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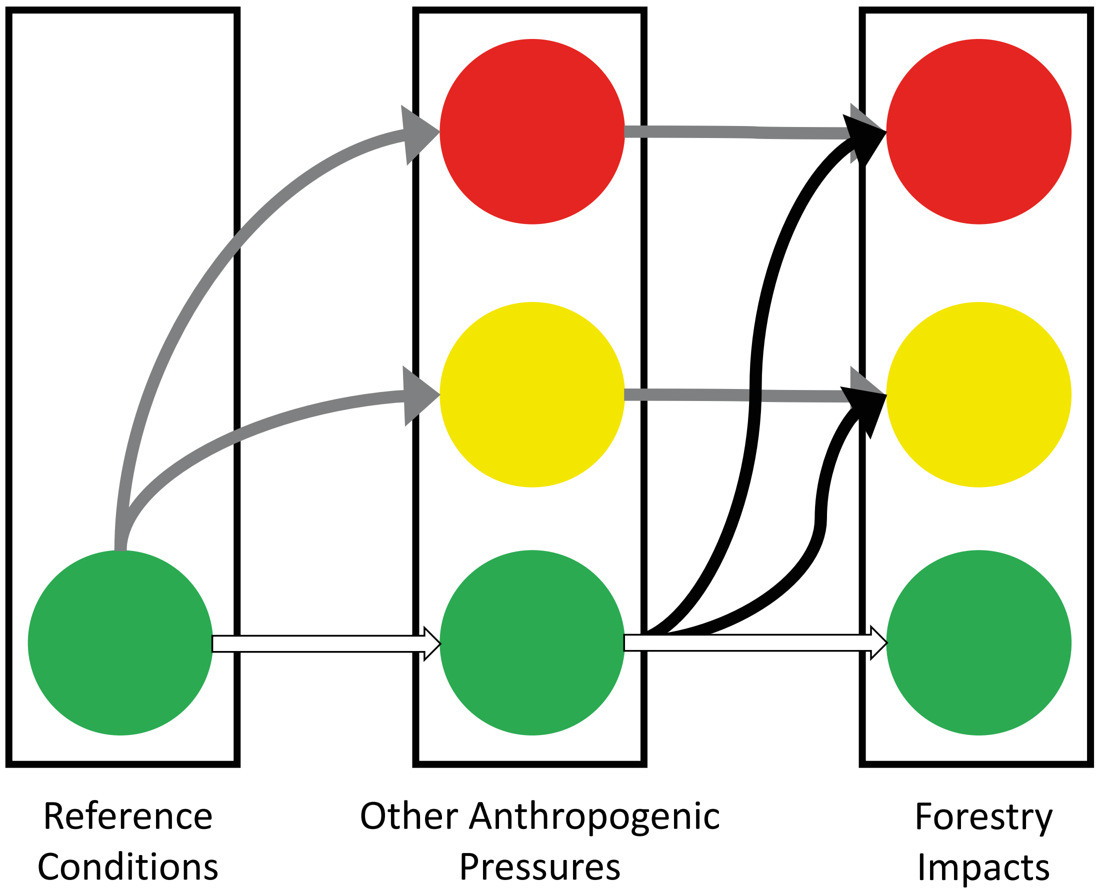
The potential effects on water quality of intensified forest management for climate mitigation in Norway



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Summary

The objective of this study was to make an overview assessment of the potential effects of intensified forest management, promoted by the Norwegian government as a climate mitigation measure, on water quality in Norwegian surface waters. This study evaluated the following measures for forest intensification: (i) afforestation, (ii) intensification of planting and (iii) nitrogen fertilization shortly before harvest. A substantial literature review was made and a further development of the DWARF- framework tailored for Norwegian conditions provided the base for the study. The assessments were made based on the potential effects after forest harvest, using different management strategies like stem-only harvest and whole-three harvest. The potential effects were analysed on multiple parameters with focus on acidification, eutrophication, heavy metals, and carbon sequestration. The study used temporal resolution to address what effects the forest management practices might lead to 1, 10 and 100 years after harvest. This study concludes that there will be trade-offs between transitioning to a low carbon society and water quality, and the severity of effects may differ if they are evaluated on an annual, decadal or century scale.

Four keywords	Fire emneord
1. Forestry	1. Skogbruk
2. Biogeochemistry	2. Biogeokjemi
3. Climate mitigation	3. Klimatiltak
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The potential effects on water quality of intensified forest management for climate mitigation in Norway

Preface

Norway is transitioning towards a low carbon emission society and forestry has been identified as one of the main sectors that can contribute to this transition. The Norwegian government has provided financial measures for forest owners to increase and intensify forest production in Norway. There are three main incentives: (i) Forest Nitrogen fertilization (ii) Afforestation on non-forested areas (iii) intensification of planting. This study aims at assessing the potential effects of these measures on surface water quality in Norway, to highlight potential trade-offs regarding climate mitigation potential of forests. In this report a literature survey has been based on a framework developed in Sweden. Salar Valinia was the task leader, Martyn Futter has done background research and data compilation, they are the two main contributors to the task. Nicholas Clarke and Øyvind Kaste have provided expertise and knowledge to the task. All authors contributed to the report writing. This project was funded by the Research Council of Norway, under the KLIMAFORSK programme. Non-financial support was provided by the Nordic Council of Ministries project BIOWATER.

Stockholm, March 2019

Salar Valinia
Leader, SURFER task 2.1

Table of contents

Summary

Norway has a long tradition of environmental stewardship and concern for the health of freshwater ecosystems. With the increasing need for climate mitigation activities and demands for a low carbon economy, Norway is undertaking an ambitious program of intensified forest management. While the carbon and climate mitigation benefits offered by more intensive forestry are clear, the consequences of these actions for water quality have been inadequately explored. Specifically, there are important questions about the water quality consequences of forest fertilization, greater rates of biomass removal at harvest, afforestation and increased seedling density when replanting. Here, we use a structured framework to assess the potential consequences of these activities for a series of key forest ecosystem processes: deposition, weathering and element accumulation, recirculation and fluxes.

We find that nitrogen (N) leaching associated with forest fertilization can have potentially negative consequences for surface water eutrophication and acidification. The benefits of greater carbon accumulation in tree biomass may be offset by negative effects caused by increased N fluxes from fertilized areas. Greater biomass removal at harvest (i.e. whole-tree harvesting of stems needles and branches versus conventional harvesting of stems only) offers increased potential for fossil fuel substitution but may have negative consequences for soil and surface water reacidification as more intensive harvest removes more base cations than conventional harvest. This is especially important in poorly buffered, slow weathering Norwegian forest soils.

Hence, forest fertilization for increased biomass growth followed by conventional (stem-only) harvesting is likely to have less negative water quality consequences than whole-tree harvesting. However, the surface water sensitivity to eutrophication and acidification should guide the selection of sites for fertilization and the choice of harvesting method.

Afforestation of heathlands and other areas may increase the deposition of acidifying substances through the “forest filter” effect and increase soil and surface water acidification in sensitive areas through greater accumulation of base cations in tree biomass. There is inadequate scientific information to evaluate the possible water quality consequences of increased seedling density when replanting.

Overall, the Norwegian commitment to more intensive forest management as part of a transition to a low carbon economy is likely to have detectable effects on surface water quality in sensitive areas. Some reacidification of soils and surface waters or slower recovery from acidification may occur in acid-sensitive regions if the intensification of forest management is not done in an environmentally sensitive manner. However, based on literature available from Norway and other Nordic countries with similar conditions there are still knowledge gaps regarding the trade-off between increased biomass yield and consequences for surface water quality. Examples of such knowledge gaps are post-harvest effects of fertilized stands on nitrogen leaching, forest harvest effects on mercury speciation and leaching, and the role of buffer zones to mitigate negative impacts. Lack of country- or

site-specific data might to some extent be compensated by spatial data from neighboring countries, international studies in similar ecosystems and similar climate zones, and by use of dynamic and process-based catchment models.

Sammendrag

Tittel: Potensielle effekter av mer intensivt skogbruk på vannkvalitet i Norge.
År: 2018
Forfatter(e): Martyn Futter, Nicholas Clarke, Øyvind Kaste, Salar Valinia
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Det er en lang tradisjon i norsk miljøforvaltning å ha et sterkt fokus på vann og vannkvalitet. Med bakgrunn i de alvorlige klimautfordringene og det økende behovet for å redusere de samlete utslippene av fossilt karbon, har norske myndigheter satt i verk et ambisiøst program for å benytte et mer intensivt skogbruk som et virkemiddel for å binde mer karbon. Mens effektene av et mer intensivt skogbruk er forholdsvis godt undersøkt med hensyn til selve klimaregnskapet, har det vært mindre fokus på hva slags effekter tiltakene kan ha for vannkvaliteten i berørte vassdrag. Flere viktige spørsmål står igjen å avklare i forhold til effekter på vannkvalitet av (i) skogsgjødsling, (ii) større biomasseuttak ved hogst, (iii) skogplanting på nye arealer og (iv) tettere planting på eksisterende skogarealer. I denne rapporten benytter vi et konseptuelt rammeverk som tidligere er brukt internasjonalt (DWARF) for å vurdere og visualisere mulige effekter av disse forvaltningstiltakene på en rekke prosesser som berører vann og vassdrag. Eksempler på slike prosesser er: atmosfærisk deposisjon, forvitring, stoffakkumulering, resirkulering og stofftap (lekkasje til vann).

Funnene fra undersøkelsen er at lekkasje av nitrogen (N) i forbindelse med skoggjødsling kan ha potensielt alvorlige konsekvenser for eutrofiering (overgjødsling) og forsuring av overflatevann. Gevinstene ved en økt karbonakkumulering i biomasse fra skog kan bli utlignet av uheldige virkninger av N-lekkasje fra gjødslete områder. Større biomasseuttak i forbindelse med hogst (dvs. heltre-hogst versus tradisjonelt uttak av trestammer) gir et økt potensial for å erstatte fossilt brensel, men har samtidig potensielt negative konsekvenser i form av jord- og vannforsuring da heltre-hogst vil føre til et større uttak av basekationer enn tradisjonell hogst. Dette vil være spesielt viktig i mange norske jordsmonn preget av lav forvitringsrate og svak bufferevne. Skoggjødsling etterfulgt av konvensjonell hogst (uttak av trestammer) vil derfor sannsynligvis ha mindre negative effekter på vannkvalitet enn heltre-hogst. Ved valg av lokaliteter for skoggjødsling og ved valg av hogstmetode bør det derfor tas hensyn til om tilliggende vannforekomster er sårbare i forhold til eutrofiering eller forsuring.

Planting av skog i tidligere åpent landskap kan føre til økt avsetning av forsuringskomponenter ved at skogen virker som et filter for forurenset luft og nedbør – og dessuten økt jord- og vannforsuring ved at en større andel av basekationene tas opp og lagres i tre-biomassen. Det er per i dag lite fagkunnskap i forhold til å kunne vurdere mulige konsekvenser for vannkvaliteten av tettere planting på eksisterende skogarealer.

Beslutningen om å benytte et mer intensivt skogbruk som et virkemiddel for å binde mer karbon vil sannsynligvis medføre merkbare effekter i sårbare vannforekomster. Gjenforsuring av jord og overflatevann eller langsommere gjenhenting etter forsuring kan bli et resultat dersom

intensiveringen av skogbruket ikke i tilstrekkelig grad hensyntar vannforekomster i foruringsfølsomme områder.

Basert på tilgjengelig litteratur fra Norge og andre nordiske land med tilsvarende naturforhold er det fortsatt kunnskapshull relatert til effekter av intensivert skogbruk på vannkvalitet. Eksempelvis er det fortsatt manglende kunnskap knyttet til nitrogenutlekking etter hogst av skog etter gjødsling, effekter av hogst på utlekking av kvikksølv og bruk av buffersoner for å dempe negative effekter på vann. Mangel på nasjonale data kan dels kompenseres gjennom studier av lignende skogøkosystemer i naboland eller områder med tilsvarende klima, eller det kan anvendes dynamiske og prosessbaserte modellverktøy for å simulere effekter av ulike skogforvaltningstiltak.

1 Introduction

1.1 Background

Forest management for greater biomass production and more intensive harvesting are increasingly recognized as tools both for sequestering carbon and for fossil fuel substitution. Carbon can be stored in standing forests and harvested materials including stems, needles and branches can be used for energy production. While the carbon benefits of more intensive forestry are widely discussed, the potential negative consequences are less well recognized. As well as concerns about reacidification of sensitive soils and waters, there are worries about the effects of more intensive forest management on water quality in drinking water reservoirs. Specifically, Norwegian experiments conducted in the 1970s documented negative effects of forest fertilization and harvesting on water quality, and it was suggested that this could have implications for drinking water supply (Haveraaen 1981).

> "*…detrimental effects may occur if several treatments like fertilization, clearfelling and herbicides are used over large areas of drinking water catchments for short periods*."
>
> Haveraaen (1981)

In two reports, jointly commissioned by the Norwegian Environment Agency and the Norwegian Agriculture Agency, new forest planting and intensified forestry are highlighted as promising ways to move towards a low emission society, providing low CO_2 emission fuel sources and complying with afforestation guidelines provided by the IPCC (Haugland et al. 2013, 2014). Three sets of measures have been proposed to achieve the goals: afforestation, intensification of planting and nitrogen (N) fertilization shortly before harvest.

Afforestation is the planting of trees on currently non-forested land. It may involve planting on either scrublands or land previously used for agriculture. Intensification of planting involves the use of a higher density of seedlings for reforestation following clearcutting. The density of seedlings should not exceed what is silviculturally optimal as planting at too high a density will result in increased mortality due to self-thinning.

N fertilization five to ten years before final harvest is widely used in the Nordic countries for increasing the amount and quality of saleable timber at harvest (Rytter et al. 2016). Traditionally, the timing of fertilizer application is dictated by economic concerns as application too early in the rotation is not seen as economically viable due to the long time between paying for fertilizer application and realizing income when the forest is harvested (Högbom, pers. comm.). While not mentioned in the three sets of measures, harvest intensity, thinning and choice of tree species are also relevant to consider. Of these, harvest intensity is also discussed in this paper.

The proposed measures reflect the fact that carbon is sequestered by growing forests throughout the rotation from planting to final harvest. Carbon can be sequestered in above ground and below

ground vegetative biomass, as well as in the soil itself. Any evaluation of the environmental consequences of the measures must also consider the whole rotation period from initial planting to final harvest. The most visible and long-lasting effects of forestry occur at final harvest, not during land conversion through afforestation, replanting or fertilization. While these three sets of measures can have immediate consequences for water quality at a local scale, they are generally short lived and minor in comparison to the environmental effects of clearcutting and harvesting.
Today, forestry in Norway is generally practiced in an environmentally and socially responsible manner, with approximately 70% of forests being certified under the Programme for the Endorsement of Forest Certification (PEFC; 2016[1]). The challenge faced by the forest sector and society is to achieve greater rates of forest production and harvesting without unduly compromising other relevant criteria such as water quality.

1.2 Aim of report

The purpose of this report is to introduce the concepts of the DWARF framework (Figure 1, Futter et al. 2016) to a Norwegian audience. The overall aim is to conceptualize and communicate the likely effects of more intensive Norwegian forestry on water quality, greenhouse gas emissions and carbon cycling. This report will use relevant, currently available data from the Nordic countries in an attempt to produce a baseline for discussion of the potential effects of more intensive forestry on surface water quality in Norway. This project does not attempt to make a thorough literature review of all Nordic forest water studies. However, we use the conclusions of these studies to inform possible outcomes in Norway and the potential effects on Norwegian surface waters. The two case studies presented in this report (Birkenes and Glitrevann) are illustrative of possible consequences. However, empirical data collection or modelling studies were outside the scope of this report.

[1] http://www.pefcnorway.org/vedl/PEFC%20N%2002_Forest%20Standard_English_31Aug%202015.pdf

2 The DWARF framework

The DWARF framework represents Deposition, Weathering, Accumulation, Recirculation and Flux processes in managed forest ecosystems (Figure 1). The framework considers both natural cycles and the consequences of anthropogenic perturbation, e.g. forest fertilization and harvesting. Understanding and communicating how more intensive forest management affects water quality, carbon and nutrient cycling in forest ecosystems are important steps for the Norwegian transition to a sustainable, low emission society.

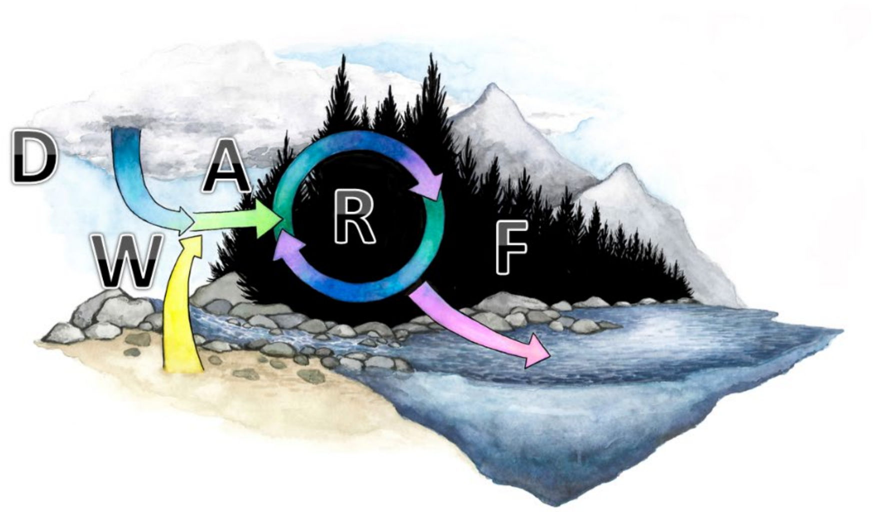

Figure 1. Illustration of the DWARF framework. From Futter et al. (2016).

2.1 Processes included

2.1.1 Deposition

Is the contribution of wet and dry input of ions and compounds from the atmosphere to a catchment, including inputs of pollutants, nutrients and water as precipitation and/or snowfall. Deposition is here taken to mean total deposition rather than for example bulk deposition or throughfall. In some places, especially close to the sea, a significant fraction of base cation inputs can be derived from atmospheric deposition (Draajiers et al 1997). In Norway, most of atmospherically deposited pollutants are a product of transboundary air pollution (Klein et al 2018). Historically, the two largest pollutants in Norway have been anthropogenic (non-marine) sulfate (SO_4^{2-}) and inorganic nitrogen (nitrate, NO_3^-, and ammonium, NH_4^+). These have caused significant large-scale acidification of soils and surface waters across the country, the effects of which are still being felt today (Austnes et al 2016). During peak acidification around the years 1980-1990 about 2.5 kg/da of sulfur and 1.7 kg/da of inorganic nitrogen were deposited annually in southern Norway. Over the past twenty years, there have been significant declines in deposition of both anthropogenic SO_4^{2-} (Figure 2) and inorganic N (Figure 3).

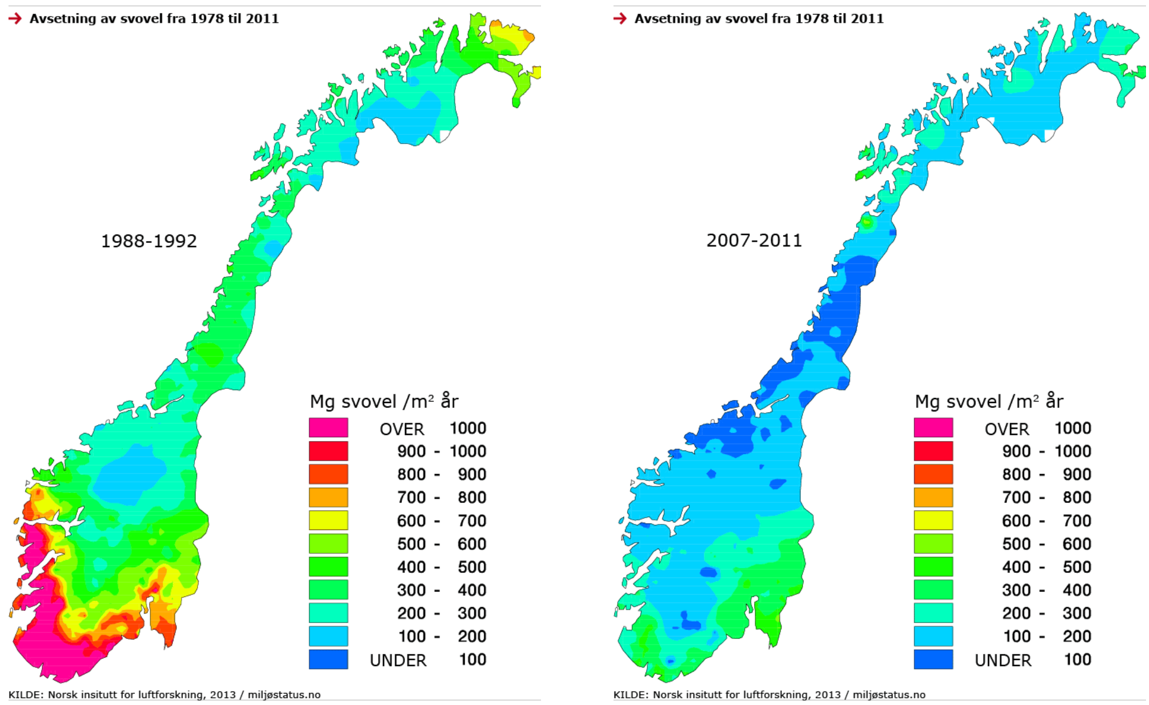

Figure 2. Annual deposition (mg/m^2/yr) of sulfate sulfur (S) between 1998-1992 (left) and 2007-2011 (right). Maps from environment.no (accessed 2018-10-19).

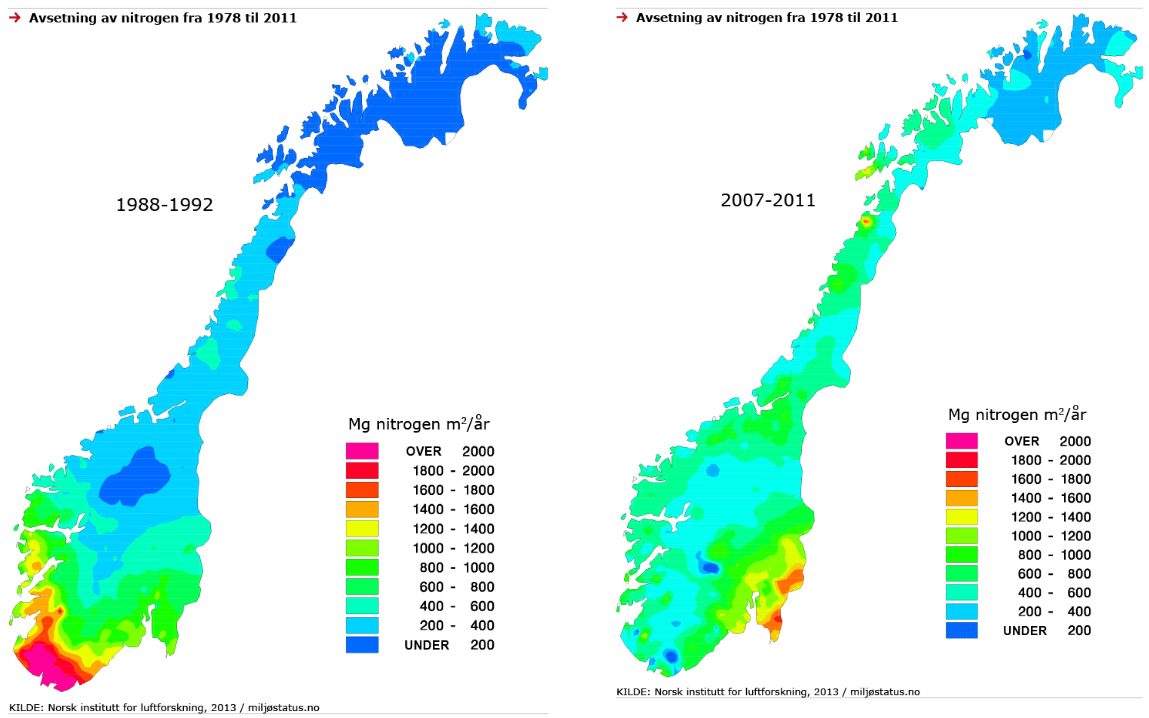

Figure 3. Annual deposition (mg/m^2/yr) of inorganic nitrogen (N) between 1998-1992 (left) and 2007-2011 (right). Maps are from environment.no (accessed 2018-10-19).

There is a pronounced geographical gradient in the deposition of SO_4^{2-} and inorganic N, with higher values in the south of the country. While deposition was historically higher in the southwest of the country, the highest rates of deposition are now seen in the southeast along the Swedish border (Figures 2 and 3).

Afforestation can increase the deposition of acidifying compounds through the so-called "forest filter" effect in which coniferous forest canopies intercept atmospheric pollutants more efficiently than other land cover types. This is reflected in the current generation of EMEP deposition scenarios, where inorganic N and sulfate deposition to forest land is higher than to other land types. Specifically, in forested regions of central Norway and Sweden, sulfate deposition is +10/-8% higher for the EMEP forest category compared to the vegetation category. The increases in modelled deposition for nitrate and ammonium are +19/-14% and +18/-18% respectively. However, measured values at ICP Forests Level II sites in Norway often, but not always, show lower deposition of non-marine sulfate and inorganic nitrogen in throughfall than in bulk precipitation (e.g. Timmermann et al. 2017). In the case of inorganic nitrogen, this might be due to canopy uptake.

2.1.2 Weathering

Weathering is the physical, chemical, or biological breakdown of geologic material. Weathering rates are also a critical factor in models of acidification and recovery. However, the high uncertainty in weathering rates is often inadequately considered (Futter et al. 2012). Due to the nature of the parent bedrock, weathering in Norway is often a very slow process, making it very difficult to estimate rates accurately. In some parts of Norway (including for example Birkenes in Aust-Agder), weathering rates approach zero and plant base cation needs are presumably supplied by atmospheric deposition (Nordic Council of Ministries 1998). Weathering is essential to plant growth and protection against anthropogenic pressures. Weathering is the ultimate source of elements including phosphorus and base cations needed for plant growth (although in coastal areas, marine inputs can be important for e.g. magnesium supply). As noted by Akselsson et al. (2007), negative consequences of more intensive forestry are more likely to be observed on low weathering sites, where the outtake of base cations associated with forest harvest will exceed replenishment rates from deposition and weathering. Although Akselsson et al (2007) conducted their study in Sweden, the results are highly relevant for low weathering sites also in Norway.

2.1.3 Accumulation

Accumulation is the process by which deposited and weathered material are incorporated into the soil or biota. Accumulation includes biological fixation of C and N from gaseous to organic form such as carbon fixation (i.e., photosynthesis) and uptake of deposited inorganic nitrogen. Thus, accumulation is the process by which carbon is sequestered in growing forests. The accumulation of other elements in growing forests is also relevant for understanding the tradeoffs between the transition to a low carbon economy and water quality. In Sweden, the recent decline in riverine N concentrations has been linked to the increase in standing forest biomass (Lucas et al, 2016). It has also been suggested that the increase in standing forest biomass, and the consequent increase in the amount of base cations stored in vegetation is a relevant factor in timing and rates of recovery from acidification (Iwald et al. 2018). In some parts of Sweden, forestry may be having a similar effect on acidification status as atmospheric deposition (Iwald et al. 2018). The effects of forestry are most pronounced in base poor, low weathering sites which are closer to conditions observed in Norway. This suggests that more intensive forestry in Norway may lead to large shifts in base cation cycling, with potential negative effects for water quality and acidification status.

Across Norway, the standing forest biomass is increasing (Figure 4, 5) which suggests that increasing amounts of nitrogen and base cations are being sequestered in biomass. The increase in forest biomass has positive implications for carbon sequestration.

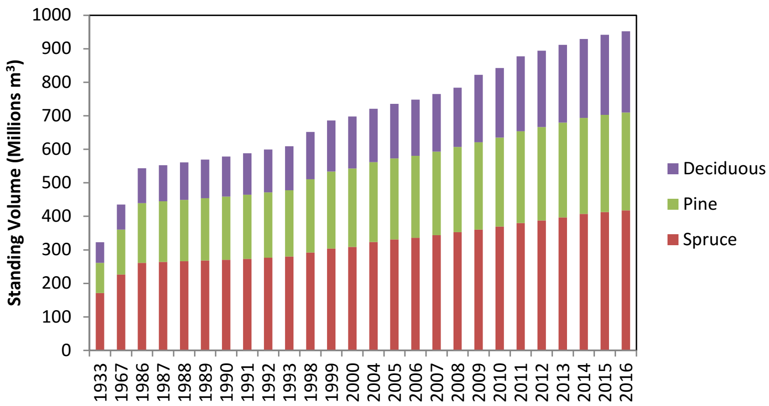

Figure 4. Trends in standing timber volume in Norway between 1933 and 2016 (data from the national forest inventory, Norway. https://www.ssb.no/en/lst (accessed, 2018-10-19)

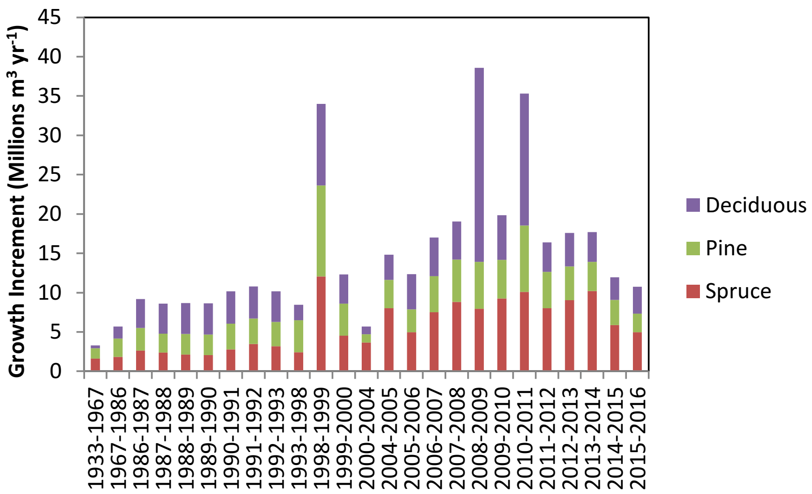

Figure 5. Annual growth increment in standing volume between 1933 and 2016. The national forest inventory, Norway. https://www.ssb.no/en/lst (accessed, 2018-10-19).

2.1.4 Recirculation

Recirculation is a term that includes recycling and redistribution of material within a forest stand. Examples of recycling processes include vertical transfers between plant and soil (as with litter fall and element uptake by roots). Redistributive processes include lateral redistribution of material within a stand including build-up of material on the forest floor, the riparian zones and wetlands, and the slow movement of contaminants through the soil profile as well as vertical redistribution. Forest harvesting has a negative effect on the recirculation of base cations as material in e.g. stemwood, branches or needles, which would have returned to the soil in an unmanaged forest, is removed for energy production and other uses.

2.1.5 Fluxes

Fluxes out of the system include gravity driven processes such as surface water runoff and the return of material to the atmosphere (e.g., via trace gas production or evapotranspiration). Redistribution of elements can be extremely important in delaying the impact of atmospheric deposition on stream water fluxes. Fluxes of C and N in forest ecosystems are particularly important for Norway as the aim with intensifying forestry is a move towards a low emission society. From the perspective of the present study, fluxes associated with forest fertilization and harvest are most relevant.

2.2 Time scales

The effects of forestry on water quality depend on the temporal scale over which the effects are analysed. In this project, we focused on what potential effects can occur after 1, 10 and 100 years after clearcut. (Figure 6). A typical forest rotation (the period of time between clear fellings) is approximately 100 years, while the effect duration following clearcutting is on the order of 10 years (see e.g. Futter et al. 2010, Oni et al. 2015), while the annual scale is relevant for short term and transient events. The severity of each water quality issue and forestry effects is assessed at all three temporal scales. Effects after one year can be substantially more severe than after 10 and 100 years. The reasoning on using these time scales is based on the rotation period for Norwegian forests and what potential effects can be seen. We argue that there are substantial differences in the effects looking at a period between 1-100 years, and the literature survey showed that some effects only last for up to 10 years post-harvest, while the long-term effects (100 years) are slow changes to the soil and waters around the forests. A challenge in this respect is the lack of long-term field experiments older than 40-50 years, making modelling predictions hard to test empirically.

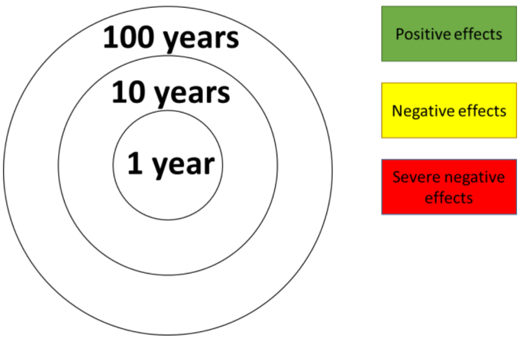

Figure 6. ”Dart board” representation of temporal scales assessed here, 1, 10 and 100 years post forest harvest and its potential effects on water quality. An effect can be identified as positive (green), negative (yellow) and severe negative (red) depending on the time scale and forest management type.

3 Norwegian forests

Forests grow relatively slowly in Norway, with an average national increment of 0.3 m^3 stemwood / da/yr on productive forest land (The national forest inventory, 2018). Forests are both more productive and more common in the south of Norway than the north (Table 1). In much of the country, forestry is limited by steep terrain or inhospitable climate.

Table 1. Areas of productive forest land in different regions of Norway along with standing timber volume and average growth rates. (from the national forest inventory, Norway. https://www.ssb.no/en/lst (accessed, 2018-10-19)

Region	Area of productive forest land	Proportion of land area	Standing volume	Growth rate
	km^2		m^2/da	m^3/da/yr
Norway	83160	26%	11.5	0.29
Østfold, Akershus, Oslo and Hedmark	19622	53%	12.0	0.36
Oppland, Buskerud and Vestfold	15257	36%	11.3	0.33
Telemark, Aust-Agder and Vest-Agder	11931	38%	12.5	0.33
Rogaland, Hordaland, Sogn og Fjordane and Møre og Romsdal	10581	18%	11.6	0.31
Sør-Trøndelag and Nord- Trøndelag	10894	26%	9.2	0.26
Nordland and Troms	11324	18%	5.4	0.14
Finnmark	3552	7%	2.6	0.06

In Norway, 83% of forests are privately owned and the remaining 17% is owned by the state. As in much of Fennoscandia, forest growth is limited primarily by N availability. Approximately 75% of forests are certified under the Programme for the Endorsement of Forest Certification (PEFC), and the Norwegian Regulation on Sustainable Forestry states that forests shall be managed in accordance with PEFC requirements (Ring et al 2017). Compared to Sweden and Finland, forestry is practiced at relatively low intensity in Norway. Most stands are harvested in a conventional manner, in which the stems are removed and the needles, branches and tops (known as forest residues) are left on site (stem-only harvesting, SOH) (Nicholas Clarke, pers. comm.).

There is a very limited harvest of forest residues for energy production, although this may change in the future. Efforts devoted to stand regeneration are increasing. In 2016, more than 185 000 da were replanted and site preparation was conducted at an additional 60 000 da. There has been limited fertilization of forests with nitrogen until recent years. In 2000, only 17 000 da were fertilized, while in 2016, 84 000 da of forest land were fertilized. These numbers are expected to increase in coming years, primarily due to government support (SSB 2018). Afforestation is currently not widely practiced in Norway although there is the potential for a significant increase, especially along the western coast.

Increasing the biomass outtake from Norwegian forests for energy production can be accomplished in a number of ways, including improved growth or higher rates of removal of the existing biomass. Improved growth can be accomplished in the short term (5-20-year time window) through forest fertilization, or over the long term (100-year time window) through use of better genetic stock or planting of unconventional (largely non-native) species. Use of non-native species is not forbidden, although the PEFC standard requires that their use is kept under control and special permission is required according to the Nature Diversity Act.

Forest fertilization has been shown to be an economically viable means of increasing forest growth in parts of Fennoscandia. One or more N fertilization treatments applied 5-7 years before harvest can lead to significant growth increases (often 0.15 m^3/da/yr, which translates to 0.12-0.14 tonnes CO_2 sequestered/da/yr) and a greater value for marketable timber (Haugland 2014). A single fertilizer treatment applied ten years before harvest has the potential to increase the volume of harvestable stemwood by approximately 4% at harvest (3.5% for pine and 4.5% for spruce). Typically, fertilizer is applied at rates of 15 kg N /da (Haugland 2014).

4 Carbon sequestration by forests

Forests can influence the overall carbon (C) balance of a region in a number of ways. In Norway, carbon sequestration in forests offset anthropogenic C emissions by circa 40% (De Wit et al. 2015). Most obviously, growing forests sequester atmospheric carbon in plant biomass. Forests and forest management also influence rates of soil C accumulation and ecosystem level CO_2 production through respiration. Most forest management activities discussed here are focused on increasing rates of C sequestration in tree biomass. These are fairly well studied. Less is known about the consequences of forestry on soil C sequestration. Forest management activities can have both positive and negative effects on soil C sequestration. For example, afforestation or fertilization may increase rates of soil C sequestration while disturbance associated with clearcutting often leads to losses of soil C, especially in the organic layer (Clarke et al. 2015). Given the uncertainties in soil C sequestration associated with intensified forest harvesting, we will focus here on the potential for forest biomass to replace other energy sources and the C budgets of forest biomass, primarily wood (tree stems), needles and branches.

4.1 Forest biomass to carbon conversions

For the purposes of this study, forest biomass can be quantified in one of three ways: as energy equivalents, mass or volume. The latter two facilitate calculation of carbon budgets. Stemwood has an energy density of 19 (broadleaves) - 19.2 (conifers) gigajoule (GJ) / tonne dry weight. Needles and branches have a slightly higher energy density of 20-22 GJ / tonne dry weight (Francescato et al 2008). There is a large amount of water in wood, so unless values for dry material are reported, mass is not so useful. Forest growth and harvests are typically reported as volumes of material harvested per unit area. Harvest volumes are typically reported as volumes of stemwood in units of m^3. Norway is one of the few jurisdictions to report forest management areas in decares (da), which are equivalent to 1000 m^2, or 0.1 hectare (ha). Forest harvest amounts are usually quantified in Norway as m^3 stemwood / da. Bark, branches and needles are not included in the calculations. Dry Norway spruce wood has a density of 0.43 tonnes /m^3 while wood from Scots pine has a density of 0.51 tonnes / m^3 (Table 2). Thus, at a first approximation, 1 m^3 conifer wood has an energy density of between 8.1 and 9.7 GJ. Conifer wood is about 50% C by weight, so there are 200-250 kg C / m^3 stemwood. As carbon comprises 27.3% of the mass of CO_2, this equates to 790-930 kg CO_2/ m^3.

Table 2. Approximate conversion factors for 1 m^3 conifer wood

Dimension	Units	Conversion Factor (per m^3)
Dry weight	Tonnes	0.43-0.51
Carbon content	Tonnes C	0.2-0.25
Greenhouse gas equivalent	Tonnes CO_2	0.79-0.93
Energy density	GJ	8.2-9.7

In Norway today, there are approximately 83 million da of productive forest land, which is almost 25% of the total land area (Table 1). The main commercial species are Scots pine, Norway spruce and a mix of broadleaf species dominated by birch (The national forest inventory 2018). The standing biomass is increasing in Norwegian forests as growth exceeds harvesting and other losses (Figures 4, 5). The most recent data from Statistics Norway indicate a national standing volume of $9.5X10^8$ m^3 and annual growth of $2.6X10^7$ m^3. It should be noted that the increase in standing volume is not the same as an increase in forest area. The area of afforested land in Norway has remained relatively constant and the increase in standing volume is primarily the result of more and / or bigger trees per unit area. The increase in forest biomass is related to land use change (reductions in summer farming, abandonment of less productive agricultural areas), reduced harvesting intensities because of decreasing economic benefits from forestry, increasing forest conservation, and to a forest planting program after the Second World War (Fjellstad and Dramstad 1999, Solberg et al. 2003).

4.2 Implications of intensified forest management for carbon sequestration

Managed forests can contribute to both carbon sequestration and carbon substitution. The most promising strategy for carbon sequestration is a combination of increasing both forest carbon stocks and rates of harvest (Bellassen and Luyssaert, 2014). Growing plants sequester atmospheric carbon. Appropriately managed forests can also sequester carbon in the soil. Using wood and other forest biomass for energy generation or as e.g., building material can contribute to carbon substitution.
In Norway, there is an ongoing increase in the standing volume of forest biomass (Figure 4). As much of this biomass is derived from the fixing of atmospheric carbon, this contributes to carbon sequestration at a national scale.

Forest fertilization enhances carbon sequestration in both biomass and soils. Fertilization leads to increased biomass growth and has the potential to reduce belowground microbial respiration (Janssens et al. 2010). In Norwegian forests, much of the nitrogen used by trees is obtained through a symbiotic association with soil microbes. If the nitrogen can be obtained from another source, e.g. fertilisation, trees can invest less energy in the symbiotic relationship, and this leads to lower soil respiration.

The limited available information suggests that forest fertilization will not be a significant source of N_2O. While there are a number of studies from peatland forestry in Finland (which indicate low rates of N_2O production) there are no empirical studies of forests relevant for Norwegian conditions. Based on expert judgement, Nordin et al. (2009) stated that between 0.5 and 1% of the N applied in fertilizer in Swedish forests would likely be re-emitted as N_2O. Harvested forest biomass can contribute to carbon substitution if it is used for producing energy that would otherwise be generated from fossil fuels.

There are large uncertainties associated with the fate of soil carbon following forest harvesting. In general, stem-only harvest (SOH) appears to lead to a reduction in C stocks in the forest floor, but not in the mineral soil (Nave et al. 2010). Nave et al. (2010) suggested an average of 8+/-3% of soil carbon is lost from temperate forests following clearcutting. Typically, this carbon is replaced during the next forest rotation. Currently available information does not support firm conclusions about the long-term impact of intensified forest harvesting on soil organic carbon stocks in boreal and northern temperate forest ecosystems, which is in any case species-, site- and practice-specific (Clarke et al. 2015).

5 Biogeochemistry of nitrogen, base cations and dissolved organic carbon

Intensified forest management can alter the cycling of nitrogen (N), base cations (BC) and dissolved organic carbon (DOC) in forest stands. These changes may in turn affect acidification, eutrophication and climate change mitigation potential.

5.1 Nitrogen

Nitrogen is an essential plant nutrient (see Binkley and Högberg, 2016) that also can limit biological processes in boreal streams (Burrows et al. 2015) and lakes (Bergström et al. 2008). Across the northern hemisphere, atmospheric N deposition has increased considerably over the past 100 years as a result of fossil fuel burning and increased fertilizer use. Tree growth in most Nordic forests is N-limited. For example, A modelling study suggests that anthropogenic N deposition may have increased forest growth by as much as 25% in southern Norway (Solberg et al. 1994). Furthermore, N fertilization is commonly recommended to increase yields. Over the course of a whole rotation, boreal forests tend to be net N sinks, in that they effectively take up the N deposition derived from fossil fuel burning in Norway and elsewhere.

Forestry activities affect the accumulation, recirculation and fluxes of N from forest stands. Any harvesting activities including thinning, stem-only harvest (SOH) and whole-tree harvest (WTH) remove N from the stand, decreasing the size of the N pool and potentially slowing rates of recirculation (Lundborg 1997; Palviainen and Finér 2012). Effects are more pronounced with WTH due to the removal of large amounts of N in needles. While N leakage can occur following final felling, the total amount lost is small relative to total atmospheric deposition (Futter et al. 2010). The concentrations of N in groundwater following final felling are elevated when compared to undisturbed forests (Mulder et al. 1997, Clarke 2018b) but not high enough to cause problems of compliance with European legislation or human health issues.

5.2 Base Cations

The base cations calcium (Ca), magnesium (Mg), potassium (K) and sodium (Na) are essential plant nutrients and some of the most important elements buffering soil and surface water acidification. Acid deposition increases the rate at which base cations are leached from the soil. Following reductions in acid deposition, surface water base cation concentrations may decline further due to a lack of mobile co-anions for transport (see, e.g. Cosby et al. 1985). The acidification caused by long-range pollutant transport is largely an issue of the past. However, modelling studies have suggested that WTH remove base cations from forest soils faster than they can be replaced by mineral weathering (Zetterberg et al 2013). This may cause further acidification of waters in low-weathering environments, typical for large parts of Norway (Akselsson et al. 2007). Some experiments suggest that more rapidly growing forests may increase weathering rates (Palviainen et al. 2012). However, there is no consensus as to the mechanism and estimated weathering rates are too uncertain to draw firm conclusions about the sustainability of forest harvesting (Futter et al. 2012).

The regional legacy of acid deposition has depleted soil base cations, resulting in still ongoing acidification of many soils and surface waters in Norway (Kirchner and Lydersen 1995, Moffatt et al. 2006, Garmo and Skancke 2018). This will be further exacerbated by any changes in forest management which either increase standing biomass or biomass removals. It has recently been suggested that the increase in standing biomass in Swedish forests may be an important factor explaining delays in recovery from acidification (Iwald et al. 2018). Biomass removal following forest harvest will reduce the BC pool in a stand, leading to reductions in the rates of recirculation and potentially lower fluxes to surface waters.

5.3 Dissolved Organic Carbon

Dissolved organic carbon (DOC) originates ultimately from plants fixing atmospheric carbon and is derived from the breakdown of plant material in soils and litter. Concentrations of DOC are increasing in many surface waters and it has been hypothesized that declines in acid deposition (Monteith et al 2007; Valinia et al 2014), historical land management practices (Meyer-Jacob et al 2015) and a changing climate (Oni et al. 2014; de Wit et al. 2016) are important drivers. This is a concern for a number of reasons. DOC is a naturally occurring acid that, if elevated above its reference condition, can contribute to a delay in acidification recovery (Futter et al. 2014). Elevated DOC concentrations can lead to significant alterations of lake ecology including changing the light environment, which inhibits gross primary productivity (Solomon et al. 2015), fueling heterotrophic processes, altering the amount and bioavailability of contaminants (Rask et al. 2014), and altering rates of mercury cycling (Braaten et al. 2018). Finally, DOC is an important part of the global carbon cycle and can make a significant contribution to lateral carbon fluxes (e.g. de Wit et al. 2016) and greenhouse gas production in forest lakes (de Wit et al. 2018).

6 Possible biogeochemical consequences of intensified forest management

6.1 Fertilization

Fertilization has a number of direct and indirect effects on forest growth, water pollution and greenhouse gas dynamics. The main goal of fertilization is increased tree growth; any added N that does not contribute to this goal can be considered wasted. There is some evidence of lower N losses when multiple, smaller fertilizer applications are made over multiple years (e.g. 5 kg N / da every second year for 6 years) compared to a single application of 15 kg N / da. Although multiple, smaller applications may be costlier, they are likely to be more environmentally friendly as there will be less leaching and potentially more biomass growth. The carbon footprint of multiple fertilizer applications should also be assessed to ensure a fuller accounting of greenhouse gas consequences.

Nitrogen fertilization can have both negative and positive greenhouse gas consequences. There is a theoretical possibility for N fertilization to cause additional N_2O production. In practice, this is unlikely to occur except if soil carbon (C) stocks are very low. Typically, such low soil C stocks are associated with low-productivity sites where fertilization would be unlikely to lead to substantial growth increases due to e.g. lack of other macronutrients. There is some evidence to suggest that N fertilization can lead to increased soil carbon accumulation due in part to decreased soil respiration. In Fennoscandia and elsewhere, forest trees exist in a symbiotic relationship with soil microbes and fungi. The trees provide carbon to fungi in return for nitrogen. If the trees can obtain N from another source, e.g. fertilization, they can reduce the amount of carbon they provide to soil fungi. This in turn can result in less CO_2 production by roots and soil organisms, and potentially greater soil C accumulation. A decrease in soil respiration following fertilization would mean less CO_2 production from a fertilized stand, and potentially, a better greenhouse gas footprint.

Soil solution and streamwater N levels are typically very low in Nordic forests (Sponseller et al. 2016). Inorganic N (primarily nitrate) concentrations are almost always below 1 mg nitrate/l, which is well below the Nitrates Directive threshold of 11.7 mg N/l as nitrate[2]. Nitrogen fertilization often leads to detectable short-term increases in soil solution N concentrations (Clarke et al. 2018a) and can also increase N concentrations in streams draining fertilized areas. The increased N concentrations have been shown to result in detectable changes to aquatic plant community composition, with a shift towards more N tolerant species. However, given the high demand for N in most Nordic forest surface waters, water quality effects are hard to detect even a few hundred meters downstream of fertilized sites (Schelker et al. 2016).

There are a limited number of recent forest fertilization experiments in Norway. Holt Hanssen and Kvaalen (2018) studied the effects of repeated fertilization of young Norway spruce forests in central Norway. They showed that fertilization with N only resulted in 14% higher standing volume

[2] 1 mg/l nitrate (NO_3) corresponds to 0.225 mg/l nitrogen (N)

compared to unfertilized controls, while fertilization with N and other nutrients resulted in average standing volume increases of 20% as compared to the control. In addition to this study, there are a number of older fertilization studies summarized in Nilsen (2001) and Sture (1984, 1986).

Spreading of wood ash in forest is currently forbidden in Norway according to the Regulation on Fertilizers etc. of Organic Origin. This regulation is currently under review. The PEFC standard requires that nutrient losses associated with fertilization be kept to a minimum and that fertilizer is not applied within 25 m of lakes, rivers and permanent streams. The standard recommends that fertilizers should not be applied to upland sites identified by certain ground vegetation communities. Furthermore, fertilizer should not be applied on peatlands unless they are already rejuvenating.

6.2 Afforestation

Afforestation may have significant regional and stand level consequences for soil and surface water acidification. Forested land generally receives higher amounts of atmospheric deposition of acidifying substances. This effect is clearly manifested in the gridded estimates used in e.g. calculations of critical loads for acid deposition. In addition, forest growth has an acidifying effect (Tamm and Hallbäcken 1988) due to hydrogen ions replacing base cations taken up by trees. Some UK studies have demonstrated negative water quality effects related to acidification following afforestation of peatlands. These results are likely due to the more effective atmospheric scavenging of dry deposition by coniferous forest as compared to peatlands. There is also a possibility that changes in soil hydrology associated with afforestation (e.g. drier soils and changing flow paths associated with root development) may have led to the observed water quality effects.

From a Norwegian perspective, the proposal to afforest large areas of coastal land is especially troubling as this may result in a significant increase in sea-salt related acidification events in acid-sensitive areas (Hindar et al. 1994, 1995, Mulder et al. 1997). Excessive deposition of sea salt can result in pronounced short term depression of pH in surface waters due to cation exchange processes in the soil (Wright et al 1988). Afforestation of heathland, or other open areas near the coast is likely to result in higher rates of sea salt deposition as the forests will more effectively scavenge cations, chloride and other anions in sea water. This in turn is likely to exacerbate any short-term acid events with unknown but potentially severe consequences for aquatic biota in acid-sensitive surface waters (Larssen & Holme 2006).

Afforestation of arable land has been proposed as a measure to mitigate or remediate groundwater nitrate pollution in Denmark. Results have been mixed. Initial studies showed that afforestation of land previously used for arable agriculture was followed by declines in groundwater nitrate concentrations, due both to cessation of agricultural fertilizer application and greater rates of N uptake by vegetation, but these results have not been consistently verified in follow-up studies (Per Gundersen, pers. comm.).

Afforestation will have predictable consequences on stand-level energy, water and nutrient cycling. Afforestation with conifers will change stand albedo (Kirschbaum et al 2011). Conifer forests typically have higher rates of precipitation interception, evaporation and transpiration compared to other land cover types. Thus, stand-level water yields can be expected to decline (Calder 1986). Afforestation with conifers typically leads to more acidic soils, both because conifer needles are acidic and due to uptake of base cation in to stand biomass. Increasing tree biomass means that more elements including carbon and base cations will be sequestered in plant tissue. Uptake of base cations by trees requires their replacement by other cations (often hydrogen ions in acidified soils) in order to preserve soil solution electroneutrality (Iwald et al 2018). The alteration in base cation cycling may lead to detectable effects on soil and surface water acidification chemistry.

Using the DWARF framework for afforestation is associated with significant uncertainties, in particular related to the biogeochemical consequences as only a few long-term studies have been conducted in Norway and elsewhere. The available literature shows that effects on sediment and DOC transport at all temporal scales will depend on the previous land use. Afforestation of previously arable land is likely to reduce sediment yield, while afforestation of pastures or scrubland may result in increased soil disturbance and higher sediment yields (Figure 7).

Afforestation is likely to lead to improvements in surface water N concentrations at the decadal scale in areas where inorganic N concentrations are too high, but these may be offset by declines in water quality at the century scale associated with forest harvesting (Figure 7). Reduction of base cation stocks are likely as forest growth will be substantial prior to canopy closure. The change of arable land to forest will likely have a positive impact on P levels in the soils. Associated land disturbance of afforestation and later removal of forest can potentially affect mercury methylation and mobilization in soils (Eklöf et al. 2018). Greater biomass growth associated with afforestation, and subsequent removal of material at harvest will reduce base cation concentrations in soils.

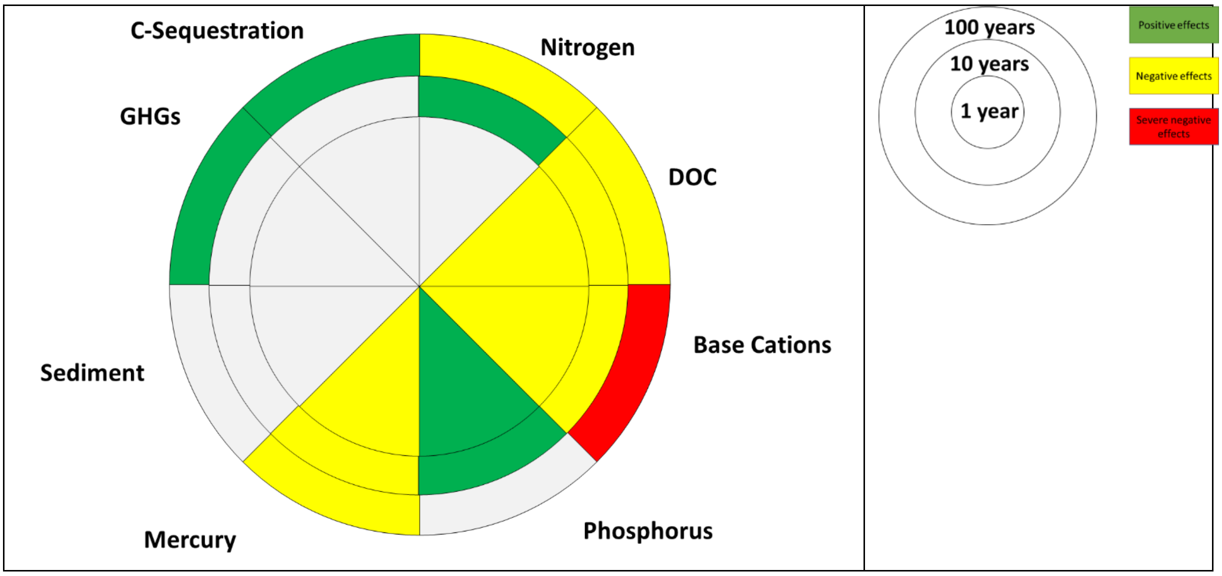

Figure 7. Possible biogeochemical effects of afforestation at 1 (inner) 10 (middle) and 100 (outer) year scales.

From the perspective of carbon sequestration, Bárcena et al. (2014) have shown that afforestation of northern European croplands, but not grasslands, has the potential to increase soil carbon sequestration over the long term (30+ years). The relevance of this finding to Norwegian conditions needs to be explored more fully.

6.3 Increased seedling density

The proposal to plant seedlings at a higher density than is currently practiced is unlikely to adversely affect water quality. Although planting density in Norway is often sub-optimal (Søgaard et al. 2015), planting seedlings at a higher density than currently practiced may have limited silvicultural value. When trees are planted at too high densities, some form of self-thinning often occurs and some of the trees die as they are not able to successfully compete against their neighbours for access to light, water and nutrients. The economic consequences of self-thinning are clear; planting at too high density means that money is wasted. The silvicultural consequences are less clear, but high rates of seedling mortality may increase the risk of pest attacks or disease.

6.4 Intensified harvesting

There are two ways of increasing the biomass outtake during harvest: harvest more often or remove more plant material at harvest. More frequent harvesting could involve more aggressive thinning (removal of trees at various points in the rotation prior to final harvesting) or earlier final harvesting. More aggressive thinning could lead to the remaining trees having a higher economic value but is not compatible with maximizing carbon accumulation (Lars Högbom, pers. comm.). While not currently recommended, earlier harvesting may become more relevant in the future if climate change increases the likelihood of early tree death due to more frequent pest outbreaks, blowdown associated with higher winds or wetter soils, or greater frequency of forest fire.

6.4.1 General effects of clearcutting

Clearcutting leads to significant and predictable disruptions in stand-level element cycles (Kreutzweiser et al. 2008). Felling and removal of trees leads to wetter soils and greater runoff as rates of both interception and transpiration decrease. These effects can typically be observed for between 5 and 25 years, depending on how long it takes for a forest to re-establish on the site. Wetter soils are generally associated with higher dissolved organic carbon (DOC) loss and may provide hotspots for mercury methylation. Furthermore, wetter soils may make it more difficult for seedlings to grow, so some form of ditching or drainage is often practiced.

Removal of plant material following clearcutting diminishes the size of element pools in the stand. Removal of base cations sequestered in plant tissue can have negative consequences for soil and surface water acidification. Furthermore, removal of nitrogen associated with plant material has been linked to reduced growth rates in the next forest rotation.

Clearcutting can have a significant effect on soil carbon storage. Increased rates of soil C mineralization and CO_2 production are typically observed following clearcutting. While there are significant uncertainties associated with estimating changes in forest soil C storage, it is likely that only a small fraction of the total soil C pool is mineralized (Nave et al. 2010). A common finding is a decline in forest floor C storage, but that this decline is not observed in the mineral soil (Nave et al. 2010).

The link between clearcutting and N leaching is well established (Haveraaen 1981, Kreutzweiser et al. 2008, Futter et al. 2010, de Wit et al. 2014, Schelker et al. 2016). Clearcutting reduces the stand level demand for N and can promote increasing mineralization of organic N stored in forest soils and decomposing residues. This decrease in demand and increase in supply is typically manifested in increased soil solution and surface water nitrate concentrations which can be observed for as much as ten years following clearcutting (Futter et al. 2010). The magnitude and duration of N leaching is generally higher in more productive stands. Thus, it can be expected that fertilization will lead to higher rates of N leaching following clearcut.

6.4.2 Stem-only harvest

Currently, stem-only harvesting (SOH) is the most common final harvest method used in Norway today (SSB 2018). During SOH, only the stem (or trunk) is removed during harvest, while branches, needles and stumps are left on site. Occasionally, bark is removed from the stems before they are transported off site. During whole-tree harvesting (WTH), the stem and logging residues (branches and needles) are removed and the stumps are left on site. It is not practical to remove all the logging residues but harvest rates of >50% can be achieved. Somewhat confusingly, complete tree harvesting involves the removal of stems, needles, branches and stumps. Whole-tree harvesting is widely practiced in Sweden and Finland, but to date has seen very limited use in Norway (Rytter et al 2016). Complete tree harvesting (WTH and stumps) is practiced on a commercial scale in Finland and for research purposes in Sweden. As stump removal is not compatible with the PEFC standard, complete tree harvesting is not likely to be practiced in Norway.

The mass of a conifer tree is divided between approximately 55-60% in the stem, 5% in bark, 20% in stump and roots and the remaining 15-20% in needles and branches. In practice, it is difficult to remove more than about 30-60% of the needles and branches. Thus, whole-tree harvesting offers the possibility to go from 60-65% removal of the forest biomass (stems + bark) using SOH to about 65-75% (stems + bark + 30-60% of needles and branches) using WTH. Thus, there is the potential for significantly greater biomass outtake with WTH than can be achieved with fertilization and conventional SOH. Clearly, the greatest permissible and practical biomass outtake would be achieved with a combination of fertilization and WTH.

6.4.3 Whole-tree harvest

Whole-tree harvesting can have a number of direct and indirect environmental consequences over the short and long term (Thiffault et al 2011; Achat et al 2015). Logging residues play an important role in site protection during harvest. It is standard practice to use the branches and needles to fill in or otherwise protect areas of soft ground which might be damaged by heavy harvesting equipment. Such protection of sensitive areas is extremely important as driving damage during forest harvest has been associated with increased rates of mercury methylation (Eklöf et al 2018) as well as erosion of sediment which has the potential to damage or destroy salmon spawning beds. Furthermore, the need for site protection may increase in the future as a warmer climate will make it increasingly difficult to conduct harvest when soils are frozen and less prone to damage by heavy machinery.

As needles have much higher N and base cation content than stemwood, the energy derived from them is more environmentally costly. Modelling studies in Sweden and elsewhere have suggested that the increased base cation removal associated with whole-tree harvesting may promote surface water reacidification. While this has not been demonstrated empirically, it should still be a concern in acid sensitive regions of Norway as well. In Sweden, spreading of ash from combusted wood products has been proposed as a solution to the base cation deficit caused by whole-tree harvesting but there is little empirical evidence of its effectiveness on mineral soils without additional N fertilization. Ash return to forests is permitted under the Norwegian PEFC standard, but not by the Regulation on fertilizers etc. of organic origin[3].

From a perspective of long-term sustainability, WTH has been linked with lower rates of stand regeneration and forest growth following thinning (Helmisaari et al. 2011) and final felling. The reasons for lower growth rates on sites subject to WTH appear to be due to removal of N in needles, which can of course be compensated by fertilization (Helmisaari et al. 2011). The high N content of needles also poses problems for combustion and use in bioenergy generation as there is a potential tradeoff between renewable energy and air pollution associated with increased N emissions to the atmosphere. The use of needles for bioenergy generation is further complicated by the low state of development of the municipal heating sector in Norway.

There are a limited number of studies of the consequences of whole-tree harvesting on water quality in Norway. Clarke et al. (2018b) reported on trends in soil solution chemistry at two sites following SOH and WTH (forest residue harvesting). At one site (Gaupen in eastern Norway), soil solution N concentrations post-harvest were much lower in plots where residues had been removed immediately than in those undergoing SOH. However, at the other site (Vindberg in western Norway with steeper topography) soil solution N concentrations were similar for both SOH and WTH. This result, which may have been due to differences in hydrological pathways, suggests that more monitoring is needed over a longer time period and at more sites to identify the factors that likely lead to elevated N leaching following WTH.

[3] https://lovdata.no/dokument/SF/forskrift/2003-07-04-951, in Norwegian

7 Example application of DWARF at two Norwegian sites

7.1 Brief description of the sites

Birkenes

Birkenes is a 0.41 km^2 coniferous-forested catchment located about 20 km from the south coast of Norway. The site is characterized by thin podsols and brown earth soils developed on patchy moraine of granitic mineralogy overlying biotite granite (Wright et al. 2007). The forest is +100 years. The climate at Birkenes is maritime, with annual precipitation about 1400 mm and runoff about 1200 mm. Winters are often characterised by frequent snowmelt periods. Deposition of seasalts at Birkenes is relatively high due to the proximity to the coast. Present N deposition levels are around 12-14 kg/ha per year.

Glitrevann

The lake area of Glitrevann is around 4 km^2 with a catchment area of 26 km^2. Glitre waterworks supplies drinking water to 140,000 inhabitants in five municipalities in the Drammen region of Norway. Today the area receives 8 kg/ha atmospheric nitrogen deposition per year and the lake is not classified as eutrophic. The Glitrevann catchment is protected due to its value as a drinking water source (Berge et al. 2004) and the main land use is forestry, owned by Statskog (the Norwegian state-owned land and forest enterprise). Statskog aims to increase forest productivity in the catchment, in accordance with the Norwegian strategy to intensify forestry as a climate mitigation measure. To achieve this intensification, a 200-ha area upstream of the drinking water reservoir was fertilized in June 2017 with a one-off application of 150 kg/ha of mineral nitrogen (N) fertilizer.

7.2 Rationale for status classification

The results in this section are qualitative judgements based on the underlying literature found in the Nordic countries on forestry effects on water quality. The results presented do not rely on data or modelling exercises from Birkenes or Glitrevann. The pie charts (Figure 8) presented are based on a combination of the available literature in the Nordic countries and expert judgement by the authors. The scientific basis of the potential effects is presented in chapter 2.3.4. We present the likely direction of change where a potential positive effect is shown in green, potential negative effects in yellow and potential strongly negative effects in red (Figure 6). Cells that are blank indicate where the knowledge gaps are too large for the authors to make an expert judgement.

As Birkenes is a long-term monitoring site, there are much longer time series available, many parameters have been monitored since early 1980s while Glitrevann has a subset of parameters linked to monitoring prior to the forest fertilization in 2017 in streams draining to the lake. The data presented for Glitrevann is from the inlet stream Sandungenbekken, which is the area subjected forests fertilization in 2017. Average concentrations of monitoring parameters are presented in Table 3. For both Birkenes and Glitrevann, we consider the consequences of SOH with and without fertilization, as well as WTH preceded by fertilization. In the following sections, we use the monitoring data available for both sites to support our assessments summarized in Figure 8.

Table 3. Average concentrations of monitored data at Birkenes (2000-2017) and Glitrevann (2016-2018). Data from Glitrevann is taken from the inlet stream Sandungenbekken.

Parameter	Units	Birkenes (2000-2017)	Glitrevann (2016-2018)
Nitrate nitrogen	µeq/l	8.5	4.0
Dissolved organic carbon	mg/l	6.4	5.1
Base cations (Ca+Mg+K)	µeq/l	51.1	n/a
Total phosphorus	µg/l	4.2	3.9
Mercury		n/a	n/a
Sediment		n/a	n/a
Greenhouse gases		n/a	n/a
C-sequestration		n/a	n/a

7.2.1 Nitrogen

The concentrations of nitrate in Birkenes are twice as high as in Glitrevann (Table 3). Birkenes has received much higher deposition of N during a long period of time and is more susceptible to leaching of N. With its shallow soils and lack of lakes the system has less ability to process excess N associated with forest harvest. Using SOH, in a 1 and 10-year perspective, there will a potentially larger increase in surface water N in Birkenes compared to Glitrevann (Figure 8 a-b). In both Birkenes and Glitrevann there is likely to be a greater leaching of N from soils following harvest post fertilization then would be expected compared to the unfertilized SOH scenario. We would expect the potential surface water effect to last between 1 to 10 years (Figure 8 c-d). The WTH scenario with N fertilization would not have as severe effect as fertilizing SOH scenario as the labile N in needles and branches are removed from the system and would not leach to surface waters (Figure 8 e-f).

7.2.2 Dissolved organic carbon

The concentrations of DOC in Birkenes and Glitrevann are similar (Table 3). In all cases, there is likely to be an increase in DOC due to wetter soils and higher water table which would occur following harvest and last until canopy closure, i.e. 10-40 years (Figure 8 a-f).

7.2.3 Base cations

For Glitrevann, there is no available data for base cations, but based on the pH (6.5) and alkalinity (0.1 mmol/l), the system does not appear to be acidified. Birkenes is slowly recovering from acidification, with current pH values around 4.8-5.0 on annual basis. The differences acidification legacy at Glitrevann and Birkenes will probably have a strong influence on the base cation response to harvesting. The SOH scenarios are likely to behave relatively similar, while the main difference becomes evident with the WTH scenario as the needles and branches contain a considerable amount of buffering base cations and there is likely to be a more significant acidification effect in the poorly buffered Birkenes compared to Glitrevann.

7.2.4 Phosphorus

The behaviour of phosphorus in catchments is complicated and therefore it's hard to predict the potential effects of a clear cut with different forest management strategies. The concentrations of phosphorus in Glitrevann are low and the stream appears to be highly oligotrophic (fig. 8 a-f).

7.2.5 Mercury

Due to lack of mercury data for both Birkenes and Glitrevann it is difficult to draw firm conclusions. Many studies have shown that forest harvest (either SOH or WTH) leads to long-term increases in surface water mercury concentrations. However, there is insufficient evidence to distinguish the different forest harvest management types.

7.2.6 Sediment

Due to lack of sediment data for both Birkenes and Glitrevann it is difficult to draw firm conclusions. Some studies have shown that forest harvest (either SOH or WTH) leads to increases in sediment influx to surface waters. These studies have identified the potential effects to last 1-10 years. The effects of N fertilisation are not significant while harvest type is. Removing needles and branches removes material that could otherwise be used to protect wet areas and limit soil damage associated with machine operation (Figure 8 a-f).

7.2.7 Greenhouse gases (GHG)

There is no monitored data on GHG fluxes at Birkenes or Glitrevann. In a short-time perspective <1 year, the mineralization of soil C will have a negative GHG effect (i.e. increased emissions). However, over the longer term (10-100 years) growing forests have a positive GHG effect as they sequester atmospheric carbon. No difference is indicated between the scenarios (Figure 8 a-f).

7.2.8 Carbon sequestration

In principle forest inventory data could be used to calculate the potential carbon sequestration at Birkenes and Glitrevann, but this was outside the scope of this task. In the SOH scenario, removal of biomass will have negative effect (1-10 years) on carbon sequestration (Figure 8 a-b). There is not enough knowledge to balance this effect of forest fertilization against the potential changes of soil respiration (Figure 8 c-f). All scenarios are likely to have a positive effect on carbon sequestration over a 100-year time frame (Figure 8 a-f).

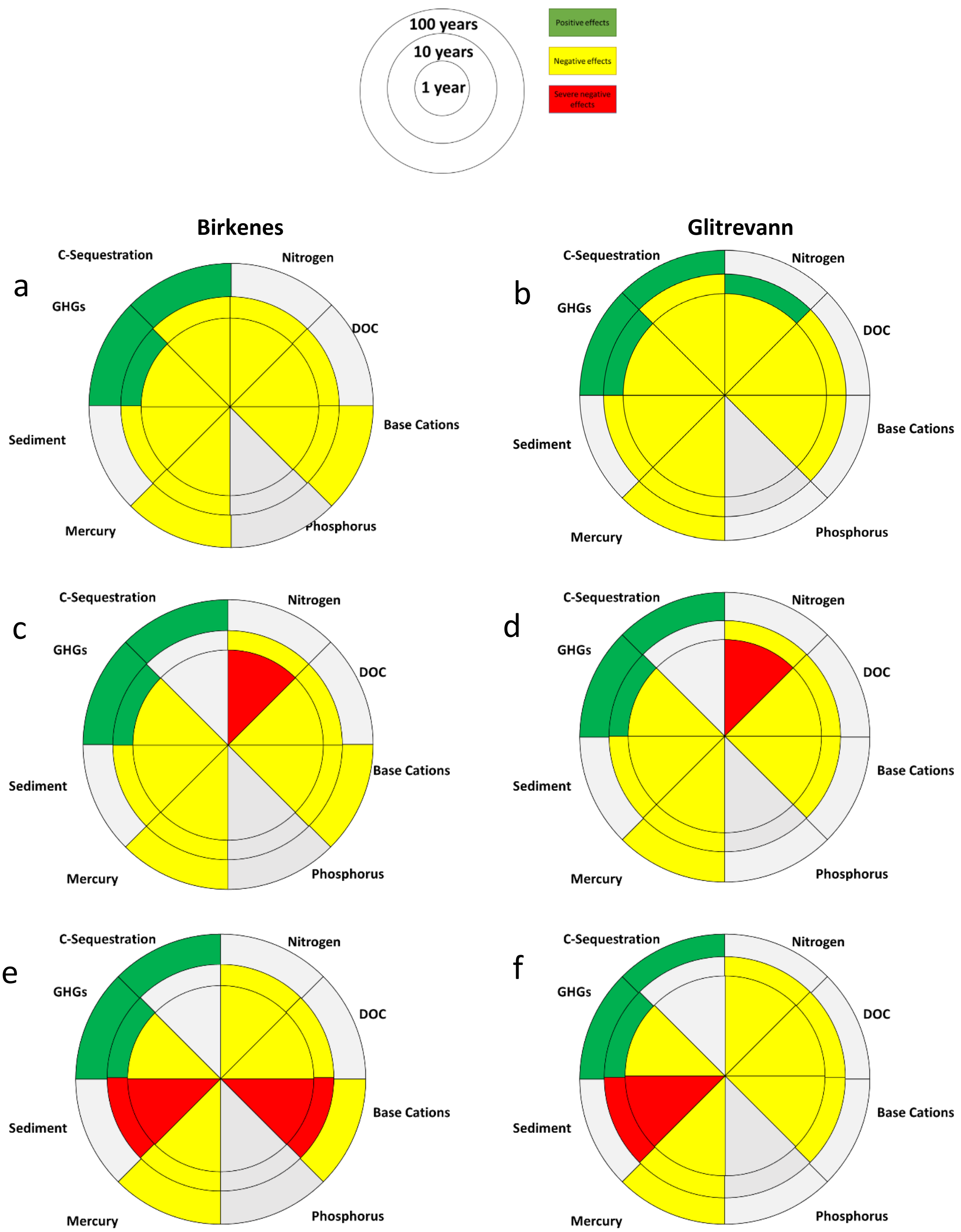

Figure 8. Example application of the DWARF framework on Birkenes (left) and Glitrevann (right). Panels a and b (upper) represent potential effects of stem-only harvest, no fertilization. Panels c and d (middle) represent fertilization and stem-only harvest, while panels e and f (bottom) represent fertilization followed by whole-tree harvest.

8 Conclusions

The DWARF framework is a useful tool to visualize the trade-offs between transitioning to a low carbon society and water quality. Hence, the tool presented in this report can be used by relevant groups to evaluate the potential positive and negative effects of intensified forestry as a climate mitigation measure in Norway.

Nitrogen fertilization for increased forest growth is likely to lead to increased N leaching and potentially re-acidification associated with greater uptake of base cations by standing forests. Whole-tree harvesting is likely to deplete soil base cation pools and may delay recovery from acidification or cause reacidification of sensitive sites. Furthermore, whole-tree harvest removes plant residues that could be used to protect sensitive soils during logging operations (driving with heavy machinery) and may remove plant nutrients that are needed for the next forest rotation.

Fertilization may thus have fewer undesirable environmental consequences than whole-tree harvesting. The unwanted effects of fertilization can potentially be minimized by careful site selection, and by applying lower doses of fertilizer more often. Unlike whole-tree harvesting, there is no evidence that fertilization reduces regrowth of stands established after final felling.

Afforestation may have minor to severe consequences for surface water acidification, depending on site-specific factors and the exposition to air pollution and sea-salts. It may also reduce runoff due to increased root uptake and higher evapotranspiration. Afforestation will increase average deposition rates slightly due more effective atmospheric scavenging of dry deposition. The potential effects of coastal afforestation on sea-salt related acidification events must be evaluated in each case as this could lead to re-acidification and damage on aquatic biota.

There is too little information on the water quality consequences of increased seedling density when replanting to make reliable projections for Norwegian conditions.

The Norwegian commitment to more intensive forest management as part of a transition to a low carbon economy is likely to have detectable effects on surface water quality in sensitive areas. However, based on literature available from Norway and other Nordic countries with similar conditions there are still knowledge gaps regarding the trade-off between increased biomass yield and consequences for surface water quality. Examples of such knowledge gaps are post-harvest effects of fertilized stands on nitrogen leaching, forest harvest effects on mercury speciation and leaching, and the role of buffer zones to mitigate negative impacts. Lack of country- or site-specific data might to some extent be compensated by spatial data from neighboring countries, international studies in similar ecosystems and similar climate zones, and by use of dynamic and process-based catchment models.

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