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Effect of Climate Change on Flux of N and C: Air-Land-Freshwater-Marine Links: Synthesis

Projected climate change might increase the deposition of nitrogen by about 10% to seminatural ecosystems in southern Norway. At Storgama, increased precipitation in the growing season increased the fluxes of total organic carbon (TOC) and total organic nitrogen (TON) in proportion to the water flux. In winter, soil temperatures near 0°C, common under a snowpack, induced higher runoff of inorganic nitrogen (N) and lower runoff of TOC. By contrast, soil temperatures below freezing, caused by little snow accumulation (expected in a warmer world), reduced runoff of inorganic N, TON, and TOC. Long-term monitoring data showed that reduced snowpack can cause either decreased or increased N leaching, depending on interactions with N deposition, soil temperature regime, and winter discharge. Seasonal variation in TOC was mainly climatically controlled, whereas deposition of sulfate and nitrate (NO_3) explained the long-term TOC increase. Upscaling to the river basin scale showed that the annual flux of NO_3 will remain unchanged in response to climate change projections.

INTRODUCTION

As a background for the studies presented in this issue, we used scenarios developed by Regional Climate Development Under Global Warming (REGCLIM) for future climate in Norway. These scenarios project long-term increases in temperature and changes in precipitation as well as increased frequency and severity of extreme events such as floods and storms (http://regclim.met.no). It has long been clear that these future changes in climate will interact with inputs of pollutants, land use change and associated management activities, and other driving factors to affect terrestrial ecosystems. One effect will be altered runoff chemistry, which in turn will impact aquatic ecosystems downstream. Nitrogen (N) and carbon (C) are of central interest. These two elements are complexly linked in processes in both terrestrial and aquatic ecosystems. Adverse effects of changed fluxes of N and C include acidification of soils and freshwaters, eutrophication of freshwater and marine ecosystems, and increased concentrations of dissolved organic matter (DOM) in drinking water supplies.

Acid deposition, much of which is in the form of N compounds, will still exceed the critical load for freshwaters in 7–12% of Norway in 2010 even with full implementation of the 1999 Gothenburg Protocol to the United Nations Economic Commission for Europe's Convention on Long-Range Transboundary Air Pollution (CLTRAP). A warmer climate can exacerbate acidification and eutrophication by increasing the release of N from soil organic matter to runoff, as shown by the CLIMEX project (1, 2). Climate-induced changes in fluxes of N and C will impinge upon future protocols under CLTRAP and the management of water resources, including implementation of the European Union Water Framework Directive and Norwegian commitments regarding nutrient loadings to the North Sea within the OSPAR Convention (the Convention for the Protection of the Marine Environment of the North-East Atlantic).

Norway is unusual at the European scale because it has 70% of land area covered by mountains, heathlands, and other unproductive seminatural ecosystems. Current estimates indicate that 50% of the N loading to the Norwegian coastal waters comes from these ecosystems (3), and much of this N ultimately comes from long-range transported air pollution (4). Other major contributors to N flux to rivers and the sea are municipal point and diffuse sources and diffuse runoff from agroecosystems. Productive forests in Norway have tight N cycles, and with rates of N deposition declining, there is little risk of a widespread increased loss of N from forests to waters (5). However, this may change under a future climate.

During the past 20–30 years, research and monitoring programs in Norway have produced extensive information on present-day rates of N and sulfur (S) deposition, transport, and fluxes in mountain and heathland ecosystems and long-term trends. Much of this research and monitoring has focused on the origin and fate of atmospherically-deposited N and has resulted in extensive data on the present day situation. These data have heretofore been used to predict future N fluxes from land to water, assuming no changes in climate.

Empirical data from monitoring programs point strongly to climate-induced changes in N retention and loss from seminatural ecosystems. Such changes are also expected, given that many of the key processes active in terrestrial ecosystems are temperature- and moisture-dependent, such as the release of N and C from soil organic matter by mineralization. Data from upland areas in the UK suggest a link between N in surface waters and the North Atlantic Oscillation (NAO) (6). The dramatic increase in dissolved organic carbon (DOC) concentrations and color in many Norwegian surface waters and drinking water supplies during the 1990s may be due to variations in climate (7) although the concurrent decline in S deposition appears to be a major factor (8). Climate might play a role in that mild winters and increasing precipitation in late summer and autumn will increase the water flow through the upper organic soil horizons and cause significant changes in the discharge of dissolved natural organic matter (9, 10).

In 1990 the Norwegian government conducted an assessment of climate change and its effects. The risk of future increased leaching of N and C from upland ecosystems was identified, and estimates were made as to the potential threat to freshwater and marine ecosystems. Predictions of future effects were largely based on models, as there were few available empirical and experimental data. For upland ecosystems, so important for Norway, there is a great need for well designed, well executed whole ecosystem experiments conducted at realistic spatial and temporal scales. The whole-catchment ecosystem is an appropriate scale for the results of such experiments to be used to predict future effects on surface waters (11).

The main objective of the studies described in this special issue of *Ambio* was to quantify the effects of climate change on flux and transport of N and C from terrestrial seminatural upland ecosystems to aquatic ecosystems in Norway. This was done by a three-pronged approach involving analysis of existing

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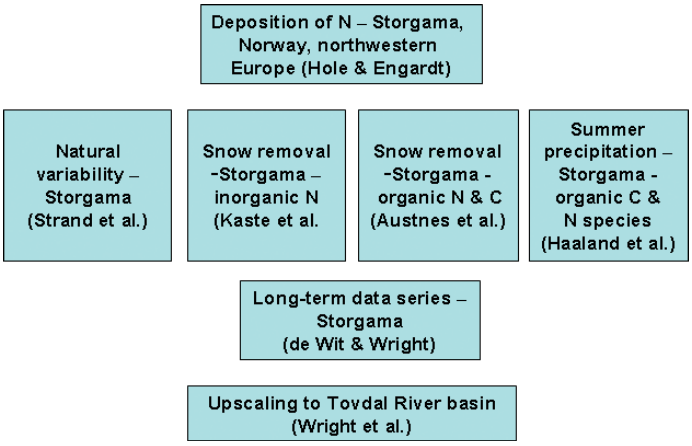

Figure 1. A schematic structure of this special issue. Authors of the articles are given in parentheses.

data from monitoring programs and previous experiments, new climate change experiments on mincatchments (30–250 m^2), and application of process-oriented models to extrapolate and scale-up the results in time and space to the river basin scale. A schematic structure of this special issue is shown in Figure 1.

THE EXPERIMENTAL SITE STORGAMA

The experimental sites were located in the Storgama area. This is a montane heatland landscape about 600 m above sea level located near Treungen, Telemark, 50 km from the southern coast of Norway. The minicatchments are located outside the large Storgama watershed and east of the Tovdal River basin used for the upscaling (Fig. 2). For the Storgama area, runoff of inorganic N was less than 5% of deposited N, whereas runoff of total organic nitrogen (TON) was nearly 20% of deposited N (Table 1). A further description of the area with an emphasis on the natural variability in soils and runoff from the minicatchments can be found in Strand et al. (12).

PRESENT AND FUTURE DEPOSITION OF NITROGEN AND SULFUR AT STORGAMA, SOUTHERN NORWAY

Dry and wet deposition of N and S compounds were measured at Storgama to estimate the relative importance of various removal processes from the atmosphere (13). Dry deposition was also estimated by a deposition module developed by Zhang et al. (14) and compared to direct measurements by Hole et al. (15). Which of the two deposition mechanisms prevails depends on a combination of a number of parameters such as atmospheric concentration of trace components, synergistic effects with other gases, surface roughness, geographical

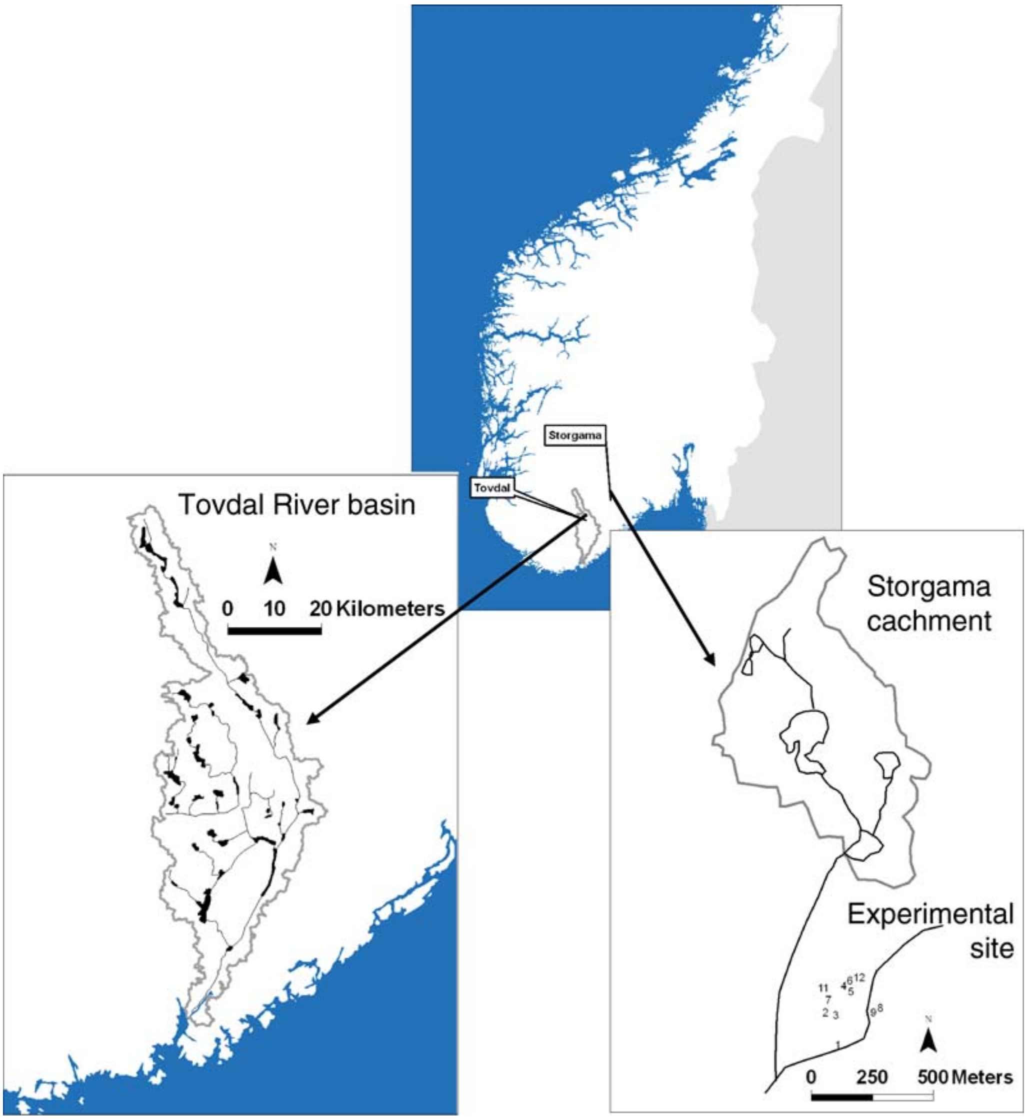

Figure 2. Maps showing the location of the Storgama area, Storgama catchments, experimental site, and the Tovdal River basin.

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Table 1. Average yearly deposition and runoff, Storgama area. The "year" is from June 2004 to May 2005. Neither TON nor TOC are measured in deposition, but fluxes of these are probably minor.

Species	Yearly deposition Storgama ($\text{g m}^{-2}\text{y}^{-1}$)	Yearly runoff Storgama catchment ($\text{g m}^{-2}\text{y}^{-1}$)	Yearly runoff minicatchment 9 ($\text{g m}^{-2}\text{y}^{-1}$)
NH_4-N	0.52	0.015	0.033
NO_3-N	0.58	0.007	0.016
TON		0.21	0.17
TOC		5.14	3.31

position, wind velocity, and distance from the sources (16, 17). At Storgama, wet deposition was the dominant process and was strongly governed by the measured rain amount. The flux maxima in early fall 2004 and in November 2005 can be ascribed to strong rain events during the sampling intervals.

The total annual mean inputs at Storgama of 1.10 g N m^{-2} y^{-1} (Table 1) and 0.63 g S m^{-2} y^{-1} are in good agreement with estimated total N deposition at 50×50 km^2 resolution for the whole country (18). For the years 1997–2001 and the region studied here, annual fluxes of 0.8–1.2 g N m^{-2} y^{-1} and 0.5–0.7 g S m^{-2} y^{-1} were reported.

The total deposition of oxidized N (NOx) over Norway is expected to increase from 96 Gg N y^{-1} to 107 Gg N y^{-1} by 2100 due solely to changes in climate, given constant N emissions in the source areas (19). A decline or rise in the N emissions will change the deposition numbers accordingly. Along the west coast, more than a 30% increase in wet deposition is expected. According to model results, dry deposition will also increase around 10% in this area, mostly because of enhanced surface affinity to NOx. For reduced N (NHy) and S compounds, the pattern is similar. More details for Norway and other countries in northwestern Europe can be found in Hole and Engardt (19).

HOW VULNERABLE IS RUNOFF FROM SEMINATURAL ECOSYSTEMS IN SOUTHERN NORWAY TO PROJECTED CLIMATE CHANGES?

Climate scenarios for the Storgama study area were based on temperature and precipitation data dynamically downscaled with the Rossby Centre Regional Climate Model (RCAO) and provided by the European Union FP6 project Prediction of Regional Scenarios and Uncertainties for Defining European Climate Change Risks and Effects (http://prudence.dmi.dk). The RCAO simulations were based on two global climate models (HadAM3 and ECHAM4/OPYC3, termed here "Hadley" and "Max Planck Institute [MPI]", respectively) run with two scenarios of greenhouse gas emissions, A2 and B2 (20). Both models use 1961–1990 as the control period and 2071–2100 as the scenario period. The downscaled data from RCAO are allocated to a 50×50 km^2 grid, of which the Storgama study area is encompassed by grid square of rotated latitude 58–rotated longitude 46.

The climate scenario data are presented as monthly mean values of precipitation and temperature for the scenario period (2071–2100) and the corresponding modeled monthly means for the control period (1961–1990) (Fig. 3). Annual means for temperature and precipitation (1961–1990) measured at Tveitsund, a meteorological station 8 km to the southwest of Storgama, are given in Strand et al. (12).

These climate scenarios are inherently uncertain. They might, however, indicate which seasons will experience the most pronounced changes in temperature and precipitation and the order of magnitude of the changes. Compared to the present winter climate (temperature and snow depth) (12), the predicted changes in winter temperatures may raise the mean winter temperatures to near zero (Fig. 1) and reduce both the thickness and duration of the snow cover. More of the winter precipitation will probably fall as rain, giving more winter runoff and less spring runoff. More precipitation in winter and autumn and less in summer (Fig. 1) may intensify this. This may lead to a colder soil because of a reduced insulating snowpack or a warmer soil due to above-zero air temperatures in winter.

Effects of Mild Winters

Based on altitude and distance to the coast, the study area represents a typical transition zone between stable and unstable winter conditions (21). Our hypothesis was that increased frequency of freezing–thawing events and higher intensity of soil freezing in winter due to decreased insulation of the snow cover will increase the leaching of N and C from soils to water. To test the hypothesis, snow was removed from two minicatchments, and two minicatchments were insulated by means of insulating mats (21, 22). The snow removal was intended to promote more frequent and intense soil freezing in winter, whereas the insulation was intended to simulate a stable and permanent snow cover and prevent soil freezing. Soil temperature measurements confirmed that the effects on soil freezing were as intended. The increased soil temperature during winter with stable snow cover and in the insulated catchments increased the mobilization of ammonium (NH_4) and nitrate (NO_3) from soils to surface waters, whereas winters with little snow or snow removal increased soil freezing and gave relatively small fluxes of NO_3 and NH_4 (21).

Snow removal gave higher total organic carbon (TOC) and total organic nitrogen (TON) concentrations; however, this effect was primarily because of a decreased water flux, whereas the impact of soil frost was small (22). The insulation caused a small decrease in concentrations and fluxes of TOC and TON (22). The results may be explained by differences in the mineralization rate. Soil temperature under permanent snow cover in the winter is usually above zero, high enough to mineralize most of DOM to inorganic N and CO_2. In winters with little snow, soil temperature can be below zero, low enough that only a small fraction of DOM is mineralized to inorganic N and CO_2 (21, 22). The results suggest that the study area is today in a delicate balance between milder winters with colder soils and milder winters with warmer soils; the result has a major effect on N leaching to surface waters (21). A summary of the directions of the effects on concentrations and fluxes of snow removal and insulation are given in Table 2.

The motivation for using large-scale field experiments to simulate an increase in temperature originated from the previous use of this type of experiments for studying long-term environmental effects of, for example, acid precipitation and N. Acid rain experiments in the Storgama area showed a quick response in water chemistry to a change in external input to the soil (23). The response of N and C runoff to the change in soil temperature induced by snow manipulations, however, was not as distinct as expected. This is perhaps because of the more indirect response to the change in temperature on processes such as mineralization and nitrification, as compared to more direct responses of changes in precipitation quality (e.g., reduced S or increased N deposition). In addition, natural variability between the experimental catchments as discussed by Strand et al. (12) is likely to cause more noise for the indirect than for the direct responses.

Effects of Increased Summer and Autumn Precipitation

The main objective of this part of the study was to quantify the effects of increased soil moisture on concentrations and fluxes

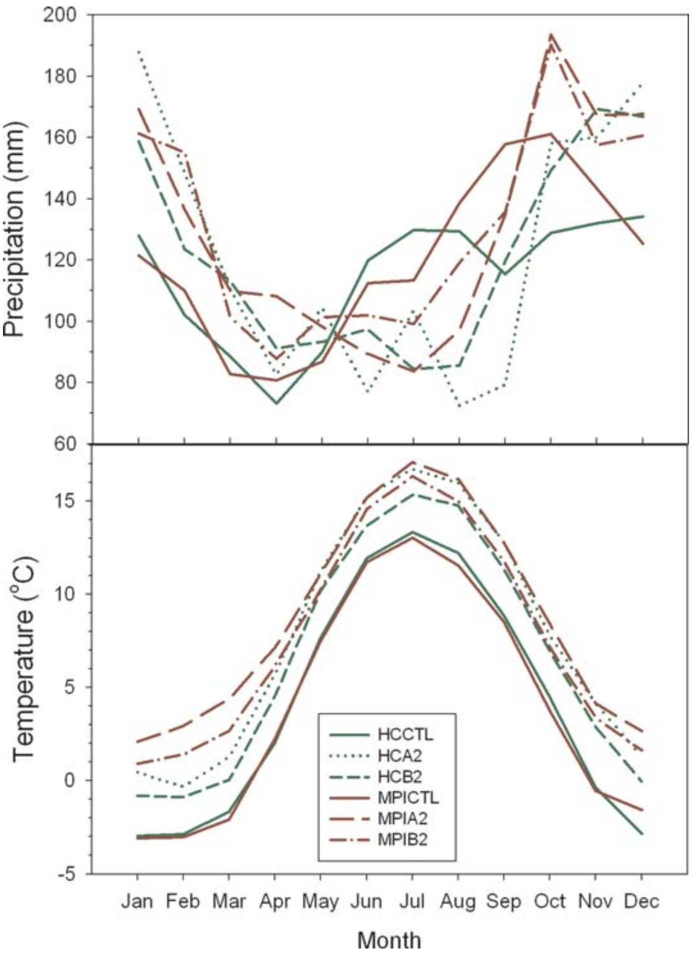

Figure 3. Monthly mean temperature and precipitation for the scenario period (2071–2100) and the corresponding monthly means for the control period (1961–1990). HCCTL = Hadley, Control scenario (1961–1990); HCA2 = Hadley, A2 scenario (2071–2100); HCB2 = Hadley, B2 scenario (2071–2100); MPICTL = Max Planck Institute, Control scenario (1961–1990); MPIA2 = Max Planck Institute, A2 scenario (2071–2100); MPIB2 = Max Planck Institute, B2 scenario (2071–2100).

Table 2. A summary of the treatment effects on concentrations and fluxes in runoff. 0 denotes no effect.

	Concentration				
	H_2O	NH_4	NO_3	TON	TOC
Snow removal		0	0	+	+
Insulation		+	+	0	−
Summer precipitation				0	0
	Flux				
Snow removal	−	−	−	−	−
Insulation	0	+	+	0	−
Summer precipitation	+			+	+

+ denotes increase; − denotes decrease.

of TOC and TON in runoff. Our hypothesis was that leaching of TOC and TON increases if soils are kept continually wet. To test the hypothesis, additional precipitation was added to two minicatchments while five untreated minicatchments served as references (24). The extra precipitation was added at a rate of 4 mm hr^{-1}, a total of 10 mm per week, by means of a sprinkler system. Additional precipitation was added in the period July to mid-October for 3 years (24).

For the watering periods as a whole, the concentrations of TOC and TON were not significantly affected by the addition of extra precipitation. Thus the fluxes of TOC and TON increased at a rate approximately proportional to the increase in water flux. This suggests that the catchment soils contain a large reservoir of mobilizable TOC and TON and that the export to streams and rivers is mainly governed by water discharge (24). With few exceptions, the mean monthly precipitation in the Storgama area was higher in the treatment years 2004 to 2006 than for the normal period 1961–1990 (12). These relatively wet conditions throughout the growing season of all three treatment years made it impossible to establish marked soil moisture differences for longer periods between the watered catchments and the references. Runoff from the reference catchments for the few short dry periods did show increased inorganic N concentrations compared to the watered catchments. This might be due to more complete mineralization of DOM to inorganic N and CO_2 in the dry periods or to changes in the water flow path in the reference catchments (12, 24). Strand et al. (12) found that soil volume and soil C content, particularly in the lower soil layers, appeared to be most important for the TOC leaching. A summary of the directions of the effects on concentrations and fluxes of increased precipitation in summer and autumn are given in Table 2.

Increased summer and autumn precipitation in the Storgama area is also expected to be accompanied by increased temperature (Fig. 3), but the experiments did not include the effect of increased soil temperature. A few heavy rainstorms followed by warm and dry periods may give a different TOC and TON runoff response than more evenly distributed precipitation. The effects of simulated heavy rainstorms as such have been studied. Preliminary results showed that desorption of potential DOM in the soils are substantial (Haaland, unpubl. data).

Climate Change Versus Land-Use Change: Can They Be Separated?

During the last century the Norwegian agricultural landscape in montane areas has been shaped by abandonment of marginal areas. The number of summer farms has declined by 90% from 1940 to 1990, and today there is nearly no harvesting of hay from marginal areas. Forest encroachment, primarily by mountain birch, has not been systematically monitored; for example, the national forest inventory only considers forest below the mountain birch tree limit. Forest encroachment is expected to continue in the future and may have important consequences for water quality in headwater catchments as the dynamics of C and N in soils are likely to change. An analysis of the effect of climate change on water quality, based on long-term data series, should consider effects of concurrent changes in land use and vegetation cover (25).

The hypothesis is that soils in the mountain birch area with a pronounced forest floor have higher concentrations and fluxes of organic C and organic N during periods of surface runoff when compared with managed grazing lands. Further reduced grazing pressure and regrowth of mountain birch should lead to more stable binding of available N (i.e., more in humus and less in inorganic forms) and thus a decreased leaching of inorganic N.

These hypotheses were approached by synoptic water sampling in three different regions in southern Norway: Venabygdsfjellet, Setesdal, and Bjerkreim (26). Total organic carbon decreased and total N increased from Venabygdsfjellet in the northeast to Bjerkreim in the southwest, also giving a decrease in the C/N ratio in DOM along the same gradient. The increase in total N was primarily due to an increase in NO_3 (26). The variations in the TOC concentrations could be explained by

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the percentage of mires and precipitation in Venabygdsfjellet, the precipitation and temperature in Setesdal, and the percentage of mires and woodland in Bjerkreim. Generally, the vegetation types with low productivity generated higher TOC concentrations as compared to the vegetation types with high productivity. Nitrate was negatively correlated with fraction of woodland, but did not correlate with the fraction of mires. Increased areas of bare rock did not give any significant change in TOC or TON concentration (26). Recently SjØeng et al. (27) showed that NO_3 runoff is strongly correlated with the fraction of bare rock in upland catchments.

The study of Martinsen (26) confirms the hypothesis that reduced grazing pressure and regrowth of mountain birch leads to more stable binding of available N and thus a decreased leaching of inorganic N. Ideally the first hypothesis could have been tested by comparing small catchments that primarily differ in land use and land cover, including long-term extensive sheep grazing and encroachment of mountain birch at different stages of development. It proved difficult, however, to find small catchments with the required characteristics. Further studies to test this hypothesis have now been established in cooperation with a Norwegian long-term sheep grazing experiment with three sheep densities. Mountain birch is established adjacent to the fenced grazing areas. The difference in altitude will be used to sort out climate change effects. Preliminary results have not given any significant differences in stream water concentrations of DOC between the grazing intensities. Concentrations of DOC from the birch forest, however, were higher compared to areas without birch.

ANALYSIS OF EXISTING LONG-TERM DATA SERIES AS A TOOL IN PREDICTING EFFECTS OF CLIMATE CHANGE

Long-term monitoring data for DOC and NO_3 concentrations indicate short-term, seasonal, and long-term trends. It was hypothesized that these signals could be explained by climatic and deposition parameters.

The four calibrated Norwegian catchments Birkenes, Storgama, Langtjern, and Kårvatn have up to 25–33 years of weekly observations of NO_3 concentrations in stream water. Three of these (Birkenes, Storgama, and Langtjern) have more than 20 years of weekly observations of TOC concentrations. The sites are part of the Norwegian monitoring program for long-range transported air pollutants, which includes measurements of the quantity and quality of precipitation and runoff (28). The catchments range in size from 0.5 km^2 to 25 km^2. Except for Kårvatn, the catchments are significantly influenced by acid deposition, and runoff was acidified when monitoring started in the mid-1970s. Birkenes is a forested catchment, Storgama is dominated by upland heathlands (described in detail by Strand et al. [12]), Langtjern is a lake whose catchment is dominated by unproductive forest on organic and thin mineral soils, and Kårvatn is a mountainous catchment in a low-deposition area in the west of Norway (29).

At Storgama and Langtjern, stream water NO_3 export declined ca. 50% over the 25-year period 1980–2005, whereas at Birkenes and Kårvatn NO_3 export increased about 20%. The most distinct trends in NO_3 were found in the winter and spring (29). Empirical models including the independent variables snow depth, discharge, temperature, and N deposition explained between 45% and 61% of the variation in weekly concentrations of NO_3 and described much of both the upward and downward seasonal trends (29). All catchments showed reductions in snow depth and increases in winter discharge. For the two sites located in areas with moderate N deposition, Storgama and Langtjern, these climatic changes seemed to drive distinct decreases in winter and spring concentrations and fluxes of NO_3. At the site with a low N deposition catchment, Kårvatn, however, an opposite effect was found with increases, especially in winter NO_3. Reduced snowpack may result in both decreased and increased catchment N leaching, depending on interactions with N deposition, soil temperature regime, and winter discharge (29).

Multiple regression models developed from the long-term data at Storgama were used to project future NO_3 levels given scenarios of climate change as given in Figure 3 and changes in acid deposition (NO_3 and SO_4) (30). The largest projected change in NO_3 discharge for the period 2071–2100 was a decrease of 86% (30). The largest uncertainty linked to these scenarios is probably the lack of understanding of the long-term fate of N retained in soil as a result of chronic elevated deposition of N (30).

In the catchments Birkenes, Storgama, and Langtjern, it was tested if the 14–26% increase in TOC (of which 90–95% is DOC) between 1985 and 2003 was related to climate, hydrology, and/or acid deposition. The tests showed that the seasonal variation in TOC was mainly climatically controlled, whereas deposition of SO_4 and NO_3 explained the long-term increase in TOC (31). A reduction in acidic deposition with a larger reduction for SO_4 than for NO_3, has apparently increased the charge density and thus the mobility of DOM. In addition, the ionic strength of soil solution has declined, thereby increasing the solubility of organic matter and thus TOC concentrations (31). Similar scenarios for TOC as for NO_3 were projected for Storgama based on the long-term data and climate change and acid deposition. The largest projected change in TOC for the period 2071–2100 was an increase of 24% (30).

UPSCALING TO THE RIVER BASIN SCALE: WHAT IS ACHIEVED AND WHAT ARE THE LIMITATIONS

An upscaling was done for the 1800-km^2 Tovdal River basin, adjacent to the Storgama area, which drains uplands very similar in character to Storgama and forests very similar in character to Birkenes. Tovdal is the major tributary to the Topdalsfjord. The mass transport model TEOTIL was used to project NO_3 fluxes from the basin. The model was developed to quantify the nutrient fluxes to the sea from land-based sources in Norway based on available regional statistical information. The same four climate scenarios as shown in Figure 3 were downscaled and used for upscaling to the Tovdal River basin (32). Results from climate experiments (2, 21) and an analysis of the time series of NO_3 (29, 31) were used to scale future temperature changes to changes in rates of N leaching (32).

Forests, upland areas, and open water surface currently account for nearly 90% of the NO_3 output flux. The largest change in N leaching will probably occur because of more water running through the terrestrial catchments during the winter due to more frequent snowmelt and more winter precipitation. More NO_3 will be delivered to the fjord in the winter and less in the spring. According to Kaste et al. (21), less snow cover may result in more soil frost and less NO_3 leaching. Further increases in temperature, however, will not only melt the snow, but will also cause soil temperature to rise above zero. Under such conditions N mineralization and NO_3 leaching may further increase. Based on the estimated future temperature, the annual flux of NO_3 from the Tovdal River to the adjoining Topdalsfjord is thus projected to remain unchanged, but with more NO_3 delivered in the winter and less in the spring. Algal blooms in the fjord can be expected to occur earlier in the year (32). The climatic scenarios investigated do not indicate a need for significant changes in environmental policy and management of land and water resources.

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There are major uncertainties linked to the projections. These include the uncertainty in the climatic scenarios and the long-term fate of N stored in soil organic matter together with the impacts on N leaching of the future management of forests as forests account for about 70% of the N flux (32).

CONCLUSIONS

It is estimated that the total deposition of N is expected to increase about 10% because of changes in climate at present emissions. Manipulation of the winter soil temperature by placing insulation mats on the ground induced higher runoff of inorganic N and lower runoff of TON and TOC. The opposite occurred when soil temperature was lowered by removing the snow. Increasing the summer and autumn precipitation by adding extra precipitation did not change the average concentrations of TOC and TON, and thus the fluxes of TOC and TON increased at a rate nearly proportional to the increase in water flux. A synoptic sampling along a deposition gradient in southern Norway showed that reduced grazing pressure and regrowth of birch leads to more stable binding of available N and, thus, in decreased leaching of inorganic N. An analysis of long-term monitoring data showed that reduced snowpack may result in both decreased and increased catchment N leaching depending on interactions with N deposition, soil temperature regime and winter discharge. Seasonal variations in TOC were mainly climatically controlled, whereas deposition of SO_4 and NO_3 explained the long-term increase. Upscaling to the river basin scale showed that the annual flux of NO_3 from the Tovdal River to the adjoining Topdalsfjord is projected to remain unchanged, but with more NO_3 delivered in the winter and less in the spring. The direction of the effects we have studied will be very much dependent on if a warmer climate will give a colder or warmer soil. The effects of the climatic changes on N and C we have seen in our studies can be ranked as small to modest, implicating that the studied ecosystems are relatively robust. Warmer soils during winter caused by climatic change, however, might be a larger threat to the environment in the studied region than an increase of soil frost events because of reduced snow cover during winter-time.

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