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Modelling nitrogen balance in two Southern Swedish spruce plantations

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Abstract

Emissions from agriculture and the combustion of fossil fuels increase the atmospheric load of reactive nitrogen (N). N deposition is projected to continue posing significant harm both for environmental and human health over the upcoming decades. Eutrophication as a result of N leaching is one of the negative effects of heavy deposition. It occurs when the input of N into an ecosystem exceeds its uptake capacity. This study analysed modelled data series on nitrogen deposition, leaching, and forest growth from 1900 to 2100 for two Southern Swedish spruce forestry stands. Moreover, several modelled N fertilisation schemes were tested. A maximum bearable nitrogen input rate indicating the retainable influx of N was estimated next to a maximum effective fertilisation rate. That threshold gave the highest application of fertiliser at which the expected biomass harvest increased. Both sites receive between 11 and 13 kg N/ha/yr of mean annual nitrogen deposition depending on the chemistry transport model applied. The first site, Hissmossa, can retain 10 kg N/ha/yr and shows harvest increase up to the single application of 20 kg N/ha per rotation period. The other study site, Västra Torup, has a maximum bearable nitrogen input rate of 12 kg N/ha/yr and fertilisers are effective up to the dose of 43 kg N/ha. In conclusion, both sites can be seen to be nitrogen saturated. Leaching should be expected, at least in reaction to biomass removal. Forest fertilisation bears only little potential to increase harvest but will probably increase the eutrophication issue.

Key words: *Atmospheric deposition, nitrogen saturation, maximum bearable nitrogen input rate , forest fertilisation, ForSAFE*

Sammanfattning

Utsläpp från jordbruk och förbränning av fossila bränslen ökar den atmosfäriska belastningen av reaktivt kväve (N). Kvävenedfall beräknas fortsätta utgöra betydande skada både för miljön och människors hälsa under de kommande decennierna. Övergödning som resultat av kväveläckage är en av de negativa effekterna av nedfallet. Den inträffar när tillförseln av N in i ett ekosystem överstiger upptagningsförmågan. Denna studie analyserar modellerade dataserier av kvävenedfall, kväveläckage och skogstillväxt mellan år 1900 och 2100 för två skånska granplanteringar. Dessutom blev kvävegödsling vid olika användningsmönster modellerat. En maximalt hållbar kvävetillförsel och en maximal effektiv gödslingsmängd uppskattades. Detta tröskelsvärde gav den högsta tillförseln av gödselmedel på vilken den förväntade skörden fortfarande ökade. Bägge skogarna fick mellan 11 och 13 kg N/ha/år genomsnittliga kvävenedfall beroende på vilken vilken atmosfärisk transportmodell som användes. Den första platsen, Hissmossa, kan hålla kvar 10 kg N/ha/år med ökande skördar upp till 20 kg N/ha per omloppstid. Den andra skogen, Västra Torup, kan hålla kvar 12 kg N/ha/år med ökande skördar upp til 43 kg N/ha per omloppstid. Sammanfattningsvis kan bägge platserna ses som kvävemättade. Kväveläckage förväntas, åtminstone som ett resultat av skörd. Skogsgödsling innebär endast små möjligheter för att öka skörden, men kommer däremot sannolikt att öka läckaget.

Nyckelord: *atmosfärisk nedfall, kvävemättning, maximalt hållbar kvävetillförsel, skogsgödning, ForSAFE*

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1 Introduction

Europe's economy is and has for almost 200 years been heavily dependent on fossil fuels (Malm 2016). Transport, medical care, construction and the production of food imply the use of coal, oil and gas either as a material or as a source of energy. This dependency has many reasons: fossil fuels are vastly available (International Energy Agency 2015), they are easily transported, and they allow for economic centralization (Malm 2016). Economic centralisation and industrialisation fuel urbanisation (Gollin et al. 2016) which poses a pressure on agriculture to produce food more work efficiently (Martin-Retortillo and Pinilla 2015). The use of nitrogen (N) fertilisation has in combination with other practices increased agricultural productivity over the last century. So has the European use of nitrogen as fertiliser increased from zero in 1900 to about 11 million tonnes in 2014, averaging to 60 kg of nitrogen yearly per hectare of agricultural land (Fertilizers Europe 2015).

Yet, using fossil fuels and fertilisers come with a range of unfavourable consequences for the biogeochemical cycles of the Earth, namely the global cycles of carbon, sulphur and indeed nitrogen. While the steady increase of carbon in the atmosphere enjoys broad scientific, public and political attention (as in IPCC (2014)) and the sulphur emission and deposition has been reduced considerably over the last decades (Amann 2015), the emission of nitrogen, especially from agriculture, is projected to continue posing significant harm for both environmental and human health over the upcoming decades (Galloway et al. 2004). Of the applied nitrogen fertiliser, a significant part is generally lost to terrestrial and coastal waters and the atmosphere (Schlesinger 2009).

Acknowledging the call for continuous high productivity for commercially used agriculture and forestry land, the environmental harm that nitrogen emission is posing has to be well understood. Soil fertility and pollution have a two sided relationship: on the one hand, atmospheric nitrogen emission and deposition act as a background fertiliser for agriculture and forestry. This is the case in forests where the growth is limited by the availability of nitrogen. On the other hand, fertilisation of agriculture and forestry can contribute to nitrogen leaching. Therefore, not just forestry managers but even people responsible for emissions need to understand the effect that atmospheric deposition and fertilisation have on a productive ecosystem to avoid the overabundance of nitrogen that would inevitably lead to excess leaching from an ecosystem.

Southern Swedish forests receive a significant amount of atmospheric nitrogen deposition (Akselsson et al. 2010) and serve as a source of timber and income. They are therefore a suitable target to investigate and estimate the balance between input of nitrogen and the output in form of timber harvest and nitrogen leaching.

1.1 Aim

The aim of this study is to investigate whether two forestry stands in Southern Sweden are nitrogen limited or if they are saturated, and if harvest could be increased by adding nitrogen fertiliser. Further, the nitrogen input in form of atmospheric deposition and different fertiliser applications shall be balanced with the leaching of nitrogen to estimate the retention of nitrogen in the forest ecosystems for future scenarios of forestry harvest, deposition and fertiliser application. The retention is analysed to find a maximum bearable nitrogen input rate at which no leaching occurs. The harvest for varying fertiliser application is analysed to estimate a maximum effective fertilisation rate after which further application does not result in increased forest biomass growth. The ForSAFE model shall be applied to obtain data series on the important parameters. The disturbing effects of enhanced nitrogen availability on biodiversity are not object of this investigation. This investigation can be seen in relation to the Swedish authority's environmental objectives "zero eutrophication", "clean air" and " sustainable forests" and as a scientific justification of the current Swedish forestry recommendation that is suggesting not to apply any nitrogen fertiliser in Southern Sweden.

2 Background

2.1 Global nitrogen cycle

As an essential component of proteins and enzymes, nitrogen cycles through the entire global ecosystem. This nutrient is vital to all forms of life and the availability of nitrogen is regularly seen as a limiting factor to an ecosystem's growth (Schlesinger and Bernhardt 2013). Throughout the cycling nitrogen appears in various chemical compounds: either inert as N_2 or chemically bound to hydrogen (as reduced nitrogen) or oxygen (then called oxidised) nitrogen. As seen in Figure 1 there are significant stocks of nitrogen in the atmosphere, the terrestrial biosphere, the oceans and the soils. The majority of atmospheric nitrogen is inert and only available to specialized microorganisms who incorporate N into the biosphere. These synthesise reactive nitrogen i.e. nitrogen in any compound except for N_2. Certain human activities add further reactive N to this cycle: fossil fuel combustion results in gases collective labelled NO_x, whereas intensive agriculture adds ammonium (NH_4^+) and nitrate (NO_3^-). Whilst the largest fraction of nitrogen in the biosphere is recycled internally (see also section 1.4), there is also a loss in the form of leaching of N into oceans and lakes via streams as nitrate and nitrite (NO_2) and volatization, where nitrogen is released back to the atmosphere.

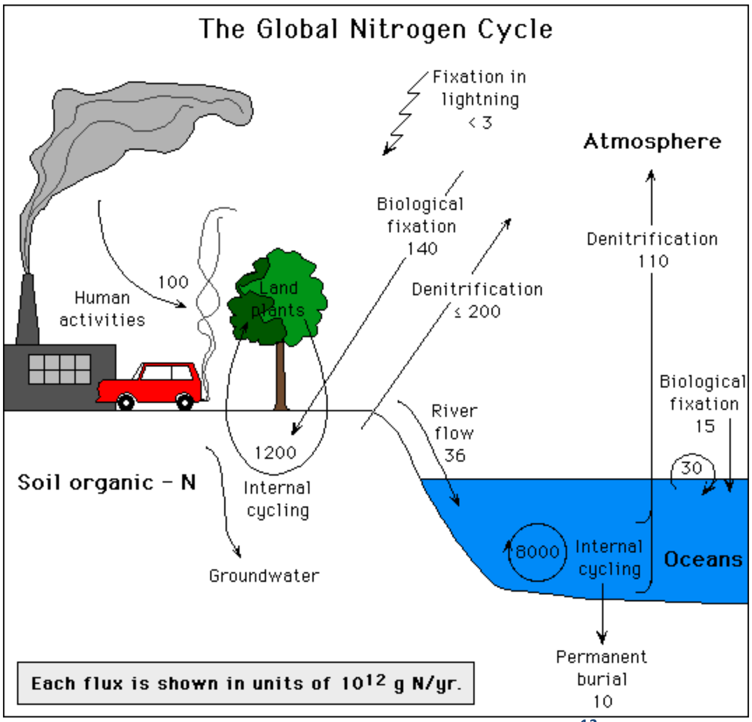

FIGURE 1 - THE GLOBAL NITROGEN CYCLE WITH FLUXES IN 10^{12} G N/YR. SIGNIFICANT STOCKS OF NITROGEN ARE FOUND IN THE ATMOSPHERE, THE TERRESTRIAL VEGETATION, IN THE SOIL AND IN THE OCEANS. FIGURE FROM SCHLESINGER AND BERNHARDT (2013)

2.2 Alteration of the N cycle and its effects

The application of artificial fertilisers in agriculture and fossil fuel combustion have increased the amount and mobility of reactive nitrogen over the last decades, and effects of that are clearly detectable (Vitousek et al. 1997). The anthropogenic nitrogen cycle alteration has a magnitude that exceeds what Rockström et al. (2009) define as safe operating space for humanity. The changes that are induced imply "irreversible and abrupt environmental change". To get a rough idea of the degree of alteration in inputs to the reactive part of the global nitrogen cycle, table 1 presents quantifications of natural and anthropogenic nitrogen inputs. It can be seen that the artificial input of nitrogen into the biosphere exceeds the natural input. Hence, the current nitrogen cycle is mainly shaped by anthropogenic activities and only partly shaped by the natural turnovers. Naturally, nitrogen is added to the land masses by biological fixation and by lightning. The main anthropogenic inputs are artificial fertilisation of cultivated lands, nitrogen fixation of cultivated plants, and fossil fuel combustion.

TABLE 1 - CHANGE IN GLOBAL PRODUCTION OF REACTIVE NITROGEN IN 1860 AND 1990. DATA FROM GALLOWAY ET AL. (2004).

Nitrogen fixation process in Tg N /yr	1860	1990
Lightning	5,4	5,4
Natural biological fixation	120	107
Cultivated biological fixation	15	31,5
Fossil fuel combustion	0,3	24,5
Artificial fertilisation	0	100
Total N input	140,7	268

The increased availability of nitrogen has multifaceted effects. Three of them will be presented in the following subsections as these effects will play a role in defining bearable nitrogen input.

2.2.2 Increased carbon uptake/forest growth

The growth of temperate and boreal ecosystems is often limited by the availability of nitrogen and hence growth increases in response to additional N input. Enhanced nitrogen availability enables such plants to take up more carbon from the atmosphere. As a result, more CO_2 is removed from the atmosphere and formerly N limited ecosystems produce more biomass (Shaver et al. 1992). Through this effect nitrogen deposition of N limited ecosystems has a fertilising effect on ecosystems and counteracts increased atmospheric CO_2 levels.

2.2.3 Biodiversity loss

On the other hand, increased nitrogen levels impact biodiversity negatively. They favour organisms that are adapted to nitrogen rich environments which gain advantage over organisms that are adapted to nitrogen poor environments. The latter have evolved to grow slowly, even so under high nitrogen inputs and are therefore outcompeted under changing conditions. In Sweden, about three fourths of the endangered species are adapted to nitrogen poor conditions (Gädenfors 2000). Especially in Southern Sweden, a clear trend of decreasing species richness with increasing nitrogen deposition has been observed (Diekmann and Falkengren-Grerup 2002). Besides land use change, alterations in the nitrogen cycle can thus be seen as a main driver of biodiversity loss.

2.2.4 Eutrophication

In aquatic environments excess nitrogen can lead to the eutrophication. Nitrate, which is easily dissolved in water, is likely to be lost from soils once it appears in the soil water solution. Leaching nitrate follows the drainage path of groundwater: through streams, lakes and rivers into coastal waters and the open ocean. Schlesinger (2009) estimated that half of the nitrogen that is transported in rivers is of anthropogenic origin. An increased availability of nitrogen can e.g. support periods of greatly enhanced algal growth, so called algal blooms. Apart from other environmental problems, the decomposition of algal blooms can deplete water of oxygen, creating environments where hardly any organism can survive. This is a problem especially in poorly mixed waters, like estuaries or the Baltic Sea (Schernewski 2008).

2.3 Atmospheric nitrogen deposition

2.3.1 Sources

Atmospheric deposition is the flux of reactive nitrogen from the atmosphere to Earth's surface. There are two main sources of reactive nitrogen in the atmosphere: it can either be emitted by soils or it can be a by-product of the combustion of fuels. Nitrogen losses from soils to the atmosphere have the highest magnitude in fertilised agricultural fields. There nitrogen is transported in the form of ammonium. On the other side, the combustion of fuels emits NO_x into the atmosphere. Reactive nitrogen is not transported endlessly but deposited within a limited range from its source. Oxidised nitrogen has a mean residence time of one day and ammonia is deposited after about five days (Schlesinger and Bernhardt 2013). Hence, local emissions of nitrogen might affect ecosystems within the range of 100s of kilometres. That is why, atmospheric nitrogen deposition often is a regional, yet transboundary issue, where the harmed community not necessarily is responsible for the pollution itself, but damaged by others' activities. Atmospheric nitrogen moves with the predominant wind direction. The deposition in Sweden is therefore generally referred to as mainly originating from the UK, the Benelux countries, Germany, Poland, and international shipping. Of the deposition over Sweden only 8% is traced back to Swedish emissions (EMEP/EEA 2013)

2.3.2 Trends

For portraying the issue of international nitrogen air transport, three variables are of interest: the emission, the atmospheric concentration and the deposition of reactive nitrogen.

Past

European nitrogen emissions peaked in the 1980s and are decreasing significantly since (European Environmental Agency 2014). Figure 2 shows that the decrease is more pronounced for the by-products of fossil fuels combustion than for reduced nitrogen that comes from agricultural sources. The atmospheric concentration of nitrogen has decreased substantially and the reduction in Sweden even exceeds the total emission reduction in Europe. Still, that decreasing trend of emissions is often not reflected in the measurements of nitrogen deposition in Sweden (Pihl Karlsson et al. 2011). Even though the problem of high emissions is addressed, nitrogen deposition rates show no clear trend in long-term measurements in Sweden. The reason for this is still debated. Difficulties in measurement techniques are suggested by Pihl Karlsson et al. (2011), while the Swedish NGO AirClim points towards the considerable yet poorly registered emissions from international shipping (Ågren, AirClim, personal communication 2016).

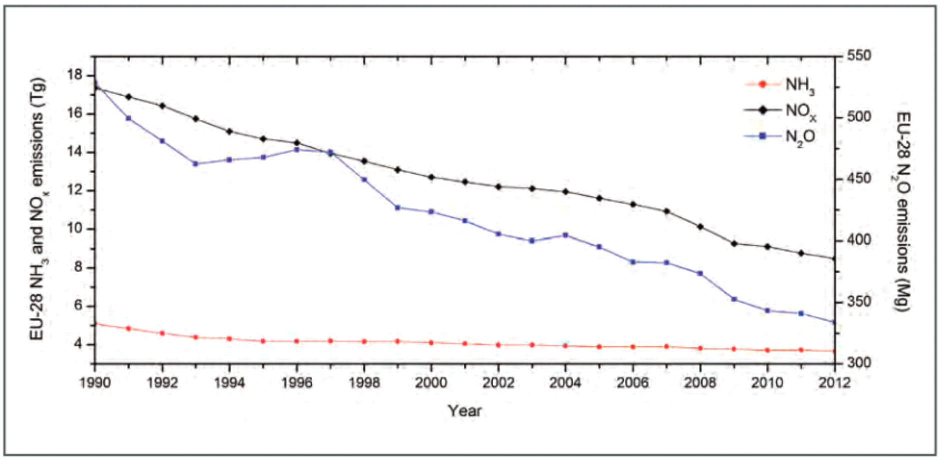

Figure 2 - Emissions of NH_3, NO_X (both in Tg) and N20 (in Mg CO_2 eq) in Europe between 1990 and 2012. From (Erisman et al. 2015).

Future
Because of its potentially harmful environmental effects, the emissions of reactive N into the atmosphere are regulated through an international framework called Convention on Long-Range Transboundary Air Pollution (CLRTAP). Work started in 1979 and resulted in the Gothenburg Protocol of 2005 which was the first setting of emission ceilings for 24 European countries and the USA for 2010 (UNECE 2015). The observed emission reductions in Europe seen in Figure 2 are a result of this convention. In 2012 the revised Gothenburg Protocol defines country-specific emission reductions between 2005 and 2020. The European Commission is suggesting further reductions until 2030 with the main objective of improving citizen's health. Further, the IIASA (International Institute for Applied System Analyses) provides a maximum technically feasible emission reduction number, that is based on no systematic economic change but a complete application of known technical measures to reduce emissions (Amann 2015).

For the emissions of NO_X the EU countries agreed to reduce their emissions by 42% from 2005 to 2020. The European Commission suggest a reduction of 65% by 2030 and the maximum technically feasible reduction of emissions up to 2030 equals to a reduction of 74%.
For the much lower emissions of NH_3 the EU countries have promised to reduce their emissions by 6% until 2020, the European Commission suggests a 7% reduction until 2030, and 35% are said to be technically feasible until 2030. All the presented data is extracted from Amann (2015).

2.3.3 Forms of deposition
Reactive atmospheric nitrogen can appear as gas, as particulate matter and dissolved in water. It can hence be deposited in the form of wet (with precipitation) and as dry deposition (as for example measured and analysed separately in Karlsson et al. (2011). Wet deposition describes the nitrogen that comes down dissolved in rain water. Dry deposition includes reactive nitrogen in gaseous form or as particulates. It deposits on obstacles, most prominently on leafs, bark, and epiphytes (canopy dwelling organisms) and measuring this correctly is more difficult. There, nitrogen can be taken up and be incorporated into plant tissues or it is washed down to the forest floor by rain. As dry deposition accumulates on structures, total deposition will be lowest on plain, levelled land.

2.4 Forestry and internal nitrogen cycling

The availability of a sufficient amount of reactive nitrogen in the soil is crucial to the effective growth and profitable harvest of trees in forestry plantations. The chemical compound in which N is present plays only a minor role as both inorganic (ammonium and nitrate) and organic (in amino compounds) nitrogen can be taken up by plants, and both oxidised and reduced nitrogen are used. However, soil microorganisms continuously drive the conversion from organic nitrogen to reduced nitrogen (mineralization), to oxidised nitrogen (nitrification), and the consumption of these (denitrification) (Schlesinger and Bernhardt 2013).

So the nitrogen that enters an ecosystem as external input is firstly taken up by plants. There is a minimum physiological nitrogen rate which plants need to take up to support healthy growth and a maximum limit to what they can take up. The difference is commonly labelled the luxury uptake (Falkengren-Grerup and Diekmann 2003). Further external N input can be stored in the soil and increase the soil nitrogen stock. The rates of those two uptakes makes up the ecosystem's nitrogen retention capacity (Tian et al. 2016),which should be zero over the long term in non-harvested ecosystems. Excess nitrogen that is not volatized is drained with the leachate.
So the leaching of nitrogen from forest soil is a clear indicator to the overabundance of nitrogen in the forest ecosystem i.e. more is available than can be taken up by the plants. At that point, tree growth is rather harmed than supported by the addition of further nitrogen (Aber et al. 1989). Moreover, negative implications for downstream ecosystems arise. Hence, it should be a general agreement that in order to apply nitrogen fertiliser to a forest ecosystem, detailed knowledge about the specific forest's nitrogen status and the projection of atmospheric nitrogen deposition is required.

2.5 Study sites

This study investigates the level of nitrogen saturation at two forest sites in Scania County in Southern Sweden: Västra Torup and Hissmossa.

Västra Torup is a spruce forest plantation situated in Northern Scania, between Perstorp and Hässleholm. The forest grows on brown podzolic soil (Zanchi et al. 2014). After it was clear cut in September 2010, the deposition and air chemistry measurements were moved to the nearby Hissmossa forestry site. That is a comparable spruce forestry stand about 5 km north of Västra Torup. Today's spruce forest in Hissmossa was planted in 1972. The open field air concentration of NH_3 might be artificially higher in Hissmossa compared to Västra Torup as the measurement device is placed on a fertilised pasture. Due to the proximity and the similarity in environmental conditions, the Hissmossa deposition data series is seen as continuing the Västra Torup data series (for example in Pihl Karlsson et al. (2015)).
Following the Köppen-Geiger climate classification, the climate in Scania is maritime, temperate (Cfb) with an annual mean temperature of 8°C and a precipitation of roughly 900 mm per year. Both winter and summer are rather mild and precipitation is distributed evenly throughout the year. This makes Västra Torup and Hissmossa temperate coniferous forests. However, the range of boreal ecosystems is not far and thus studies concerning those ecosystems might show comparable results.

Map of deposition over Sweden and the position of the study sites.
Figure 3 shows the position of Hissmossa and Västra Torup in Scania. It also shows the deposition of nitrogen in 2000 as estimated by a model developed by the Swedish Meteorological and Hydrological Institute.

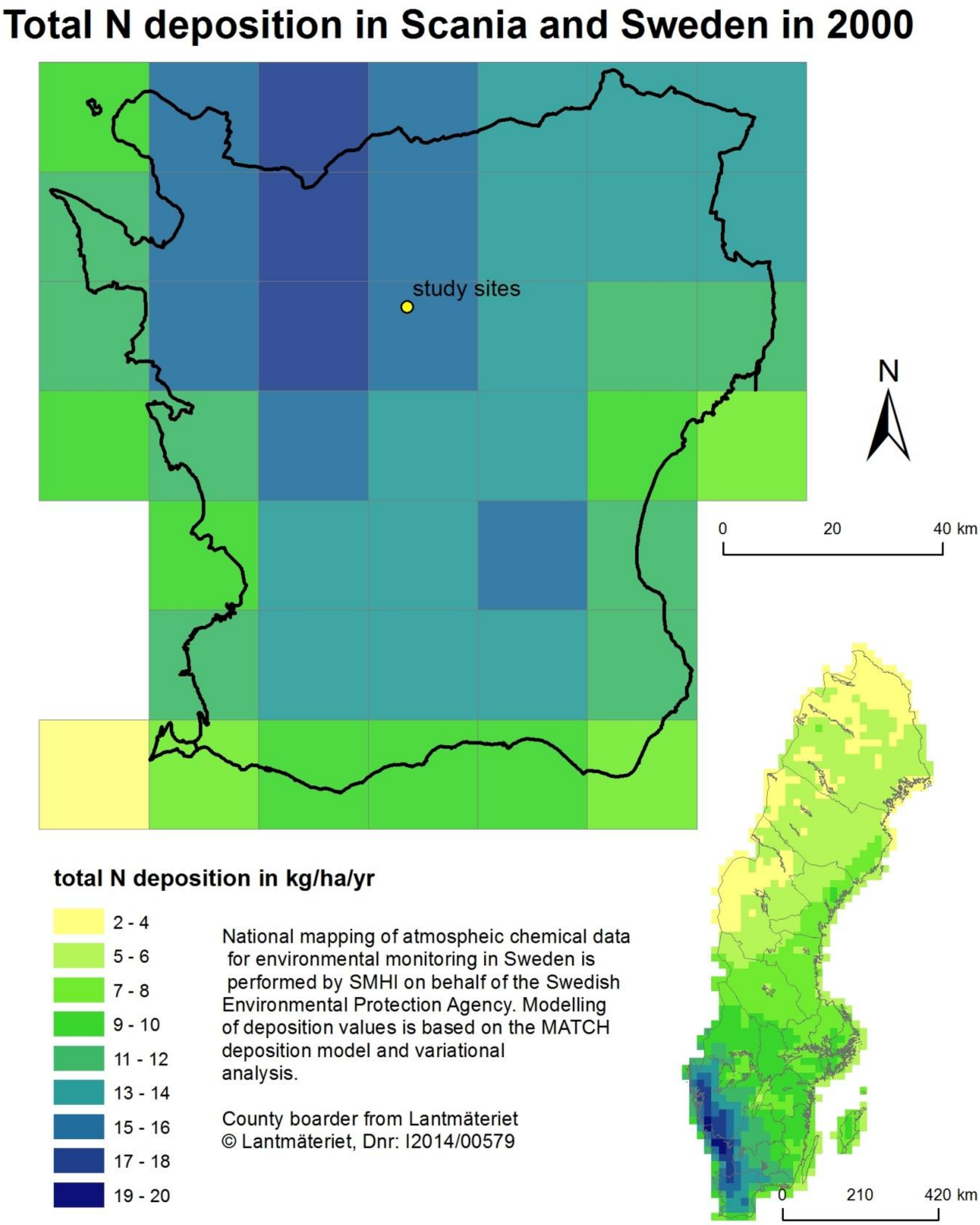

Figure 3 - Two maps showing modelled deposition of reactive nitrogen in Scania and Sweden in 2000. The modelling was done by SMHI. The Scania map shows the location of both study sites in one point as they are separated by a distance of only 5 kilometres. It can be seen that the study sites are in the area with rather high deposition compared to entire Sweden.

3 Data and model

3.1 Observational data

As this study analyses data series which stretch into past and future it relies mainly on modelled values. However, measurements are incorporated when possible or used to estimate the certainty of the modelled data. Observation data and all information on how it was obtained come from SWETHRO, the Swedish Throughfall Monitoring Network (http://krondroppsnatet.ivl.se/) that is organized by IVL Swedish Environmental Research Institute and mainly financed by regional air quality protection associations (luftvårdsförbund) and local county administrative boards (länsstyrelser). The network measures atmospheric concentration, open field and throughfall deposition and soil water chemistry for various significant elements including oxidized and reduced nitrogen.

3.1.1 Soil water chemistry

The data from SWETHRO includes samples on the soil water concentration of e.g. nitrogen in the form of both nitrate and ammonium in mg/l. It is measured three times per year. The minimum detectable concentration is 0.002 mg/l for nitrate and 0.01 mg/l for ammonium. Soil water samples are obtained from five low-pressure lysimeters per site. Those lysimeters are placed at a depth of 50 cm, a depth that can be seen as being below the rooting zone of the forest’s trees. For each sampling, the lysimeters are soaked with soil water for two days before the water from the site’s five lysimeters is mixed and analysed for the compounds of interest (Karlsson et al. 2011).

3.1.2 Deposition

Further, monthly cumulative throughfall deposition and open field deposition of nitrogen in the form of both nitrate and ammonium is measured. Depositions are recalculated and given in kg/ha/yr. The deposition of nitrogen from the atmosphere is measured by collecting precipitation in sampling buckets and analysing the concentration of the compounds of interest in the caught water. Throughfall and open field depositions are measured with the exact same device. The difference is that throughfall devices are placed under a forest canopy whereas open field deposition catches undisturbed precipitation and that there are ten measurement devices under the canopy for throughfall while there is one for open field deposition.

Forms of measured deposition: open field and throughfall

Open field deposition measurements count the wet deposition. As throughfall is measured under a forest canopy it contains both wet and dry deposition. Moreover, nitrogen uptake and release by the canopy and by canopy dwelling organisms (epiphytes; for example mosses and lichens) affect the throughfall. A part of the released/leached nitrogen is volatized into the atmosphere.

Throughfall = wet deposition (coming with the rain) + dry deposition (interception of gases and aerosols by canopy) – uptake by leafs, bark and epiphytes + leaching by leafs, bark and epiphytes – loss to the atmosphere

Except for the volatized nitrogen, all nitrogen that is deposited will eventually be an input into the ecosystem. The part that is not detected as throughfall should enter the soil as litter fall.
In areas of low dry deposition (e.g. Northern Sweden) throughfall can be less than open field deposition as plant leaf and epiphytes do not just take up all the dry deposition but even parts of the wet deposition (Karlsson et al. 2011).

3.1.3 Table of time ranges for measurement data.
Time ranges for measurement series are presented in Table 2.

TABLE 2 - TABLE OF TIME RANGES FOR MEASUREMENT DATA. THE YEARS GIVE THE RANGE IN WHICH MEASUREMENTS WERE TAKEN. THE SERIES ARE NOT COMPLETE, THOUGH.

	Västra Torup	**Hissmossa**	**Incorporated data series**
Throughfall deposition	1988-2010	2011-2014	Yes
Open field deposition	1988-2010	2011-2014	No
Soil water concentration	1996-2014	2010-2014	No

3.2 The ForSAFE model

Model result data used in this study comes from the ForSAFE model. This is an integrated process-oriented forest model designed for long-term sustainability assessment on a forest stand scale (Wallman et al. 2005; Belyazid et al. 2006). The model simulates the dynamic cycling of carbon, nitrogen, water and base cations between vegetation, soil organic matter and the soil solution and can be used to assess the effects of for example climate change, forestry management and deposition. It consists of four sub models: the soil chemistry and weathering model SAFE (Alveteg 1998), the vegetation growth and photosynthesis model PnET-CN (Aber and Federer 1992),the decomposition model Decomp (Walse et al. 1998; Wallman et al. 2006) and the soil hydrology model PULSE (Lindström and Gardelin 1992). Those four models interact and have feedbacks within ForSAFE. The model is based on monthly input and output data, it does not consider horizontal spatial variation in any parameter and is designed to run over several forestry rotation periods (over centuries).

Technically, ForSAFE is not the only model that could have been applied for this study. MERLIN is an older dynamic model that can also estimate nitrate leaching dependent on N input at a forest stand scale. In that task the model reaches satisfactory accuracy/precision (Emmett et al. 1997), but it cannot incorporate changes in climate. As climatic conditions have significant influence on ecosystem functions over the long run and as these vary over the past and coming decades, ForSAFE is the better alternative for estimating data for this outlook.

3.3 Inputs to ForSAFE

The model is fed with a plurality of parameters. Some are site specific and constant and describe the local preconditions like soil texture. Others are variables/drivers and those shall be presented shortly:

3.3.1 Climate data

Climate inputs come in a monthly temporal resolution. The model is fed with mean temperature and minimum and maximum temperature in a day for each month as inputs. Moreover, total monthly precipitation, photosynthetically active radiation (PAR) and the atmospheric CO_2 concentration are also used as input variables to model the ecosystem's behaviour. Temperature, precipitation and CO_2 concentration data for past and future are based on the Global Climate Model ECHAM and adopt the climate scenario A2 from the fourth IPCC report from 2007. Historical values were calibrated using SMHI weather station observational data (Zanchi et al. 2014). The A2 scenario assumes ongoing economic growth and a global warming of around 3.4 degrees Celsius by 2100 as compared to preindustrial conditions (IPCC 2007). The PAR data comes from the NCEP/NCAR Reanalysis project for solar radiation (Zanchi et al. 2014).

3.3.2 Deposition data

The yearly atmospheric deposition of reactive nitrogen was the central input of interest to the ForSAFE model in this study. Modelled deposition values were provided by EMEP (European Monitoring and Evaluation Program) for the entire simulation period (1900-2100), and downscaled based on SWETHRO measurements at Västra Torup and Hissmossa sites for the period from 1988 to 2014. Two future scenarios for deposition were tested and portrayed in figure 4: one with higher deposition (EMEP) and one with lower (MATCH). Those scenarios of atmospheric N deposition are based on a regional climate model that can model winds, precipitation and temperature. Further, an emission scenario is needed to estimate the input of reactive nitrogen into the atmosphere. Lastly, an atmospheric deposition model can simulate atmospheric chemistry, transport and deposition (Naturvårdsverket 2016). Both applied deposition scenarios are based on IPCC's RCP 4.5 climate scenario and on emission levels following the Current Legislation Scenario from the Gothenburg Protocol. The former scenario was based on the atmospheric chemistry transport model from EMEP whereas the latter is called MATCH (Engardt and Langner 2013).

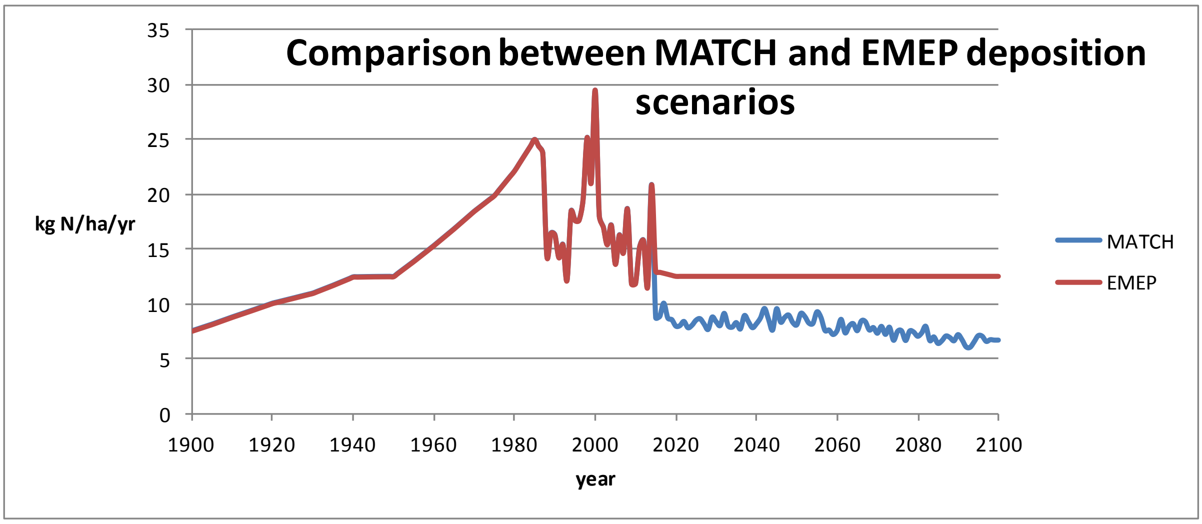

FIGURE 4 - COMPARISON BETWEEN MATCH AND EMEP DEPOSITION SCENARIOS. IT SHOWS THE YEARLY ATMOSPHERIC NITROGEN DEPOSITION ACCORDING TO THE TWO DATA SERIES. VALUES APPLIED IN THIS STUDY DIFFER ONLY FOR FUTURE SIMULATIONS. LIKE ALL CLIMATE PARAMETERS DEPOSITION DATA CONTAINED THE SAME VALUES FOR HISSMOSSA AND VÄSTRA TORUP.

3.3.3 Fertilisation experiments

To assess the impact of further N input to the forest the application of N fertilizer was added to the atmospheric deposition data series. Onto the EMEP deposition scenario several nitrogen fertilisation schemes were tested by the model. There were additions of 150 kg N/ha at one, two or three incidents through the rotation period. For Hissmossa these were: 2055, 2075 and 2095, whereas for Västra Torup these were 2025, 2045 and 2065. These dates dictate the fertilizer application at the forest age of 15, 35, and 55 years respectively. The three possible timings of one fertilisation, the three possible combinations of two applications and the fertiliser application at all three time slots were modelled for both sites. This gives eight combinations where the forest sites receive either 0, 150, 300 and 450 kg N/ha of additional fertiliser per rotation period.

The addition of no, 150, 300 and 450 kg N/ha per rotation period are the legal limits for forest nitrogen fertilisation in Sweden (7:26 SKSFS). No addition is allowed in the Southern part where the two test sites are located. Successive more addition is allowed the further north one gets in Sweden.

3.3.4 Forest management

Forest management practices in the past were based on interviews in 2015 with Dag Åkesson representing the forest management. Common forestry practice defined the date of modelled future thinning and clear cutting. In Hissmossa, there was a clear cut in 1972. The present forest was thinned in 2003 and 2010. In the model, forest thinning is set to a removal of 25% of the wooden biomass. For the future a clear cut is modelled for 2040 followed by modelled thinning in 2065 and 2085 where 25% of the wooden biomass is removed each time.

In Västra Torup the previous forest was planted in 1940 and thinned in 1965 and 1985. A storm in 2005 caused a damaged that equals a removal of 5% of the wooden biomass. The forest was harvested completely in 2010. The modelling assumes future thinning in 2035 and 2055 and a clear cut in 2080. A similar scheme was used by Zanchi et al. (2014).

4 Analysis methods

4.1 Data preparation

The modelling with ForSAFE was performed by Jörgen Olofsson. The output data from ForSAFE came in tab delimited text files. For the analysis and graphical presentation, it was converted to MS Excel files. Out of the extensive output parameters, few were extracted for addressing the objective of this study:

- the concentration of NO3 in the soil water solution for each month in mill equivalents per litre. This was used to compare model results with observations.
- the leaching of nitrogen from the forest ecosystem for each year
- the amount of total biomass harvested wood per model period
- the woody biomass for each year to compare the harvest prediction ability of ForSAFE

Woody biomass, harvested wood and leaching were converted to the unit of kg/ha. The analysis also included the input of yearly atmospheric deposition of nitrogen in reduced and oxidised form summed up and a set of modelled additions of fertilisers to the forest. These were input parameters to the ForSAFE model and are also converted to kg/ha. Deposition, fertilisation rate and leaching are converted to the pure weight of nitrogen so that the different molar weights of all important nitrogen compounds do not affect the results.

4.2 Comparing model output with measurements

To get an idea of the extent to which the model output can be used, its values were compared to the observations that were available. Because of the temporal scope into past and future, the observations covered only a limited range compared to the modelled time frame. Moreover, not every modelled parameter was also measured in the forestry sites. It shall be pointed out that this study did not conduct a detailed model validation. Rather, in addition to the comparison between observed and modelled data, there is extensive reference in section 6.2 to other studies with similar objectives that used the ForSAFE model and that give further indication on its applicability.

There is no measured data on the rate of leaching from neither Hissmossa nor Västra Torup. The best possibility to judge the precision of the modelled leaching rate was to compare the modelled nitrate concentration in the soil water solution with measured nitrate concentration. Even though soil water concentration was not part of the later analysis, the model uses it as one parameter to estimate leaching. Previous studies used the soil water concentration of nitrate as indicator of the risk of nitrogen leaching (for example Akselsson et al. (2010)). To prove that point the modelled leaching rate was also presented.

When comparing the model output to measured data, the former was presented in monthly values which was the finest temporal resolution available. That was done to include potential seasonal effects on the values and because the measurement series did not stretch over too long periods.

4.3 Data processing

4.3.1 Temporal resolution

For their thorough analysis the model outputs are presented in yearly temporal resolution. The reason for this was that the effect of the seasons was not objective of this study and some parameters lost clarity over the course of the 200 years of study period.

4.3.2 Deposition and retention

The deposition data came in the unit of meq/m^2/yr. Using the molar weight of nitrogen this was converted to kg N/ha/yr. The sum of deposition and fertilisation was used to calculate the total input of nitrogen into the forest ecosystem. The difference between the total N input and yearly leaching rates was seen as the retention of nitrogen by the forest. This simplification assumes that nitrogen loss by volatization is negligible and that the stock of nitrogen in the soil is constant. A soil N budget presented by Schlesinger and Bernhardt (2013) justified these assumptions. Then, the nitrogen retention is equal to the uptake of nitrogen by vegetation. Still, the forest retention calculation is very sensitive to an accurate modelling of leaching rates.

4.3.3 Accumulative values

The effects of different nitrogen inputs on yearly leaching and forest growth can be well understood when presented as a timeline. Yet, effects might be marginal and appear over long periods. That is why yearly accumulated values of leaching and wood harvest were also presented. A further reason to apply accumulated values is that they are more robust to potential temporal inaccuracies in modelled leaching rates. Compared to yearly rates, accumulative values are independent of the accurately modelled timing of leaching in response to biomass extraction or nitrogen input.

Total sums of nitrogen input, leaching, retention and harvest outputs were used to point out the ecosystem's behaviour. Both the natural delay of leaching after fertilisation and the difficulty in modelling the delay accurately motivated this presentation method.

4.3.4 Forest age at fertilisation application and fertiliser uptake efficiency

Moreover, it proved useful to distinguish scenarios of equal fertiliser input between those that applied extra nitrogen at an early stage in the forest rotation period and those that applied it later in the life span of one generation of trees. The uptake of nitrogen from fertilisation could be estimated not just in relation to the amount of fertiliser application but even in relation to its timing. The difference in total leaching and harvest was compared to the EMEP deposition scenario. By that the permanent nitrogen retention by the forest and the effect on forest growth could be estimated. Permanent fertiliser nitrogen uptake was calculated as the difference between the fertiliser input and the difference between accumulative leaching for the given scenario and the baseline scenario.

4.4 Maximum bearable nitrogen input rate for each forest site

This study focused on the rate of nitrogen input to the forest at which leaching contributes to downstream eutrophication. Therefore, the maximum bearable nitrogen input rate was defined as a fertilisation rate that does not lead to any N leaching from the forest soil into groundwater. Practically, no leaching is not a feasible option in forestry stands like Hissmossa and Västra Torup. Forest management will ensure a decent level of nitrogen in the soil to support the effective growth of trees. Throughout forest growth at these two sites, the rate at which nitrogen is made available for trees roughly equals the rate at which the trees take up nitrogen. When trees are removed for harvest, their significant uptake of soil nitrogen ceases while mineralization and nitrification continue and leaching inevitably occurs. The same effect in smaller magnitude can be seen after thinning and storm damage. Subsequently, many forestry soils will leak some nitrogen over the course of a rotation period or afterwards. Having said this, the maximum bearable nitrogen input rate in this study should equal the total retention over a time frame exceeding one rotation period divided by the number of years of the time frame. This is to acknowledge the fact that substantial leaching of nitrogen input throughout one rotation period occurs in the years following the final harvest. The maximum bearable nitrogen input rate was defined using the scenario were most nitrogen was retained totally. Unfortunately, this analysis was not able to sketch changes of the maximum bearable nitrogen input rate with changing climatic conditions as the values were very much controlled by thinning and harvesting of the trees. Whether the threshold increases or decreases over the course of the study period was not examined. However, it can be used as a point of reference when estimating potential damage due to atmospheric deposition and when estimating critical loads. Theoretically, the maximum bearable nitrogen input rate should equal the nitrogen that leaves the forest ecosystem with the harvested biomass.

4.5 Maximum effective fertilisation rate

The maximum bearable nitrogen input rate is most interesting from a landscape conservationist perspective. For the forestry management it is more interesting to know the N input with highest yield. Hence, the maximum effective fertilisation rate on the other hand is the rate at which additional application of fertilisers does not increase forest growth and thus the expected harvest. This might, however, not be dependent on the amount of fertiliser but the timing of its application in the course of the rotation period. In the modelled scenarios, fertilisers were applied 15, 35 or 55 years after the forest had been planted or at two or three of these occasions. The maximum effective fertilisation rate was defined as the total retention of applied fertiliser under the scenario that yielded the highest total harvest. The maximum effective fertilisation rate and the obtained harvest surplus could be used as arguments when assessing the value of the Swedish forestry law that prohibits the application of any nitrogen fertiliser in Southern Sweden.

5 Results

5.1 Comparing model output with observational data

5.1.1 Woody biomass

The modelled woody biomass in Västra Torup fits the measured values rather well. As seen in figure 5 the development over the 15 years of observation is roughly the same for modelled and measured values.

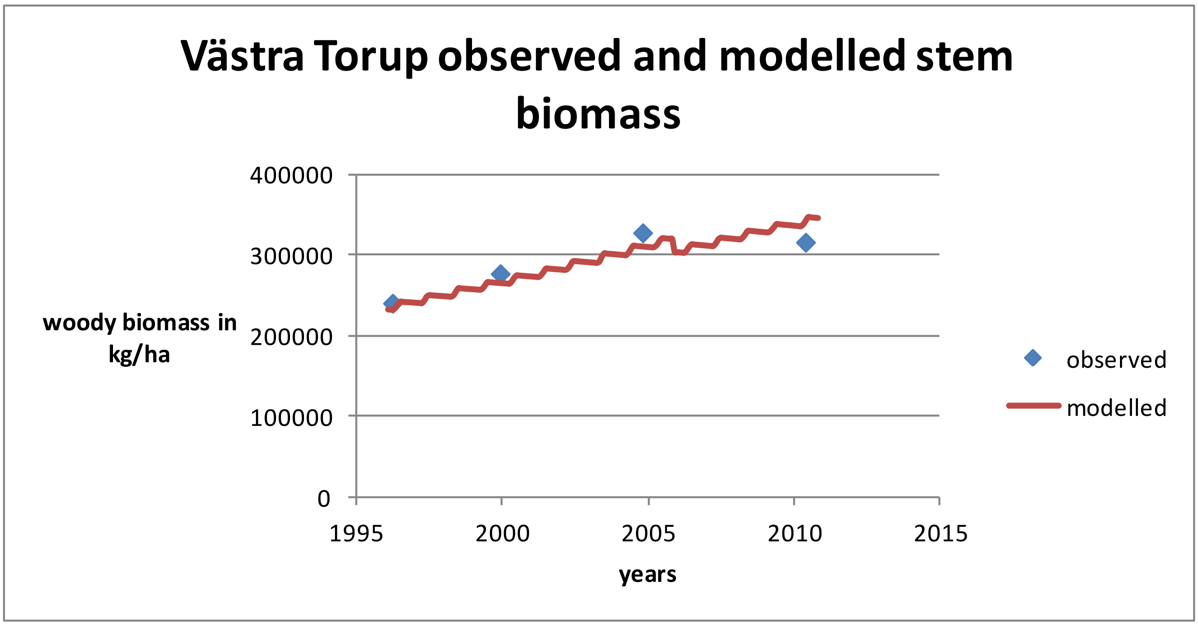

FIGURE 5 - COMPARISON BETWEEN OBSERVED AND MODELLED WOODY BIOMASS IN VÄSTRA TORUP.

There was only one measurement of biomass in Hissmossa (August 2011). Table 3 shows the comparison between measured and modelled value for August 2011 for Hissmossa, which indicate an underestimation of modelled biomass. The average measured values and modelled counterparts for Västra Torup are also shown.

TABLE 3 - WOODY BIOMASS COMPARISON FOR HISSMOSSA (ONE PAIR OF NUMBERS) AND V TORUP (FOUR PAIRS OF NUMBERS).

	Modelled woody biomass (kg/ha)	**Observed woody biomass (kg/ha)**
Hissmossa (Aug 2011)	147,692	187,260
Västra Torup (average)	288,791	290,870

5.1.2 Soil water concentration of nitrate

Due to its longer time series the model comparison in Västra Torup gives more information than the Hissmossa series. As seen in Figure 6 the most obvious outcome is that the model is rather good in giving zero nitrate concentration when there was measured zero nitrogen concentration. The Västra Torup forest was harvested completely in 2010. As a result the measured concentration of nitrogen in the soil water increased dramatically until 2014 when the concentration reached zero again. The modelled nitrate concentration increases simultaneously but with a smaller magnitude. It does not reach zero again before much later. Comparisons between measured and modelled nitrate concentrations in other study areas indicate that the modelled peak is generally much flatter. However, the peak is broader, i.e. it lasts longer. These two distortions result in the observation that the total amount of nitrate in the soil solution that is exposed to the risk of leaching is almost equal in both measured data and data modelled with ForSAFE (Olofsson, pers. communication, 2016).

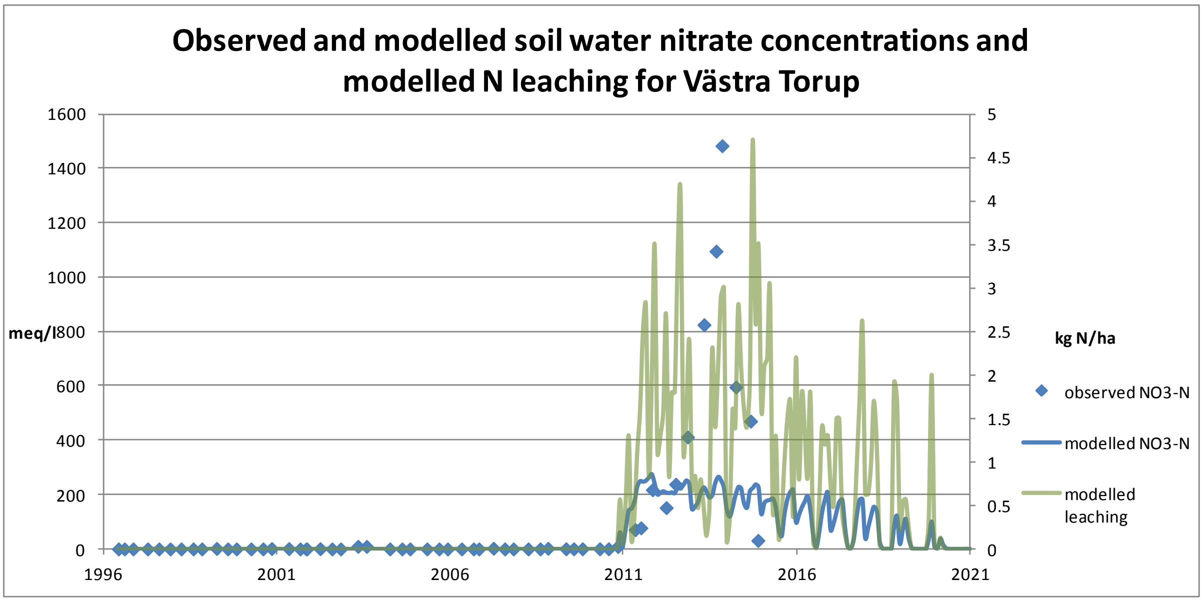

FIGURE 6 - COMPARISON BETWEEN OBSERVED AND MODELLED SOIL WATER NITRATE CONCENTRATION. THE LAST MEASUREMENT WAS TAKEN IN 2014, BUT MODELLED RESULTS ARE SHOWN UNTIL 2021. THIS EXTENSION ALLOWS TO SHOW THE BALANCING EFFECT THAT FLATTER, BUT LONGER MODELLED PEAKS HAVE ON THE TOTAL SOIL WATER NITRATE CONCENTRATION. AS THAT VALUE IS DIRECTLY CONTROLLING THE LEACHING RATE, THAT PARAMETER IS SHOWN IN THE BACKGROUND, TOO.

5.2 Hissmossa forest's reaction to varying increasing input

Nitrogen leaching occurs mostly in temporal reaction to the extraction of biomass and only sometimes in reaction to nitrogen input (Figure 7). Even without fertilisation, the magnitude of leaching in the 21st century is higher than in the 20th. The deposition scenario MATCH yields considerably lower leaching than the EMEP scenario. In the MATCH scenario leaching occurs mostly in reaction to the two clear cuts and the two thinnings in a short time in 2003 and 2010, whereas later thinning does not show any impact on N loss.

For the scenarios with fertiliser application in 2055 the increased leaching is not directly initialized by the application but by the biomass removal (thinning) in 2065. Fertiliser application in 2095 is the clearest example of leaching in direct temporal reaction to fertiliser application. This indicates that the forest N uptake is already saturated before that application independent of any previous treatment. Reasons for this could either be the removal of a considerable amount of biomass in 2085 or the rather mature age of the forest at that point.

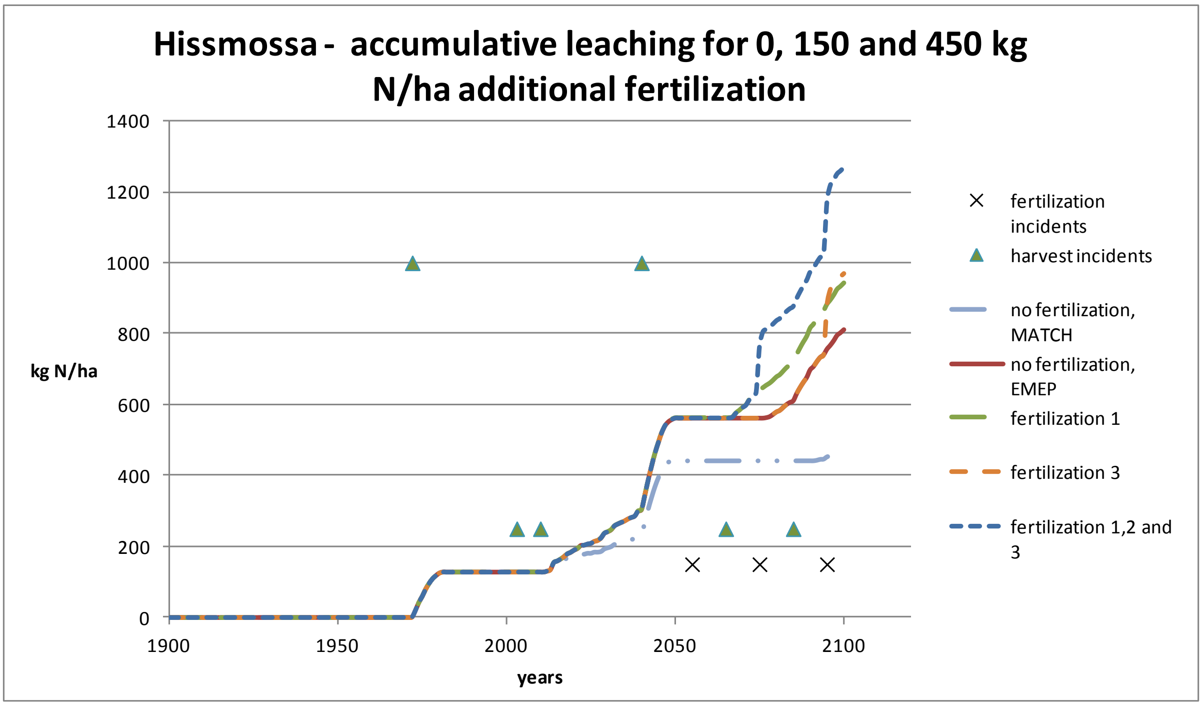

FIGURE 7 - ACCUMULATIVE LEACHING RATES FOR TWO DEPOSITION SCENARIOS (MATCH AND EMEP) AND FERTILISATION SCHEMES ONTO THE EMEP SCENARIO FOR HISSMOSSA. THE CROSSES INDICATE POTENTIAL INCIDENTS FOR FERTILISER APPLICATION IN 2055 (INCIDENT 1), 2075 (INCIDENT 2) AND 2095 (INCIDENT 3). THE DOSE OF A SINGLE FERTILISER APPLICATION IS ALWAYS 150 KG N/HA, SO THAT THE BLUE, DASHED LINE RECEIVES 450 KG N/HA IN TOTAL. TRIANGLES INDICATE INCIDENTS OF HARVEST, WHERE THE UPPER TRIANGLES REPRESENT CLEAR CUTS AND THE LOWER REPRESENT A THINNING.

Total leaching and harvest compared to the total nitrogen input

Figure 8 shows the accumulative N leaching on the primary vertical axis and the total harvest over the entire study period on the secondary vertical axis, dependent on the total accumulated N input on the horizontal axis. The latter is the sum of accumulative deposition and respective nitrogen fertilisation. Under the different nitrogen input scenarios the total biomass harvest varies by 0.4 percent or 2000 kg/ha. The lowest value is for the MATCH scenario without any fertiliser addition. The highest value is seen in all fertilisation scenarios that received 150 kg N/ha in 2055. Applying additional fertiliser at a later stage did not affect the total harvest. In Figure 8 it can also be seen that the total leaching for 150 and 300 kg of extra nitrogen resulted in different total leaching dependent on the time of application. For 150 kg N/ha the total leaching varies by 28 kg N/ha. Lowest leaching is modelled for the application in 2055 and highest is seen for the application in 2095. In Hissmossa nitrogen input and leaching have a seemingly linear relationship.

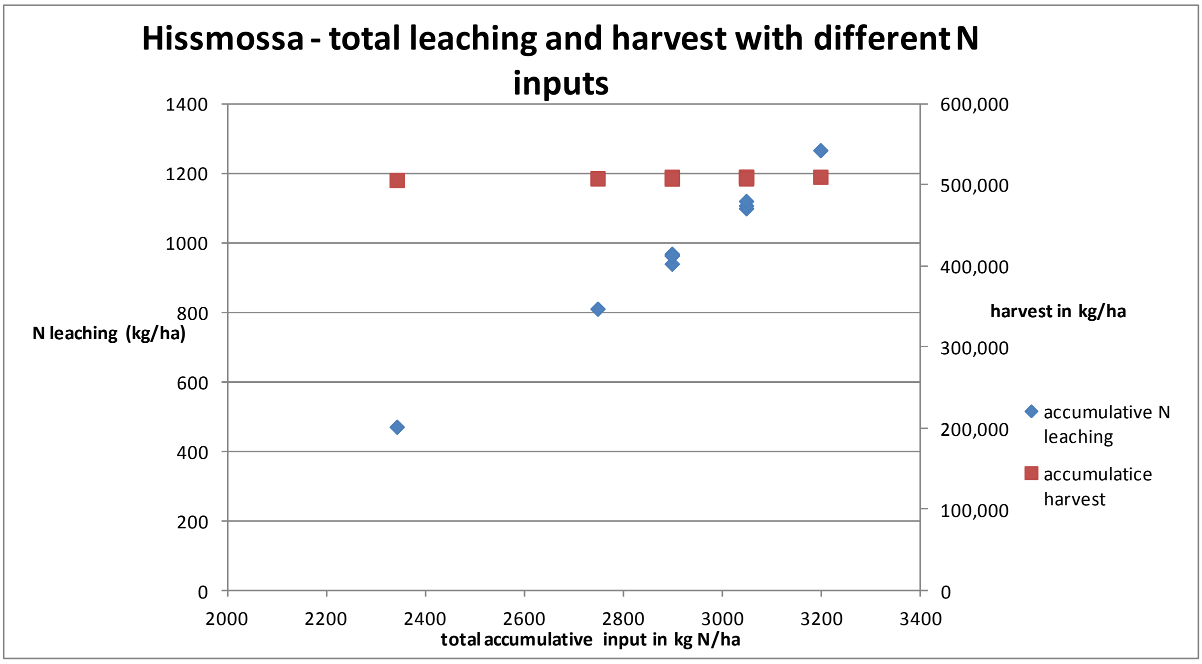

FIGURE 8 - TOTAL LEACHING AND TOTAL HARVEST IN RELATIONSHIP TO DIFFERENT TOTAL N INPUTS FOR HISSMOSSA. TOTAL N INPUTS ARE THE SUM OF THE ACCUMULATIVE DEPOSITION AND THE APPLIED N FERTILISERS.

For 300kg of total fertiliser application, the total leaching varies by 21 kg N/ha where application in 2055 and 2075 yield the lowest leaching, and the application in 2055 and 2095 yield the highest. Not applying fertilisers in 2075 but in the first and last time slot, i.e. application spread over the longest time, yields a medium leaching.

Figure 9 gives a more detailed picture of the importance of forest age at fertilisation. The figure gives the fertiliser uptake and harvest gain in relation to the forest's age at first fertiliser application. It shows that fertilising Hissmossa can only be effective when done at a young forest age. Otherwise, harvest does not increase and the total leaching exceeds the N input (something that can be seen in the negative fertiliser uptake for these scenarios).

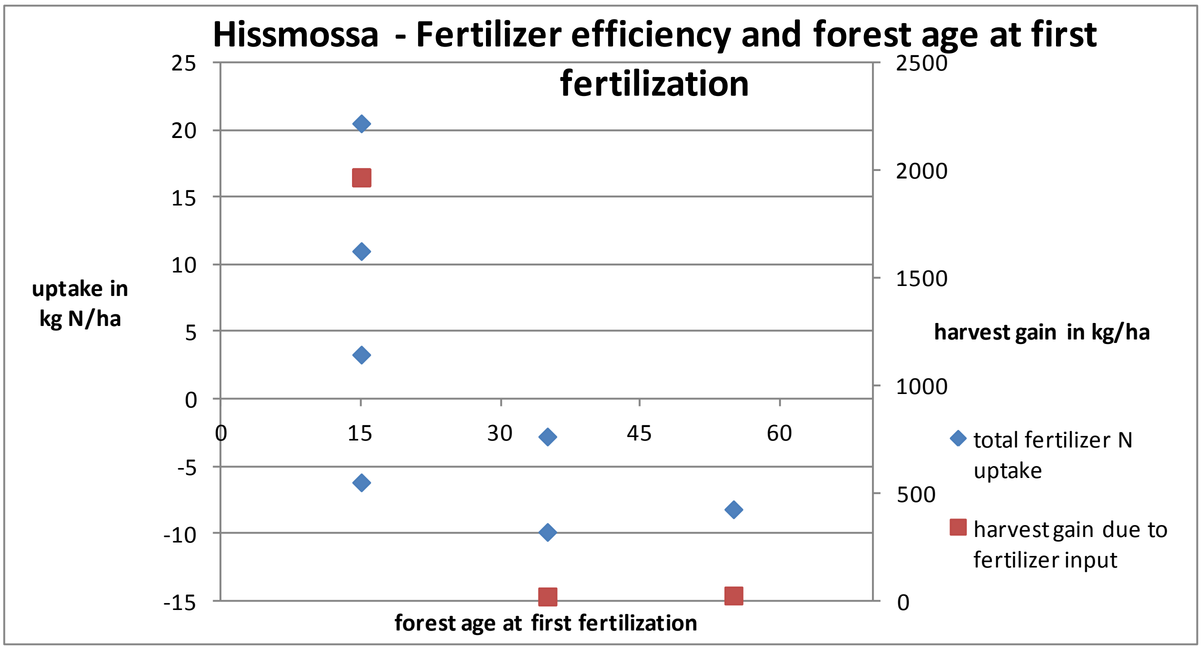

FIGURE 9 - THIS FIGURE GIVES THE FERTILISER EFFICIENCY BASED ON HISSMOSSA FOREST'S AGE AT THE FIRST INCIDENT OF APPLICATION. THE EFFICIENCY IS GIVEN BY THE TWO PARAMETERS FERTILISER UPTAKE AND HARVEST GAIN DUE TO FERTILISER APPLICATION. NOTE THAT THE PRIMARY VERTICAL AXIS (WITH FERTILISER UPTAKE) HAS NEGATIVE VALUES, WHILE THE SECONDARY VERTICAL AXIS (HARVEST GAIN) DOES NOT. NEGATIVE FERTILISER UPTAKE ARISES WHEN THE APPLICATION OF A GIVEN AMOUNT OF NITROGEN RESULTS IN THE LEACHING OF THAT AMOUNT AND LITTLE MORE. THERE ARE SEVERAL VALUES PER FOREST AGE AS THERE HAVE BEEN SEVERAL FERTILISATION SCHEMES WHICH BEGAN WITH THE APPLICATION OF FERTILISER AT THE FOREST AGE OF 15 YEARS.

5.3 Västra Torup forest's reaction to varying increasing input

In Västra Torup there is no direct increase in leaching in response to the application of fertiliser in 2025 and neither after the thinning in 2035. However, effects can be seen both after another fertiliser application in 2045 (in the dark blue line of Figure 10) or after the second thinning in 2055 (green line). The orange line shows concentrated leaching as a direct result after the application of fertiliser in 2065. The reduced tree biomass as a result of the thinning in 2045 might, however, also play its role in the rapid leaching. Each scenario, except for MATCH without fertilisation, shows a slight leaching in the decade before the final harvest (from 2070 to 2080). Mature forest age could be a reason for decreased N uptake. It is remarkable that the application of the same amount of fertilisation at different times in the forest's growth period results in significant temporal and total variation in leaching. Early application results in lower leaching rate and in lower total leaching than the late application. Under the MATCH deposition scenario, leaching occurs only in temporal reaction to clear cuts and not to thinning. While the clear cut in 1940 initialises a minor leaching event, the clear cuts in 2010 and 2080 result in very similar, larger leaching events. As in Hissmossa, the total leaching in the 21st century exceeds the 20th century leaching.

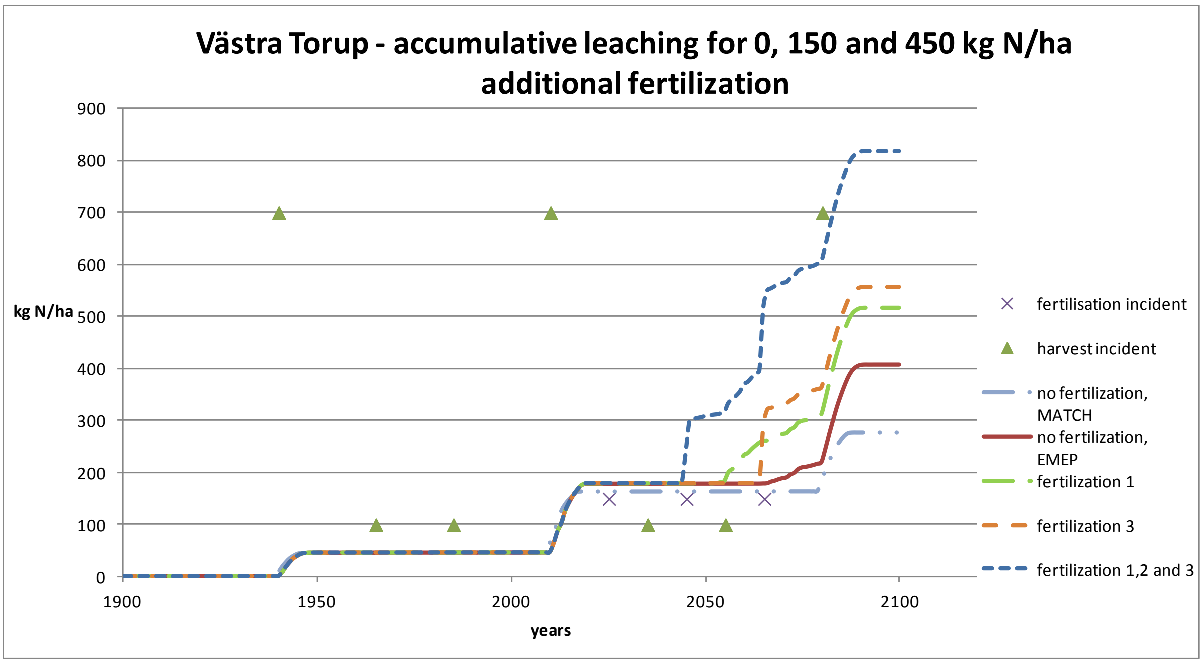

FIGURE 10 - ACCUMULATIVE LEACHING RATES FOR TWO DEPOSITION SCENARIOS (MATCH AND EMEP) AND FERTILISATION SCHEMES ONTO THE EMEP SCENARIO FOR VÄSTRA TORUP. THE CROSSES INDICATE POTENTIAL INCIDENTS FOR FERTILISER APPLICATION IN 2025 (INCIDENT 1), 2045 (INCIDENT 2) AND 2065 (INCIDENT 3). THE DOSE OF A SINGLE FERTILISER APPLICATION IS ALWAYS 150 KG N/HA, SO THAT THE BLUE, DASHED LINE RECEIVES 450 KG N/HA IN TOTAL. TRIANGLES INDICATE INCIDENTS OF HARVEST, WHERE THE UPPER TRIANGLES REPRESENT CLEAR CUTS AND THE LOWER REPRESENT A THINNING.

Figure 11 shows total leaching and harvest in relation to the total accumulative N input for Västra Torup just like Figure 8 does for Hissmossa. In Västra Torup the total harvest varies by 11,000 kg/ha. The maximum harvest is 1.6% higher than the lowest. No fertilisation yields the lowest harvest, late fertilisation a medium and early fertilisation results in the biggest total harvest. Those scenarios with the first and the second fertiliser application yield about 300 kg/ha more than those with the first but without the second. The first application is much more effective than the second one.

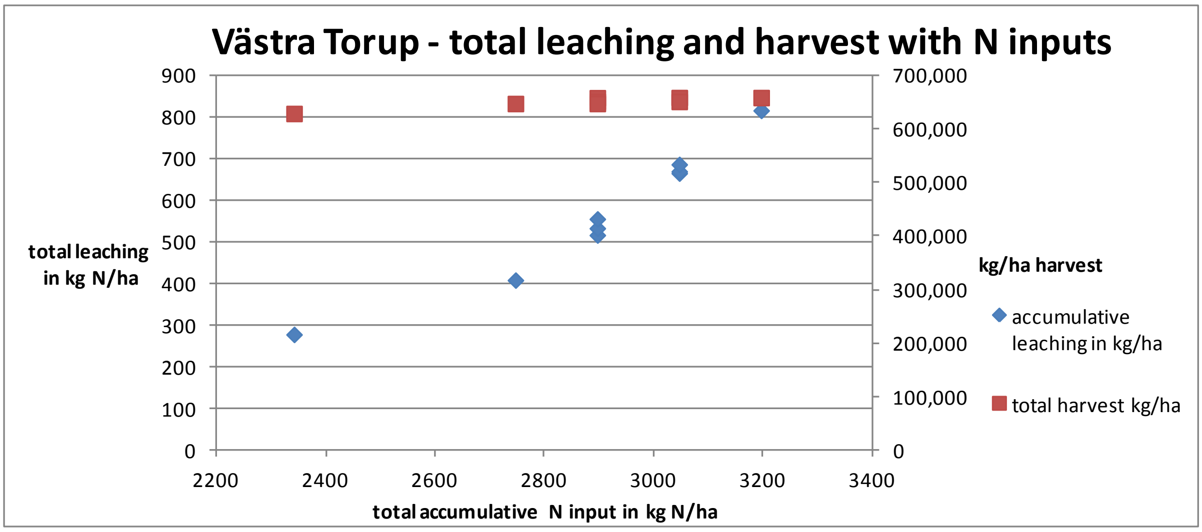

FIGURE 11 - TOTAL LEACHING AND TOTAL HARVEST IN RELATIONSHIP TO DIFFERENT TOTAL N INPUTS FOR VÄSTRA TORUP. TOTAL N INPUTS ARE THE SUM OF THE ACCUMULATIVE DEPOSITION AND THE APPLIED N FERTILISERS.

The opposite pattern can be seen for the total leaching rate. For the application of 150 kg N/ha, the earliest application results in a total leaching of 40kg N/ha less than the last application. Interestingly, the latest application of 150 kg N/ha fertiliser results in a total leaching of 147 kg N/ha more compared to the application of no fertiliser at all. Seen from another perspective, the forest can permanently retain 43 kg N/ha if fertiliser is applied 15 years after the forest was planted whereas it can retain only 3 kg N/ha if it is fertilised at an age of 55 years. Figure 12 shows this relationship between fertiliser retention and forest age. Contrary to Hissmossa, Västra Torup does not show any excess N loss due to the application of fertilisers. Moreover, total harvest in Västra Torup can actually be increased when applying fertiliser also at the forest age of 35 years.

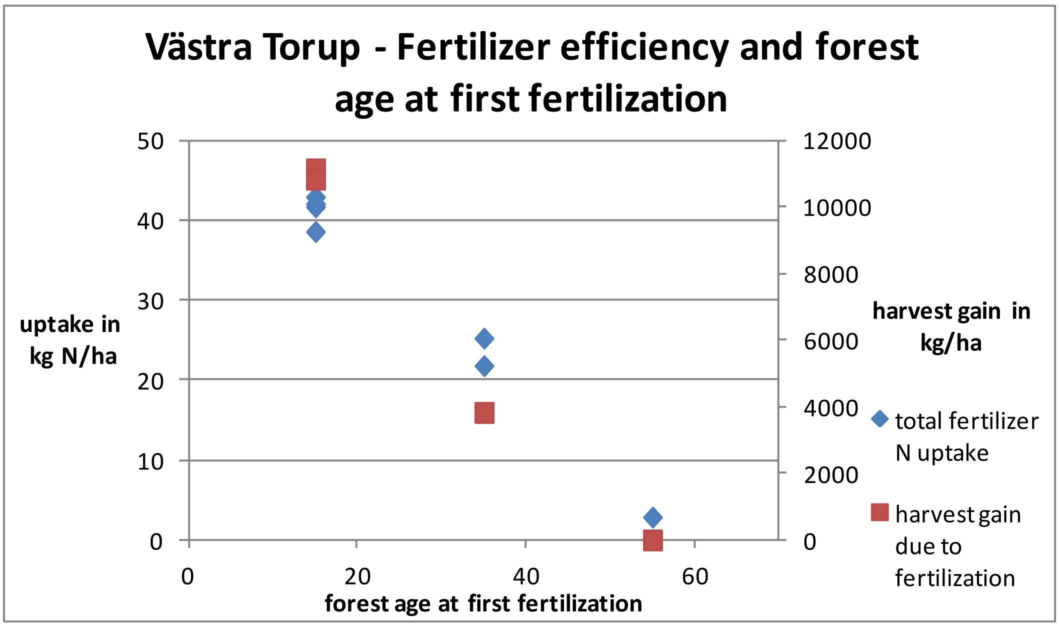

FIGURE 12 - THIS FIGURE GIVES THE FERTILISER EFFICIENCY BASED ON VÄSTRA TORUP FOREST'S AGE AT THE FIRST INCIDENT OF APPLICATION. THE EFFICIENCY IS GIVEN BY THE TWO PARAMETERS FERTILISER UPTAKE AND HARVEST GAIN DUE TO FERTILISER APPLICATION.

5.4 Maximum bearable nitrogen input rate

The difference between input and leaching gave the retention of nitrogen in the forest ecosystem. This value was interpreted as being the maximum bearable nitrogen input rate. Table 4 shows the values for both study sites over the 200 year study period. The total retention in Hissmossa was highest in the scenario at which nitrogen fertilisation of 150 kg N/ha was applied 15 years after planting the trees. In Västra Torup total retention was highest when fertilisers were applied both at the forest age of 15 and of 35 years. To relate, the average deposition of nitrogen per year is also shown. That value is higher than the maximum bearable nitrogen input rate both in Hissmossa and Västra Torup.

TABLE 4 - THE MAXIMUM BEARABLE NITROGEN INPUT RATE IS THE TOTAL RETENTION DIVIDED BY THE 200 YEARS OF STUDY PERIOD. RETENTION IS THE DIFFERENCE BETWEEN INPUT AND LEACHING UNDER THE ASSUMPTION THAT ALL OTHER NITROGEN FLUXES FROM THE ECOSYSTEM ARE NEGLIGIBLE. THE TABLE SHOWS VALUES FOR THAT SCENARIO WITH THE HIGHEST MAXIMUM BEARABLE NITROGEN RETENTION RATE. THE AVERAGE DEPOSITION ACCORDING TO THE EMEP SCENARIO IS SHOWN FOR COMPARISON.

Site	Total input kg N/ha	Total leaching kg N/ha	Total retention Kg N/ha	Maximum bearable nitrogen input rate kg N/ha/yr	Average Deposition Kg N/ha/yr
Hissmossa	2,897	941	1,956	9.8	13.7
Västra Torup	3,047	665	2,381	11.9	13.7

5.5 Maximum effective fertilisation rate

As seen in Table 5 the theoretical fertilisation rate with the highest yields was 20.5 kg N/ha in Hissmossa and 43 kg N/ha in Västra Torup. Results show better effect for the early application than for the late.

TABLE 5 - THE TOTAL FERTILISER RETENTION IS SHOWN FOR THAT SCENARIO WITH THE HIGHEST RETENTION AND HIGHEST HARVEST INCREASE DUE TO THE FERTILISATION. AS THE FERTILISATION EXPERIMENTS ASSUME THE EMEP DEPOSITION SCENARIO, THAT SCENARIO WAS CHOSEN AS THE BASELINE TO CALCULATE HARVEST INCREASE AND FERTILISER RETENTION. THE LAST COLUMN GIVES THE CHOSEN SCENARIO.

	Harvest increase due to fertilisation kg/ha	Total fertiliser retention kg N/ha	Forest age at application
Hissmossa	1,968	20.5	15
Västra Torup	11,145	43	15 and 35

For Hissmossa four fertilisation scenarios yielded a harvest increase of 1968.2 kg/ha. These are all the scenarios where fertiliser was applied for the first time when the forest was 15 years old. However, if more fertilisers were applied at later stages the total fertiliser uptake decreased to the point where there is actually a net loss of fertiliser. In the scenario where 150 kg N/ha fertiliser is applied at the age of 15, 35 and 55 years (total 450 kg N/ha fertiliser application) the total leaching is 456,2 kg N/ha higher as compared to no application of any fertiliser. This means that the high dose of nitrogen drains the ecosystems of this nutrient rather than adding it.

In Västra Torup two scenarios (fertilisation at 15 and 35 and fertilisation at 15, 35 and 55 years) yielded the same gain in harvest and they retained nearly the same amount of nitrogen fertiliser. That induces that the third application of fertilisers was of no use to the forest.

6 Discussion

6.1 The ForSAFE model's applicability

Comparisons in this study indicate an uncertainty connected to the in- and output from the ForSAFE model. The woody biomass, directly controlling the harvestable wood, is overestimated in Hissmossa and modelled rather accurate in Västra Torup. This tendency to overestimate seems to be consistent in other studies that apply the ForSAFE model in Sweden (Belyazid et al. 2006). Figure 13 shows comparisons between modelled and measured biomass data for 16 Swedish forestry sites where it becomes clear that the model calculates higher biomass values than what are observed. That problem was still evident in Belyazid et al. (2011) but not in Zanchi et al. (2014). The latter study is only concerned with Västra Torup. This suggests that even the calculated harvest gain due to fertilisation probably is an overestimation. It should be significantly lower.

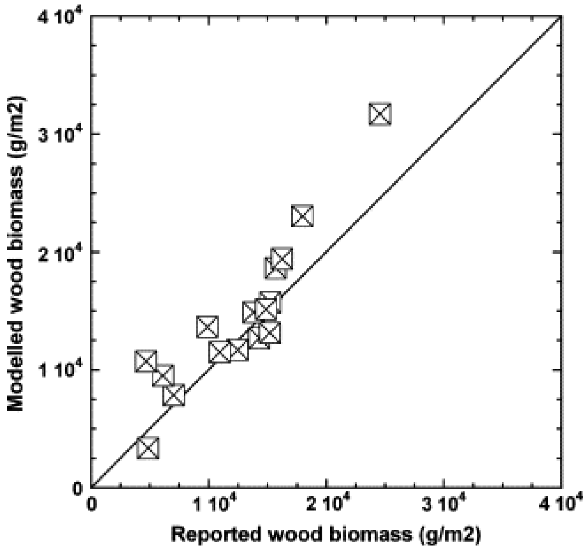

FIGURE 13 - MODELLED AND REPORTED WOOD BIOMASS FOR 16 SWEDISH FOREST SITES IN 1995 AND 1996. FROM BELYAZID ET AL. 2006).

The nitrate concentration in the soil water solution is modelled very well for the instances of no or very low concentrations. It is only in effect to biomass harvest that measured and modelled concentration increase. As mentioned, the modelled values peak flatter but longer, potentially with a balancing effect, resulting in a rather accurate total leaching over the long run. This can also be seen in Akselsson et al. (2010) who compared methods to estimate leaching rates in Sweden. However, Belyazid et al. (2011) point out that neither the nutrient uptake by understory vegetation nor the retention of inorganic nitrogen in soil compounds are part of ForSAFE and that ignoring these fluxes might lead to an overestimation of N leaching. They even observed this in a study of 32 Swiss forestry sites (Belyazid et al. 2011). For this study that would mean that the retention values can rather be seen as the nitrogen uptake by trees than as the actual retention of nitrogen in the ecosystem. This gives further

value to the maximum effective fertilisation rate as it is mainly concerned with the uptake of additional nitrogen by trees with the purpose of increasing growth. On the other hand, it indicates a slight underestimation of the maximum bearable nitrogen input rate. Thus the forests might actually be able to bear a higher input than given in this study.
Unfortunately, no study was found that compared modelled leaching rate in response to fertilisation with observations from fertilisation experiments.

ForSAFE was designed to estimate long-term effects and as an accepted trade-off it performs less accurate under short-term variations. Akselsson et al. (2010) estimated the risk of nitrate leaching over study sites evenly distributed in Sweden with four different methods. It is emphasize that the dynamic modelling is only working reliably on well examined, small scale forest stands (low spatial coverage) but can be useful on a large temporal scale assessing the impact of climate change, forestry methods and atmospheric deposition on nitrogen cycling. Concluding, the ForSAFE model has certain well known limitations but it works reliably in the context of this study. Moreover, results could be cross checked with other approaches.

6.2 Cross checking the modelled maximum bearable nitrogen input rate with critical loads from the literature

Commonly, studies that assess the effect of nitrogen deposition estimate a threshold called "critical load". Critical loads are defined as "a quantitative estimate of an exposure to one or more pollutants below which significant harmful effects on specified sensitive elements of the environment do not occur according to present knowledge" (Grennfelt and Nilsson 1988). In this definition significant harmful effects can for example be the increase of N leaching or the alteration in species composition.
The threshold values for changes in leaching or biodiversity differ from ecosystem to ecosystem and hence some critical loads might be defined in terms of leaching rates while others concern alterations in species composition. A thorough analysis of ecosystems types throughout Europe showed that coniferous forests are characterized by a critical load of 5-15 kg N/ha/yr (de Vries et al. 2015). Northern European forests as Hissmossa and Västra Torup tend to have a lower critical load than southern European forests. Their decreased growth rate causes this. Coniferous forests show a decrease in the biomass of fine roots and mycorrhiza, changes in soil fauna and nutrient imbalances when the critical load for nitrogen deposition is exceeded (de Vries et al. 2014). In their summary of findings from the Swedish "Abatement Strategies for Transboundary Air Pollution" research project Nordin et al. (2005) suggest a critical load of 6 kg N/ha/yr for boreal forests in Sweden. They do so mainly because changes in species composition were observed, not because soil chemistry was altered. Others set the critical load for forests in Scania to 5 kg N/ha due to the risk of over fertilisation (Pihl Karlsson et al. 2015).
The maximum bearable nitrogen input rate for Hissmossa and Västra Torup was found to be 10 and 12 kg N/ha/yr respectively. The observation that Swedish coniferous forests have critical loads that are defined rather by other factors than nitrogen leaching explains why the maximum bearable nitrogen input rate is higher than critical loads from the literature. Still, this study seems to indicate the same magnitude for thresholds as others. Moreover, the point

that the Southern Swedish forests receive more N from the atmosphere than what they can take up is consistent in this and other studies.

6.3 Changes in biomass harvest due to fertilisation

Compared to the EMEP scenario for deposition (the higher deposition scenario), total harvest over 200 years increased by 2000 kg wood/ha in Hissmossa and by 11,000 kg wood/ha in Västra Torup due to applied fertilisation. In Hissmossa the largest harvest gain was achieved for all fertilisation regimes that applied nitrogen when the forest was 15 years old. Whether additional fertiliser was applied at a later occasion or not did not influence the harvest. Calculating the retention of applied fertiliser revealed that 20 kg N/ha was retained permanently in the case of fertilisation application only to the young forest. In conclusion, the application of that rate at a young forest age is the most effective way to increase harvest. This gain does not imply that the fertiliser application pays off economically. The harvest increase by 2000 kg wood/ha corresponds to about 1% of a clear cut harvest in Hissmossa. In Västra Torup harvest increased the most when fertilised twice at the age of 15 and 35 years. However, the single application at the age of 15 years yielded only marginally lower harvest. The total fertiliser retention amounted to 42 kg N/ha. The harvest gain equalled a 6% increase at the end of a rotation period compared with a clear cut harvest without any previous fertilisation and under the high deposition scenario.

The observation that fertiliser efficiency is highest in young forest is in line with results from other studies (Bergh and Hedwall 2013). Yet, both harvest increase and fertiliser application suggested by other studies reach a different magnitude than what this analysis estimates. Harvest increases of 30% are reported as results of fertiliser application of 150 kg N/ha in Nordic spruce forests over the course of one rotation period (Ingerslev et al. 2001). Binkley and Högberg (2016) claim that growth increases in Swedish forestry stands could be seen at application rates of 20 to 50 kg N/ha/yr. This difference in magnitude leads to the conclusion that forest growth in Hissmossa and Västra Torup does not profit considerably compared to other forests by the application of N fertiliser.

6.4 Implications forest fertilisation and the Swedish law on forest fertilisation

Forest managers are obliged not to harm the local environment (7:26 SKSFS). Therefore, the forest protection law prohibits the application of nitrogen fertiliser in Scania completely but allows for more and more nitrogen addition further north in the country up to a maximum of 450 kg N/ha/rotation period in the four northernmost counties (Norrbotten, Västerbotten, Västernorrland and Jämtland). The marginal increase of harvested wood biomass and the comparatively low uptake of fertiliser nitrogen on the one side, and the potentially destructive effects of leaching nitrogen on the other support this clause. Even though the two investigated forestry sites differ in potential biomass harvest gain and even though harvest can actually increase with the application of nitrogen fertilisers they do not indicate that harvest in Scania is far below what it could be if fertilisation was allowed. Deposition in this part of the country is very close to sufficient to cover all the nitrogen the forest could ever take up. Moreover, it was shown that significant increases in nitrogen leaching rates can be expected with the increase of N availability in Scanian forests. The Rönne Å river and its catchment area to which both forests belong, suffers already from rather bad water quality due to overabundance of nitrogen (VISS 2014). The regulation can hence also be seen as a practical measure to achieve the environmental objective of "zero eutrophication".

6.5 Nitrogen emissions and forest saturation

Temperate and boreal forest have for a long time been seen as nitrogen limited (Shaver et al. 1992). This means that the growth rate (i.e. the Net Primary Production NPP) is directly dependent on the amount of available nitrogen rather than the amount of sunlight, temperature, water, CO_2 or other necessities. Nitrogen is said to be the limiting factor. Theoretically, the growth rate should therefore increase with the addition of nitrogen, that should result in higher uptake of CO_2 by the forest and that should in turn decrease the CO_2 level in the atmosphere. Exactly this decrease is observed on a global scale but is more than cancelled out by anthropogenic emissions of CO_2 (LeBauer and Treseder 2008). Yet, as nitrogen deposition increases the fertilising effect that it has on forest ecosystems decreases. Nitrogen limitation ceases and the ecosystems' growth instead becomes limited by another factor, like the availability of water (Tian et al. 2016).

A temperate forests' stages from being nitrogen limited to being nitrogen saturated are conceptualized by Aber et al. (1989) and reviewed later by Aber et al. (1998). These stages shall be presented with the intention to set the nitrogen balance in Hissmossa and Västra Torup in that perspective.
The effects of increasing nitrogen input into a forest ecosystem can be described in four stages where each stage represents a new ecosystem reaction to enhanced N input. The effects of single increasing inputs are comparable to constant low input. The reactions of significant environmental parameters to increasing nitrogen levels can be seen in figure 14.

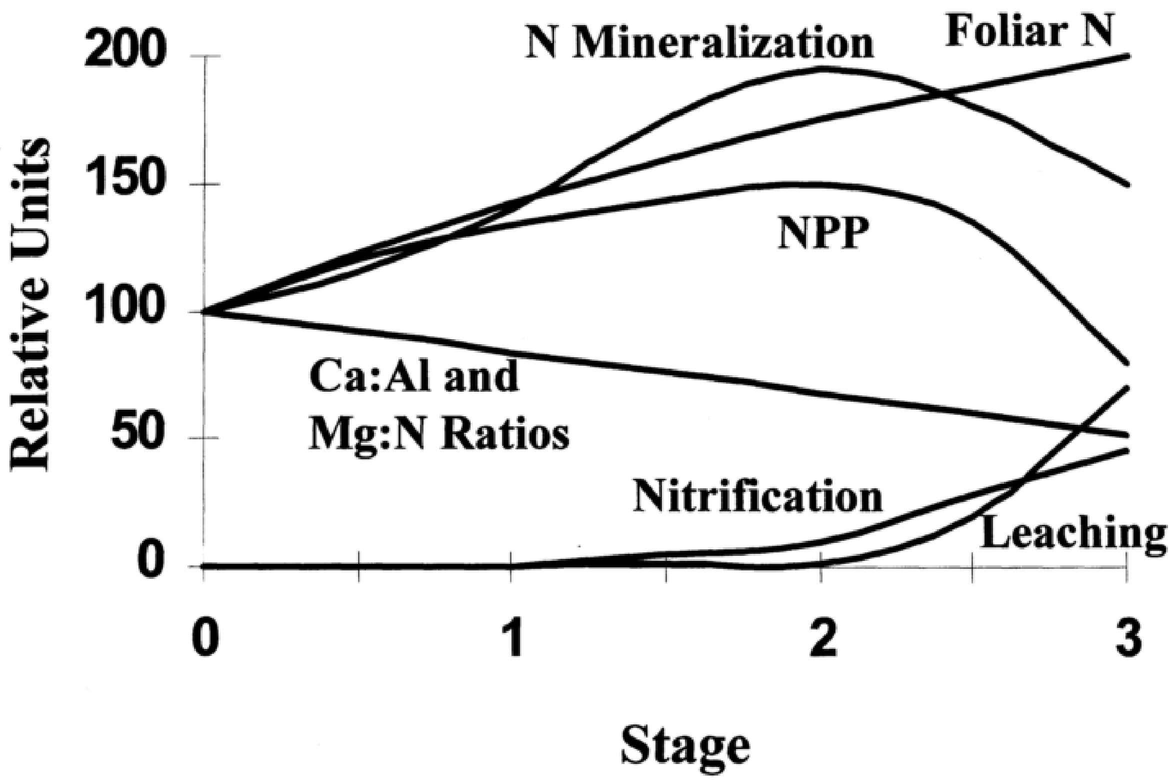

FIGURE 14 - HYPOTHESES ON THE BEHAVIOUR OF SIGNIFICANT ENVIRONMENTAL PARAMETERS UNDER INCREASING NITROGEN INPUT. THE MOST IMPORTANT FOR THIS STUDY ARE NPP (NET PRIMARY PRODUCTION) AND LEACHING. STAGE ZERO INDICATES NITROGEN LIMITATION WHEREAS STAGE TWO INDICATES NITROGEN SATURATION. FROM ABER ET AL. (1998).

Stage 0- nitrogen limited forest growth
In stage 0 the forest growth is nitrogen limited. NPP is proportional to the availability of nitrogen. The recycling and use of nitrogen is at its most effective so that no leaching occurs.

Stage 1 - Initial effects of N addition
As more nitrogen is added to the ecosystem this is taken up by plants directly. NPP increases in accordance with the input. However, the relationship between nitrogen uptake and NPP is dependent both on the plant type and the absolute amount of added nitrogen. This so called Nitrogen Response Efficiency (NRE; label from Tian et al. (2016), others use the more functional term Nitrogen Retention Efficiency (de Vries et al. 2014) which indicates the same flux) decreases slightly as growth becomes less N limited. Even though plants soon experience sufficient levels of nitrogen they take up further nitrogen and increase the N concentration in their tissues above a physiologically necessary level. This effect where plants take up more nitrogen than they would need is sometimes called luxury uptake (Falkengren-Grerup and Diekmann 2003). The decrease in NRE with increasing N availability ends the linear relationship between growth and nitrogen input (Tian et al. 2016).

Stage 2 - Nitrogen saturation
The plant uptake capacity for nitrogen is reached as plant growth is limited by other factors. The fact that not all soil ammonium is taken up by plants creates the possibility for nitrifying soil microbes to thrive and produce nitrate (Schlesinger and Bernhardt 2013). This form of

nitrogen is more soluble in water and mobile in the soil. Leaching and volatization begin. Nitrogen is lost from the ecosystem. Increasing input will not enhance plant growth. The forest ecosystem is nitrogen saturated.

Stage 3 - Forest decline
The leaching and overabundance of nitrogen induce the leaching of other nutrients like base cations from the soil. Additionally, high nitrogen levels can lead to soil acidification. These effects result in a decline in forest growth at a very high rate of nitrogen input.

Whether an ecosystem is nitrogen limited or not is to a large part controlled by the plants' N uptake which in turn follows plant biomass and growth rate. For disturbed or harvested ecosystems like the forestry sites of this study neither plant biomass nor growth rate is constant. Subsequently, the characteristic of being saturated or not is a temporal characteristic. Even with a constant nitrogen deposition level a forestry site can undergo all stages described above.

Modelling Hissmossa's and Västra Torup's leaching rates in reaction to different nitrogen input levels allows placing the forestry sites in that stage system. Throughout the range of tested scenarios the total amount of leaching nitrogen in Hissmossa increases almost linearly with nitrogen input while the biomass harvest remains fairly stable (Figure 8). This indicates that Hissmossa is not limited by nitrogen even at the lowest amount of input (2340 kg/ha from 1900 to 2100). Figure 7 shows that saturation occurs temporarily as a result of biomass extraction or extreme fertilisation whereas the magnitude of leaching is controlled by the nitrogen input during the preceding years. The modelled increase in harvest due to fertilisation is marginal in comparison to the increase that could be expected in a truly nitrogen limited ecosystem. Yet, there is a slight biomass increase up to the application of an additional 20 kg N/ha per rotation period and the high deposition scenario. The total addition of 2760 kg N/ha can therefore be seen as an indication for stage two nitrogen input level.

In some of the modelled fertilising schemes the total N leaching sums up to more than the amount of nitrogen added as fertilisers. This decrease in retention is a further indication of the complete nitrogen saturation (de Vries et al. 2014). In this case, saturation is not a result of a high dose of nitrogen but of a dose applied to an adult forest.
In Västra Torup a significant increase in harvest and an arising linearity between N input and leaching can be seen when increasing the nitrogen input from the low deposition scenario (2340 kg N/ha) and up to the high deposition scenario with application of 42 kg N/ha (total 2790 kg N/ha). This indicates that the forest is in stage one at the low deposition scenario. As total N retention does never decrease Västra Torup seems not to exceed stage two under the given N input scenarios.

One should be aware that there are other definitions of nitrogen saturation as well. Binkley and Högberg (2016) define saturation as the point there the leaching rate equals the input rate. Following this definition inputs need to be much higher than the ones tested in this study.

Accordingly, Binkley and Högberg (2016) find no sign of nitrogen saturation in Swedish forests.

Summarising, with the same N input scenario Hissmossa is at a higher saturation stage than Västra Torup. That difference might be a function of the higher maximum bearable N input rate of Västra Torup, probably defined by the local environmental conditions (e.g. soil characteristics). In Hissmossa, the risks for leaching and forest growth decline are higher and hence special attention should be given to that site.

To prevent eutrophication and biodiversity loss, forests should not receive more nitrogen than what they can permanently retain. The ruling law on forest fertilisation is necessary to control the risk of leaching and forest growth decline. The increased total leaching throughout the 21st century even without fertiliser application can be traced to higher deposition. Emission reductions agreed upon in the Gothenburg Protocol lack the strength to stop nitrogen leaching in Southern Sweden.

7 Conclusion

The average deposition of reactive nitrogen exceeds the maximum bearable nitrogen input rate for both study sites and for both the EMEP and the MATCH deposition scenarios. According to the presented definition, both forests are nitrogen saturated. Yet, the retention capacity based on ForSAFE outputs might be slightly underestimated reducing that gap between deposition and retention. Nevertheless, both sites are likely to leach nitrogen in the future, at least in reaction the extraction of biomass. For this reason and because the expected harvest is not likely to increase considerably, the current regulation prohibiting forestry nitrogen fertilisation in Southern Sweden is justified. As emission regulation and fertiliser prohibition are insufficient measures to stop nitrogen leaching, the issue of eutrophication will probably be ongoing throughout the coming decades.

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