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Recovery of acidified mountain lakes in Norway as predicted by the MAGIC model

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ABSTRACT

As part of the EU project EMERGE the biogeochemical model MAGIC was used to reconstruct acidification history and predict future recovery for mountain lakes in two regions of Norway. Central Norway (19 lakes) receives low levels of acid deposition, most of the lakes have undergone only minor amounts of acidification, and all are predicted to recover in the future. Central Norway thus represents a reference area for more polluted regions in southern Norway and elsewhere in Europe. Southern Norway (23 lakes), on the other hand, receives higher levels of acid deposition, nearly all the studied lakes were acidified and had lost fish populations, and although some recovery has occurred during the period 1980-2000 and additional recovery is predicted for the next decades, the model simulations indicated that the majority of the lakes will not achieve water quality sufficient to support trout populations. Uncertainties in these predictions include possible future N saturation and the exacerbating effects of climate change. The mountain lakes of southern Norway are among the most sensitive in Europe. For southern Norway additional measures such as stricter controls of emissions of air pollutants will be required to obtain satisfactory water quality in the future.

Key words: mountain, Norway, lakes, MAGIC, acidification, recovery

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1. INTRODUCTION

More than 100 years of acid deposition has caused acidification of lakes in Norway and damage to fish and other aquatic organisms (Overrein *et al.* 1980). Sulphur deposition in Norway peaked in the 1970s, declined by about 60% from 1980 to 2000, and is expected to decline further to about 80% by 2010 relative to 1980. Nitrogen deposition peaked in the 1980s, has declined by 20% by 2000, and is expected to decline further to about 50% by 2010 relative to 1980 (Schöpp *et al.* 2003). The decrease in acid deposition is largely the result of international agreements to reduce the emissions of acidifying pollutants to the atmosphere, conducted under the auspices of the UN-ECE Convention on Long-Range Transboundary Air Pollution (LRTAP) (Bull *et al.* 2001; UNECE 2002).

Lakes in Norway have begun to recover in response to the declining deposition of strong acids. First indications came in the late 1980s (Skjelkvåle & Henriksen 1995) and became extensive and widespread in the 1990s (Skjelkvåle & Wright 1998; Skjelkvåle *et al.* 1998; Skjelkvåle *et al.* 2001b). Similar trends in recovery have been reported from lakes elsewhere in Fennoscandia (Skjelkvåle *et al.* 2001a), Europe (Evans *et al.* 2001; Skjelkvåle *et al.* 2003), and North America (Stoddard *et al.* 1999).

Mountain lakes are inherently more sensitive to acid deposition, and thus are typically more severely impacted than forest lakes and require greater reductions in acid deposition to achieve comparable degree of recovery. This is the case for Norwegian mountain lakes (Skjelkvåle & Wright 1998) and mountain lakes elsewhere in Europe (Mosello *et al.* 1995).

Mountain lakes have been the object of European-wide research projects over the period 1991-2003 under the auspices of the European Union (EU). These projects encompass studies of acid deposition and lake chemistry and include AL:PE I (Acidification of mountain Lakes: Paleolimnology and Ecology; 1991-93) and AL:PE II (1993-95) (Mosello *et al.* 1995), MOLAR (Measuring and modelling the dynamic response of remote mountain lake ecosystems to environmental change: A programme of Mountain Lake Research; 1996-99) (Mosello *et al.* 2002), and EMERGE (European Mountain lake Ecosystems: Regionalisation diaGnostics and socio-Economic evaluation; 2000-03) (Marchetto & Rogora 2004).

Mountain lakes in two districts of Norway (central and southern Norway) have been part of these projects. In the EMERGE project the experimental design entailed a "flagship" site in each district at which detailed long-term studies have been carried out (initiated by AL:PE), and a group of about 20 additional lakes in each of the districts at which less intensive data were collected. Here we used an acidification model (MAGIC version 7; Cosby *et al.* 1985a, b, 2001) to reconstruct acidification history and to predict future recovery of lakes in the two lake districts, central Norway and southern Norway.

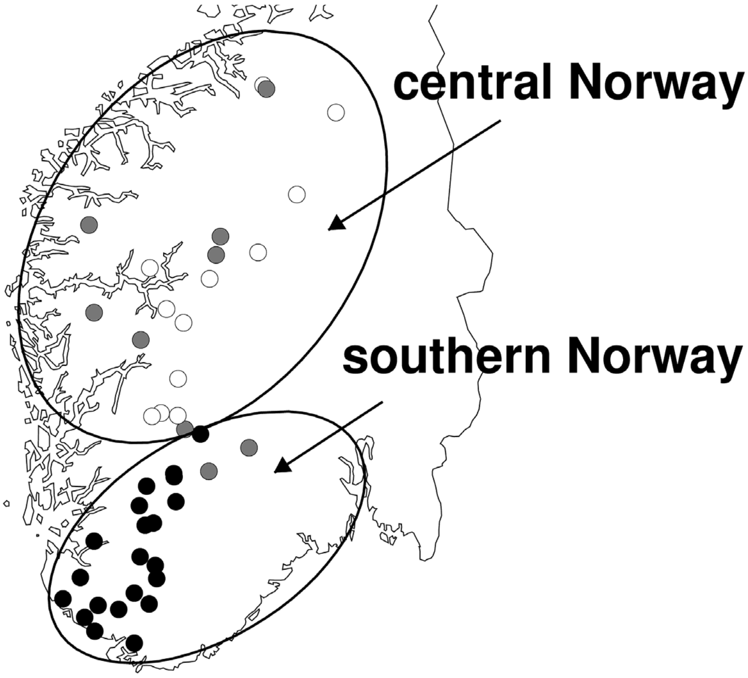

Fig. 1. Map of southern Norway showing locations of the 19 lakes in the dataset central Norway and the 23 lakes in the dataset southern Norway. Symbols indicate the present-day ANC levels in the lakes (light: >20 µeq l^{-1}; medium: 0-20 µeq l^{-1}; dark: <0 µeq l^{-1}).

2. METHODS

2.1. Site descriptions

The central Norway dataset consists of 22 lakes, of which 19 have complete data necessary for calibration of MAGIC (Appendix 1) (Fig. 1). Lake Øvre Neådalsvatn is the flagship site in this dataset, and has been intensively studied during the AL:PE, MOLAR and EMERGE project periods. The other lakes in the data set were selected subjectively largely from sites for which some data previously existed from earlier studies, and to represent a range in biological habitats. Most of the lakes are situated in areas receiving low levels of acid deposition (year 1995 median non-marine S deposition 12 meq m^{-2} y^{-1}, N deposition 15 meq m^{-2} y^{-1}), are at most only slightly acidified, and thus serve as a set of unimpacted reference lakes.

The southern Norway dataset consists of 23 lakes located in the four counties of Telemark, Aust-Agder, Vest-Agder and Rogaland (Appendix 2) (Fig. 1). The lakes are part of the Norwegian monitoring programme for long-range transported air pollutants and have been sampled annually for water chemistry since 1986 (15 lakes) or 1995 (8 lakes) (SFT 2002). They are the non-forested sites of the 60 lakes studied as part of the RECOVER project (Wright & Cosby 2003). Stavsvatn is the flagship site in this dataset. The southern Norway region receives substantial acid deposition (year 2000 median non-marine S deposition 33 meq m^{-2} y^{-1}, N deposition 44 meq m^{-2} y^{-1}); most of the lakes are acidified and have damaged fish populations.

2.2. The MAGIC model

MAGIC is a process-oriented biogeochemical model for acidification of soils and surface waters originally developed in the 1980s (Cosby *et al.* 1985a; Cosby *et al.* 1985b) and recently modified and expanded (version7; Cosby *et al.* 2001). MAGIC requires as input data information on soil, deposition and surface water chemistry as well as a time sequence of acid deposition from pre-acidification time (usually assumed to be mid-1800s) to a time in the future for which forecasts are to be made (often 2050). The deposition sequences for S and N come from estimates prepared by EMEP for southern Norway (Fig. 2) (Schöpp *et al.* 2003).

2.3. Calibration

MAGIC was calibrated in detail to the flagship sites using both the measured water chemistry data for the calibration year (or years) and also the time trends in measured data. The deposition sequences were scaled to each lake based on the assumption that sulphur output was at steady-state with sulphur input for the calibration year. For nitrogen a "best case" assumption was made in which the present-day % retention of incoming N was assumed constant over time (i.e. no N saturation). The calibration followed the procedure given by Wright & Cosby (2003). The steps are first to calibrate each of the three acid anions Cl^-, SO_4^{2-} and NO_3^- separately, then the base cations Ca^{2+}, Mg^{2+}, Na^+, and K^+ together, and finally the weak acids and base ions Al^{n+} (sum of positively-charged aluminium species), A^- (organic anions) and HCO_3^-. The values for acid neutralising capacity (ANC)

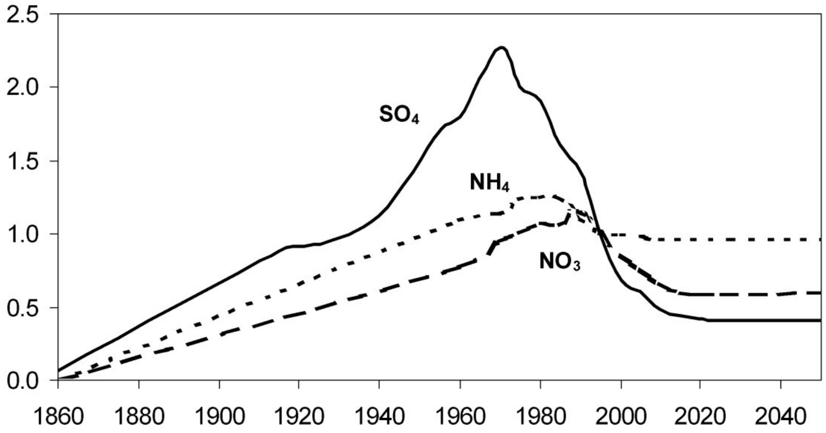

Fig. 2. Historical and future deposition of non-marine SO_4^{2-}, NO_3^- and NH_4^+ used in MAGIC applications for Norway. The curves were scaled to the calibration period (central Norway 2000; southern Norway 1995-97) (data from Schöpp *et al*. 2003).

and H^+ provide a measure of the closeness of the calibration. ANC is defined in the usual manner as the equivalent sum of base cations minus the equivalent sum of strong acid anions. Input data are given in Appendix 1 and 2. An automatic calibration routine was used to calibrate the two regional datasets.

2.4. Link between water chemistry and biological response

Surveys of lakewater chemistry and fish population status in Norwegian lakes show a clear empirical relationship between ANC and fish status. For brown trout, the most common fish species in Norwegian mountain lakes, lakes with ANC > 20 µeq l^{-1} have 95% probability of good population, lakes with ANC 0-20 µeq l^{-1} have sparse population, while lakes with ANC <0 µeq l^{-1} have 95% probability of extinct population (Lien *et al.* 1996). Similar empirical relationships exist between other fish species as well as acid-sensitive invertebrate species.

Toxicity of acid water to brown trout is primarily due to increased concentrations of Al^{n+}, with pH and concentration of Ca^{2+} secondary factors (Baker & Schofield 1980; Muniz & Leivestad 1980). Statistical analysis shows that ANC, however, explains nearly as much of the variance, because of the high correlation between ANC and pH, Al^{n+} and Ca^{2+} (Bulger *et al.* 1993; Cosby *et al.* 1994). As biogeochemical models such as MAGIC predict ANC much better than pH or Al^{n+}, we use ANC levels to interpret water chemistry changes to biological effects.

3. RESULTS

3.1. Central Norway

The calibration for Øvre Neådalsvatn showed very little change in lakewater ANC over the entire 200-year simulation (Fig. 3). The values for 1991-2000 agreed well with the observations (yearly mean values). Seventeen of the 19 lakes in the dataset had simulated ANC trends similar to that of Øvre Neådalsvatn, with only minor changes over time. The remaining two lakes showed larger changes in ANC; this was due to the somewhat higher S deposition and very thin soil cover at these sites as compared to the bulk of the dataset. For the dataset as a whole the median change in ANC due to acid deposition was only about 10 µeq l^{-1}. Less than 50% of the lakes acidified to below the threshold of ANC 20 µeq l^{-1} where damage to brown trout might be expected. The simulations indicated that these lakes have recovered substantially since the peak year of acid deposition in the 1970s and will continue to recover slightly during the next decade. Less than 25% of the lakes will have ANC <20 µeq l^{-1} in the future (Fig. 4).

The MAGIC simulations also provided an indication of changes in soil base cation pools (% base saturation) due to acid deposition. Again with the exception of two lakes, there were only very small changes in %BS over the 200-year period. The simulations showed, however, clear asymmetry; the pool sizes decreased in many lakes during the past 100 years, whereas the replenishment predicted starting in the 1970s is much smaller (Fig. 3; lower left-hand panel). The MAGIC simulations indicate that while soils were acidifying in 1980, the decline in acid deposition since then has stopped further acidification and base cation pools in soils in some catchments will be replenished in the future (Fig. 4).

3.2. Southern Norway

The calibration for Stavsvatn showed significant decline in ANC during the period up to about 1980, partial recovery to the year 2000, and prognosis of a minor amount of additional recovery during the next 20 years (Fig. 3). Stavsvatn is the least acidified lake of the 23 in the dataset; the other lakes all acidified to ANC <0 µeq l^{-1} during the 1900s. With the exception of Stavsvatn,

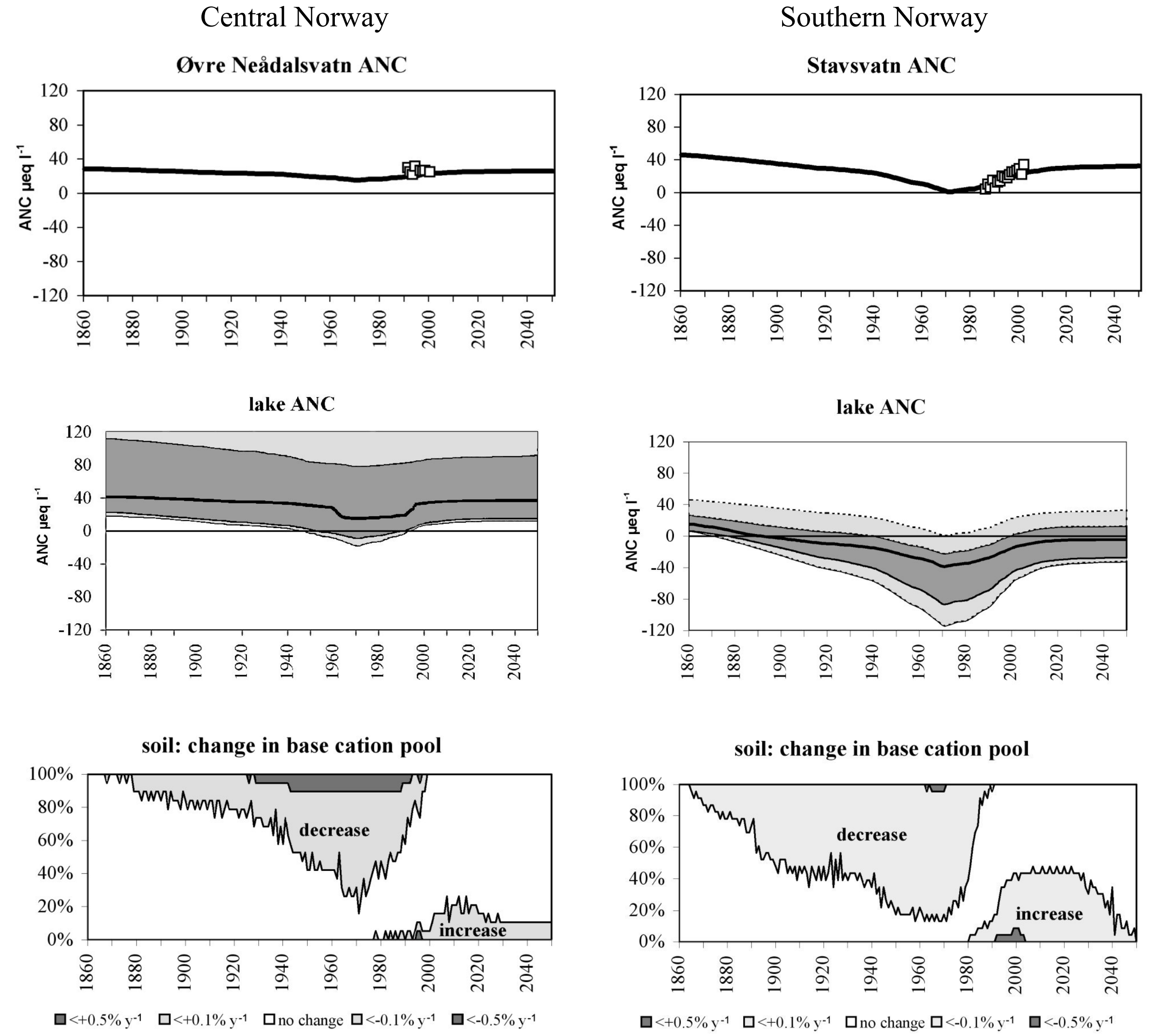

Fig. 3. ANC in lakewater and changes in base cation pools in soils in the lake districts central Norway (left-hand panels) and southern Norway (right-hand panels) as simulated by MAGIC. Upper panels: ANC in lakewater at the flagship site as simulated by MAGIC and the 1986-2000 yearly measured values. Middle panels: the frequency distribution of the lake datasets (heavy black line: median; dark shading: 10-90 %-tile; light shading: minimum-maximum). Lower panels: percent of lakes with annual change in base cation pool (shaded area: decrease or increase in pool; white: no change).

which is stocked every second year by the owners, most of the lakes were barren of trout in the 1980s. ANC levels have recovered substantially since then, and the MAGIC simulations predict that additional recovery will come during the next 20 years. Only Stavsvatn, however, is predicted to recover to ANC >20 µeq l^{-1}, and about 60% of the lakes are predicted to remain ANC <0 µeq l^{-1} in 2016 (Fig. 4).

The MAGIC simulations indicated that the soils at these sites have acidified during the past 100 years, and that the base cation pools will not be fully replenished in the next 50 years. As in central Norway the simulations showed a marked asymmetry with more acidification and less recovery. The simulations indicate that impoverishment of pool of base cations in soil has largely ceased by 2000 and that in about one-half of the catchments the pools will begin to be replenished in the future (Fig. 4).

4. DISCUSSION

The lakes in the region central Norway were intended to serve as unacidified reference sites for the more acidified and impacted lakes in the southern Norway region. The MAGIC hindcasts, however, indicate that many of the lakes in the central Norway region have been slightly acidified and that 5 of the lakes had ANC levels <0 µeq l^{-1} during the period of maximum acid deposition in the 1970s and 1980s (Figs 3 and 4).

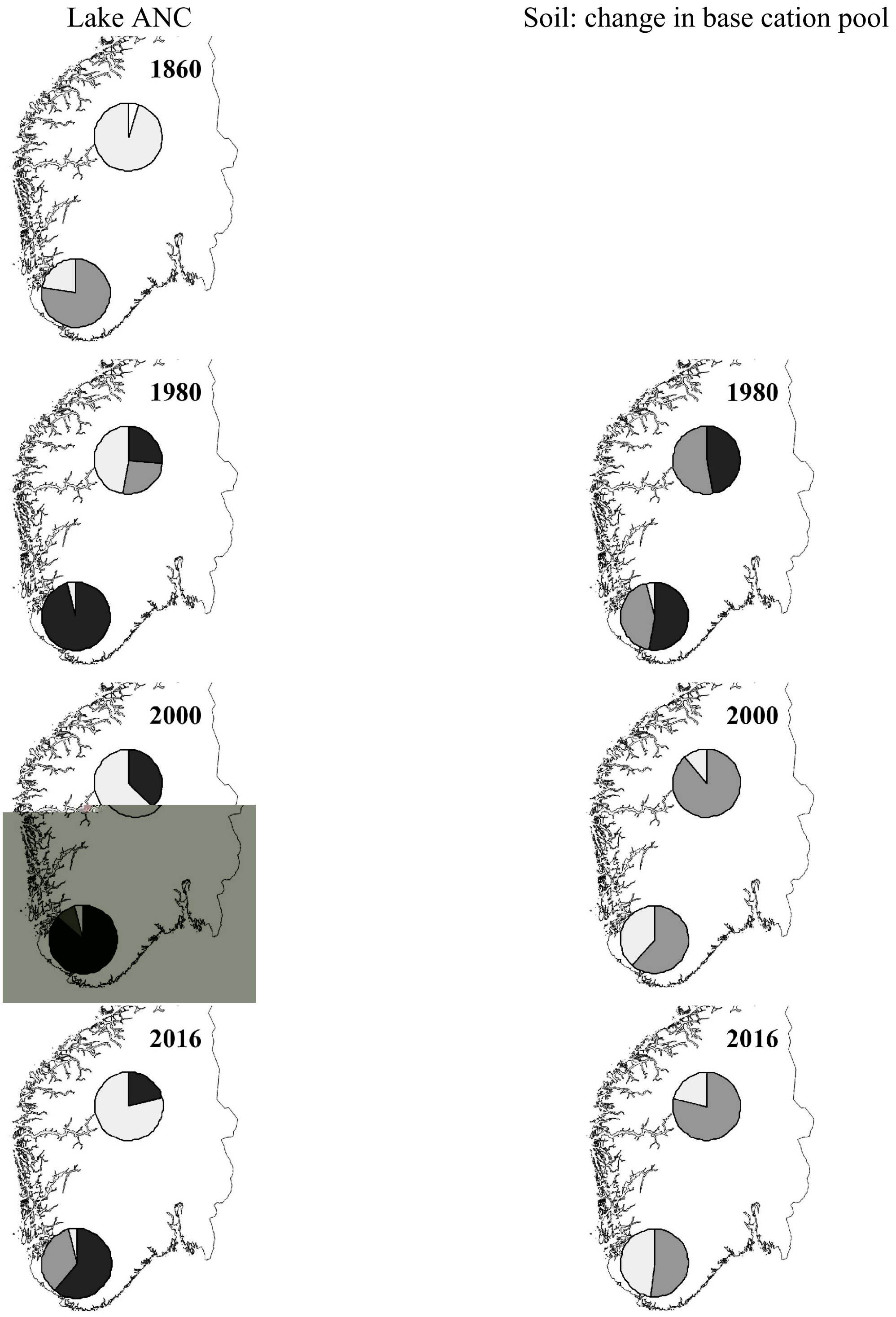

Fig. 4. ANC levels in lakes and annual changes in soil base cation pools in central and southern Norway for key years as predicted by MAGIC. Left-hand panels: % of lakes in each of three ANC categories corresponding to fish population status. Light shading: ANC >20 µeq l^{-1} (good); medium shading: ANC 0-20 µeq l^{-1} (sparse); dark shading: ANC <0 µeq l^{-1} (barren). Right-hand panels: annual incremental change in pools of base cations. Dark shading: pool change <0.1% y^{-1}; medium shading: no change; light shading: pool change >0.1% y^{-1}.

Acidification in central Norway, however, has been much less than that in southern Norway. The difference in degree of acidification between central Norway and southern Norway is due largely to the relatively larger input of acid deposition to the southern region. In addition several of the central Norway lakes are less sensitive to acid deposition; these lakes have higher concentrations of Ca and bicarbonate.

The model predictions indicate that recovery of the lakes to ANC levels >20 µeq l^{-1} will not occur by the year 2016. For central Norway a larger fraction of the lakes will still fall in the category ANC 0-20 µeq l^{-1} in 2016 as compared to the pre-acidification reference year 1860 (Fig. 4). For southern Norway recovery by year 2016 will be insufficient; fully 2/3 of the lakes will continue to have ANC <0 µeq l^{-1}. This is in part because although levels of acid deposition are predicted to continue to decrease to the year 2010 if the Gothenburg protocol to the LRTAP Convention is implemented (Fig. 2), there will still remain a small but significant S and N deposition in the future.

Part of the incomplete recovery is due to the hysteresis in the size of the pool of base cations in the soil over time. This pool is depleted by cation exchange with acids deposited from the atmosphere and leaching to runoff, and replenished by weathering of soil minerals. The MAGIC simulations indicate that depletion exceeded replenishment during much of the 1900s, but by year 2000 acid deposition had decreased sufficiently to allow replenishment to begin (Fig. 3; lower panels). The simulations indicate that the replenishment of the soil base cation pool will require many decades.

The 23 mountain lakes in the southern Norway dataset are a subset of the 60 lakes in the region modelled by Wright & Cosby (2003) as part of the RECOVER:2010 project. The mountain lakes are in general more sensitive to acid deposition, and leach a higher % of incoming N as compared to the lowland, forest lakes. These features are typical for mountain lakes in general (Skjelkvåle & Wright 1998).

All predictions for the future entail a degree of uncertainty, and these predictions for the future acidification of Norwegian mountain lakes are no exceptions. Uncertainties are associated with measured input data, estimated parameters, model formulation and structure, and with factors not considered in the model. The assumption of constant % retention of N is a source of uncertainty. The magnitude of this uncertainty was evaluated by Wright & Cosby (2003) for the MAGIC predictions for the 60 lakes in southern Norway of the RECOVER dataset. Three different scenarios for N retention were run; these were constant % N retention, % N retention linked to C/N ratio of the organic matter in soil with carbon pool of the whole soil, and % retention linked to C/N ratio with carbon pool only 1/3 of the total. Although nitrate concentrations predicted by MAGIC for the year 2036 differed by a factor of two among these scenarios, the median resulting effect on ANC levels differed by only 5 µeq l^{-1}. Thus the uncertainty to predictions of ANC over the next 20-30 years caused by unknown degree of future N saturation is minor.

Future climate change with increased temperature represents another uncertainty factor for future recovery of lakes. Higher soil temperature can cause increased decomposition of soil organic matter and release NO_3 to soil solution and runoff thus increasing acidification. Whole-ecosystem experiments with air and soil warming conducted in southernmost Norway (the CLIMEX project) showed increase in NO_3 concentrations in runoff of about 3-7 µeq l^{-1} (Lükewille & Wright 1997; Wright 1998). These experiments lasted only three years, however, and thus do not give information as to whether the induced NO_3 leaching would increase, stay elevated, or disappear over the long term.

The MAGIC prognoses here already indicate that a substantial fraction of mountain lakes in southern Norway will not recover sufficiently by year 2016 (or indeed by year 2036) to allow reestablishment of good brown trout populations. Both N saturation and future climate change are factors that would exacerbate acidification in southern Norway in the future. Sufficient recovery requires additional measures such as stricter air pollutant emission measures in Europe. Mountain lakes in southern Norway are among the most acid-sensitive lakes in Europe, and MAGIC simulations conducted as part of the RECOVER and EMERGE projects indicate that of all the studied regions in Europe, the acidification situation for mountain lakes will be worst in southern Norway in the future (Jenkins *et al*. 2003).

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REFERENCES

Baker, J.P. & C.L. Schofield. 1980. Aluminium toxicity to fish as related to acid precipitation and Adirondack surface water quality. In: Drabløs, D. & A. Tollan (Eds), *Ecological Impact of Acid Precipitation*. SNSF-project. Ås, Norway: 292-293.

Bulger, A.J., L. Lien, B.J. Cosby & A. Henriksen. 1993. Brown trout (*Salmo trutta*) status and chemistry from the Norwegian thousand lake survey: statistical analysis. *Can. J. Fish. Aquat. Sci.*, 50: 575-585.

Bull, K.R., B. Achermann, V. Bashkin, R. Chrast, G. Fenech, M. Forsius, H-D. Gregor, R. Guardans, T. Haussmann, F. Hayes, J.-P. Hettelingh, T. Johannessen, M.

Krzyzanowski, V. Kucera, B. Kvæven, M. Lorenz, L. Lundin, G. Mills, M. Posch, B.L. Skjelkvåle & M.J. Ulstein. 2001. Coordinated effects monitoring and modelling for developing and supporting international air pollution control agreements. *Water Air Soil Pollut.*, 130: 119-130.

Cosby, B.J., A.J. Bulger & R.F. Wright. 1994. Predicting recovery of freshwater ecosystems: trout in Norwegian lakes. In: Steinberg, C.E.W. & R.F. Wright (Eds). *Acidification of Freshwater Ecosystems. Implications for the Future*. Wiley & Sons, Chichester, UK: 355-374.

Cosby, B.J., R.C. Ferrier, A. Jenkins & R.F. Wright. 2001a. Modelling the effects of acid deposition: refinements, adjustments and inclusion of nitrogen dynamics in the MAGIC model. *Hydrol. Earth System Sci.*, 5: 499-518.

Cosby, B.J., G.M. Hornberger, J.N. Galloway & R.F. Wright. 1985b. Modelling the effects of acid deposition: assessment of a lumped parameter model of soil water and streamwater chemistry. *Water Res. Research*, 21: 51-63.

Cosby, B.J., R.F. Wright, G.M. Hornberger & J.N. Galloway. 1985. Modelling the effects of acid deposition: estimation of long term water quality responses in a small forested catchment. *Water Res. Research*, 21: 1591-1601.

Evans, C.D., J. Cullen, C. Alewell, J. Kopácek, A. Marchetto, F. Moldan, A. Prechtel, M. Rogora, J. Veselý & R.F. Wright. 2001. Recovery from acidification in European surface waters. *Hydrol. Earth System Sci.*, 5: 283-298.

Jenkins, A., L. Camarero, B.J. Cosby, R.C, Ferrier, M. Forsius, R.C. Helliwell, J. Kopácek, V. Majer, F. Moldan, M. Posch, M. Rogora, W. Schöpp, & R.F. Wright. 2003. A modelling assessment of acidification and recovery of European surface waters. *Hydrol. Earth System Sci.*, 7: 447-455.

Lükewille, A. & R.F. Wright. 1997. Experimentally increased soil temperature causes release of nitrogen at a boreal forest catchment in southern Norway. *Global Change Biology*, 3: 13-21.

Lien, L., G.G. Raddum, A. Fjellheim & A. Henriksen. 1996. A critical limit for acid neutralizing capacity in Norwegian surface waters, based on new analyses of fish and invertebrate responses. *Sci. Tot. Environ.*, 177: 173-193.

Marchetto, A. & M. Rogora. 2004. Measured and modelled trends in European mountain lakes: results of fifteen years of cooperative studies. *J.Limnol.* 63 (1): 55-62.

Mosello, R., A. Lami, A. Marchetto, M. Rogora, B.M. Wathne, L. Lien, J. Catalan, L. Camarero, M. Ventura, R. Psenner, K. Koining, H. Thies, S. Sommaruga-Wögrath, U. Nickus, D. Tait, R. Thaler, A. Barbieri, & R. Harriman. 2002. Trends in the water chemistry of high altitude lakes in Europe. *Water Air and Soil Pollution: Focus*, 2 : 75-89.

Mosello, R., B.M. Wathne, L. Lien, & H.J.B. Birks. 1995. AL:PE projects: water chemistry and critical loads. *Water Air Soil Pollut.*, 85: 493-498.

Muniz, I.P. & H. Leivestad. 1980. Toxic effects of aluminium on the brown trout (*Salmo trutta* L.). In: Drabløs, D. & A. Tollan (Eds), *Ecological Impact of Acid Precipitation*. SNSF-project. Ås, Norway: 320-321.

Overrein, L., H.M. Seip & A. Tollan. 1980. *Acid precipitation - Effects on forest and fish. Final report of the SNSF-project 1972-1980*. Fagrapport FR 19-80, Oslo-Ås, Norway: 175 pp.

Schöpp, W., M. Posch, S. Mylona & M. Johansson. 2003. Long-term development of acid deposition (1880-2030) in sensitive freshwater regions in Europe. *Hydrol. Earth System Sci.*, 7: 436-446.

SFT. 2002. *Overvåking av langtransportert forurenset luft og nedbør. Årsrapport - Effekter 2001*. Statlig program for forurensningsovervåking Rapport 854/02, Statens forurensningstilsyn, Oslo, Norge: 194 pp.

Skjelkvåle, B.L., C.D. Evans, T. Larssen, A. Hindar & G.G. Raddum. 2003. Recovery from acidification in European surface waters: A view to the future. *Ambio*, 30: 170-175.

Skjelkvåle, B.L. & A. Henriksen. 1995. Acidification in Norway -- status and trends. Surface and ground water. *Water Air Soil Pollut.*, 85: 629-634.

Skjelkvåle, B.L., J. Mannio, A. Wilander & T. Andersen. 2001a. Recovery from acidification of lakes in Finland, Norway and Sweden 1990-1999. *Hydrol. Earth System Sci.*, 5: 327-338.

Skjelkvåle, B.L., K. Tørseth, W. Aas, & T. Andersen. 2001b. Decrease in acid deposition - Recovery in Norwegian surface waters. *Water Air Soil Pollut.*, 130: 1433-1438.

Skjelkvåle, B. L. & R. F. Wright. 1998. Mountain lakes: sensitivity to acid deposition and global climate change. *Ambio*, 27: 280-286.

Skjelkvåle, B.L., R.F. Wright & A. Henriksen. 1998. Norwegian lakes show widespread recovery from acidification: results of national surveys of lakewater chemistry 1986-1997. *Hydrol. Earth System Sci.*, 2: 555-562.

Stoddard, J.L., D.S. Jeffries, A. Lükewille, T.A. Clair, P.J. Dillon, C.T. Driscoll, M. Forsius, M. Johannessen, J.S. Kahl, J.H. Kellogg, A. Kemp, J. Mannio, D. Monteith, P.S. Murdoch, S. Patrick, A. Rebsdorf, B.L. Skjelkvåle, M.P. Stainton, T.S. Traaen, H. van Dam, K.E. Webster, J. Wieting & A. Wilander. 1999. Regional trends in aquatic recovery from acidification in North America and Europe 1980-95. *Nature*, 401: 575-578.

UNECE. 2002. http://www.unece.org/env/lrtap/.

Wright, R.F. 1998. Effect of increased CO2 and temperature on runoff chemistry at a forested catchment in southern Norway (CLIMEX project). *Ecosystems*, 1: 216-225.

Wright, R.F. & B.J. Cosby. 2003. Future recovery of acidified lakes in southern Norway predicted by the MAGIC model. *Hydrol. Earth System Sci.*, 7: 467-483.

APPENDIX 1

Central Norway dataset. Site, lake chemistry and soil data. Catchment area includes the lake area. P=precipitation. Q= runoff.

ID	Name	Latitude	Longitude	elevation (m a.s.l.)	catchment (km^2)	lake (km^2)	Bedrock	P (m yr^{-1})	Q (m yr^{-1})
CN0001	Vonavatn	61.6131	6.0054	466	88.8	1.65	granite	2.52	2.37
CN0002	Vestre Kvammavatn	60.9004	6.1556	990	1.9	0.3	phylite	1.14	0.99
CN0003	Slondalsvatn	60.6921	6.9489	751	41.5	0.6	gabbro	2.29	2.14
CN0004	Halsavatnet	61.2793	7.0656	820	1.5	0.27	phylite	1.32	1.17
CN0005	Litlosvatn	60.0738	7.1708	1172	61.2	1.53	phylite	1.52	1.37
CN0006	Valgardsvatn	60.1028	7.3184	1324	11.8	1.8	phylite	1.39	1.24
CN0007	Hornsvatnet	60.9501	7.3625	1289	2.1	0.3	gneiss	1.58	1.43
CN0008	Dargesjåen	60.0844	7.5890	1209	17.3	0.55	gneiss	1.14	0.99
CN0009	Skiftesjøen	60.3842	7.5797	1239	5.6	0.95	phylite	1.69	1.54
CN0010	Holmavatnet	60.8420	7.6514	1525	8.1	0.8	gabbro	1.76	1.62
CN0011	Urdevatn	59.9734	7.7120	1329	24.5	1.5	granite	1.38	1.23
CN0012	Grønevatnet	61.2011	8.0790	1184	16.3	1.3	granite-amphibolite	1.36	1.21
CN0013	Kvitevatnet	61.3957	8.1781	1396	8.5	1.4	gabbro	2.04	1.89
CN0014	Leirvatnet	61.5478	8.2493	1401	12.5	1.0	gneiss	1.38	1.23
CN0015	Øvre Heimdalsvatnet	61.4188	8.8970	1088	24.4	0.78	gabbro	0.94	0.79
CN0016	Øvre Neådalsvatn	62.7778	8.9824	728	16.0	0.5	gneiss	1.95	1.80
CN0017	Fallbekktjørna	62.7500	9.0372	1043	3.7	0.27	gneiss	1.95	1.80
CN0018	Høvringvatn	61.8898	9.5650	1121	2.5	0.18	quartzite	0.62	0.47
CN0019	Lille Innsjøen	62.5522	10.2659	938	5.1	0.4	schist	0.58	0.43
CN0020	Haltdalstjønna	62.7743	11.0670	1058	1.9	0.08	gabbro	0.72	0.57
CN0021	Gjeltsjøen	62.7160	11.6009	799	19.9	0.55	phylite	0.72	0.57
CN0022	Øvlingen	62.9029	11.7848	844	1.2	0.2	gabbro	0.72	0.57

Lake chemistry. Alk= alkalinity titrated to fixed pH 4.5 less 32 µeq l^{-1}.

ID	Year	Date (ddmm)	pH	Ca (µeq l^{-1})	Mg (µeq l^{-1})	Na (µeq l^{-1})	K (µeq l^{-1})	Cl (µeq l^{-1})	SO$_4$ (µeq l^{-1})	NO$_3$ (µeq l^{-1})	Alk (µeq l^{-1})	TOC (mg l^{-1})	R-Al (µg l^{-1})	org-Al (µg l^{-1})	in-Al (µg l^{-1})	tot-P (µg l^{-1})	tot-N (µg l^{-1})
CN0001	2000	0929	5.84	15	10	39	3	42	15	2	7	1.1	19	14	5	2	96
CN0002	2000	1009	5.95	18	7	30	3	31	17	3	7	0.0	3	3	0	4	117
CN0003	2000	1007	5.94	15	6	17	3	14	15	3	6	0.4	3	3	0	3	80
CN0004	2000	1025	6.64	72	12	22	6	23	21	2	52	2.0	11	11	0	2	117
CN0005	2000	1210	6.79	82	17	17	1	14	33	2	55	0.2	3	3	0	1	60
CN0006	2000	1110	6.47	115	7	23	2	20	83	3	31	0.3	3	3	0	0	72
CN0007	2000	0905	6.25	27	8	14	5	8	19	0	20	0.7	3	3	0	2	56
CN0008	2000	1110	6.43	45	9	23	3	11	23	0	27	0.8	6	5	1	0	83
CN0009	2000	0922	6.75	101	13	21	2	14	50	0	56	0.6	3	3	0	3	90
CN0010	2001	1016	6.48	51	23	35	6	19	24	0	47	4.6	29	31	0	4	155
CN0011	2000	1110	6.07	24	6	16	2	11	19	1	9	0.8	6	5	1	0	57
CN0012	2000	0913	6.45	33	9	17	4	14	15	1	27	0.3	3	3	0	2	75
CN0013	1995	0918	5.99	23	5	9	1	6	21	4	15	0.1	5	5	0	1	81
CN0014	2000	0916	6.29	25	6	9	2	3	17	2	23	0.2	3	3	0	1	71
CN0015	2000	0915	6.93	80	30	26	6	3	31	0	88	0.8	6	3	4	2	75
CN0016	2000	0818	6.22	17	7	30	3	23	10	0	17	0.7	12	10	2	1	62
CN0017	2000	0818	6.09	18	8	30	3	25	12	1	13	0.2	8	5	3	1	41
CN0018	1995	1015	6.79	67	23	20	6	6	27	1	55	1.2	5	5	0	0	62
CN0019	2001	1003	7.65	445	31	32	23	17	31	0	467	2.1	16	3	14	2	137
CN0020	2000	1024	6.14	16	6	8	4	6	15	1	10	0.3	3	3	0	2	74
CN0021	1995	0920	7.20	207	43	21	10	20	15	1	232	2.8	5	5	0	4	210
CN0022	2001	0824	7.65	347	119	50	27	42	56	0	413	1.6	16	3	14	3	105

Soil chemistry. Depth=estimated average for catchment. CEC=cation exchange capacity by 1M NH_4NO_3. BD=bulk density. Exchangeable base cations in % of CEC. N/A= not available.

ID	soil data source	Depth (m)	CEC (meq kg^{-1})	BD (kg m^{-3})	Ca (%)	Mg (%)	Na (%)	K (%)	C (mol m^{-2})	N (mol m^{-2})	C/N (mol mol^{-1})
CN0001	Naustdal	0.75	62	800	7.9	3.6	4.4	2.4	N/A	N/A	N/A
CN0002	Vosso1	0.30	98	542	7.5	5.5	1.3	4.1	1340	36	37
CN0003	Vosso4	0.20	52	1099	0.7	0.6	0.6	0.8	502	21	23
CN0004	Hardangervidda	0.50	120	643	14.5	1.7	1.6	2.0	1679	82	20
CN0005	Hardangervidda	0.50	120	643	14.5	1.7	1.6	2.0	1679	82	20
CN0006	Hardangervidda	0.50	120	643	14.5	1.7	1.6	2.0	1679	82	20
CN0007	Hardangervidda	0.50	120	643	14.5	1.7	1.6	2.0	1679	82	20
CN0008	Hardangervidda	0.50	120	643	14.5	1.7	1.6	2.0	1679	82	20
CN0009	Hardangervidda	0.50	120	643	14.5	1.7	1.6	2.0	1679	82	20
CN0010	Hardangervidda	0.50	120	643	14.5	1.7	1.6	2.0	1679	82	20
CN0011	Hardangervidda	0.50	120	643	14.5	1.7	1.6	2.0	1679	82	20
CN0012	Hardangervidda	0.50	120	643	14.5	1.7	1.6	2.0	1679	82	20
CN0013	Hardangervidda	0.50	120	643	14.5	1.7	1.6	2.0	1679	82	20
CN0014	Hardangervidda	0.50	120	643	14.5	1.7	1.6	2.0	1679	82	20
CN0015	Hardangervidda	0.50	120	643	14.5	1.7	1.6	2.0	1679	82	20
CN0016	Kaarvatn	0.35	91	764	5.9	5.3	8.0	1.8	2397	103	23
CN0017	Kaarvatn	0.35	91	764	5.9	5.3	8.0	1.8	2397	103	23
CN0018	Rondane	0.23	373	941	11.5	0.8	0.3	1.0	N/A	N/A	N/A
CN0019	Rondane	0.23	373	941	11.5	0.8	0.3	1.0	N/A	N/A	N/A
CN0020	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
CN0021	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
CN0022	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

APPENDIX 2

Southern Norway dataset. Site, lake chemistry and soil data. Relative area: lake area/catchment area. Q= runoff.

ID	Name	NIVA-Id	Latitude	Longitude	Elevation (m a.s.l.)	RelArea (%)	Q (m yr^{-1})
SN0002	St. Eitlndsvt	1004-13	59.6350	8.1100	1053	0.4	0.789
SN0011	Stigebottsvt	1026-210	58.7560	7.3150	814	4.4	1.577
SN0013	Troldevatn	1032-14	58.2260	6.9930	278	4.0	0.946
SN0015	Trollselvvtn	1034-8	58.5470	7.2060	617	2.4	1.419
SN0017	Heievatn	1037-17	58.6300	6.9700	500	3.8	1.892
SN0019	Skreppevatn	1046-111	58.9280	7.0460	812	2.5	1.735
SN0023	Måkevatn	1111-23	58.3120	6.3800	272	4.0	1.577
SN0024	Ljosvatn	1111-3	58.4180	6.2110	150	4.0	1.577
SN0025	Gjuvvatn	1112-15	58.5220	6.4090	389	4.0	2.208
SN0028	Homsevatn	1119-602	58.5620	5.8610	142	6.7	1.419
SN0029	Kråtjørni	1122-1-9	58.7410	6.1210	534	0.7	2.208
SN0030	Tvaravatnet	1129-1-13	59.0410	6.3100	720	4.0	1.892
SN0036	Heddersvatn	827-601	59.8300	8.7560	1136	1.7	0.789
SN0041	Folurdkaldevatn	833-2-21	59.3840	7.5930	1074	4.0	0.789
SN0042	Skurevatn	833-603	59.5870	7.5530	1269	6.5	0.789
SN0043	Hemletjørnane	834-1-12	59.6110	7.5440	1104	16.0	0.789
SN0044	HOH 1394	834-1-32	59.9380	7.9640	1394	1.8	0.789
SN0045	Stavsvatn	834-614	58.4930	6.7350	392	1.3	1.577
SN0054	Storolavsvatnet	938-3-4	58.8580	7.2860	848	12.2	1.577
SN0056	HOH 1227	940-2-9	59.1850	7.1080	1227	4.0	1.892
SN0059	Skammevatn	940-527	59.2050	7.2420	1074	0.6	1.892
SN0060	Reinsgrovtjørnane	941-2-23	59.3410	7.0060	1121	4.0	1.892
SN0061	Bånevatn	941-24	59.5040	7.1130	1115	8.9	0.789

Lake chemistry. Alk= alkalinity titrated to fixed pH 4.5 less 32 µeq l^{-1}.

ID	Year	pH	Ca (µeq l^{-1})	Mg (µeq l^{-1})	Na (µeq l^{-1})	K (µeq l^{-1})	Cl (µeq l^{-1})	SO_4 (µeq l^{-1})	NO_3 (µeq l^{-1})	Alk (µeq l^{-1})	TOC (mg l^{-1})	R-Al (µg l^{-1})	org-Al (µg l^{-1})	inorg-Al (µg l^{-1})
SN0002	1995	4.89	22	31	125	4	147	57	15	0	0.5	137	7	130
SN0011	1995	4.90	14	10	39	5	42	28	6	0	2.3	88	32	56
SN0013	1995	4.55	17	30	133	4	147	59	25	0	1.0	180	15	165
SN0015	1995	4.58	17	18	59	2	60	38	5	0	8.1	125	93	32
SN0017	1995	4.65	19	18	68	3	71	42	5	0	5.6	150	115	35
SN0019	1995	5.10	12	9	34	2	38	25	8	0	1.1	88	17	71
SN0023	1995	4.73	26	52	197	5	245	76	28	0	0.7	322	27	295
SN0024	1995	4.75	26	47	194	5	236	71	26	0	0.5	268	30	238
SN0025	1995	4.83	17	32	127	4	150	55	16	0	0.6	189	15	174
SN0028	1995	4.81	31	53	207	6	248	74	25	0	0.8	231	11	220
SN0029	1995	4.82	17	30	124	3	148	44	8	0	2.1	120	59	61
SN0030	1995	5.02	11	21	89	4	103	31	10	0	0.8	88	17	71
SN0036	1995	5.85	31	9	15	4	16	30	9	8	0.7	18	11	7
SN0041	1995	5.64	18	7	18	4	18	25	6	3	0.1	41	5	36
SN0042	1995	5.44	16	8	19	1	27	21	10	0	0.2	58	5	53
SN0043	1995	5.64	18	8	19	1	19	24	8	2	0.4	50	5	45
SN0044	1995	5.48	17	7	11	3	8	25	11	1	0.4	25	5	20
SN0045	1995	5.93	41	9	20	4	16	33	4	16	1.0	65	22	43
SN0054	1995	5.08	12	10	40	2	45	27	11	0	0.8	98	11	87
SN0056	1995	5.32	10	6	16	1	17	19	7	1	0.2	34	5	29
SN0059	1995	5.56	14	6	22	2	23	19	6	3	0.4	41	5	36
SN0060	1995	5.22	8	8	22	2	25	17	6	0	0.3	25	5	20
SN0061	1995	5.33	11	7	26	2	31	17	8	0	0.2	40	5	35

Soil chemistry. Depth=estimated average for catchment. CEC=cation exchange capacity by 1M NH_4NO_3. BD=bulk density. Exchangeable base cations in % of CEC. N/A= not available.

ID	Depth (m)	CEC (meq kg^{-1})	BD (kg m^{-3})	Ca (%)	Mg (%)	Na (%)	K (%)	C (mmol m^{-2})	N (mmol m^{-2})	C/N (mol mol^{-1})
SN0002	0.38	44	689	5.2	3.1	4.1	4.3	2073	124	17
SN0011	0.14	72	552	13.9	7.3	2.6	5.0	770	53	15
SN0013	0.33	112	553	13.2	8.7	4.7	3.1	752	39	19
SN0015	0.12	39	558	9.6	5.8	2.2	4.5	489	33	15
SN0017	0.50	189	192	8.7	8.7	4.5	3.6	4674	141	33
SN0019	0.89	12	855	7.3	5.1	2.9	2.2	4944	137	36
SN0023	0.56	58	499	7.2	4.1	3.5	2.2	3140	178	18
SN0024	0.28	69	907	11.6	6.6	2.8	3.3	2073	124	17
SN0025	0.28	69	907	11.6	6.6	2.8	3.3	2910	151	19
SN0028	0.75	201	374	33.9	13.3	5.3	2.0	7114	351	20
SN0029	0.40	102	617	17.1	11.4	3.2	4.0	4112	184	22
SN0030	0.22	232	378	14.5	12.5	2.3	4.2	1793	58	31
SN0036	0.22	65	668	14.9	4.1	3.9	2.8	1019	33	31
SN0041	0.16	65	553	10.2	3.5	2.4	2.9	1042	34	30
SN0042	0.22	65	668	14.9	4.1	3.9	2.8	1019	33	31
SN0043	0.22	65	668	14.9	4.1	3.9	2.8	1019	33	31
SN0044	0.22	65	668	14.9	4.1	3.9	2.8	1019	33	31
SN0045	0.22	65	668	14.9	4.1	3.9	2.8	1019	33	31
SN0054	0.53	36	877	39.5	6.7	2.4	2.7	770	53	15
SN0056	0.22	232	378	14.5	12.5	2.3	4.2	1793	58	31
SN0059	0.22	232	378	14.5	12.5	2.3	4.2	1793	58	31
SN0060	0.22	65	668	14.9	4.1	3.9	2.8	1793	58	31
SN0061	0.22	65	668	14.9	4.1	3.9	2.8	1019	33	31