum (Mo), and chlorine (Cl). (Yara, 2017.)

The growth and condition of the forest stand depends on the light, temperature, water, nutrient content, and soil properties. The level of growth is determined by the so-called the limiting factor i.e., the one is needed the least. In heathlands the limiting factor is generally nutrients, especially nitrogen deficiency. On peatlands after drainage, the limiting factor is often nutrient deficiency or imbalance. The need for nutrients increases after drainage when the forest cover growth and amount increases. The amount of nutrients and their interrelationships also change as the bog develops to peatland. (Yara, 2017.)

The coniferous ecosystem has adapted to scarce nutrient resources. In particular, the nitrogen and phosphorus cycles are fairly closed, i.e., in these nutrient leaching losses are low. Only about 1 % of the earth's nitrogen resources are in form that can be used by plants as ammoniacal and nitric nitrogen. Phosphorus is mainly bound to soil organic matter. The circulation of potassium in the forest ecosystem is faster than that of nitrogen and phosphorus. Calcium plays a role both as a nutrient and as a regulator to soil acidity. Micronutrients cycles are not as well-known as the main nutrients cycle. (Martikainen et al., 1994.)

Nitrogen (150 kg N/ha) has been mainly used in fertilization of heath forests (Martikainen et al., 1994). Heath forests can be found throughout Finland and cover more than 95 % of the forest area. The main tree species in the heath forest usually are either pine, spruce, birch, or other deciduous trees. Traditionally, heath forests have been divided into site types based on the fertility of the land. Site types include herb-rich, mesic, sub-xeric, xeric, and barren heath forests. (Ympäristöhallinto, 2019.) N fertilization has increased volume growth by 22–36 % in Norway spruce on mesic sites and Scots pine on sub-xeric sites in Finland. In Scots pine, the effect of nitrogen fertilizer lasts around 7 years, whereas in Norway spruce, it lasts about 10 years. In northern Finland, repeated N fertilization improved the volume growth of Norway spruce stands by 56–81 %. (Heinonen et al., 2017.) On drained peat soils, the fertilization effect is longer than on mineral soils, depending on the fertilizer, 15–30 years. Fertilization can be carried out several times during the rotation period. (Äijälä et al., 2019.)

On nitrogen-rich drained boreal peatlands, other fertilizers such as wood ash, phosphorus, and potassium are used (Heinonen et al., 2017). Phosphorus (20 kg P/ha) has been commonly used in spruce forests. PK (phosphorus-potassium) fertilizer has been the most widely used fertilizer on peatlands (40 kg P/ha and 80 kg K/ha). (Martikainen et al., 1994.) On drained peatlands, PK fertilization has resulted in positive long-term growth responses (Heinonen et al., 2017). Ash is obtained when organic matter burns and nitrogen and, for the most part, sulfur are removed from it. Inorganic ingredients, as well as nutrients needed by trees, remain in the ash in approximately the same amounts as they are present in the material being burned. In wood ash, calcium is usually present in between 10 % and 30 %, potassium between 2 % and 6 %, and phosphorus between 1 % and 3 % of the dry matter. Ash also contains important micronutrients such as boron, copper and zinc. In addition to plant nutrients, ash include heavy metals and other compounds. Several metals, such as manganese, copper and zinc are necessary micronutrients in nature, while others, cadmium (Cd), chromium (Cr), lead (Pb), and nickel (Ni) are harmful or even toxic in high concentrations for the environment, animals, and humans. (Motiva, 2009.) Cadmium and lead are present in ash as a very slowly soluble form due to its high pH (Huotari, 2012).

Boron has been added to bog fertilizers since 1973 (Martikainen et al., 1994) Boron deficiency causes growth disturbances in forests that have previously been treated with slash-and-burn cultivation. Boron fertilizers can mitigate these disturbances. Lime (CaO) is also used as a forest fertilizer. (Pukkala, 2017.) Slow-release fertilizers containing apatite, biotite and methylene urea accessed the market in the early 1990s (Martikainen et al., 1994).

Fertilization is increasingly based on the results of nutrient analysis and customized fertilizers. In older bog forests, phosphorus is rarely required, while potassium and boron are usually sufficient to maintain soil fertility. Fertilizers have not been applied to snow for a couple of decades and slow-soluble fertilizers are used in bog forests. Strong imbalances in nitrogen and other nutrients can lead to nitrogen leaching. (Farmit, n.d.)

TABLE 1. Yara's fertilizers for growth fertilization.

Product name	For growth fertilization			
	Nutrient	Amount	Recommended use	Use
YaraMila METSÄN NP	N, P, B, Mg, Zn	25, 2, 0.3, 1, 0.1	600–800 kg/ha Every 6–8 years	Spruce and pine trees in heathlands and birch forests. Application to snow-free soil.
YaraBela METSÄSALPIETARI	N, K, S, B, Mg	27, 1, 4, 0.15, 1	550–750 kg/ha Every 6–8 years	Nitrogenous fertilizer for pine trees in heathlands. Spruce-dominated forests. Application from spring to early autumn.
UREA	N	46	330-430 kg/ha, every 6-8 years (in heathlands) 150-200 kg/ha, every 10-15 years (in bog forests)	Nitrogenous fertilizer for fertilizing pine trees in heathlands. Application from early autumn until the arrival of permanent snow.

(Yara, 2022a.)

TABLE 2. Yara's fertilizers for the remediation of boron deficiency.

Product name	For the remediation of boron deficiency			
	Nutrient	Amount	Recommended use	Use
YaraVita BORTRAC 150	B	150 g/l	15-20 l/ha	Applied to soil and / or undergrowth using, for example, a backpack pump, atomizer, or tractor sprayer. Water should be added to ensure even application. Should be spread evenly over the entire area.
				(Yara 2022a.)

In December 2021, Yara launched three new recycled fertilizers called YaraSuna ™. These fertilizers are based on recycled nutrients. The main raw material for recycled forest fertilizers is wood ash from bioenergy production. The products are suitable for the remedial fertilization of peatland and heathland forests at different stages of growth. (Farmit, 2021.)

- YaraSuna ™ BOREA is an ash-based micronutrient fertilizer for boron-deficient forests.
- YaraSuna ™ HORUS is an ash-based product suitable for fertilizing peatland forests. It corrects phosphorus, potassium, and boron deficiencies, neutralizes the substrate and releases nutrients.

- YaraSuna ™ CINIS+ is suitable for basic fertilization that is performed in conjunction with forest cultivation of afforestation support areas in peatlands. (Farmit, 2021.)

2.5 Impacts of fertilizers on the environment

Due to the demands of a growing world population, a pressing need to mitigate climate change by increasing carbon dioxide (CO_2) absorption in forests, and a shift from fossil fuels to biofuels, interest in fertilization forests has increased since (Hedwall et al., 2010). It is significant to point out that forest fertilization can increase productivity and change the species composition of the ground vegetation. Additional knowledge on potential negative effects is necessary in order to evaluate how commercial forest fertilization conforms to sustainable forest management and biodiversity preservation principles. (Strengbom & Nordin, 2008.) Notably, it has been demonstrated that nitrogen fertilizer in heathlands has negative effects on microbial biomass and carbon mineralization, despite increasing net nitrogen mineralization (Lindroos et al., 2022). There is a significant chance that methods such as fertilizer and forest thinning will result in the loss of biodiversity (Jörgensen et al., 2021; Strengbom & Nordin, 2008).

Hedwall et al. (2013) discovered in their study that low nitrogen deposition areas experienced more substantial vegetation changes following nitrogen addition than high deposition areas, demonstrating a complex connection between nitrogen and vegetation impact. In locations with poor deposition, they also noticed that even low levels of nitrogen had an important influence. (Hedwall et al., 2013.) Another study by Strengbom et al. (2017) showed that fertilization and thinning have different effects on various forest values and ecosystem services. Nitrogen fertilizer limits biodiversity and negatively impacts lichens, whereas thinning promotes ground vegetation diversity and lichen growth, providing a potential protective measure to nitrogen's negative effects. (Strengbom et al., 2017.)

Nitrogen addition often leads to moss and lichen species in the forest ground layer to decrease, whereas dwarf shrub and grass species in the field layer eutrophicate

(Issakainen & Moilanen, 1998). PK fertilization had a detrimental impact on berry production, especially bilberry yields, whereas nitrogen fertilization's impacts were not as obvious, though it appeared to increase cowberry in some situations and support bilberry for a short period of time. The effect of ash fertilization on wild berry yields is still unclear as it has been linked to both higher yields and a decline in berry production, as well as temporary increases in nutrient contents and heavy metal concentrations (Huotari, 2012; Päivinen et al., 2017).

According to Strengbom & Nordin (2008), the impacts of fertilizing forests can last for more than 20 years and have an impact on succeeding generations of forests. Due to a few dominant N-favored species in fertilized stands, biodiversity tends to be decreased, which lowers dwarf shrub and berry production. These effects may be enhanced by clear-cutting, which may reduce the ground vegetation's susceptibility to N-induced alterations throughout several forest generations. (Strengbom & Nordin, 2008.) Furthermore, according to Granath & Strengbom (2017), N fertilization decreased fruit output in cowberry due to decreased plant cover and in bilberry due to increased fungal infections, whereas thinning had a favorable impact on fruit production, particularly for cowberry.

As most forests experience N limitation, using nitrogen fertilizer in forest management may increase carbon (C) uptake in trees, potentially enhancing C storage in the organic horizon. Extensive thinning may reduce photosynthesis and C fluxes to biomass and soils, necessitating a careful balance when managing forests to enhance C sequestration. However, the interacting effects between thinning and fertilization can also affect C sequestration. (Jörgensen et al., 2021.)

2.5.1 Positive impacts of fertilizers on the environment

The aim of forest fertilization is to promote photosynthesis and tree growth. Forest fertilization can increase the carbon sequestration of the forest, as trees retain carbon dioxide in the wood and soil as they grow. Forests act as significant carbon sinks, as Finnish forests bind about one third of Finland's total carbon dioxide emissions. When forests no longer continue to grow, they act as carbon storages. The additional growth of forest stands caused by forest fertilization is about 15–20

m^3/ha during the period of fertilization, i.e., about 6–8 years. This amount of additional growth absorbs about 11,000 kg of carbon dioxide and corresponds to the carbon footprint of one Finnish year. (Yara, 2022b.) The growth of forest stands binds carbon and higher litter production has an increasing effect on the growth of carbon storages in the soil. Litter production is thought to be one of the most important factors in the development of the soil's carbon storage. It is important when evaluating the role of forests in carbon sequestration in connection with climate change mitigation. (Lindroos et al., 2022.)

The research from Jörgensen et al. (2021), discovered that preserving Scots pine forests from fertilization and thinning had a significant effect on carbon storage. Overall C accumulation in stands was decreased by thinning, whereas fertilization significantly increased tree growth and C sequestration. After the addition of nutrients, there was an increase in the organic horizon C stock, which suggests lower decomposition rates. Variance in decomposition rates appears to be the main factor affecting the below-ground C pool. In the absence of thinning, fertilization had the most beneficial impact on below-ground C sequestration. Furthermore, the addition of extra P to N fertilizer increased organic horizon C sequestration even further. It is yet uncertain whether the fertilization-induced soil C sink would be stable over time. (Jörgensen et al., 2021.)

Game animals, as such moose *(Alces alces)*, appear to prefer the plants more after the forest has been fertilized (Löyttyniemi, 1981; Päivinen et al., 2017). Löyttyniemi (1981) evaluated the connection between nitrogen fertilization and the nutrient content of the needles on the palatability and subsequent browsing damage by moose in *Vaccinium*-type Scots pine plantations in southern Finland. The degree of damage was positively correlated with seedling growth and the increased nitrogen content of the needles, and fertilization increased the vulnerability to browsing damage. The nitrogen concentration of undamaged and damaged pine seedlings in unfertilized plantations, however, demonstrated only minor variations. Other nutrients (P, K, Ca, and Mg) were not clearly correlated with one another, despite the fact that the phosphorus and calcium concentrations in the needles of damaged trees were on average slightly greater than in the undamaged trees. (Löyttyniemi, 1981.) At the same time, eutrophication of ground vegetation provides protection and food for animals. Mountain hares (*Lepus timidus*) seem to rather move to fertilized areas. (Päivinen et al., 2017.) The intensification of forest vegetation is beneficial to the fauna of the forest, which the plants provide for nourishment and protection (Äijälä et al., 2019).

2.5.2 Negative impacts of fertilizers on the environment

The environmental risks of forest fertilization are related to the leaching of nutrients into watercourses or groundwater and, to the acidification of the soil in mineral soils. The risk of leaching caused by nitrogen fertilization is greatest in the first two years after fertilization. (Äijälä et al., 2019.) The reaction of the ground cover vegetation, including changes in community composition and biodiversity loss, has been the focus of the consequences of boreal forest fertilization up until now. Dwarf shrubs, lichen, and mosses are covered less when old forests are fertilized over a long period of time (more than 15 years), favoring grasses and nitrophilous herbs instead. Similar detrimental impacts to long-term fertilization of mature forests can be shown with short-term nutrient optimization in young spruce plantations. (Rodríguez et al., 2021.)

At least temporarily, N fertilization may slow the pace at which soil organic matter decomposes. Then again nitrogen fertilizer, particularly if high amounts of nitrogen are utilized, may have negative long-term impacts on soil carbon balance since it may gradually start to raise the decomposition rate of dead organic matter. N fertilizer may also lead to an increase in nitrous oxide (N_2O) emissions from forest soils. Carbon emissions are also produced during the production and distribution of fertilizers. (Pukkala, 2017.)

The effects of fertilization and clear-cutting on the vegetation of the understory are quite similar. The composition of the forest floor vegetation frequently changes as a result of clear-cutting in boreal forests. (Hedwall et al., 2010.) Fertilization affects the ground vegetation of forests by changing competitive interactions, favoring fast-growing graminoids and herbs while decreasing the quantity of slow-growing species including dwarf shrubs that produce berries (Gundale et al., 2013; Strengbom & Nordin, 2008). Studies have shown that nitrogen addition promotes the competitive advantage of nitrophilous forbs and grasses over dwarf shrubs and bryophytes after disturbance if the system is nitrogen-limited (Hedwall et al., 2013). It has been demonstrated that nitrogen fertilizer reduces ectomycorrhizal fungi's biomass, which may have an impact on trees' nutrient uptake (Pukkala, 2017). Fertilization may increase berry and mushroom yields, yet yields can also decrease as vegetation cover eutrophicates (Äijälä et al., 2019).

In ash-fertilized areas, heavy metal concentrations in vegetation or trees are generally low. In the early years, the concentrations may rise slightly in the vegetation, however, later they fall to the starting level or even below it. Despite the minor changes, the concentrations of heavy metals in the vegetation remain within the limits of the natural concentration variation of the plants in the ash areas. In the longer term, the nutrient concentrations of berries and mushrooms remain elevated in ash areas, however the concentrations of heavy metals generally decrease. The reason is the liming effect of ash, which lowers the solubility of heavy metals in the soil. (Motiva, 2009.) Cadmium in the ash has been observed to bind to the soil for tens of years in bog forests and heath forest sites. In some studies, the quantity of cadmium that dissolves in soil water, or its bioavailability, increases temporarily throughout the course of the first five years. (Huotari, 2012.) As far as ash fertilization is concerned, there has still been a need for further studies related to the dissolution and movement of heavy metals possibly contained in the ash along with soil water (Huotari, 2012; Lindroos et al., 2022).

Forest fertilization can increase the nutrient load of watercourses and in some cases can pollute groundwater. Mineral soils are almost always fertilized with nitrogen fertilizers, which can be seen as an increase in the nitrate (NO^{3-}) concentration of groundwater. In mineral lands phosphorus binds to iron and aluminum (Al) compounds in the soil. Potassium is not harmful to watercourses. (Kaukonen et al., 2022.) Although nitrogen is severely limited in boreal forests, adding N may cause trees to become N saturated, resulting to leaching and water eutrophication (Jörgensen et al., 2021).

Phosphorus is the most significant nutrient that regulates the eutrophication of watercourses. Use of phosphorus fertilizers however, in mineral soils do not significantly increase the phosphorus load in watercourses because the phosphate used in fertilizers is chemically bound to the iron and aluminum compounds in the soil. Nowadays, in peatlands, ash-based fertilizers and wood ash are most commonly, in which the components necessary for the chemical bonding of phosphorus are contained in the fertilizer itself. According to recent studies, ash fertilization in peatlands does not cause significant harmful effects changes in runoff water quality. (Leppä, 2018.)

Ash itself does not contain nitrogen, yet the reduction of soil acidity caused by ash fertilization and the activation of decomposition can increase the release of nitrogen in nitrogen-rich areas. Then the risk of nitrogen leaching also increases. (Huotari, 2012.) In the soil, heavy metals and phosphorus bind to the ground surface and are not leached from fertilization areas into watercourses. The water-soluble nutrients in the ash, potassium and boron are partially leached, yet they do not have a eutrophication effect on watercourses. (Motiva, 2009.) However, there is a heavy metal risk that is associated to ash fertilization (Kaukonen et al., 2022). Studies have shown that if ash does not get directly into ditches during fertilization, the leaching of phosphorus and harmful heavy metals from ash fertilized areas is very low (Huotari, 2012).

3 MATERIALS AND METHODS

The Master thesis is based on a literature review and data from the SIMO forest growth simulator. The simulation data was already generated with SIMO from a previous study. The literature used in the thesis was mainly electronically searched articles from Web of Science, Google Scholar, and forestry-related literature and reports. The aim was to be able to answer the research questions with these methods that were used.

3.1 Literature search using Web of Science

On 9th February 2022, I conducted a search on Web of Science using the keywords "fertiliz* AND boreal AND forest AND biodiversity," resulting in 39 articles. The search aimed to find articles in the Fennoscandian region, and it included Sweden and Norway. After refining the search, 18 articles from the years 1995 to 2021 were found. On the same day, another I performed another search with the keywords "fertiliz* AND boreal AND forest AND ecosystem servi*," which resulted in 12 articles. This search focused on Sweden in the Fennoscandian region and found four articles, two of which were duplicates from the previous search.

On 14th April 2022, I conducted a third search using the keywords "fertilis* AND boreal AND forest AND biodiversity," resulting in 8 articles. The selected countries for this search were Finland, Norway, and Sweden. After refinement, 7 articles remained, with one duplicate from the previous search removed. The fourth search on the same day used the keywords "fertiliz* AND boreal AND forest AND bilberry," which yielded 7 results from Web of Science Core Collection, focusing only on Sweden. After removing duplicates, 4 articles were left.

I collected articles and organized them into an Excel spreadsheet with specific titles related to the master's thesis topic: Type of fertilizer, Amount of fertilizer applied, Time frame, Forest type, and whether any Ecosystem service/Biodiversity indicator was included. To expand the information in the thesis, I conducted three more searches on Web of Science. On 18th November 2022, a search using "fertili* AND myrtillus AND impact* AND forest" was done for Finland, Sweden, and Norway, resulting in 15 articles, with one duplicate from a previous search removed. Four articles were selected from this search. A second search on 22nd November 2022, with the keywords "fertiliz* AND vegetation

AND boreal AND biodiversity," focused on Sweden and Norway, and listed 11 articles, with one article selected as the others were duplicates or not relevant.

Another search on 13th December 2022 used "fertiliz* AND carbon sink AND boreal" and yielded 78 articles. From Sweden and Finland, 24 articles were selected, including three new ones and three duplicates from previous searches. Since most searches led to the same articles, no further searches were conducted on Web of Science. I compiled all the gathered articles from Web of Science into a separate Excel spreadsheet for further investigation.

3.1.1 Different forest management regimes in SIMO

The data used in this study were obtained from forest growth simulations performed using the SIMO forest growth simulator, and I added the results was to an Excel spreadsheet. SIMO is a forest management planning framework that allows users to create a variety of forest growth and yield simulators, combine them with optimization methods, and apply the results to a variety of planning challenges (Rasinmäki et al., 2009). The spreadsheet contained information on different forest management strategies. The selection of forest management was filtered then to: BAU (thinning, no fertilizers) and BAU F (thinning with fertilization). The spreadsheet also included data on different ecosystem services, including bilberry, cowberry, and carbon sink. I analyzed the data using Excel. The first step in the analysis was to create a Pivot table to organize the data according to the different forest management strategies and ecosystem services. In the simulation data, the total number of forest plots was 90,938 with BAU and BAU_F, and the location was Central Finland. Time period was 100 years from the year 2021 to 2116 in intervals of 5 years.

<u>Business as usual (BAU) or rotation forestry:</u>

The regimes are based on Finland's "best practices guide" for forest management. Based on this standard business as usual management regime, several modifications have been developed. Regimes are determined by decision rules that are based on the site type, the dominant tree species' height, and the age of the stand. To perform a final felling, the dominant height must be higher than 16 or 14 meters, and the age must be between 70 and 90 years. The stand is prepared and artificially regenerated after the final felling (either by planting or seeding). To enhance growth and reduce competition, pre-commercial thinning can be applied. (Blattert et al., 2022.)

Business as usual with fertilization (BAU_F):

Standard BAU procedures and shorter rotation times are employed in conjunction with fertilization. This method implies extremely intense management techniques; before, it was considered that spruce and pine stands with basal areas between 14 and 20 m^2 per hectare would benefit from an additional 300 kg of nitrogen per hectare. (Pukkala, 2017.) The Kukkola and Saramäki model was used to calculate the impact on growth (Kukkola & Saramäki, 1983).

The table below (Table 3) was provided by María Triviño (supervisor). The list describes two different provisioning and cultural ecosystem services, which are bilberry and cowberry and one regulating service that is carbon storage. The aim is to focus on these different ecosystem services and to see that how the forest fertilizers affect them. The focus is on those three ecosystem services as they were the only ones clearly studied in empirical studies. Once the indicators are selected, it will be possible to create correction coefficients and perform calculations with SIMO and have for example a linear regression that is tested with and without fertilization. After this the evaluation of projection of indicators will be performed with or without correction coefficients.

TABLE 3. List of ecosystem services included in SIMO forest growth simulator and analyzed in this study.

Indicator	Description	Units	Type	References
Bilberry	Yield of bilberry (*Vaccinium myrtillus*)	kg ha^{-1}	Provisioning & Cultural ES	Miina et al. (2009); Turtiainen et al. (2016)
Cowberry	Yield of cowberry (*Vaccinium vitis-idaea*)	kg ha^{-1}	Provisioning & Cultural ES	Turtiainen et al. (2013)
Carbon storage	Combined habitat suitability model of 6 indicator vertebrate species	ha^{-1} (range between 0 and 1)	Biodiversity indicator	Mönkkönen et al. (2014)

3.2 Analyses

The idea was to compare how well the fertilization impact on ecosystem services from the simulated data (obtained from SIMO) matched with the empirical data (obtained from the literature review). For every selected species, such as bilberry, I created a pivot table to a separate tab in Excel.

3.2.1 Selection of studies

The research article *Nitrogen fertilization reduces wild berry production in boreal forests* written by Granath & Strengbom (2017), was used to compare bilberry and cowberry to the simulation data. In this article the forest type was pine dominated and the average age of trees were 32-54 years. Then I selected pine-dominated forest stands. The number of stands was not mentioned in the article. In order to compare this, in the simulation data years were selected from 2056 to 2071. (Granath & Strengbom, 2017.) The age 6 selection method was employed to ensure that the forest stands selected for analysis had originated from a 0 age in 2021 as in the simulation data. This ensures that the stands analyzed were between the ages of 32 and 54 during the period of 2056 to 2071. To minimize variability in the data, the same stands selected at age 6 in 2026 were used for analysis, avoiding potential changes in values due to different selection of stands. The reason why selected forest stands were 6 years old in 2026 is because in the simulation data there were not trees in 2021 and it was not known whether the forests would be pine or spruce dominated forests. The total number of selected pine-dominated 6-year-old stands was 27 in 2026.

The research article *Forest management to increase carbon sequestration in boreal Pinus sylvestris forests* written by Jörgensen et al. (2021), was used to compare carbon storage to the simulation data. In this article the forest type was pine dominated, the average age of trees was also 32-54 years, and the number of stands was 29. In order to compare this, in the simulation data years was selected from 2056 to 2071. (Jörgensen et al., 2021.)

3.2.2 Comparison among managements from forest growth simulators

I summed the values in the simulation data to have the accumulative effect for the longer period. Then I calculated these values for each combination of forest management strategy and ecosystem service. The values were used to create column charts to compare the different forest management strategies with respect to their impact on each ecosystem service.

3.2.3 Comparison of estimates from forest growth simulator and empirical studies

The coefficient shows the percentage difference, allowing for comparison between simulated and empirical data. For instance, if the coefficient is 1.11 for bilberry yield, it signifies an 11% growth for bilberry yield. This coefficient was derived by considering various factors: the impact of thinning alone, the comparative effect of thinning versus unfertilized stands, and the difference between nitrogen-fertilized (no thinning) and unfertilized stands. The calculation involved adding Thinning, (Thinning - unfertilized stands), and (N fertilized and no thinning - unfertilized stands) to achieve this coefficient.

4 RESULTS

4.1 Ecosystem services

4.1.1 Bilberry

I applied two filters to the simulated data from SIMO: first I selected stands which average age is 32-54 years old and I then selected stands from the time period 2056 to 2071 to be able to compare empirical data and simulation data (Figure 2). In the other years analyzed when using the whole data set, although the difference was not as significant, the yield of bilberry demonstrated a gradual decrease. The bilberry yield showed a decrease of 1.41 % in the thinned yet not fertilized (BAU) stands compared to the thinned and fertilized (BAU_F) stands, with a yield of 7.12 kg/ha-1 and 7.02 kg/ha-1, respectively.

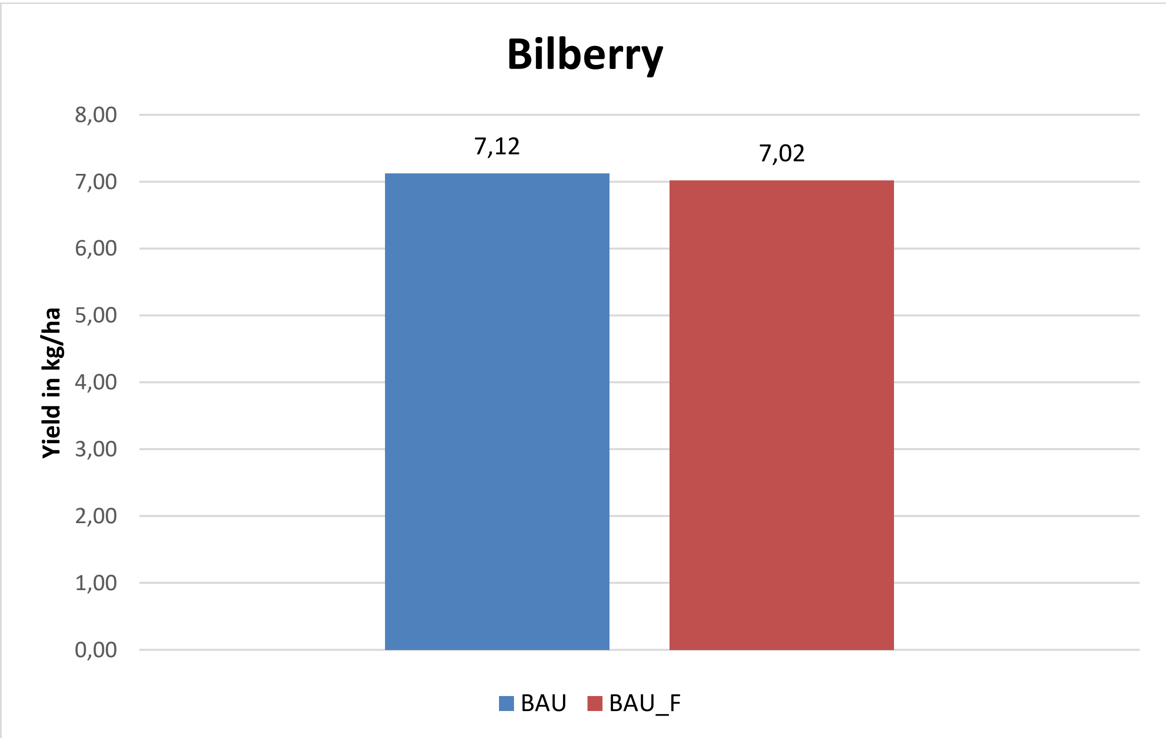

Figure 2. Comparison of bilberry yield measured in kg/ha in thinned pine stands with and without fertilization; sum for simulated years 2056-2071.

The article *Nitrogen fertilization reduces wild berry production in boreal forests* written by Granath & Strengbom (2017) is similar to previous research article *Forest* *management to increase carbon sequestration in boreal Pinus sylvestris forests* written by Jörgensen et al. (2021) as the average tree age was 32-54 years and the time frame was approximately 45 years. The forest was also pine dominated and the study was conducted in Sweden. Nitrogen fertilization in thinned stands significantly reduced bilberry production 37–47 %. Bilberry yield was measured also in kg/ha. The coefficient (Appendix 1) was 0.61 which is an odds-ratio, i.e., for one unit increase in the predictor the response change with this factor and therefore it means a 39% decrease of the response. This shows that there is a decrease of 39 % in bilberry production in empirical data. According to the study, direct effects are prevalent for bilberry. Additionally, bilberry demonstrated a minor N-induced effect through a parasitic fungus's enhanced illness incidence. (Granath & Strengbom, 2017.)

4.1.2 Cowberry

I applied two filters to the simulated data from SIMO: first I selected stands which average age is 32-54 years old and I then selected stands from the time period 2056 to 2071 to be able to compare empirical data and simulation data (Figure 3). Cowberry yield was measured in kg/ha. In the other years analyzed when using the whole data set, although the difference was not as significant, the yield of cowberry demonstrated a gradual decrease. In the simulation data the cowberry yield showed a decrease of 6.01 % in the thinned yet not fertilized (BAU) stands compared to the thinned and fertilized (BAU_F) stands, with a yield of 38.98 kg/ha-1 and 36.71 kg/ha-1, respectively.

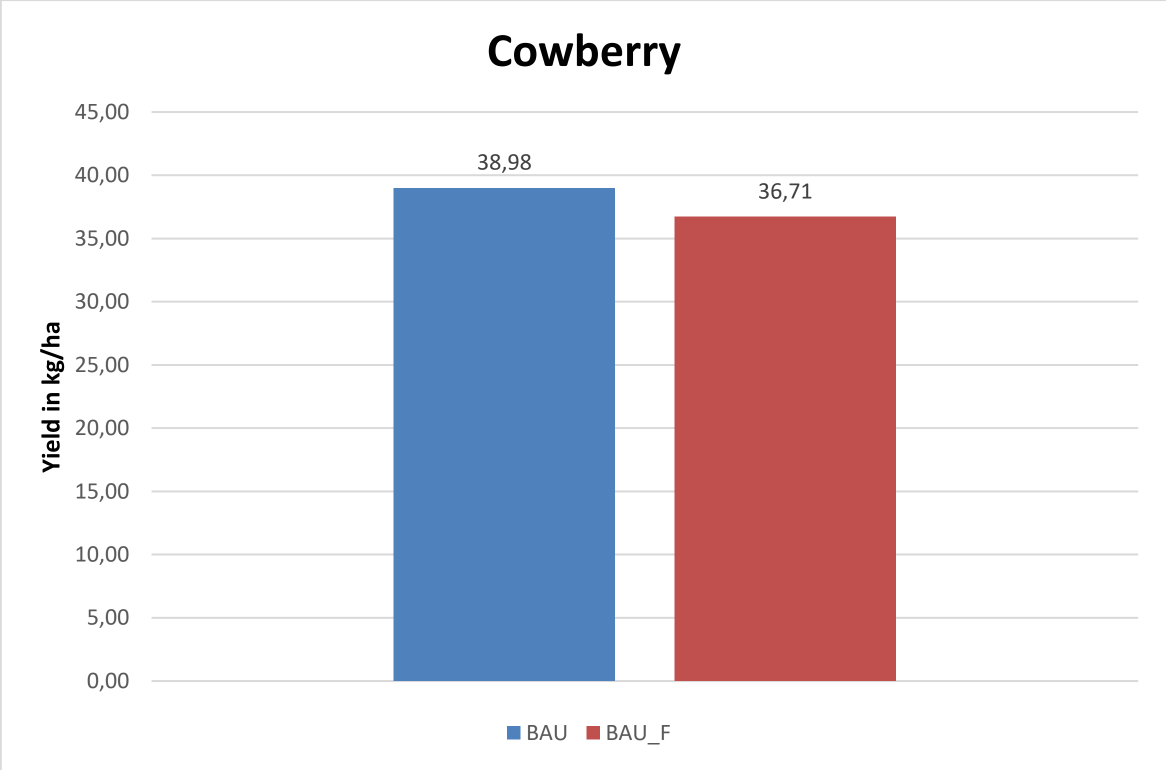

Figure 3. Comparison of cowberry yield measured in kg/ha in thinned pine stands with and without fertilization; sum for simulated years 2056-2071.

The article *Nitrogen fertilization reduces wild berry production in boreal forests* written by Granath & Strengbom (2017) is similar to previous research article *Forest management to increase carbon sequestration in boreal Pinus sylvestris forests* written by Jörgensen et al. (2021) as the average tree age was 32-54 years and the time frame was approximately 45 years. The forest was also pine dominated and the study was conducted in Sweden. Nitrogen fertilization in thinned stands significantly reduced cowberry production 91–94 %. Cowberry yield was measured also in kg/ha. The coefficient (Appendix 1) was 0.31 and that shows that there was a decrease of 69 % in cowberry production in empirical data. According to article, for cowberry this effect in decrease was mainly due to reduced plant cover. (Granath & Strengbom, 2017.)

4.1.3 Carbon storage

I applied two filters to the simulated data from SIMO: first I selected stands which average age is 32-54 years old and I then selected stands from the time period 2056 to 2071 to be able to compare empirical data and simulation data (Figure 4). Carbon storage was measured in m^3/ha.

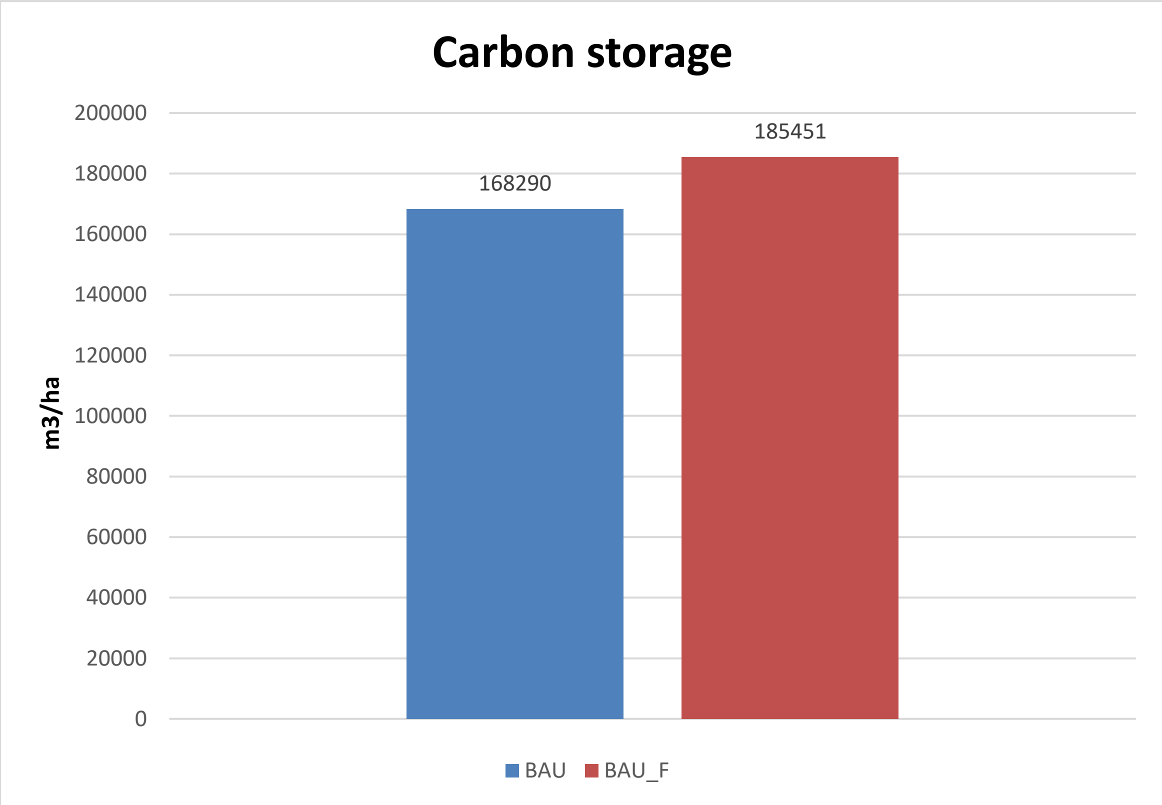

Figure 4. Comparison of carbon storage measured in m^3/ha in thinned pine stands with and without fertilization; sum for simulated years 2056-2071.

In the simulation data the carbon storage showed an increase of 13.86 % in thinned and fertilized (BAU_F) stands compared to thinned yet not fertilized (BAU), with a yield of 185,451 m^3/ha and 168,290 m^3/ha, respectively. The coefficient (Appendix 1) was 1.10 and that shows that there was an increase of 10 % in carbon storage in empirical data. This result was calculated from the empirical data as a mean value from standing tree C, soil C, removed tree C, total ecosystem C gain - excluding removed C and total ecosystem C gain – including removed C. Soil carbon in old forest increased much more than in younger forests on 40 years old. Older forests might now grow much in timber; however, they might grow more in litter. It also needs to be considered that the soil carbon growth is not linear.

TABLE 4. Comparison of the results between simulated and empirical data

Indicator	Comparison	Simulated	Empirical
Bilberry	BAU_F vs. BAU	-1.4 %	-39 %
Cowberry	BAU_F vs. BAU	-6.01 %	-69 %
Carbon storage	BAU_F vs. BAU	+13.86 %	+10 %

5 DISCUSSION

5.1 Aims

The investigation of fertilizer effects on forest ecosystem services and biodiversity, as well as its implications for recommendations on forest management, are the main topics of this master's thesis. In my thesis, I focused on reviewing the current state of knowledge regarding the impacts of fertilizers on the ecosystem services and biodiversity of boreal forests. This part is essential since it establishes the basis for comprehending the knowledge gaps that exist now and identifying areas where improvements may be made. Then I further investigated in the study how fertilizers impact biodiversity and ecosystem services in boreal forests in the Fennoscandia region. The thesis aims to collect observational data that are relevant to the context and may form the basis for specific methods of management by focusing on a specific region and ecosystem type. The study has a quantitative component with the use of indicators such bilberries and cowberries in forest growth simulators, enabling a more thorough evaluation of the impacts of fertilization.

Furthermore, I compared observational data from the literature review to simulated data from forest growth simulation models to assess their reliability in the thesis. This comparison not only allows to improve these models' estimating abilities, however, also allows for understanding the reliability and accuracy of these models. The study aims to improve future suggestions for forest management that take into account the effects of fertilizers on ecosystem services and biodiversity by evaluating the advantages and disadvantages of these models.

The main idea suggests more sustainable practices that reduce the possibility of negative impacts to the environment can be obtained by taking the effects of fertilizers into account while managing forests. The results of this study could influence practices and policies in forest management in the context of the objectives of the European Union and the need for balancing extraction of natural resources with nature protection. Overall, this thesis contributes to the present discussion regarding the complex interactions between forest management, ecosystem services, biodiversity, and fertilization, ultimately establishing the way for greater knowledge and comprehensive strategies to the usage of forest resources.

5.2 Simulations

A key aspect of this master's thesis is the comparison of empirical data collected by revising many academic articles with simulation data obtained by the SIMO forest growth simulator framework. This SIMO framework, featuring data import, simulation, optimization, and reporting components along with the use of a hierarchical data model, is a complex tool for planning forest management components (Rasinmäki et al., 2009). I investigated the alignment of simulation and empirical data in this study, with a focus on the impacts of different forest management regimes, such as business as usual (BAU) and business as usual with fertilization (BAU_F), on berry production and carbon storage.

The study includes carbon storage, where distinct yet linked trends may be seen in both empirical results and modeling data. While empirical data indicate a 10 % increase in carbon storage (Results section), simulation data show a 13.86 % difference in carbon storage between BAU and BAU_F. Due to the complexity of carbon dynamics in forest ecosystems, which are influenced by factors such standing tree carbon, soil carbon, and ecosystem gains (Results section), this difference is expected. Here, the discrepancy between simulation and empirical data highlights the complexity of carbon sequestration and emphasizes the need for thorough modeling tools that accurately represent these processes.

In conclusion, the comparison of empirical data from relevant research articles with simulation data from the SIMO framework provides important insights into the similarities and differences between these two sources of information. Examples of both convergence and divergence between simulation and empirical data are shown in the study of the impacts of forest management regimes on the yields of bilberries and cowberries as well as carbon storage. The SIMO framework's potential to improve forest management decision-making based on its alignment with actual empirical observations is highlighted by this investigation's strengths and limitations.

5.3 Positive impacts of fertilizers

The results present insights of the impacts of fertilization on bilberry, cowberry, and carbon storage. The observed decrease in bilberry yield seen in both simulated and empirical data emphasizes any potential risks associated with fertilization use. While it can result in greater numbers of trees growing, it may have a negative impact on the production of some ground vegetation species, such bilberries, and cowberries. This observation is in line with the findings of Granath & Strengbom's (2017) study, which highlights the complex interactions between fertilization and the dynamics of plant species.

Examining carbon storage provides important information regarding how the ecosystem responds to fertilization. The potential for fertilization to have an impact on carbon sequestration is demonstrated by the simulation results, which shows a 13.86 % difference between the thinned and fertilized (BAU_F) stands and the thinned yet not fertilized (BAU) stands. Empirical data show a 10 % increase, indicating that while fertilizer can improve carbon storage, the connection may not be linear and is impacted by variables including stand age and soil carbon dynamics. The results suggest that the application of fertilization in thinned forest management scenarios can increase carbon storage in the long term, with BAU_F showing a higher rate of increase compared to BAU. With carbon storage, both empirical data and simulation data found out that fertilization has a positive effect on carbon storage. Jörgensen et al. (2021) found out, that repeated N fertilization increased the ecosystem C stock by 12 t C ha^{-1} in thinned stands and by 33 t C ha^{-1} without thinning, while the simulation data showed that the application of fertilization in the thinned forest management scenario led to a higher carbon storage rate in the long term. Furthermore, Jörgensen et al. (2021) finds that the positive effect of fertilization on carbon sequestration was again higher without thinning compared to thinned stands. In contrast, the simulation data found that the application of fertilization in the thinned forest management scenario led to a higher carbon storage rate in the long term. Understanding the differences and similarities between these two texts can help inform forest management practices for carbon sequestration in the future.

In conclusion, this study explains the complex interactions between fertilizing forests and their positive impact on the ecosystem. Although fertilizer can promote better tree growth and carbon sequestration, it is important to consider any potential trade-offs, including impacts on species of understory vegetation and the intricate dynamics of carbon storage. These results add to a more thorough understanding of the potential advantages and difficulties of using fertilization of forests as a technique to improve the environment and prevent climate change. To further understand these dynamics and guide sustainable forest management techniques, more investigation is necessary.

5.4 Negative impacts of fertilizers

Study written by Strengbom & Nordin (2008) indicates that fertilizing forests may have negative effects on the composition of species and biodiversity, particularly in ground vegetation. Fertilization might promote fast-growing species such grasses and nitrophilous herbs while inhibiting the growth of slow-growing species as dwarf shrubs and lichens. This imbalance may cause changes in community composition and a decline in biodiversity, which could decrease the ecosystem's overall resilience. Furthermore, Lindroos and colleagues (2022), observed in their research that nitrogen fertilizer can alter the mechanisms of nutrient cycling in heathlands by negatively affecting microbial biomass and carbon mineralization.

In addition to contributing to water eutrophication and posing hazards to aquatic ecosystems, nitrogen fertilization carries the risk of nutrients leaching into groundwater and watercourses. Nitrogen fertilizer may result in higher nitrate concentrations in groundwater, which may have an impact on water quality. (Kaukonen et al., 2022.) Similarly, the use of ash-based fertilizers might affect the levels of heavy metals in the soil and vegetation, which raises questions about the possible release into watercourses. Although ash-based fertilizers may initially raise the concentrations of heavy metals, their long-term impacts could vary, with some metals continuing to be chemically linked to the soil. (Motiva, 2009; Huotari, 2012.)

Additionally, forest resources that directly benefit people, such berries and mushrooms, are also affected by fertilization. The reduction in wild berry production caused by nitrogen fertilizers have been observed to have an adverse impact on the environment and the local communities that depend on these resources. (Granath & Strengbom, 2017.) Complex factors, including fungal infections, plant cover, and nutrient availability, affect how fertilization impacts berries and mushrooms (Issakainen & Moilanen, 1998). In addition, there is a complex interaction between fertilization, forest management, and carbon sequestration. The effects of fertilization, which may improve carbon uptake and sequestration in trees and soil, are influenced by a number of variables, including as thinning methods and the potential for accelerated decomposition rates. (Jörgensen et al., 2021.)

The results of this study suggest that the treatment effects on bilberry plant cover were relatively significant, with an absolute difference of approximately 39 % observed between nitrogen-fertilized and thinning treatments, in contrast to the 1.41 % decrease in simulation data. Specifically, thinned yet not fertilized (BAU) areas had higher yields compared to fertilized (BAU_F) areas. However, the treatment effects on cowberry plant cover were significant, with an absolute difference of approximately 69 % observed between nitrogen-fertilized and thinning treatments, in contrast to the 6.01 % decrease in simulation data. The decrease in cowberry plant cover was more significant over a longer period. These findings highlight the importance of considering the impact of different treatments on specific plant species and the potential for variations in treatment effects over time. The results of the empirical study indicate that while thinning may mitigate the negative effects of large-scale fertilization, it will still have a negative impact on ecosystem services related to berry production in pine forests. The comparison also identifies that the simulated and empirical data is not aligned. Therefore, it becomes apparent that a more thorough investigation is required to resolve this discrepancy.

In conclusion, fertilizers' negative impacts on the environment include changes in biodiversity, nutrient leaching, alterations to water quality, disturbances in the growth of berries and mushrooms, and complex interactions with carbon sequestration processes. These effects underline the importance of properly balancing the potential advantages of enhanced productivity with the preservation of biodiversity and sustainability. Fertilizer application methods in forest management should take this into account. Further in-depth research is needed to better understand the extent of the negative impacts of forest fertilizers on ecosystem services and biodiversity as currently there are limited information on research data on this.

6 CONCLUSIONS

On ecosystem services and biodiversity in boreal forests, nitrogen fertilizer can have both positive and negative effects. On the one hand, nitrogen is an essential nutrient for plant growth, and applying fertilizer can increase forest productivity, resulting in more carbon being stored and possibly more income being made from cutting the forest. Excessive nitrogen inputs, however, can also harm biodiversity and ecosystem services. Nitrogen fertilizers can cause eutrophication, which can lower water quality. Moreover, it can change the composition of plant communities by favoring fast-growing competitive species over slower growing, less adapted species. Loss of biodiversity and alterations to the structure and operation of forest ecosystems may result from this.

Overall, the effects of fertilizers on ecosystem services and biodiversity in boreal forests in the Fennoscandian area depend on the specific type and amount of fertilizer used, as well as the surrounding environmental conditions. Proper control and monitoring of fertilizer use can help reduce negative impacts while optimizing the benefits to the ecosystem.

Studying the effects of heavy metal concentrations on the growth of wild berries and mushrooms was out of the scope of this thesis. However, I found out in previous studies that I examined that heavy metal concentrations increase after applying ash fertilizer (Huotari, 2012; Päivinen et al., 2017). It will be important that future studies consider the levels of heavy metals in these collectable goods.

The existing research suggests that there's insufficient information available regarding the impact of forest fertilization on ecosystem services and biodiversity. Further investigation is important to gain a deeper understanding of this matter.

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APPENDIX 1. CORRECTION FACTOR TABLE WITH COEFFICIENTS

Correction factor table with calculated coefficients from the collected articles selected from Web of Science and organized into an Excel spreadsheet with specific titles.

Indicator	Type	Units	Coefficient	Fertilizer type	Fertilizer amount	Frequency	Study area	Forest type	Number of stands	Average tree age (years)	Average tree height (m)	Time frame (years)	Reference
Standing tree carbon	Regulating ES	t ha^{-1}	1,11	1. Nitrogen as ammonium nitrate (NH4NO3), 2. Phosphorus was added as superphosphate (CaSO4 + Ca(H2PO4)3)	1. 100–150 kg N ha−1, 2. 100 kg P ha−1	Every 5th year for the first 25 years & later every 7th year	(56–67°N) in Sweden	Pine dominated	29	32-54, in 2016, the stands were between 65–99	12-16	40	Jorgensen et al.
Soil carbon	Regulating ES	t ha^{-1}	1,18	1.NH4NO3, 2. CaSO4 + Ca(H2PO4)3	1. 100–150 kg N ha−1, 2. 100 kg P ha−1	Every 5th year for the first 25 years & later every 7th year	(56–67°N) in Sweden	Pine dominated	29	32-54, in 2016, the stands were between 65–99	12-16	40	Jorgensen et al.
Removed tree carbon	Regulating ES	t ha^{-1}	1,00	1.NH4NO3, 2. CaSO4 + Ca(H2PO4)3	1. 100–150 kg N ha−1, 2. 100 kg P ha−1	Every 5th year for the first 25 years & later every 7th year	(56–67°N) in Sweden	Pine dominated	29	32-54, in 2016, the stands were between 65–99	12-16	40	Jorgensen et al.
Total carbon - excluding removed C	Regulating ES	t ha^{-1}	1,12	1.NH4NO3, 2. CaSO4 + Ca(H2PO4)3	1. 100–150 kg N ha−1, 2. 100 kg P ha−1	Every 5th year for the first 25 years & later every 7th year	(56–67°N) in Sweden	Pine dominated	29	32-54, in 2016, the stands were between 65–99	12-16	40	Jorgensen et al.
Total carbon including removed C	Regulating ES	t ha^{-1}	1,08	1.NH4NO3, 2. CaSO4 + Ca(H2PO4)3	1. 100–150 kg N ha−1, 2. 100 kg P ha−1	Every 5th year for the first 25 years & later every 7th year	(56–67°N) in Sweden	Pine dominated	29	32-54, in 2016, the stands were between 65–99	12-16	40	Jorgensen et al.
Mean value			**1,10**										
Bilberry (*Vaccinium myrtillus*)	Provisioning & Cultural ES	t ha-1	**0,40**	N	150 kg N ha−1	Fertilized twice (30 and 22 years prior to study) with NH4NO3.	Central Sweden	Spruce and pine mix	29	8-11	1.5–2.5	20	Strengbom & Nordin
Cowberry (*Vaccinium vitis-idaea*)	Provisioning & Cultural ES	t ha-1	**0,64**	N	150 kg N ha−1	Fertilized twice (30 and 22 years prior to study) with NH4NO3	Central Sweden	Spruce and pine mix	29	8-11	1.5–2.5	20	Strengbom, J; Nordin, A
Bilberry	Provisioning & Cultural ES	Odds-ratios	**0,61**	N, Phosphorus (P)	At the northern sites (above latitude 61), 100 kg N ha−1 was applied, and at the southern sites (below latitude 61) 150 kg N ha−1 was applied,	N every 5th year the first 30 years & later every 7th year. P was applied at the start of the experiment and after 21–22 years.	1400 km south-north gradient within Sweden	Pine dominated		32-54	12	45	Granath, G; Strengbom, J
Cowberry	Provisioning & Cultural ES	Odds-ratios	**0,31**	N, P	N sites: 100 kg N ha−1 & S sites: 150 kg N ha−1	N every 5th year the first 30 years & later every 7th year. P was applied at the start of the experiment and after 21–22 years.	1400 km south-north gradient within Sweden	Pine dominated		32-54	12	45	Granath & Strengbom
Soil C (forest floor)	Regulating ES		**1,50**	N	50–100 kg N ha−1 yr−1	One of the 15-ha plots (F) has been fertilized annually since 2006	5 km south of Vindeln, Sweden (64°10′N, 19°45′E, 145 m. a.s.l.)	Pine dominated		100		15	Marshall et al.
Soil C (mineral soil)	Regulating ES		**1,22**	N	50–100 kg N ha−1 yr−1	One of the 15-ha plots (F) has been fertilized annually since 2006	5 km south of Vindeln, Sweden (64°10′N, 19°45′E, 145 m. a.s.l.)	Pine dominated		100		15	Marshall et al.