Acidification Remediation Alternatives: Exploring the Temporal Dimension with Cost Benefit Analysis

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Abstract Acidification of soils and surface waters caused by acid deposition is still a major problem in southern Scandinavia, despite clear signs of recovery. Besides emission control, liming of lakes, streams, and wetlands is currently used to ameliorate acidification in Sweden. An alternative strategy is forest soil liming to restore the acidified upland soils from which much acidified runoff originates. This cost–benefit analysis compared these liming strategies with a special emphasis on the time perspective for expected benefits. Benefits transfer was used to estimate *use values* for sport fishing and *nonuse values* in terms of existence values. The results show that large-scale forest soil liming is not socioeconomically profitable, while lake liming is, if it is done efficiently—in other words, if only acidified surface waters are treated. The beguiling logic of “solving” an environmental problem at its source (soils), rather than continuing to treat the symptoms (surface waters), is thus misleading.

Keywords Cost-benefit analysis · Forest soil liming · Surface water liming · Acidification recovery · Aquatic ecosystem services

Introduction

Acidification of soils and surface waters caused by atmospheric acid deposition is still an important environmental problem in parts of southern Scandinavia, even though there are clear signs of recovery both in Europe and North America (Stoddard et al. 1999; Monteith et al. 2007). In southwestern Sweden, approximately 30% of the lakes >1 ha were significantly acidified in 2005 (Bertills et al. 2007). Fish populations are especially affected, reducing benefits from recreational fishing (Henrikson and Brodin 1995; Paulrud 2001), while loss of biodiversity is another concern involving lost existence values (Krutilla 1967).

Recovery from acidification is a slow process, and liming of lakes, streams, and wetlands has been used for decades to reduce the acidity of surface waters and the toxic effect of metals, especially aluminum (Henrikson and Brodin 1995; Lydersen et al. 2002). Sweden has invested heavily (3.8 billion SEK in 1983–2006) (Bertills et al. 2007) in this remediation technique, despite its temporary effects, since streams and lakes continually receive new runoff from acidified catchments. Surface water liming must thus be repeated regularly. Liming acidified forest soils to reduce acidity in runoff from those soils is an alternative strategy. Forest liming is therefore seen as an attractive long-term solution, and a large-scale program has been suggested by the Swedish Forest Agency (2002). However, no attempts have been made to socioeconomically judge whether forest soil liming, with decadal delays between treatment and expected benefits, is a better alternative than continued surface water liming.

While effects on aquatic and terrestrial ecosystems due to acidification have been widely studied for decades (Likens and Bormann 1974; Gorham 1976; Wright and Gjessing 1976), economic effects of acidification have not

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been studied to the same extent. Exceptions include Bateman et al. (2005), who value benefits, but not costs, of liming projects in Scotland, and Vermoote and De Nocker (2003), who explore the possibilities for valuing the impacts of acidification and eutrophication through abatement costs of emission reductions. A cost–benefit analysis (CBA) in Norway showed that liming was socioeconomically profitable in certain specified water bodies (Navrud 1993a, b, c). Iivonen et al. (1995) found that even non-fishing residents around a limed lake were willing to finance the cost of liming, due to opportunities for recreation and swimming. Bengtsson and Bogelius (1995) used benefits transfer from the Navrud studies to make CBAs on nine sites in Sweden. Although ecosystem benefits were disregarded, results showed that surface water liming was socioeconomically profitable in most cases.

In this CBA, we study socioeconomic consequences over a 50-year period of different scenarios for large-scale liming strategies in southwestern Sweden, where one strategy is continued surface water liming. Given the marked (ca. 90%) reductions in atmospheric sulfur deposition since the 1970s (Bertills et al. 2007), this strategy addresses the symptoms of recovery from acidification in surface waters. A complementary alternative is forest soil liming, although this method has a delayed effect on surface waters. These two remediation strategies will be compared to a no liming case, as well as combinations of soil and surface water liming. The natural recovery from acidification is included in all of these analyses. Forest soil liming and surface water liming are interesting to compare socioeconomically, due to their differences in time perspective. With lake liming, benefits accrue immediately, while benefits from forest soil liming are assumed to slowly increase and reach a peak 20–30 years after treatment (Swedish Forest Agency 2002).

Methods and Materials

Monetary Valuation

Costs and benefits are measured in present value terms throughout this analysis. The costs include costs of planning, distribution of lime, and evaluation. These costs are summarized in Table 1.

The benefits resulting from liming activities are *use values* in terms of recreational benefits of sport fishing and *nonuse values* in terms of ecosystem benefits (Krutilla 1967). Benefits transfer (Rosenberger and Loomis 2003) was used to generate monetary estimates of the nonmarket values derived from liming activities, using transfer values from existing monetary valuation studies (see following sections).

Table 1 Costs of different liming methods expressed per hectare soil (forest soil liming) or lake area (surface water liming) (1 SEK ≈ 0.16 USD)

Method	Distribution cost ^a (SEK ha ⁻¹)
Forest soil liming	
Helicopter distribution	
Lime, Mg 4%, 0, 2–2 mm	3,600
Planning and evaluation	200
Ground distribution	
Lime, Mg 4%, 0, 2–2 mm	1,875
Planning and evaluation	300
Surface water liming	
Boat distribution	670
Planning and evaluation	100

^a Sources: S. Andersson, Swedish Forest Agency; K. Hallin, Movab AB, Landskrona, and F. Nilsson, County Administration Board of Västra Götaland

Regarding the possible effects of liming on forest growth, Sikström (2001) and Anderson and Hildingsson (2004) have shown that no significant effects can be detected 15–25 years after liming. Similarly, low-dose liming has shown restricted long-term effects on groundwater chemistry, such as pH and inorganic aluminum (Löfgren et al. 2008). In addition, the heavy metal concentrations in groundwater and surface water are low in Scandinavia (Lydersen et al. 2002). The effects on biodiversity are also expected to be restricted. Actually, the long-term effects are assumed to be less important than those caused by normal forestry operations regarding, for example, species compositions of vascular plants, mosses, lichens, and saprophobic fungi found in soils [Dahlberg and Hallingbäck, The Swedish Species Information Centre (Bostedt et al. 2007)]. Differences in species composition, and probably the function, of ectomycorrhiza fungi have been demonstrated, but how these changes should be valued are unclear (Kjøller and Clemmensen 2009). Due to the uncertainty of the long-term effects on forest production, heavy metal concentrations in groundwater, and biodiversity, these variables were not individually valued from an economical point of view. Instead they were assumed to be insignificant or included in the ecosystem values derived from the benefit transfer (see below).

Ecosystem Benefits

Given the lack of studies on the benefits of preserving ecosystems from acidification, valuations derived from the preferences of policymakers were used as a substitute. In this CBA, the effects of acidification on terrestrial and aquatic ecosystems are valued as a benefit transfer derived

from a political agreement on air pollution reduction programs in the EU [see Protocol of Gothenburg on the Convention on Long-range Transboundary Air Pollution (1999) and European directive 2001/81/EC on National Emission Ceilings for some air pollutants].

The willingness to pay (WTP) of European society for protecting 1 ha of ecosystem from acidification and eutrophication was estimated using the standard price approach (SPA) by Vermoote and De Nocker (2003). The SPA is based on the notion of using abatement costs of emission reductions as a proxy for revealed WTP for improvements in ecosystem health. Abatement costs were based on the most cost-effective emission reduction programs. Policymakers are implicitly assumed to act rationally and to carefully balance abatement costs with the benefits of the emission reductions.

To estimate the WTP to protect 1 ha year⁻¹ of ecosystem from acidification and eutrophication, the numbers of hectare of ecosystems where critical loads were exceeded for acidifying and eutrophying deposition, and the total costs to reduce the emissions, have been calculated. The WTP ha⁻¹ ranges between 63 and 350 € ha⁻¹ year⁻¹ (Vermoote and De Nocker 2003), the variation depending on the selected emission reduction program. The WTP that best reflected the EU was based on the Protocol of Gothenburg and the European directive 2001/81/EC (Vermoote and De Nocker 2003), and equaled 100 € ha⁻¹ year⁻¹, or SEK 920 ha⁻¹ year⁻¹ (1 € ≈ 9.2 SEK). As this estimate involves measures to protect ecosystems from *both* acidification and eutrophication, it is an overestimate of the WTP to protect ecosystems from acidification. On the other hand, as pointed out by Nerhagen et al. (2005), the most recent costs agreed upon to reach the Protocol of Gothenburg are not included in the estimates by Vermoote and De Nocker (2003), making them underestimates in that sense. Vermoote and De Nocker state a figure of 350 € ha⁻¹ year⁻¹ as an upper margin for marginal WTP, including all proposed emission reduction programs in Europe. However, measures intended to reduce acidification are a subset of these programs since they also include measures to protect ecosystems from both eutrophication and the impacts of ozone.

Recreational Benefits

Paulrud (2001) estimated recreational benefits connected with sport fishing in the Bohus region of southwestern Sweden. This region is part of the heavily acidified area where forest liming is contemplated. In Paulrud (2001), recreational benefits are related to specific fishing sites in southwestern Sweden, which are then divided into different types of fishing, or angling: “ordinary angling” and “put-and-take angling.” Ordinary angling is fishing in lakes that do not have salmonid species, while put-and-take angling is

conducted in lakes with salmonid species. Ordinary angling and put-and-take angling gave a WTP of SEK 53 days⁻¹ and SEK 83 days⁻¹, respectively. We used benefits transfer from Paulrud (2001) in order to estimate the recreational value of liming activities, with the highest value per angling day (SEK 83) used to estimate the value of what a liming activity may generate. According to Paulrud (2001), the annual amount of angling day ha⁻¹ was around 4 days ha⁻¹, which gives a WTP of SEK 332 ha⁻¹ year⁻¹.

This is based on the assumption that limed acidified lakes and watercourses will be completely restored to a nonaffected fishing state, which is most likely an overestimate.

Discounting

Costs and benefits from liming activities occur over different time periods and are thus not directly comparable. To convert costs and benefits to present values, the discount rate during the first time period (years 0–30) was 3.5 and 3% in the second period (years 31–50), corresponding to discount rates recommended by the British government for CBAs of public projects (Cairns 2006).

Acidification Status and Recovery Trends

In order to estimate the socioeconomic costs and benefits, information about the area of acidified forest soils suited for liming and the water bodies it affected were estimated. According to the national survey of Swedish lakes in 2005, there were 3,363 acidified lakes larger than 1 ha in southwestern Sweden (Bertills et al. 2007), corresponding to an estimated lake area of approximately 53,000 ha. This area is estimated based on data from a subsample of 161 randomly selected acidified lakes in southwestern Sweden. For the subsample, the quartile distance for lake area is 5–21 ha. Due to a very skewed distribution, we have used 16 ha as an “average” size to estimate the total lake area for the 3,363 acidified lakes. These lakes are surrounded by approximately 485,000 ha of catchment area. This estimation is based on the same approach as lake area, with the use of a 160-ha catchment area as “average” size (skewed distribution, quartile distance is 58- to 450-ha catchment area for the subsample). It was assumed that approximately 65% of the terrestrial part of the catchment area (144 ha) is acidified forestland suited for forest soil liming (approximately 310,000 ha). The rest of the area, such as mires, rock outcrops, clear-cuttings, and agricultural land, is unsuitable for forest liming. Our estimate of acidified forestland is in agreement with the 200,000–350,000 ha considered for forest soil liming by the Swedish Forest Agency (2002).

Over the years, there has been a reduction of emissions of acidifying pollutants, which has resulted in a slow recovery from acidification of Swedish forest soils and surface waters

Fig. 1 Estimated percentage of acidified lakes in different regions of Sweden. The prognosis from 2000 to 2020 was modeled based on expected developments in acid depositions given existing legislation and treaty commitments (modified from Bertills et al. 2007)

(Bertills et al. 2007). Estimates based on data from the national Swedish lake surveys (in 1990, 1995, 2000, and 2005) and model calculations show that the recovery of acidified lakes and streams will proceed in future (Moldan et al. 2004). The recovery trends of acidified lakes and watercourses in different parts of Sweden are illustrated in Fig. 1. This recovery coupled to emission reductions was taken into account when defining the scenarios.

Scientific Workshop for Scenario Building

In order to estimate expected benefits for different liming strategies, a scientific workshop was organized by the Swedish University of Agricultural Sciences (SLU) in June 2007 to get expert opinions. The aim of the workshop was to obtain quantitative predictions of the effects of forest soil liming on surface water quality, aquatic and terrestrial biodiversity, and forest growth. During the workshop, the effects of forest soil liming on the status of soil and water chemistry, the biological effects on aquatic and terrestrial ecosystems, the recreational value of fishing, and the timetable for the appearance of liming effects were all discussed, as were the expected effects if acidified ecosystems are left untreated. The workshop members consisted of three experts on liming from the Swedish Forest Agency and the County Administrative Board of Västra Götaland, three senior researchers in soil science (SLU), three hydro-biogeochemists (SLU), an aquatic biologist (SLU), and two economists (SLU). The experts had different opinions on when the effects of liming would occur and on the degree of the effect, as measured by the percentage of acidified lakes and watercourses that would have recovered both chemically and biologically.

Four of the 12 experts believed that more than 75% of the water bodies would have recovered from acidification due to forest liming and “natural recovery” within 10–100 years,

with most viewing recovery to occur between 25 and 50 years. Two of the experts were more pessimistic, and believed that only 50–60% of the water bodies would recover within 25–75 years. The most pessimistic experts believed that only 20–25% of the water bodies would be recovered within 50–70 years. Regarding the percentage of the water bodies that will reach a specific goal of less than 50 µg inorganic aluminum (a critical limit for serious acidification effects on fish fauna and other gill-breathing organisms), only two experts believed that the goal would be achieved in 25% or more of the currently acidified water bodies.

While there was a considerable range in the expert opinions, the workshop made it possible to create three scenarios based on the experts’ opinions about liming effects: optimistic, intermediate, and pessimistic forest soil liming scenarios. These were complemented by surface water liming scenarios based on the expectations of constant or decreasing lake liming activity in the future. Furthermore, one scenario combined surface water liming with forest soil liming.

Scenarios

By using scenarios from the workshop with existing data from national inventories, such as the 2005 national survey of Swedish lakes (Wilander and Fölster 2007) and Bertills et al.’s (2007) comprehensive evaluation of acidification, it was possible to estimate how different assumptions concerning the effects of different liming methods affect the results. A key factor is the expected time it will take for forest soil liming to lead to enough improvements in the acidity status in soils and aquatic ecosystems. A poor biological state in lakes and watercourses will have to be accepted for some time until forest soil liming has a significant effect on runoff water quality. In the scenarios, based on the water chemical results from the experimental forest soil liming program administrated by the Swedish Forest Agency (Löfgren et al. 2009), it is assumed that during the first 15 years after forest liming occurs, no socioeconomic values will rise. The amount of benefit between years 16 and 50 then differs between the scenarios.

It should also be noted that all scenarios take into account the natural recovery of acidified lakes and watercourses, that is, the reference scenario, which has been defined based on the models that are used to classify acidification (Bertills et al. 2007). Water is defined as acidified if the pH level is more than 0.4 units lower than the natural state (Bertills et al. 2007).

The Reference Scenario

In the reference scenario, no liming against acidification is undertaken. The predicted result is a gradual decline in the

Fig. 2 Acidification development in the different soil liming scenarios. The starting point (year 0) corresponds to 2005

number of acidified lakes and watercourses in southwestern Sweden (Fig. 2). The recovery is solely coupled to the reductions in atmospheric deposition of acid compounds (Bertills et al. 2007).

Approximately 29% of the lakes >1 ha in southwestern Sweden were acidified in 2005 (Wilander and Fölster 2007), which is year 0 in all of the defined scenarios. The recovery of acidified lakes was assumed to be $0.5\% \text{ year}^{-1}$ during the first 10 years, then $0.3\% \text{ year}^{-1}$ during years 11–20, $0.2\% \text{ year}^{-1}$ during years 21–30, and finally to $0.1\% \text{ year}^{-1}$ up to year 50 (Bertills et al. 2007; Moldan et al. 2004) (Fig. 1). The recovery trend was assumed to be the same in the streams. Using these recovery rates, approximately 16% of the lakes in southwestern Sweden will be acidified by the end of the 50-year study period, according to the reference scenario (Fig. 2).

Forest Soil Liming: The Optimistic Scenario

This scenario describes the most optimistic prognosis for the effect of large-scale forest soil liming as a counter-measure against acidification. In this scenario, the forest liming will lead to a rapid decrease in the amount of acidified lakes and watercourses in southwestern Sweden. The assumption is that large-scale forest soil liming has such a positive effect on acidified surface waters that by year 35, the share of acidified lakes and watercourses will have reached 0% (Fig. 2).

It is also assumed that, from years 0 to 15, there will be only a natural recovery of acidified lakes—in other words, the forest soil liming will benefit the lakes only after year 16. This is based on the results from 15 year-long studies in the 10 limed SKOKAL-streams in southwestern Sweden. The SKOKAL-streams are test sites for forest soil liming, where SKOKAL stands for SKOgsmarksKALKning (forest soil liming in Swedish). According to results of those studies made available after the expert workshop (Löfgren et al.

2009), it is difficult to show a recovery created by forest soil liming that substantially differs from the recovery in non-limed streams. The optimistic scenario is therefore unrealistic according to the results from Löfgren et al. (2009).

Forest Soil Liming: the Intermediate Scenario

In the intermediate scenario, large-scale forest soil liming will benefit aquatic ecosystems at a much slower rate than in the optimistic scenario. It is assumed that after 50 years, 12% of the lakes will still be acidified despite forest liming in their catchments, as opposed to 0% after 35 years in the optimistic scenario (Fig. 2). The effects of the forest liming will start benefiting some of the lakes after year 15, but the recovery of the water chemistry state will only occur in approximately 25% of the acidified waters. The rate of recovery, an annual decrease in the area of acidified lakes and watercourses by 0.3%, was a “middle-of-the-road” view at the expert workshop.

This less optimistic scenario is justified by an assumed poor recovery in terms of the inorganic aluminum concentrations in lakes and watercourses after forest liming. The aluminum fraction is very toxic for fish and other gill-breathing organisms (Poleo et al. 1997; Gensemer and Playle 1999). At the expert workshop, the consensus view was that forest soil liming could reduce the inorganic aluminum concentrations below toxic levels in less than 25% of the acidified waters.

Forest Soil Liming: the Pessimistic Scenario

In the most pessimistic scenario, large-scale forest soil liming gives no further recovery in the number of acidified lakes and watercourses in the future. The only visible effect is coupled to the reductions in atmospheric deposition of acidifying compounds. Therefore, the number of acidified lakes will be the same as in the reference scenario (Fig. 2), and will be 16% by the end of the time period (year 50). This reflects the views of the most pessimistic participants in the expert workshop regarding the expected aquatic ecosystem benefits due to forest soil liming in southwestern Sweden.

Lake Liming: Constant Level

Today, lake liming is one of the most common liming strategies. In order to maintain the positive environmental effects, lakes must be limed at regular intervals. This is because the water in lakes is constantly replaced with acidified water from the catchment area (Henrikson and Brodin 1995).

In this scenario, the share of acidified lakes that are unlimed is 16% in year 0, which reflects the actual situation in 2005 (Bertills et al. 2007). Thereafter, we have assumed

Fig. 3 Acidification development in the different lake liming scenarios compared to the reference scenario. The starting point (year 0) corresponds to 2005

that the recovery of acidified lakes and watercourses will follow the same recovery as used in the reference scenario, and that the liming activity will continue at the same level as today. After year 40, the number of acidified lakes will be less than 5%, and by the end of the study period (year 50) it will be 3% (Fig. 3).

Lake Liming: Progressively Decreasing

In this scenario, the natural recovery of acidified lakes is allowed to influence the amount spent on surface water liming so that the proportion of acidified lakes will remain constant during the entire study period. Surface water liming will be progressively reduced after year 0, reaching 16% acidified lakes in the region by year 50 (Fig. 3).

Combination of Forest Soil Liming and Lake Liming

Since the benefits that arise from large-scale forest liming have a different development over time when compared with repeated surface water liming, it was interesting to analyze the economic consequences when large-scale forest soil liming is combined with lake liming. In this “combination” scenario, large-scale forest soil liming, based on the optimistic scenario, is combined with lake liming. Benefits will accrue during the entire time period since lake liming will continue until the effect of forest soil liming benefits the lakes, obviating the need for further surface water liming to maintain adequate water quality for the biota. In this scenario, a turning point occurs at year 31 when lake liming is discontinued (Fig. 3).

Large-scale forest soil liming, based on the intermediate scenario, does not have a larger effect on the recovery of acidified lakes than constant lake liming. Therefore, a cost–benefit scenario using the “middle-of-the-road” recovery rate estimate was deemed unnecessary to understand the consequences.

Results

Costs and Benefits

Based on the optimistic scenario, large-scale forest soil liming is unprofitable in socioeconomic terms, yielding a benefit/cost (B/C) ratio less than 1.0 for both 30- and 50-year time periods (Table 2). The B/C ratio increases, however, from 0.18 to 0.60 as the time period increases from 30 to 50 years. The intermediate forest soil liming scenario generates an even further decreased B/C ratio, 0.01 and 0.06, for the 30- and 50-year time perspective, respectively. In the pessimistic scenario, there are no benefits, yielding a B/C ratio of 0 (Table 2).

Current surface water liming has a B/C ratio of 0.49, which indicates unprofitable socioeconomic conditions. The reason is that 70% of the Swedish lakes that were limed in 2005 were not acidified and, hence, do not yield any benefits (Bertills et al. 2007). If surface water liming is only performed on the 30% of the water bodies that are acidified, the B/C ratio will be 1.63 for both time periods. Thus, efficient surface water liming is profitable in socioeconomic terms, while surface water liming according to the current practice—that is, liming two unacidified lakes for every acidified lake—is not socioeconomically profitable.

If the present level of 16% acidified lakes is held constant, the need for remediation measures would decrease over time in proportion to the natural recovery. Such a progressively decreased lake liming would yield a B/C ratio of 1.63, in other words, equal to constant lake liming.

If large-scale forest soil liming is combined with lake liming, benefits may rise during the whole time period. However, the B/C ratio will never exceed 1.0 and this is thus unprofitable, even though the B/C ratio is higher than for pure forest soil liming.

Sensitivity Analysis

To address uncertainties concerning assumptions in this study, it is important to assess the effect on the results of changes in the values of different parameters. One important parameter is the discount rate used for calculating the present value of costs and benefits, where the baseline discount rates were 3.5% for years 0–30 and 3% for years 31–50. If instead the discounting rate is set to 0%, all future economic consequences will have the same value as if they occurred today.

Table 3 gives results from the different scenarios with the discount rate set to 0%. Here, the B/C ratio for forest soil liming, based on the optimistic scenario, exceeds 1.0 for the 50-year time period. For the intermediate and pessimistic scenarios, forest soil liming is not profitable. The

Table 2 Costs and benefits in present value terms and B/C ratios for different liming methods and scenarios (1 SEK $\approx$ 0.16 USD)

Scenario	Year	Cost (MSEK)	Benefits (MSEK)	B/C ratio
Forest soil liming, optimistic	0–30	562	101	0.18
Forest soil liming, intermediate		562	5	0.01
Forest soil liming, pessimistic		562	0	0.00
Surface water liming, constant		356	579	1.63
Surface water liming, constant*		1,175	579	0.49
Surface water liming, decreased		217	354	1.63
Combination of forest soil (optimistic) and surface water liming (constant)		779	354	0.45
Forest soil liming, optimistic	0–50	562	335	0.60
Forest soil liming, intermediate		562	36	0.06
Forest soil liming, pessimistic		562	0	0.00
Surface water liming, constant		469	762	1.63
Surface water liming, constant*		1,547	762	0.49
Surface water liming, decreased		229	372	1.63
Combination of forest soil (optimistic) and surface water liming (constant)		779	587	0.75

*Many lakes in Sweden are limed without being acidified. If only 30% of the water bodies are acidified, costs must be multiplied by 3.3 to correctly represent the low efficiency of lake liming in Sweden

Table 3 B/C ratios for the different scenarios with a 0% discount rate

Scenario	B/C ratio years 0–30	B/C ratio years 0–50
Forest soil liming, optimistic	0.37	1.54
Forest soil liming, intermediate	0.02	0.19
Forest soil liming, pessimistic	0	0
Surface water liming, constant	1.63	1.63
Surface water liming, decreased	1.63	1.63
Combination of forest soil (optimistic) and surface water liming (constant)	0.52	1.32

B/C ratios for surface water liming are unaffected by changes in the discount rate (B/C ratio of 1.63) and remain more effective than forest soil liming from a socioeconomic perspective.

Reducing the discount rate to 0%, together with optimistic assumptions about the effects of forest soil liming, makes forest soil liming almost as profitable as lake liming (B/C ratio of 1.54). The combination scenario, again with optimistic assumptions about the effects of forest soil liming, is profitable over a 50-year timeframe, but not if the time perspective is only 30 years.

Looking further at discount rate effects, the combination scenario is more profitable than pure, large-scale forest soil liming for discount rates exceeding 0.8%. Furthermore, pure forest soil liming (optimistic assumptions) is profitable for discount rates below 1.3% (Fig. 4). As Fig. 4 shows, pure lake liming is always more profitable than the other scenarios, and forest soil liming, based on anything less than very optimistic assumptions regarding the effects of liming, will never be profitable. For surface water

Fig. 4 The B/C ratio as a function of the discount rate, averaged over 50 years, for different acidification remediation scenarios

liming, the choice of discount rate is unimportant since the relationship between costs and benefits is the same for all periods.

Since the costs of liming are fairly well known, while benefit estimates are more likely to be uncertain, a sensitivity analysis was performed where benefit values are varied in the optimistic forest soil liming scenario, using original discount rates. This shows that, to make forest soil liming profitable, the recreational benefits must be multiplied by 4; alternatively, the ecosystem benefits must be doubled [note here the uncertainty regarding the baseline WTP estimate in Vermoote and De Nocker (2003), on which the ecosystem benefits are based]. However, increasing these benefits also increases the B/C ratio of surface water liming, making to retain its competitive advantage over soil liming. This is an important conclusion that increasing benefit estimates does not change the ranking between surface water and soil liming.

Discussion

Comparing forest soil liming with surface water liming is an interesting socioeconomic problem due to their inherent differences in time perspective. In this study, we have focused on the 50-year time period with consideration given to uncertainties and how different assumptions affect the results. For forest soil liming, it takes a long time for the treatment to affect the aquatic ecosystems—if it ever does—implying that a poor biological state in the lakes and watercourses will have to be accepted.

The results show that, under baseline discount rates—that is, 3.5% in years 1–30 and 3% during years 31–75—forest soil liming is not profitable in socioeconomic terms in southwestern Sweden. Lake liming is, however, profitable only if liming is done efficiently, that is, if only acidified lakes are treated. Today, many lakes in Sweden are limed without being acidified. Progressively decreased lake liming in accordance with the natural recovery is also profitable in socioeconomic terms, although with this scenario, 16% of the lakes will remain acidified throughout the 50-year study period. The fact that large-scale forest soil liming is not socioeconomically profitable does not imply, however, that liming cannot be profitable in certain specific water bodies.

The present uncertainty about areas of acidified soils and water bodies in southwestern Sweden will not affect the B/C ratios since values of both the numerator and the denominator are based on the same area of acidified lakes.

It should be noted that the recreational benefits included in the analysis do not take into account the possible effects of acidification on the benefits of swimming and boating. A rough calculation based on real estate values in a report on Swedish environmental accounts for sulfur dioxide and nitrogen oxide emissions (National Institute of Economic Research (NIER) 1998) shows that if acidification reduces the annual yield of services from the house from 5 to 4.75%, this amounts to benefits on the order of 3 MSEK annually, based on a time period of 20 years. To put this into perspective, this figure is slightly less than half the annual fishing benefits provided by surface water liming. However, Iivonen et al. (1995), in their study of the Finnish lake Alinenjärvi, argue that “the immediate benefits of the liming on the recreational use of the lake will be negligible.” Based on this, we have chosen to disregard the benefits of swimming and boating in the main analysis.

Using benefit transfer to estimate the benefits of liming activities is not an entirely satisfactory approach, and there is a need to increase the number of valuation studies specially designed for benefit transfer applications. An important field for future research is valuation studies of the environmental value of different ecosystem services, especially when long-term perspectives are involved.

Conclusion

Despite uncertainties involved in the choice of discount rate, as well as the valuation of costs and benefits, this study has several clear outcomes. The first clear finding is that surface water liming is always more efficient than even the most optimistic forest liming scenario. Thus, the beguiling logic of “solving” a serious environmental problem at its source (aluminum in acidified runoff derived from forest soils) rather than continuing to treat the symptoms (aluminum toxicity to fish) has been shown to be misleading. The second finding is the critical importance of knowing when, and to what extent, forest soil liming will improve the acidification status of surface waters. The wide range of expert views on this, from no improvements after 50 years to complete remediation of all acidified waters after 30 years, reflects the uncertainties. A recent evaluation by Löfgren et al. (2009) of the experimental forest soil liming program administrated by Swedish Forest Agency (2002) shows that treatment with 3 t ha^{-1} , which was the dose proposed for large-scale forest soil liming, is insufficient to improve the acidification status in the streams of the limed catchments.

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