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Quantifying the nitrogen retention capacity of natural wetlands in the large-scale drainage basin of the Baltic Sea

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Abstract

We estimate the nitrogen retention capacity of natural wetlands in the 1.7 million km^{2}Baltic Sea drainage basin, using a wetland GIS data base. There are approximately 138,000 km^{2}of wetlands (bogs and fens) in the Baltic Sea drainage basin, corresponding to 8% of the area. The input of nitrogen to natural wetlands from atmospheric deposition was estimated to 55,000–161,000 ton y^{-1}. A map of the deposition of both wet and dry nitrogen is presented. The input from the human population was estimated to 255,000 ton y^{-1} in terms of excretory release in processed sewage water. There may also be leakage from forests and agricultural land into the wetlands. Due to lack of data on hydrology and topography, such potential nitrogen sources are not accounted for here. The capacity of the wetlands to retain the atmospheric deposition of nitrogen was estimated to 34,000–99,000 ton y^{-1}. The potential retention by wetlands was estimated to 57,000–145,000 ton y^{-1} when the nitrogen input from the human population was added. If drained wetlands were to be restored and their area added to the present wetland area, the nitrogen retention capacity was estimated to increase to 196,000–261,000 ton y^{-1}. Our results indicate that existing natural wetlands in the Baltic Sea drainage basin annually can retain an amount of nitrogen which corresponds to about 5–13% of annual total (natural and anthropogenic) nitrogen emissions entering the Baltic Sea. The ecosystem retention service performed by wetlands accounts for a substantial nitrogen removal, thereby reducing the eutrophication of the Baltic Sea.

Introduction

The Baltic Sea drainage basin is a large scale landscape in Northern Europe about 1.7 million km^2. About 85 million people in 14 countries live in the drainage basin (Figure 1), which covers an area about 4 times that of the Baltic Sea. Habitat fragmentation and other human activities are changing the mosaic of ecosystems in the drainage basin (Sweitzer et al. 1996). For example the wetland ecosystems have been seriously affected by human activities. During the last century vast areas of wetlands have been drained, and in some countries as much as 90% of all wetlands have been lost (Rydlöv et al. 1991).

Wetlands are multifunctional in the sense that they generate several ecosystem services such as, supplying habitat for many plants and animals, including endangered species, mitigating floods, recharging aquifers, and improving water quality by removing organic and inorganic nutrients and toxic metals from the water that flows across the wetlands (Mitsch and Gosselink 1993).

Increasingly, ecologists are engaged in quantifying and evaluating such ecosystem services (Odum 1975; Ehrlich and Mooney 1982; Folke 1991a; de Groot 1992; Daily 1997). Many studies address services generated by local ecosystems (e.g., Costanza et al. 1989; Folke 1991b) or stress the value of global ecosystem services like pest control (Ehrlich and Naylor 1997), primary production (Vitousek et al. 1986) or the aggregated value of ecosystem services (Costanza et al. 1997). Few studies have quantified the ecosys-

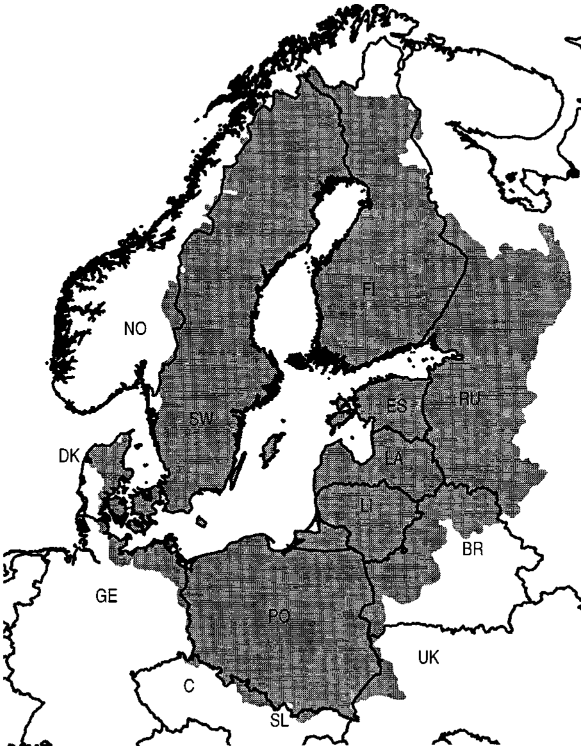

Figure 1. The Baltic Sea drainage basin. FI = Finland; SW = Sweden. NO = Norway, GE = Germany, PO = Poland, C = Czech Rep., SL = Slov. Rep., UK = Ukraine, BR = Belarus, LI = Lithuania, LA = Latvia, ES = Estonia, R = Russian Federation.

tem services at the landscape level and linked them to human activities (van Wilgren et al. 1996; Norton and Ulanowich 1992). Here we focus on the capacity of the wetlands in the whole Baltic Sea drainage basin to retain nitrogen from atmospheric deposition and human activities. By retention, we mean the annual uptake of nitrogen by a wetland. Here, the uptake is a function of vegetation, storage in soil/peat and denitrification (Leonardsson 1994).

The reason for analyzing this capacity is the serious eutrophication of the Baltic Sea. During the last century the nitrogen load to the Baltic Sea has increased four times. Since biological production in the Baltic Proper is nitrogen limited, the nitrogen emissions from the countries in the drainage basin have been an important cause for the eutrophication of the Baltic (Larsson et al. 1985). In Sweden, large amounts of money are spent on sewage treatment plants to further increase nutrient removal capacity. But sewage treatment plants can not reduce non-point source pollution. Using wetlands as filters between land and sea is an increasingly applied abatement technology (e.g., Ewel and Odum 1984; Baker 1992; Mitsch 1992; Knight 1992), and appears to be cost-effective (Andréasson-Gren et al. 1991). Also, wetland restoration seems to have great potential as a means of increasing nitrogen removal (Leonardsson 1994; Mander and Mauring 1995).

Several site specific studies of wetlands as nitrogen filters have been performed (e.g., Jansson et al. 1994; Jacks et al. 1994). There are also studies of specific large wetlands in sub-drainage basins of the Baltic area, in Louisiana, and the Everglades (Krysanova et al. 1989; Costanza et al. 1990; Fitz et al. 1993, in press). To our knowledge there has been no study that investigates the nutrient removal capacity of a mosaic of wetlands in a large-scale drainage basin.

In this article we try to quantify current and potential retention by natural wetlands in the Baltic Sea drainage basin, using a geographical information system (GIS). We estimate the annual nitrogen retention capacity in three scenarios: (i) In the first scenario we estimate wetland retention when only atmospheric deposition of nitrogen is considered. This scenario provides a minimum retention estimate.

(ii) In the second scenario we estimate potential retention capacity by adding to the atmospheric deposition the nitrogen in excretory release from the human population. We assume that excretory release is processed in sewage treatment plants, and that wetlands receive the nitrogen in the water discharged from these plants.

Since wetland restoration is considered a viable and cost-effective nutrient abatement technology, we also (iii) estimate the nitrogen retention potential in the Baltic Sea drainage basin in a scenario where drained wetlands would be restored. The analysis is based on the best available data on nitrogen retention as well as sources of nitrogen emissions that exist in the region and elsewhere. Leakage of nitrogen from forests and in particular agricultural ecosystems is substantial in the region. But due to lack of information on basic hydrology and topographic location, we could not estimate how much of the leakage that can be retained by the wetlands. The analysis illuminates that there are still large gaps in the empirical ecological knowledge on the role of wetlands in the Baltic Sea drainage basin. Their links to other ecosystems like agriculture and forests, to water and nutrient flows between systems and to human activities affecting these systems, are poorly investigated. The results are discussed in relation to the potential of using wetlands as an engineering technique for nitrogen abatement in comparison to conventional measures, such as improving sewage treatment.

Method

The GIS database

A recently developed GIS database of the Baltic Sea drainage basin was used to derive information on the geographical distribution of wetland area and population densities (Sweitzer et al. 1996). According to the database there are approximately 138,000 km^2 of natural wetlands in the Baltic Sea drainage basin (Table 1). The geographical distribution of natural wetlands is presented in Figure 2. The grid cells of the data base are 50 × 50 km (Sweitzer et al. 1996).

Nitrogen sources

Atmospheric nitrogen deposition includes both wet and dry deposition. The deposition also consists of nitrogen emission from human activities such as transportation and livestock farming. Data on total nitrogen deposition were derived from Iversen et al. (1991). The data are mean measurements for 1985, 1987, 1989 and 1990. To be comparable with the wetland distribution map, the data were transferred from the 150 × 150 km EMEP grids into 50 × 50 km grids.

Table 1. Wetland and total area by country in the Baltic Sea Drainage Basin.

Country	Estimated total area (km^2) [1][2]	Present wetland area (km^2)[3]	Present wetland area (%)
Belarus	88566	3723	4.2
Denmark	32693	554	1.7
Estonia	45300	10092	22.3
Finland	304100	42092	13.8
Germany	27802	576	2.1
Latvia	64410	3161	4.9
Lithuania	64790	1554	2.4
Norway	18127	2206	12.2
Poland	310488	13124	4.2
Russia	322620	11700	3.6
Sweden	442457	48941	11.1
Total:	1734862	137723	7.9

[1] Estimates derived from the GIS data base by Sweitzer et al. (1996); [2] Refers only to the area of a country that is situated within the Baltic Sea drainage basin; [3] Data derived from various statistical sources as reported in Andersson (1994).

The nitrogen in urine and feces from the human population, what we refer to as *human excretory release*, is approximately 4 kg N person $^{-1}$ y^{-1} (Torell 1977). In the second scenario we assume that the excretory release is processed in sewage treatment plants and that the nitrogen in the water discharged from the plants will pass through wetlands. Alternative techniques, such as septic tanks, also remove anthropogenic nitrogen discharge. These alternatives are not included in the study. At present several cities are or will be connected to sewage treatment plants. Some municipalities have created wetlands to process sewage water (e.g., Klochak 1993). Based on empirical data we assume that the nitrogen in excretory release was reduced by 20% in sewage treatment plants in Eastern European countries and by 40% in Western European countries (Gren et al. in press) We made this assumption in order not to over estimate the nitrogen load from the human population. Nitrogen retention potential is derived from measurements in 60 Swedish sewage treatment plants. For Polish plants we only acquired information on ton nitrogen purified per year, but no information on input amounts. Thus, no retention potential could be estimated first hand from Polish plants. However, Polish plants, with the ability to re-

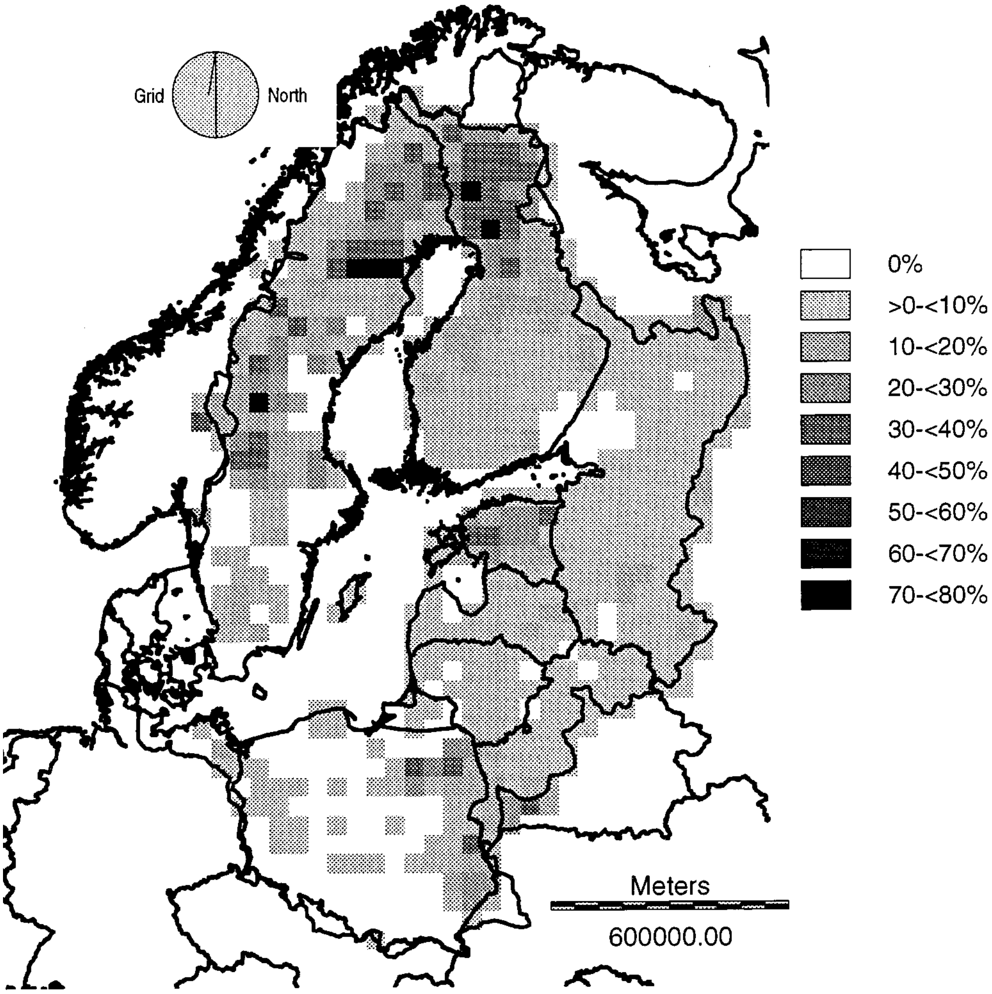

Figure 2. Distribution of wetlands in the Baltic Sea drainage basin. Map derived from the GIS-data base created by Sweitzer et al. (1996). Each square represents an area of 50 × 50 km.

tain nitrogen, employ the same techniques as Swedish plants. We have thus assumed an equal retention potential in Polish plants as in Swedish plants. In Poland about 50% of the population is connected to plants that have no nitrogen retention (Gren et al. in press; Sweco et al. 1992). We have extrapolated retention estimates from Sweden to other Western European countries and Polish estimates to Eastern European countries.

Nitrogen sinks

The wetland ecosystems included in the study are bogs and fens. The GIS-database does not differentiate between wetland ecosystems. But as 95–96% of the natural wetlands in former USSR and Europe are bogs or fens (USSR 61% bogs, 35% fens; Europe 35% bogs, 60% fens) (Aselmann and Crutzen 1989), we assume all wetlands identified in the database to be either bogs or fens.

The relationship between nitrogen load and retention by wetlands was obtained from a number of studies (Table 2). In many studies (e.g., Malmer 1962; Small 1972; Tilton 1977) scientists have found nutrient uptake rates in bogs to be lower than in fens. Retention data of bogs and fens compiled by Mander and Mauring (1995) also support this view, showing considerably higher retention values for fens (up to 75% higher). However, different methods were used for measuring retention in wetlands in the studies presented by Mander and Mauring (1995). Retention estimates for fens are based on the TIN-method (the total inorganic nitrogen method measure only inorganic fractions) and for bogs on the TN-method

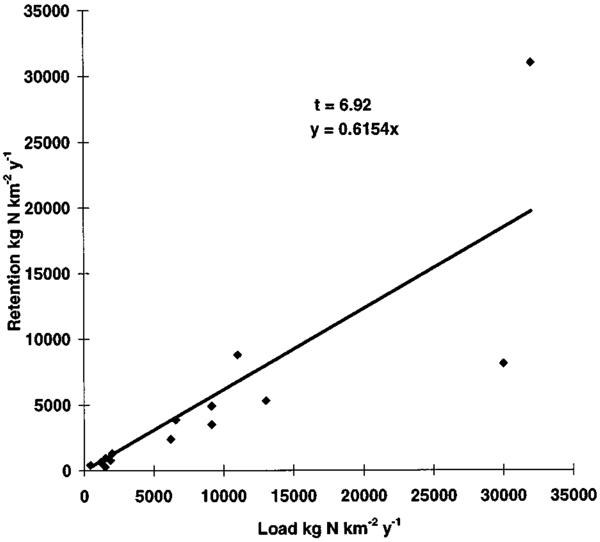

Figure 3. Regression line of load-retention relation. Y = 0.6154x, n = 14. The intercept has been set at origo to avoid a situation of nitrogen leakage despite no addition of nitrogen. Based on available literature data for bogs and fens (see Table 2 and text).

(the total nitrogen method measure all fractions of substances). According to Leonardsson (1994) measurements based on a single fraction can be misleading due to new formation of the fraction in question, e.g., release of ammonia due to decomposition of organic material or the formation of nitrate through oxidation of ammonia. Also, the duration of the different retention experiments differed. All bog investigations are whole year studies, while none of the fen investigations exceed nine months. Although there is retention all year around, albeit much lower during the winter months (W. Mitsch, University of Ohio, pers. comm.) we assumed the retention for the time period not included in the fen studies to be zero. Hence the potential nitrogen retention service performed by natural wetlands is an underestimate.

The regression on load and retention

The load/retention regression line based on the estimates from both bogs and fens is presented in Figure 3. The regression line is derived to be able to obtain quantitative estimates of effects of various nutrient loading. It is derived from empirical information from various sources (see Table 2) with consequent uncertainties associated to them. The data points have been fitted to a linear regression, since other attempts to describe load/retention relation for much higher loads than the ones included in this study have been best described by a linear regression (e.g., Mander and Mauring 1995). To capture some of the uncertainty in the regression we varied the slope by plus or minus 1 standard deviation (stdev = 0.008891). A change by 1 stdev brings about not more than 10–15% change in the retention results. There are two observations in the regression with loads of 30,000 and 32,000 kg km^{-2}y^{-1} respectively. They represent studies of nitrogen retention in bogs in which nitrate or sewage water have been artificially added. These observations are of value for scenario 2 where sewage water is assumed to enter natural wetlands. The slope of the line is similar to the one presented by Mander and Mauring (1995) (0.61) that includes a broader set of wetlands and riparian ecosystems than in our study. Therefore, we have chosen not to omit any of the extreme points. Since there are no other observations on bogs and fens exposed to higher nitrogen loads, we have set an upper value on the nitrogen load in each grid to 32,000 kg km^{-2} y^{-1}. The intercept has been set to origo in order to avoid a situation of nitrogen leakage despite no addition of nitrogen.

Calculating load and retention

Total load and retention were calculated using a grid cell based GIS (IDRISI). The study area was divided into 50 × 50 km grids with information on the distribution of wetland area and population in each specific grid. The relation between load and retention was estimated in the following way. Each grid was treated as a

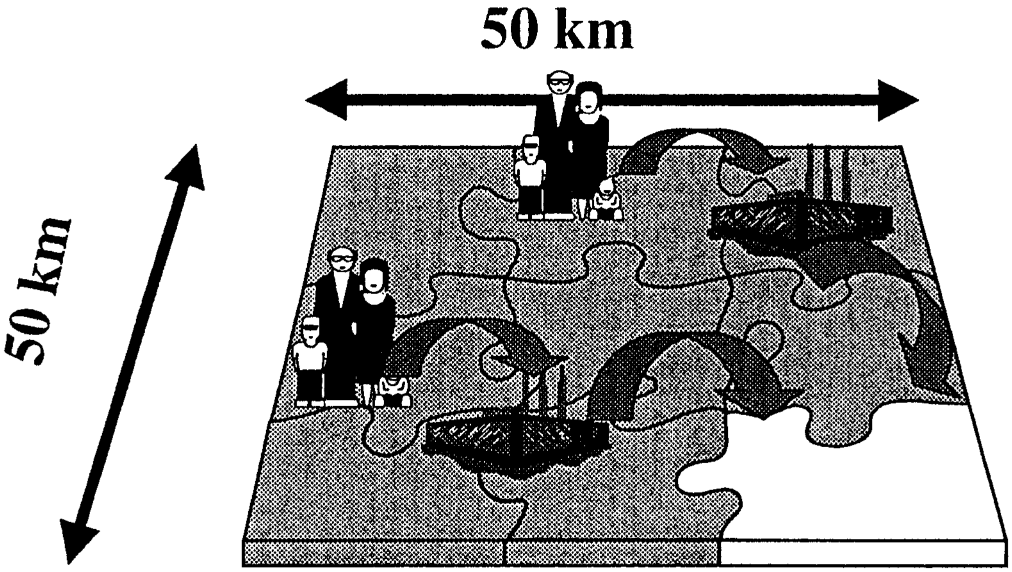

Figure 4. Flow of nitrogen load within a grid cell from the human population via sewage treatment to natural wetlands. The white area represents the natural wetland area within a grid cell.

separate unit. The nitrogen retention capacity within a grid was estimated as a function of the load that can be processed by wetlands within a grid based on the regression equation (Figure 3). The atmospheric nitrogen deposition per km^2 was assumed to be the same within each grid, but varied between grids in accordance with the EMEP data (Iversen et al. 1991). Excretory release in each grid was a function of the number of people in each grid. Hence, the method assumes no processing of excretory release by wetlands in grids without people. Similarly, in grids without wetlands there is no retention of atmospheric deposition or excretory release (see Figure 4). This approach implies that we are neither concerned with nitrogen leakage from wetlands, nor with nitrogen flows between grid cells. The Baltic Sea drainage basin (the Baltic Sea excluded) consists of about 700 grid cells. Description of variables used in the equations below, are presented in Appendix 1.

Scenario 1

Total atmospheric nitrogen deposition in wetlands for all grid cells were estimated:

$$_{t}\mathrm{ATMD}_{g} = \mathrm{ATMD}_{g} \times \mathrm{WA}_{g} \tag{1}$$

$$_{t}\mathrm{ATMD} = \Sigma_{t}\mathrm{ATMD}_{g} \tag{2}$$

By placing total atmospheric deposition estimates per grid cell in the regression equation (Figure 3), we estimated the atmospheric nitrogen retention by wetlands for all grid cells:

$$_{t}\mathrm{RATMD}_{g} = {}_{t}\mathrm{ATMD}_{g} \times 0.6154 \tag{3}$$

$$_{t}\mathrm{RATMD} = \Sigma_{t}\mathrm{RATMD}_{g} \tag{4}$$

Scenario 2

Total nitrogen load from the population and retention in each grid cell was estimated:

$$_{t}\mathrm{ANTD}_{g} = \mathrm{ANTD}_{cap} \times \mathrm{POP}_{g} \tag{5}$$

$$\mathrm{ANTD}_{g} = \mathrm{tANTD}_{g}/\mathrm{Wa}_{g} \tag{6}$$

$$_{t}\mathrm{RANTD}_{g} = {}_{t}\mathrm{ANTD}_{g} \times 0.6154 \tag{7}$$

$$_{t}\mathrm{RANTD} = \Sigma_{t}\mathrm{RANTD}_{g} \tag{8}$$

By adding the various loads from all grids, we could estimate total nitrogen load from the population entering the wetlands. We assumed that water with nitrogen from human excretory release discharged from sewage treatment plants were processed in wetlands. Furthermore, we assumed that nitrogen load from a population in a grid would be processed by wetlands located in the same grid. In order to avoid situations where the population in densely populated grids would discharge into very small wetland areas, we set an upper load limit at 32,000 kg N km^{-2} based on the maximum value included in our regression.

Table 2. Literature compilation of nitrogen load-retention measurements.

Wetland type	Measuring method	Load ($kg\ km^{-2}\ y^{-1}$)	Retention ($kg\ km^{-2}\ y^{-1}$)	Time	Reference
Bog	TN	420	420	year	Rosswall and Granhall 1980[1]
	TN	1200	630	year	Verry and Timmons 1982[1]
	TN	1530	950	year	Horner 1986[2]
	TN	2000	1200–1400	year	Aerts et al. 1992[1]
	TN	11000	8800	year	Burke 1975[2][3]
	TN	13000	5300	year	Slapokas 1991[1]
	TN	30000	8100	year	Slapokas 1991[1]
	TN	32000	31000	year	Slapokas 1991[1]
Fen	TIN	9130	4880	apr–nov	Kadlec 1979[2,3]
	TIN	6570	3850	march–nov	Kadlec and Tilton 1978[2,3]
	TIN	9130	3480	june–nov	Kadlec 1981[2,3]
	TIN	6210	2380	june–nov	Kadlec 1980[2,3]
	TIN	1900	765	may–sept	Tilton and Kadlec 1979[2,3]
	TIN	1500	285	aug–oct	Kadlec and Tilton 1977[2,3]
	Interval:	420–32000	420–31000		

[1] After Leonardsson 1994; [2] After Mander and Mauring 1992; [3] Cited in Nichols 1983.

By using the regression equation we estimated the total nitrogen retention for the nitrogen in human excretory release, after it has been processed in sewage treatment plants. Finally we added the estimated total atmospheric nitrogen retention to the load from the population.

Scenario 3

Wetland restoration is increasingly applied as a nitrogen removal technique in the Baltic region. In this scenario we estimated the retention potential if the drained wetland areas would be restored, and added that area to the present wetland areas. We have only included atmospheric deposition as a source of nitrogen. We only accounted for this nitrogen source, since the geographical location of the potentially restored wetlands to the human population is unknown. Data on percentage of drained wetlands could only be identified for Denmark, Estonia, Finland, Latvia, Poland and Sweden as reported in Andersson (1994) (Table 3). The scenario thus includes only these countries and is therefore an underestimate.

Statistics on drained wetland area were available only on country level. As we did not know the geographical location of the drained wetlands, we assumed that they would receive nitrogen loads per unit area corresponding to the average atmospheric load of the country the restored wetlands would be located in (see Table 3). For Swedish wetlands we assumed they would receive an atmospheric deposition corresponding to the average deposition in the south of Sweden, since 90% of all drained Swedish wetlands are located in this area (Rydlöv et al. 1991).

Results

Load from the different nitrogen sources

Total atmospheric deposition was estimated at 55,000–161,000 ton nitrogen y^{-1}. The atmospheric nitrogen load entering wetlands per grid in the Baltic Sea drainage basin is shown in Figure 5. Total load from the population in the basin was estimated at 255,000 ton nitrogen y^{-1}. The geographical distribution of the excretory release of nitrogen in processed sewage water from the human population in the drainage basin is shown in Figure 6.

Retention of nitrogen

Scenario 1

Nitrogen retention of atmospheric deposition in natural wetlands was estimated to 34,000–99,000 ton nitrogen y^{-1}.

Scenario 2

Nitrogen retention adding the nitrogen in processed

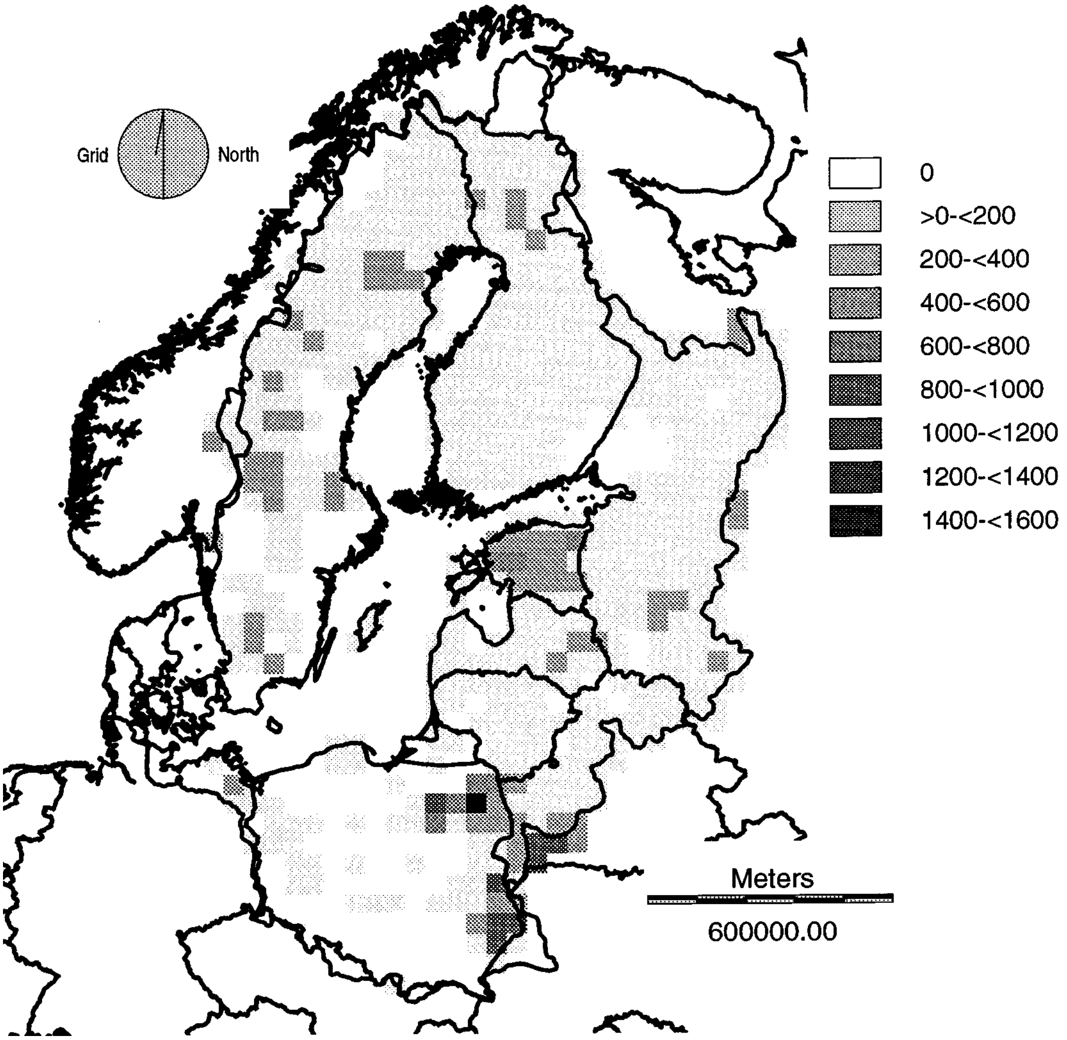

Figure 5a. Low range of atmospheric nitrogen deposition entering wetlands. Ton nitrogen grid^{-1} y^{-1}.

sewage water from the population was estimated to 57,000–145,000 ton nitrogen y^{-1}.

Scenario 3

Retention, in the scenario where drained wetlands would be restored, was estimated at 196,000–261,000 ton nitrogen y^{-1}.

Discussion

Total nitrogen input from the atmosphere and from land entering the Baltic Sea (including Baltic Proper, Bothnian Sea, Bothnian Bay, Gulf of Finland and Gulf of Riga) has been estimated to approximately 1,170,000 ton per year, based on average emission data between 1970–1990 (A.-K. Hallin Dept. Systems Ecology, Stockholm University, pers. comm). Gren et al. (in press) estimated the annual total nitrogen input to the Baltic Sea at 1,095,000 ton per year. According to our results the existing natural wetlands of the Baltic Sea drainage basin have the potential to retain an amount of nitrogen corresponding to 5–13% of the total annual nitrogen emissions to the Baltic Sea. If drained wetland areas would be restored the estimated nitrogen retention capacity could be approximately 18–24% of the total annual emissions entering the Baltic. When we varied the slope of the regression on which the quantifications are based by plus or minus 1 standard deviation the results were changed by 10–15% in both directions.

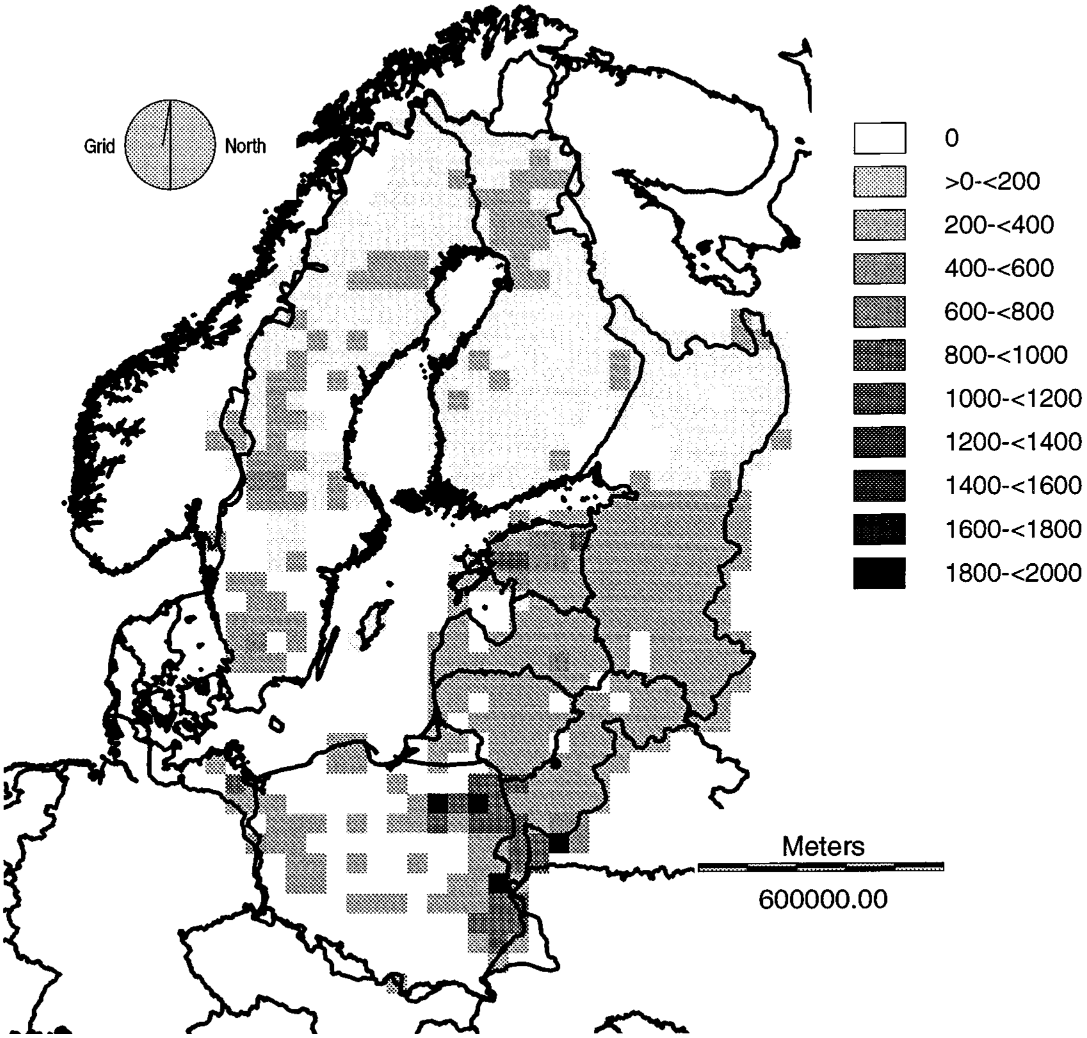

Figure 5b. High range of atmospheric nitrogen deposition entering wetlands. Ton nitrogen grid^{-1} y^{-1}.

Other substantial nitrogen sources in the landscape are leakage from forests and agricultural areas, contributing 104,000 (nitrogen leakage from forests was estimate to approximately 100–235 kg km^{-2} y^{-1} based on Löfgren and Olsson (1990)) and 807,000 ton N y^{-1}(nitrogen leakage from arable land areas was estimated at 400–5000 kg km^{-2} y^{-1} (Elofsson 1997)), respectively. The amounts of this leakage that reach the Baltic Sea are unknown. These sources were not included due to lack of information on basic hydrology and topographical location of both sources (forests and agricultural areas) and sinks (wetlands). If these sources could be included, the amount of annually retained nitrogen by wetlands would presumably increase. However, the location of the wetlands in the landscape strongly influence their capacity to act as nutrient filters (Johnston et al. 1990). A visual assessment of maps indicate that the areas in the drainage basin with high concentration of wetlands are not located near the intense agricultural zones (Sweitzer et al. 1996).

In the following section we will discuss our estimates in relation to nutrient loads, retention capacity, and measures to reduce the eutrophication of the Baltic Sea.

Wetlands located high up in a drainage basin are often thought of as sources rather than sinks. In Sweden, for example, 9.5% of the nitrogen load to the Baltic Sea originates from wetlands, and 88% of those 9.5% are from wetlands located north of the Baltic

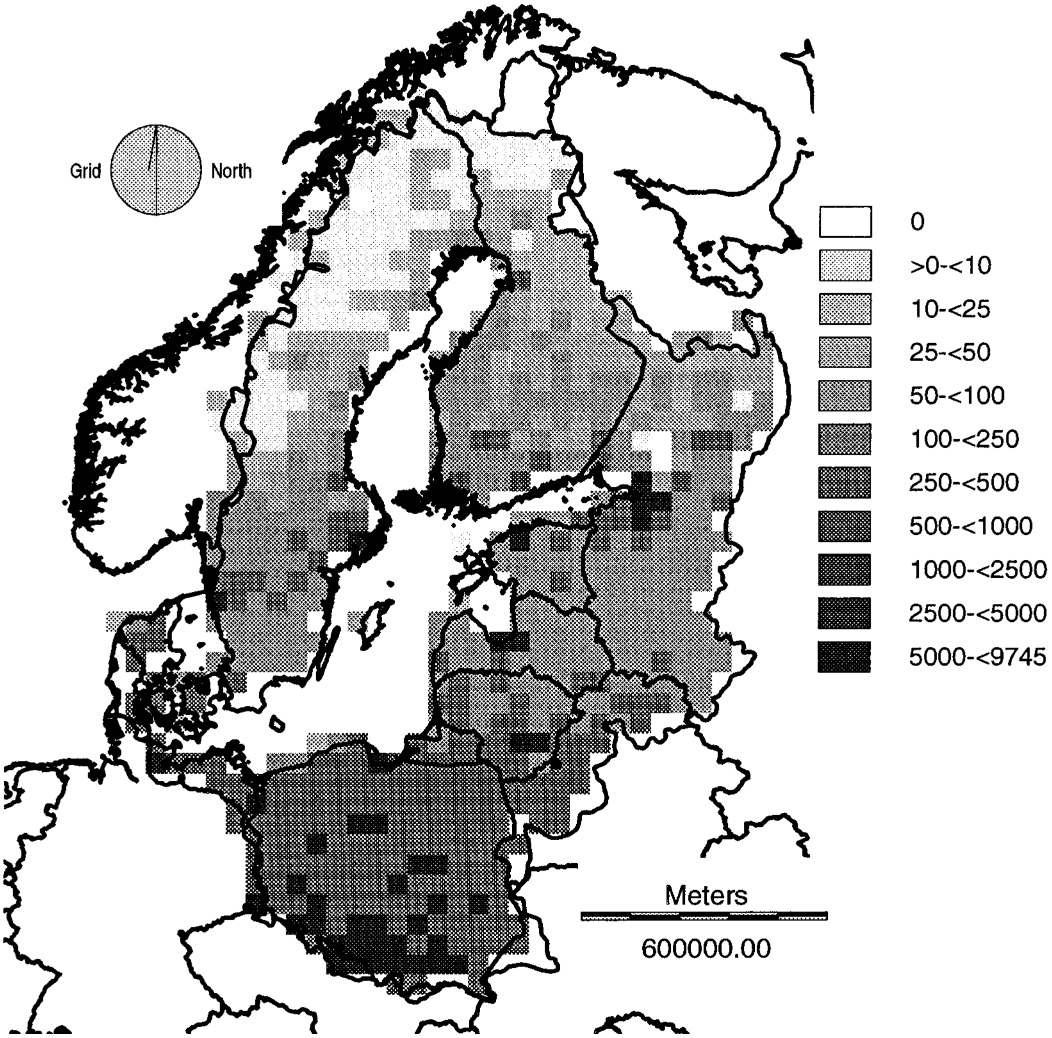

Figure 6. Distribution of anthropogenic direct extretory discharge. Ton nitrogen grid^{-1} y^{-1}.

Proper (Löfgren and Olsson 1990), in areas with low population and agricultural density. We have not been able to distinguish between sources and sinks since it would require information with a much higher resolution than presently available for the region as a whole. Instead we have estimated a range of retention capacities. The load in the first scenario (i) is a conservative estimate including only deposition of atmospheric nitrogen to wetlands in the drainage basin. This is the minimum load that all wetlands actually receive although it varies between the grids. It includes nitrogen emissions to the air from human activities like industry, transportation, and livestock farming. In the second scenario (ii) we add loads of nitrogen in processed sewage water from the human population. It is difficult to judge how realistic this scenario is. In one sense it is an overestimate since we assume that all processed sewage water with excretory release is discharge into wetlands. On the other hand it is an underestimate since we only account for the part of human excretory release that remains in processed sewage water, and since we do not account for leakage from forests and agricultural land.

We set the maximum load allowed to enter the wetlands to 32,000 kg N km^{-2} y^{-1}, since this was the highest load reported in the literature on retention estimates of bogs and fens. We set this limit as we do not know the shape of the regression line above this load value. Fleischer et al. (1991) have argued that the higher the load the higher the nitrogen reten-

Table 3. Drained wetland areas in the Baltic Sea drainage basin. Source is Rydlöv et al. (1991), except for Latvia (Hägerhäll, B. pers. comm.)

Country	Drained wetland area (km^2)	Average N load ($kg\ km^{-2}\ y^{-1}$)[1]
Denmark	1293 (1034)[2]	1519 ± 423
Estonia	3364	797 ± 135
Finland	98215	390 ± 78
Latvia	18	1024 ± 121
Poland	118116	1786 ± 152
Sweden	12235	787 ± 123
Total:	221982	

[1] Average nitrogen load in a country, derived from Iversen et al. (1991), with a 95% confidence interval; [2] As we do not know the geographical location of the drained wetlands, we assume that these drained wetlands when restored will be spread evenly in the country, in order not to overestimate the potential of restored wetlands to retain nitrogen inside the drainage basin. About 20% of Denmark is located outside the boundaries of the basin (derived from Sweitzer et. al.(1996) and WRI (1994)), we thus assume 20% of the restored wetlands will be located outside the boundary of the drainage basin (figure in parenthesis).

tion in wetlands, on an absolute scale. Mander and Mauring (1995) found the regression between load and retention to be linear in wetland ecosystems. They included load levels as high as 1,000,000 kg $km^{-2}y^{-1}$, which is considerably higher than our maximum load. However, their regression is based on load and retention estimates from several wetland types, and several of the investigations do not extend throughout an entire year. Still, the wetlands in the region may have the potential to retain considerably higher loads than assumed here (Fleischer et al. 1991, Mander and Mauring 1995).

Howard-Williams (1985) concludes that the comparative advantage of using wetlands as nutrient sinks lies in their capacity to remove diffuse nutrient runoff at low concentrations. Even if there seems to be no limit to retention on an absolute scale (Fleischer et al. 1991, Mander and Mauring 1995), it may not be as effective to use wetlands to retain or eliminate high concentrations of nutrients. Although wetlands are used to process human wastewater (Etnier and Guterstam 1991, Ewel 1997), sewage treatment plants will always be needed in more densely populated areas.

A political decision has been made to reduce the input of nitrogen to the Baltic Sea by 50%. Several measures are being taken for this purpose, including increasing the capacity to process nitrogen in sewage treatment plants. Existing wetlands in the drainage basin, particularly in the Eastern Europe part, are under pressure from various interests, e.g., expansion of agricultural land. If wetlands are drained the ecological retention service is reduced and ultimately lost (although the subsequent land use may also have a certain potential to retain nitrogen).

To avoid nitrogen leakage to rivers, lakes and ultimately to the Baltic Sea, loss of wetland services are often replaced with fossil fuel-based technologies (Folke 1991b). These technologies have to be built and maintained by an industrial infrastructure in order to provide the nitrogen removal service that wetlands provided for free. However, studies have shown that despite the implementation of these technologies the environmental consequences tend to remain, which implies that such “solutions” often only partly replace wetland services (Folke 1991b). Studies on the economic value of wetland services have been reviewed by Gren and Söderqvist (1994). Cost-efficient measures for reducing the nitrogen load to the Baltic, using wetlands as one of the abatement technologies are analyzed in Gren et al. (in press).

Conclusions

In this article we have estimated a minimum and a potential nitrogen retention service performed by existing and potentially restored wetlands in the Baltic Sea drainage basin. It is a first attempt to quantify the role of a mosaic of wetlands as nitrogen processors in a large-scale drainage basin. The results are derived from several empirical load/retention studies with associated uncertainties. Varying the slope of the regression by plus or minus one standard deviation bring about a 10–15% change in the results.

An effective management of eutrophication of the Baltic Sea needs to account for land use change and other anthropogenic impacts in the entire drainage basin. According to our estimates natural wetlands in the basin can retain an amount of nitrogen corresponding to about 5–13% of total nitrogen emissions entering the Baltic Sea annually. A restoration of drained wetlands could retain an additional 160,000 ton of atmospheric nitrogen deposition in the Baltic Sea drainage basin annually. The ecosystem retention service performed by wetlands accounts for a substantial nitrogen removal, thereby reducing eutrophication of the Baltic Sea. We conclude that the nitrogen retention service of wetlands is of significant value and should be taken into account in decisions on land and water use. The analysis highlights that we need better to understand the mosaic of ecosystems in drainage basins and how they affect and are affected by human activities.

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Appendix 1

Description of variables included in equation 1–8.

Variable	Unit	Description
WA_g	$\mathrm{km}^2\ \mathrm{grid}^{-1}$	Wetland area in a grid
ATMD_g	$\mathrm{kg}\ \mathrm{km}^{-2}$	Atm. deposition in a grid
${}_t\mathrm{ATMD}_g$	$\mathrm{kg}\ \mathrm{grid}^{-1}$	Tot. atm. deposition in a grid
${}_t\mathrm{ATMD}$	kg	Tot. atm. deposition
${}_t\mathrm{RATMD}_g$	$\mathrm{kg}\ \mathrm{grid}^{-1}$	Tot. retained atm. deposition in a grid
${}_t\mathrm{RATMD}$	kg	Tot. retained atm. deposition
ANTD_g	$\mathrm{ton}\ \mathrm{km}^{-2}$	Anthropogenic discharge in a grid
ANTD_{cap}	$\mathrm{ton}\ \mathrm{capita}^{-1}$	Anthropogenic discharge per capita
POP_g		Pop. in a grid
${}_t\mathrm{ANTD}_g$	$\mathrm{ton}\ \mathrm{grid}^{-1}$	Tot. anthropogenic discharge in a grid
${}_t\mathrm{ANTD}$	ton	Tot. anthropogenic discharge
${}_t\mathrm{RANTD}_g$	$\mathrm{ton}\ \mathrm{grid}^{-1}$	Tot. retained anthropogenic discharge in a grid
${}_t\mathrm{RANTD}$	ton	Tot. retained anthropogenic discharge

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