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Consequences of More Intensive Forestry for the Sustainable Management of Forest Soils and Waters

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Abstract: Additions of nutrients, faster growing tree varieties, more intense harvest practices, and a changing climate all have the potential to increase forest production in Sweden, thereby mitigating climate change through carbon sequestration and fossil fuel substitution. However, the effects of management strategies for increased biomass production on soil resources and water quality at landscape scales are inadequately understood. Key knowledge gaps also remain regarding the sustainability of shorter rotation periods and more intensive biomass harvests. This includes effects of fertilization on the long-term weathering and supply of base cations and the consequences of changing mineral availability for future forest production. Furthermore, because soils and surface waters are closely connected, management efforts in the terrestrial landscape will potentially have consequences for water quality and the ecology of streams, rivers, and lakes. Here, we review and discuss some of the most pertinent questions related to how

increased forest biomass production in Sweden could affect soils and surface waters, and how contemporary forestry goals can be met while minimizing the loss of other ecosystem services. We suggest that the development of management plans to promote the sustainable use of soil resources and water quality, while maximizing biomass production, will require a holistic ecosystem approach that is placed within a broader landscape perspective.

Keywords: soils; streams and rivers; sustainability; forestry; biomass production; nitrogen fertilization

1. Introduction

Developing management strategies for the sustainable use of soil and water resources is recognized as a major environmental challenge for future generations [1,2]. Both soil and water resources are likely to become increasingly exploited and threatened by a growing human population, changes in biogeochemical cycles, and major land-use transitions at global scales [3]. Even in sparsely populated boreal regions, soils and waters are being affected by long-range transport and atmospheric deposition of pollutants, climate change, and land use activities, including forest management [4,5]. In order to manage forests in a sustainable way, decision making must be based on a sound understanding of the relationships between environmental change and ecosystem function. To develop this understanding, we need to improve our basic knowledge of the underlying mechanisms behind forest ecosystem dynamics and land-water interactions across the range of spatial and temporal scales relevant to land management.

Greater pressure is being placed on forests as the demand for wood products increases, and forest biomass becomes increasingly popular as an alternative to fossil fuels [6,7]. For example, the use of forest products in district heating in Sweden has dramatically increased from 1 PJ (~0.15 million m³ tree biomass) in 1980 to 92 PJ (~13.8 million m³ tree biomass) in 2008 [8]. In an effort to meet the rising demand for forest products, it has been suggested that forestry should be intensified by increasing the use of fertilizers and by using genetically improved seedling stocks to increase biomass production, and thereby decrease rotation periods. Whole-tree harvesting and full-tree harvesting (defined respectively as the removal of all above-stump tree biomass and the removal of all tree biomass including the stump) are two other forestry techniques that could potentially be used to meet the increased demands for forest biomass [9].

Intensified harvesting, in combination with other forest management practices, could have large ecological consequences for both terrestrial and aquatic ecosystems, including effects on the storage and availability of carbon (C), nitrogen (N), calcium (Ca), potassium (K) and other nutrients [10–12]. Because forestry operations typically affect the biological, physical and chemical properties of soils [9,13], it has been suggested that preserving forests in reserves is the best way to protect several ecosystem services, including the sequestration of soil C [14]. However, Berg *et al.* [15] used 41 years of soil survey data across all forested areas of Sweden and showed an average accumulation in the humus layer of 250 kgC ha⁻¹ yr⁻¹. The corresponding accumulation in predominately managed forests in the northern part of the country estimated by Berg *et al.* [15] was actually higher than that estimated

to accumulate in soils of the same region of undisturbed, old-growth forests during periods with no human or fire disturbance [16]. Thus, for Swedish forest soils, forestry may lead to an increased C accumulation, presumably by maintaining a lower average stand age, which is associated with greater rates of growth and detrital inputs to soil, when compared to old-growth forests. While conventional forest management may lead to increased carbon sequestration above and below ground, it is critical to understand how more intensive forestry approaches may influence the entire suite of ecosystem services that these landscapes provide.

The potential combined effect of new forest management approaches and climate change on the long-term sustainability of soil and water resources on soil and water resources also needs consideration. Of particular interest is whether and how the environmental impact of intensified biomass production and harvest will be affected by predicted climate changes that may alter both temperature and precipitation in Sweden. Soils and surface waters are closely linked by groundwater and runoff that transport dissolved nutrients and other solutes from terrestrial to aquatic ecosystems. As a consequence, climate-induced changes in plant productivity, soil biogeochemistry, and catchment hydrology will likely also affect the water quality and ecology of streams and lakes [17]. The potential downstream consequences of the combined effects of intensified biomass production and climate change will ultimately depend on how individual landscape elements or small catchments are affected, the distribution and arrangement of these affected subsystems, and how biogeochemical changes are propagated in time and space among hydrologically linked areas.

One critical management goal is to develop and implement strategies that increase tree biomass yield while maintaining the long-term sustainability of forested landscapes, which is defined here as the ability of the soil ecosystem to support desired rates of biomass production over several rotation periods without significantly affecting water chemistry and/or aquatic biodiversity. To better assess and predict the impacts of more intensive forestry in a changing climate on soils and streams, a more holistic ecosystem approach needs to be taken that includes perspectives from silviculture, ecology, hydrology, and biogeochemistry. Here we review and discuss some of the most pertinent questions, from a Swedish perspective, relevant to the future of both forest soils and waters. Additionally, we suggest approaches that can be used to provide much needed answers to questions about the long-term management of soil and surface water resources in the Swedish forested landscape. Our long-term objective is to move towards an enhanced mechanistic understanding that will lead the way to improved predictive models of ecosystem functioning under changing land use and climate scenarios. The more immediate goal is to provide knowledge that can direct future research efforts and help improve the decision support for forestry and land management communities in order to minimize environmental impacts on soils and waters associated with future biomass production.

2. Impacts of Nutrient Additions

Critical to the development of plans that promote the sustainable use of forest soil and water resources is an understanding of the controls over nutrient availability and retention within terrestrial ecosystems. One nutrient of particular importance is nitrogen (N), which is necessary for plant growth, and in many forests of boreal and temperate regions is the primary limiting factor for net primary production [18,19]. Because most N in soils is bound in relatively recalcitrant soil organic matter not

easily accessed by the trees [20], the decomposition of large macromolecules to peptides, amino acids and inorganic N-forms, and the relationships between trees and their symbiotic mycorrhizal fungi are particularly important to the supply of N to primary producers [21,22]. Given the role of N as the primary limiting nutrient in boreal forests, one plan for intensified forestry in the future involves more frequent application of N-based fertilizers to specified production areas [23]. This includes frequent nutrient additions with a mineral balance based on the nutritional requirements of the forest stand [24]. This type of fertilization approach in Norway spruce stands of Sweden can increase stem wood production by more than 200% [25]. It remains unclear, however, whether achieving this increase in production is possible at broad spatial scales, and how such a management approach would affect other ecosystem services that these landscapes provide.

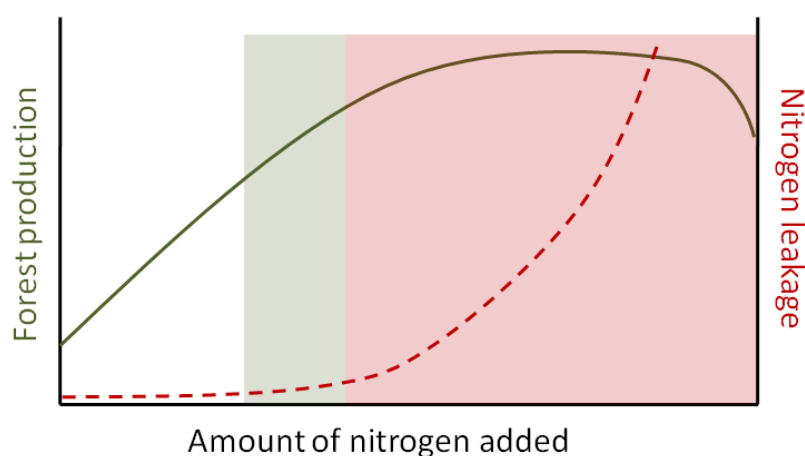
Over the past century, the N economy of forests in many parts of the globe has changed dramatically following increases in atmospheric N deposition linked to the combustion of fossil fuels and intensive agriculture [26]. These increases in N inputs have had major consequences for the ecological and biogeochemical dynamics of forest ecosystems. In general, for N-limited forests, small to moderate N additions (e.g., between 3 and 20 kgN ha⁻¹ yr⁻¹) stimulate photosynthesis per unit foliage and increase the biomass of leaves and needles, as well as elevate above-ground biomass production relative to that below-ground [27]. Thus, moderate levels of N addition can positively stimulate tree growth, which could represent an important ecosystem C sink. Moreover, N addition may further increase ecosystem C sequestration as these inputs in some cases can have a retarding effect on the decomposition of soil organic matter [28,29].

Data from Swedish forests typically show that N fertilization can increase C sequestration [4]. This relationship is non-linear, however, and at higher levels of fertilizer addition, forest ecosystems become saturated as the availability of mineral N exceeds the demand of plants and microbes [30,31]. Under these circumstances, forests lose retentive capacity and begin to leach N from soils to groundwater and streams (Figure 1), mainly in the form of nitrate (NO₃⁻) as this is the most mobile form [32-34]. From a forest owner perspective, added N that is not captured by trees or retained in soil, and which is instead lost from the system, is a costly and unwanted effect of fertilization. Thus, finding a management formula for forest fertilization that will optimize biomass production, while minimizing N leaching, represents a major research priority and will be essential for plans to increase biomass yield and carbon sequestration without seriously affecting water quality (Figure 1).

Because NO₃⁻ can act as a pollutant in surface waters [35], an increase in stream N would be an undesirable consequence of more intensive forest fertilization. The potential loading of N to streams following forest fertilization will likely depend on how fertilizer is added (*i.e.*, the timing and application rate), tree nutrient demand (phase of the growth cycle or rotation period), and soil processes that act to retain N in the terrestrial ecosystem [23]. Most terrestrial ecosystems have a large capacity to retain N, but the threshold at which forests begin to lose N, and the mechanisms by which N can be retained within landscapes are not fully understood. If fertilizers are added at low to moderate rates, at times of high plant demand, it is possible that long-term fertilization would have few consequences for nutrient loading in Swedish streams and downstream in the Baltic Sea. Forestry operations, specifically final felling, is presently a minor contributor to NO₃⁻ pollution in Swedish surface waters [36,37]. However, escalating the use of fertilizers may cause greater N pollution if this practice is not based on a solid, fundamental understanding of the factors that regulate nutrient

retention in forest ecosystems. On the other hand, increased N retention in young, managed and productive stands may help reduce N leakage, compared to old-growth forests at “steady state” [38].

Figure 1. A conceptual model to describe how additions of N increase tree biomass production (black line) and nitrogen leakage (red line). Increased rates of fertilization result in greater biomass production until tree growth levels off as other factors become limiting. Up to a point, this added N is retained within forest ecosystems, but eventually these systems become saturated, as the availability of mineral N exceeds the demand of plants and microbes, and begin to leak N from soils to groundwater and streams. Nitrogen fertilization schemes should aim for the grey, shaded area, where a high forest production is combined with low leakage of N.



Nitrate leakage with increased fertilization intensity could contribute to the eutrophication and reduction of species diversity in surface waters [39]. Once in the stream, the fate of NO_3^- depends upon the strength and nature of nutrient limitation, the types and rates of biological processes that occur locally (e.g., assimilation vs. denitrification), and the balance between biological demand and hydrologic transport. There is evidence that in-stream processing can reduce the downstream losses of N from some landscapes [40], but understanding the role of streams and rivers in this regard remains an active area of research. Nutrient enrichment in streams is often associated with a suite of other land use changes (e.g., transitions to agriculture) that also alter habitat structure and the light regime, which together influence local communities and ecosystem processes. The effects of nitrogen enrichment in streams draining intact forests, however, are less clear. Evidence from a multi-year enrichment experiment (of N and P) in a temperate forest stream suggests that nutrient loading can increase invertebrate secondary production [41], alter detritus processing and the overall stream carbon balance [42], and result in unexpected, long-term changes in macroinvertebrate community composition [43]. It is not clear how similar enrichment would influence small, humic-rich boreal streams. There is, however, some evidence for N limitation of dissolved organic carbon (DOC) processing by microbes in streams and lakes in northern Sweden [44], but the broader potential consequences of enrichment at community and ecosystem levels are largely unknown. Of particular interest is whether and how changing inorganic nutrient dynamics in forests will alter the delivery, form and processing of organic nutrients in adjacent and downstream aquatic ecosystems.

Elevated levels of NO_3^- in streams and lakes also pose additional environmental concerns. For example, such increases in concentration are known to promote denitrification and associated production of N_2O , a known greenhouse gas [45]. This risk is expected to be lower in forest, than agricultural and urban streams, which commonly are more enriched with anthropogenic NO_3^- [40]; however, these microbial processes remain to be evaluated in boreal forest streams subject to elevated N loading. Additionally, NO_3^- leaching may cause soil acidification. As NO_3^- ions percolate through the soil into the stream water, accompanying base cations (*i.e.*, Ca^{2+} , Mg^{2+} and K^+) or other cations from forest soils move out of the soil into stream water as well. As more base cations are leached, the capacity of forest soils to buffer changes in pH will be reduced. This could lead to more acidification of susceptible soils and undesirable cation movements from the soil to stream water (*i.e.*, H^+ , Al^{3+}). An increasing proportion of the acidity in surface waters in North America and Europe is related to NO_3^- export [46], which can be especially problematic in areas where large amounts of N fertilizer have been added such as intensively managed forests or agricultural land [9,47]. Thus, increased N inputs over long time-scales could actually reduce the fertility of forest soils [47]. Although not an issue in Sweden so far, base cation depletion has been a major problem in parts of central Europe, where levels of atmospheric N deposition have been up to 30–40 $\text{kgN ha}^{-1} \text{yr}^{-1}$ [48,49], which is several times higher than anywhere in Sweden.

3. Impacts of Tree Harvesting

Tree harvesting has obvious and dramatic effects on the structure and function of terrestrial ecosystems [9]. With the introduction of whole-tree and full-tree harvesting, greater attention has been devoted to understanding the effects of felling operations on forest soils, including effects on biodiversity [50], and the potential for long-term sustainability of tree production owing to increased nutrient losses [51,52]. In addition to these effects on forest and soil properties, it is also long recognized that forest harvesting can influence the ecology and biogeochemistry of adjacent headwater streams [53,54]. Indeed, the general recognition of key linkages between terrestrial landscapes and their associated streams has a long history in ecology [55,56], and a rich scientific literature exists investigating the relationships between forest management practices, water chemistry, and stream discharge, illustrating how closely linked small streams are to their surrounding forests [57,58]. From this work, it is well established that clear-felling results in altered hydrology: decreased evapotranspiration, increased groundwater tables, and therefore greater runoff [59,60].

Given the central role of the hydrologic regime in the ecology and biogeochemistry of catchments, changes to the hydrologic cycle following forest harvesting are likely to have consequences for both terrestrial and aquatic ecosystems. The effects of altered flow may include changes in the rates of biogeochemical processes in both terrestrial and aquatic habitats (*e.g.*, decomposition, nutrient cycling), and the timing and magnitude of downstream hydrologic transport of dissolved and particulate materials. For example, recent research has shown that clear-cutting can increase both the concentration and total flux of DOC in streams of boreal regions [61,62]. Such an increase is particularly important in boreal landscapes, not only because DOC represents a potentially important flux in the regional C cycle [63], but also because DOC acts as an important transport-vector for

contaminants such as mercury [64] and persistent organic pollutants [65], and because it represents a major source of energy to foodwebs in downstream lakes [66].

In addition to these effects on DOC, forest harvesting also can result in losses of nutrients and other elements from forest soils with corresponding increases in the concentration of these materials in adjacent streams [54]. There is some evidence, however, that whole-tree harvesting may actually reduce short term NO_3^- losses [67]. According to this hypothesis, removing tops, branches, and needles substantially reduces logging residues and the corresponding detrital N pool, which could potentially reduce NO_3^- leaching immediately following harvesting [68-70]. However, base cations are also lost from sites during whole-tree harvesting [70]. Given the role of base cations for controlling pH in surface waters [71], the long-term consequences of whole-tree harvesting needs further evaluation before it is used as a means to reduce short-term N losses from catchments, particularly as an intensification of forestry in the future could have substantial effects on weakly-buffered streams in Sweden [72].

Forestry activities, including clear-felling and off-road transports, also have the potential to increase toxic methyl mercury concentrations in surface waters [73,74]. Further research is needed on the link between forestry and elevated levels of methyl mercury in surface waters. It is possible that the elevated levels of methyl mercury are related to the wetter ground conditions often seen after final harvest, or to soil disturbance associated with harvest and site preparation. More recent results have also suggested a large degree of variation in the sensitivity of different catchments to harvest operations with respect to mercury response [60]. Understanding the causes of the varying sensitivity may hold the key to more effective measures to mitigate the effects of forestry operations on mercury outputs.

Forest harvesting can also influence streams and rivers through alterations of key habitat features, which may persist for variable lengths of time [53]. For example, removal of streamside vegetation can temporarily increase incident light, which may elevate stream temperatures [75], and stimulate in-stream primary production and ecosystem respiration [76]. These effects of increasing light on benthic metabolism may be exacerbated when coincident with elevated nutrient concentrations [77]. Consistent with this, studies of clear-cutting in boreal streams show increases in benthic algal and bacterial productivity that correspond to both elevated incident light, and increases in stream nutrient availability [78,79]. Tree harvesting and near-stream management can also greatly impact sediment delivery and inputs of woody debris, both of which can have long-term effects on channel structure [80], and play a key role in the ecology and biogeochemistry of forest streams [81]. This effect of forestry on channel form has received little attention in boreal regions; however, a study of streams in Finland and Russia has demonstrated that forest management can affect the structure of stream channels, including a reduction in both the abundance of coarse woody debris and fine detritus [82].

As suggested above, the effects of forestry on aquatic resources at multiple time scales could be exaggerated by expected future increases in precipitation [83]. In Scandinavia, global climate models predict there will be shorter winters and precipitation events will likely be more variable, both in intensity and frequency [84]. Consequently, the length of the snow-covered season, the timing and magnitude of spring runoff, and the number of extreme events could be altered in the future [85]. Shorter periods with frozen ground could have profound influences on the physical effects of harvesting on forest soils. For example, forest machinery operating on unfrozen, wet ground will

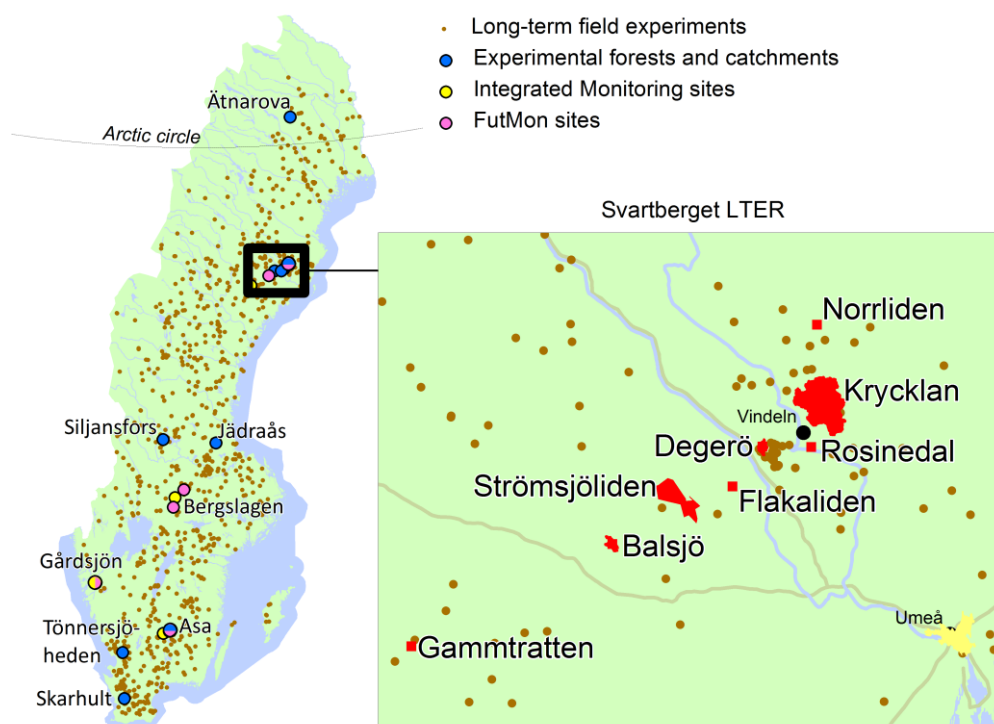
potentially have much larger and longer-lasting impacts on soil physical structure and surface water quality, when compared to these same activities on frozen ground. This could be further exaggerated when logging residues are harvested as part of a whole-tree or full-tree harvesting strategy instead of the conventional use as bedding on the skid road to avoid soil damages [86]. Overall, understanding the interactive effects of potential climate change and land management on aquatic resources represents an important research goal, and progress along these lines will require close collaboration among foresters and scientists.

4. Future Research Needs

To address the above problems and incorporate them into practical use, forest management has to be based on sound scientific understanding, and an improved dialogue between foresters and multiple scientific communities. Reaching this goal will require the integration of scientific approaches that span traditional disciplinary boundaries. This integration should include compiling available data from long-term descriptive and experimental studies, new innovative experimental manipulations, and both analytical and simulation modeling to evaluate questions across a range of scales, using multiple methods of inference. These research efforts need to be designed *a priori* to address questions relevant to forest management, and should also include interaction and feedback from stakeholders and managers according to an adaptive forest management approach. Such an approach may help to provide answers to questions required for the transition into a new era of environmental stewardship that focuses on maintaining, or even increasing, biomass production without jeopardizing soils or waters.

Historically, a main limitation to answering questions that integrate large spatial and temporal scales of forest, soils, and streams has been the availability of well organized, high-quality field data. There is, however, a unique opportunity emerging in Sweden to use recently compiled field data from hundreds of forest and soil experiments across the country, several established in the first half of the 20th century, and others more newly established within the Long-term Ecological Research (LTER) platform (Figure 2). The integration of research efforts among these sites would serve to establish an extensive network of geographically distributed experiments that also includes well-studied ecosystems within the network. One example of such an LTER platform is the Svartberget LTER site that constitutes the base for several large-scale, long-term research programs. Field research began in this area in the early 1920s and includes ecological studies on the effects of different forest management practices [27,58,87,88], climate change [89,90], and long-range transport of air pollutants on soils and water quality [65,91]. This area has also been used to develop a complete carbon budget of boreal mires and forests [92], and is home to long-term experiments on tree-soil interactions following conventional fertilization and nutrient optimization [27,93], and whole-tree harvesting [11,94-96]. As a result of these research activities, the Svartberget LTER infrastructure provides outstanding opportunities to study how different silvicultural practices influence soils and water quality in boreal forests.

Figure 2. Location of long-term forest experiments in Sweden, as well as sites for integrated monitoring (IM), experimental forests, and forest monitoring (FutMon). The insert shows the Svartberget long-term ecological research (Svartberget LTER) site that includes several unique long-term field research programs that combine process-based research with long-term environmental assessment and modeling. The Svartberget LTER includes the 6900 ha Krycklan Catchment Study which is one the most ambitious projects integrating water quality, hydrology, and aquatic ecology in running waters of the boreal region. The Balsjö Clear-Cut Catchment Experiment is a site where the effect of final felling on water quality has been studied since 2004. Strömsjöleden Production Park is a 2900 ha research facility for inter-disciplinary experimental research on the environmental and socio-economic consequences of increased biomass production on a landscape scale. Norrliden was started in 1971 and is home to one of the most comprehensive tree nutrition studies in the world, comprising more than 100 plots. Flakaliden is a large scale nutrient optimization experiment commenced in 1987. Rosinedal is an experimental forest for studying atmospheric fluxes of CO₂, H₂O and energy using three eddy-correlation towers. Degerö Stormyr is currently one of the most intensively instrumented and studied mire ecosystems for biogeochemical research, including the third longest carbon balance record in the world for a mire ecosystem.



Future forest management that includes an increased use of fertilizers will need to be based on a clear understanding of the underlying mechanisms of N cycling and retention in boreal forest ecosystems. A key aspect of this cycle involves symbiotic relationships between plants and mycorrhizal fungi, and determining the effects of N addition on this relationship remains an important research frontier. One testable hypothesis in this context is that the mycorrhizal fungi play a key role in

N retention in boreal forests and that these groups are negatively affected by increased N supply [97]. An important question is whether functional populations of these fungi can be maintained under conditions of high N supply and if not, what happens to the capacity of forest ecosystems to retain nutrients? To move from merely speculation, based on individual studies, to an understanding of the long-term consequences of N fertilization there is a need to combine controlled, experimental case-studies with larger meta-analyses that involve in-depth reviews of published data. Together, these approaches can help deliver predictive models to forest managers that describe the effects of atmospheric N deposition and forest fertilization on mycorrhizal populations, and provide insight into how altering the activity of these soil fungi will influence broad-scale biogeochemical cycles.

To better understand how both conventional and future tree harvesting strategies will influence soil and water quality, we need a better mechanistic understanding of the processes controlling the delivery of materials from terrestrial to aquatic ecosystems, and the associated ecological and biogeochemical consequences of these transfers. One important question in this context centers on the availability of base cations in the soil. While there may not be an immediate threat to the long-term productivity in Sweden [98], little is known about how intensified forestry, in combination with potentially longer growing seasons, will affect soil base cations. Results from weathering models indicate that forest growth will be negatively affected by deficiencies in the supply of base cations in the soil following both conventional and whole-tree harvesting [99]. Furthermore these models predict that forest soils will take decades or centuries to recover from such losses [100]. Conversely, large-scale experimental manipulations suggest that decreases in the concentration of exchangeable base cations in soils do not necessarily limit forest growth in Sweden [98]. Recent results also suggest that the rate of base cation recovery following the termination of N addition is much more rapid than predicted by weathering models [93]. In a recent study from the Svartberget LTER, Klaminder *et al.* [101] showed that seven different weathering models produced contrasting results with a precision far from what is needed in order to predict any forestry related effects on the base cation pool. This type of result demonstrates the need for further research on this topic, the potential pitfalls associated with the over-reliance on individual models, and the benefits of using model ensembles to produce more realistic results and estimates of uncertainty [102].

Another research priority is to understand how proposed management practices will affect aquatic ecosystems, and how strategies can be developed that may mitigate these effects. For example, how might changes in water chemistry and habitat quality resulting from forest management be propagated through aquatic foodwebs, and downstream through drainage networks that also include wetlands and lakes? In this context, what is the role of landscape heterogeneity, and what are the ranges of spatial and temporal scales at which these management effects are manifested in aquatic ecosystems? Finally, to what degree are these land-water linkages buffered by riparian vegetation and organic soils? Indeed, refining our understanding of the role of riparian zones seems particularly important [103]. There is evidence that certain aspects of water quality may be maintained by riparian processes, which can include the retention of nutrients and sediments from upslope terrestrial habitats [104]. Given the many functions of the riparian zone, leaving buffer zones at harvesting has become a standard procedure along streams and rivers in Sweden. More could be done, however, to improve the functionality of these areas by better incorporating aspects related to riparian ecology, erosion control, biogeochemical hotspots, and groundwater discharge into the management decision.

Other management approaches that are promising from a water quality perspective involve organizing landscapes into areas that are highly sensitive to both traditional and intensive forestry and those locations that are less so. By applying this ‘landscape sensitivity’ approach, greater care can be devoted to protecting certain areas from (for example) off-road transport or intensive forest harvesting practices. One example of this is that areas at the interface of mineral and organic soils are hotspots of methyl mercury production. If these locations are also in close connection to streams, rutting by forest machinery could cause not only increased methylation, but also rapid hydrological connection to adjacent surface waters. This general management approach will require more input from scientists related to how intrinsic properties of forest ecosystems (e.g., landscape position, slope, underlying geology, soil texture, *etc.*) influence this degree of sensitivity to various harvesting practices. Another way forward will include the use of planning tools designed to help managers develop strategies for maximizing forest yield in the long term, while maintaining particular water quality parameters below specific thresholds [105]. Furthermore, optimized use of fertilizers, differential management of sensitive forest stands, a better understanding of the functionality of riparian areas, and implementation of improved planning tools could lead the way towards more productive and sustainable forestry in the future.

5. Summary

Trees, soils and water are at the center for understanding how Swedish forests will be affected by intensified biomass production and climate change. While increased production of forest biomass will potentially help mitigate predicted climate changes, the negative effects on soils and/or the deterioration of water quality that may arise could influence other ecosystem services such as future forest productivity, biodiversity, and recreation. However, some of these potential negative impacts can be reduced by prudent forest management. While we are beginning to better understand how forestry affects forest soils and waters, the synergistic effects of climate change and land management are almost entirely unknown. Reliance on inadequate knowledge of the relationships among climate change, tree harvesting, and soil and water quality represents a profound risk of mismanaging two of the most abundant, but also most precious natural resources in Sweden. Future research therefore needs to provide applicable information about plant–soil and soil–water interactions that is valuable to society and forest managers and that ensures intensified forestry is performed without jeopardizing forest soils and water quality.

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