

Nitrogen budgets of the Polish agriculture 1960–2000: implications for riverine nitrogen loads to the Baltic Sea from transitional countries

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Abstract The Oder and the Vistula rivers are responsible for about 25% of the total riverine nitrogen input to the Baltic Sea and of this 60% have been estimated to originate from diffuse sources. In this study we have tested the hypothesis that changes in agricultural practices in Poland have changed the riverine nitrogen export from the rivers Oder and Vistula to the Baltic Sea. We calculated agricultural long-term nitrogen budgets (1960–2000) for the catchments of the Oder and the Vistula rivers.

Poland went through severe economical changes in the early 1990s, which led to a drastic decrease in fertilizer consumption. The role of the calculated nitrogen surplus as an eutrophication capacitor and the potential to reduce this important capacitor to improve the environmental state of the Baltic Sea is discussed. N surplus for the entire country showed a maximum in 1980 ($58 \text{ kg ha}^{-1} \text{ sown area}^{-1}$) and it dropped to $39 \text{ kg ha}^{-1} \text{ sown area}^{-1}$ in 2000. The surplus was, however, up to two times lower than that in other transitional countries, and much lower than in Western Europe with intensive agriculture. An observed decrease in nitrogen concentrations in both Polish rivers is not ascribed to drop in fertilizer use, but it results from nutrient removal in municipal wastewater treatment plants with tertiary treatment facilities. Comparison of trends in nitrogen concentrations in different transition countries indicates that factors other than reduced fertilizer application influenced the inertia of the water quality response. Hence, the potential to reduce diffuse nitrogen emissions from agriculture by reducing fertilization is constricted in areas with low-nitrogen surplus. In transitional countries like Poland the largest potential for nutrient reductions seem to be in improving the connectivity to waste water treatment plants with tertiary treatment.

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Abbreviations

AU	Animal unit
EU	European union
EMEP	Co-operative programme for monitoring and evaluation of the long-range transmission of air pollutants in Europe; http://www.emep.int
FAO	Food and agriculture organization of the United Nations; http://www.fao.org
GDP	Gross domestic product
GNP	Gross national productivity
GUS	Central statistical office of Poland; http://www.stat.gov.pl/english/index.htm
ha	Hectare
HELCOM	Helsinki commission-Baltic marine environment protection commissions; http://www.helcom.fi
MWWTP	Municipal waste water treatment plant
N	Nitrogen
NH ₃ -N	Ammonia
NUR	Nutrient utilization ratio
TN	Total Nitrogen
UNECE/ EMEP	United Nations Economic Commission for Europe/Co-operative programme for monitoring and evaluation of long range transmission of air pollutants in Europe
US	United States
yr	year

Introduction

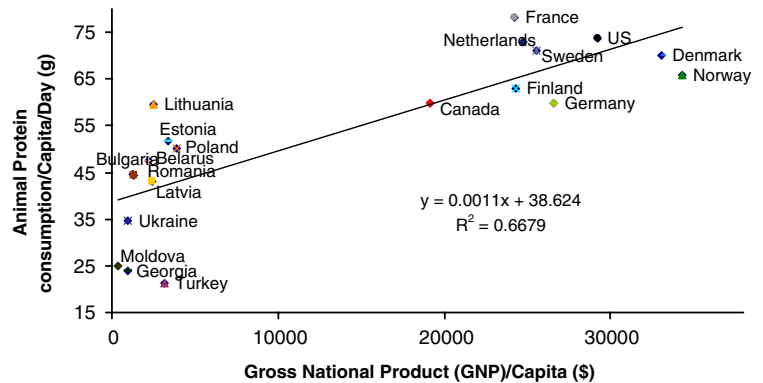
Cultural eutrophication, leading to environmental problems in all kinds of aquatic ecosystems and especially inland seas, has been a hot scientific topic for the last decades. The problem of eutrophication is worldwide and efforts are needed to reduce the nutrient emissions (Galloway et al. 2004). A lot of research has been focused on the causes and effects of eutrophication, the qualitative relationships are well understood (Arheimer et al. 2004; Wassmann and Olli 2004), but quantitative relationships disentangling man made changes from natural changes, is more complex and still not completely known. The load of nitrogen (N) to the Baltic Sea has not changed significantly during the last 20 years (HELCOM 2004) and the load today is estimated to be about

four times higher than a hundred years ago (Larsson et al. 1985) with adverse effects for the brackish ecosystem of the Baltic Sea (Wassmann and Olli 2004).

The inputs of nutrients can be divided into natural sources and anthropogenic nutrient emissions. The anthropogenic emissions can further be divided into atmospheric deposition, point sources and diffuse emissions. Diffuse or nonpoint sources of nutrients, i.e., nutrients from agriculture and managed forestry, are nowadays believed to be one of the largest causes for the eutrophication of our coastal seas (Green et al. 2004) and of the Baltic Sea in particular (HELCOM 2004). The relative amount of nutrients that originate from diffuse sources is increasing since the point sources are easier to manage than nonpoint sources (Carpenter et al. 1998). Agriculture is known to be one of the largest diffuse sources for N and phosphorus to our lakes, streams and oceans (Andersson and Arheimer 2003; Arheimer and Brandt 2000; Behrendt et al. 1999). Large amounts of N are introduced in agriculture as fertilizers, in animal feed but also through the use of N fixing crops. The N surplus that cannot be accounted for in agricultural products either leaks from the agricultural land to air and water or accumulates in the soil. N losses from agriculture occur mainly as nitrate, since nitrate is extremely mobile. N may also escape from agricultural systems via volatilization of ammonia, via N₂ from denitrification, gaseous emissions of nitrogen oxides, and via particulate organic N bound to mineral particles. Large losses of nutrients from agricultural soil are often caused by intensive use of fertilizers, especially in situations when fertilizer use exceeds the nutrient requirements of the crops (Ilnicki 2004; Oenema 1999).

There is a strong relationship between gross national productivity per capita (GNP) of a country and the animal production seen as protein consumption per capita and day (Smil 2002; FAOStat126 2005; WorldBank 1998) (Fig. 1). The protein consumption of a country is in turn a proxy for amount of N used in the agricultural sector. Generally North America and western European countries have higher protein consumption than the transitional economies in Eastern Europe and former Soviet republics. The admission of many countries into the European Union (EU) and the development of stronger economies are likely to lead to a higher

Fig. 1 Correlation between the gross national productivity per capita (*GNP*) and the animal production seen as protein consumption per capita and day for 20 countries in Europe and North America (Data from World Bank and FAO)



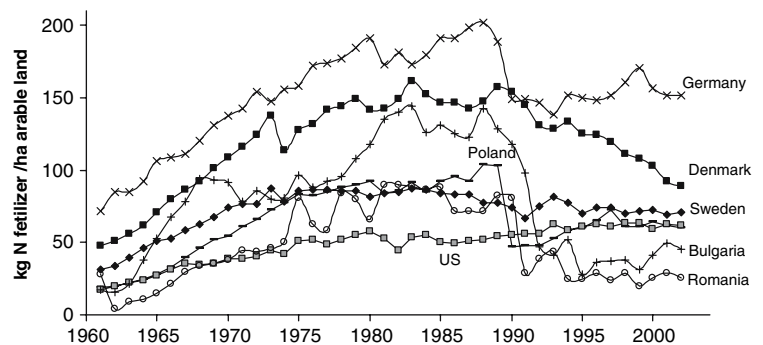
GNP per capita and thereby to a higher demand of N in these countries. This may have severe consequences for the receiving coastal water bodies, especially for the eutrophication sensitive enclosed seas such as the Baltic Sea or the Black Sea. The extensive use of fertilizers started in the 1950s and increased rapidly during the following decades. However, the use of fertilizers varies a lot between different countries depending on agricultural practices (Fig. 2).

The total riverine load of N to the Baltic Sea in 2000 was 706,000 tonnes, of that the Oder River contributed with 53,600 tonnes N per year and the Vistula with 117,000 tonnes per year (HELCOM 2004). Poland is thereby the largest contributor of the riverine N to the Baltic Sea (24%) and about 60% of the N is estimated to originate from diffuse sources (HELCOM 2004). Agriculture has been estimated to be the largest source of N to the Baltic Sea (HELCOM 2004), thus, detailed analysis of this sector is needed, especially for transitional countries where drastic changes in agricultural practices can be foreseen with increasing gross national product (Fig. 2).

Most studies on N budgets for river catchments have been made in North America and western Europe (Bechmann et al. 1998; Boyer et al. 2002; Carpenter et al. 1998; Howarth 1998; Hussian et al. 2004; Kronvang et al. 2005), but such studies are lacking in transitional regions. There are studies, on quantifying the nutrient load from the agricultural land surrounding the Baltic Sea made for Sweden, Finland, Denmark, Lithuania, Estonia, and Latvia (Löfgren et al. 1999; Stålnacke et al. 2003; Vagstad et al. 2001). Although Poland is the largest contributor of nutrients to the Baltic Sea (HELCOM 2004) only a few small scale studies have been made focusing on the N surplus from Polish agriculture (Dzikiewicz 2000; Fotyma and Fotyma 1996; Fotyma and Terelak 1994; Jankowiak et al. 2003). Most of these studies focused only on short time scales during the last 20 years and mainly on smaller river catchments or economical regions.

In this paper, a detailed and long-term analysis of Polish agriculture is presented and it emphasizes how individual agricultural factors in Poland have developed and how they contributed to the N surplus in comparison to the more intensive agriculture in

Fig. 2 Consumption of N fertilizers per hectare arable land ($\text{kg N ha}^{-1} \text{ year}^{-1}$) in Germany, Denmark, Sweden, Poland, Bulgaria, United States, and Romania



western countries. Moreover, trends in point sources, i.e., emissions from municipal waste water treatment plants (MWWTP's), together with trends in river nutrient loads and concentrations are briefly analyzed. The detailed agricultural N-budgets for the two most significant watersheds in the Baltic Sea catchment in terms of nutrient mass fluxes may indicate whether changes in agricultural practices in Poland is a meaningful strategy to reduce riverine N export to the Baltic Sea as often discussed (Behrendt et al. 1999; Jansson and Stålvant 2001). Moreover, the agricultural practices in these mid sized watersheds of the Oder and Vistula may be characteristic for other watersheds in transitional countries.

Materials and methods

Poland: land use and development

Poland has a total area of 312,683 km² and borders the Baltic Sea and Russia in the north, Lithuania, Belarus, and Ukraine in the east, Czech and Slovak Republics in the south, and Germany in the west. Almost 60% of the land is agricultural land, which is mainly characterized by sands and loams, with a mean fertility being less than four times below the EU average (André 2003). The population in Poland has grown from around 25 million in 1950 to almost 39 million in 2000, leading to a population density of 210 persons per km⁻² agricultural land in year 2000 (Table 1).

The climate in Poland is moderate, between the marine and continental. This results in either fairly wet or mild winters, with average monthly temperature of around 0°C, or strong and dry winters, with average monthly temperature of -10°C. A similar

variation in air temperatures and precipitation occurs in the summer season, especially during the vegetation period. Hot and dry summers (with less than 20 mm of rainfall in June, July, and August) may alternate with cold and wet summers with a monthly rainfall up to 150 or even 200 mm. Annual isotherms range between 6.5 and 8.5°C; average temperature in January and June range from -1 to -5°C and 17–19°C, respectively. The lowland region has a vegetation season from 190 to 220 days. Average annual rainfall ranges between 500 and 600 mm. Almost whole Polish territory (99.7%) belongs to the Baltic Sea drainage basin. Most of the land belongs to the large drainage basins of the Vistula River (54%) and the Oder River (34%). The remaining area (12%) consists of small rivers draining directly to the Baltic Sea.

After the World War II, the economy in Poland was reorganized according the model of state socialism. Although the industry became mainly state owned, the agricultural resources remained largely in private hands during the communistic period. The state though influenced the agricultural sector in other ways, e.g., through taxes, controls on materials, and limits on the size of private plots. After the political changes in 1989 a shift in the economical structure occurred, and an extensive reform program followed that in 1990. This program included privatization of all parts of the Polish economy and a rapid shift from the state planning system to market economy. However, the reforms in Poland did not lead to large changes in Polish agriculture since this sector had remained private even during the period with state planning and most of the former state farms were leased to farmer tenants (Ingham et al. 1998; Jankowiak et al. 2003).

Table 1 Basic data on Polish land use (km²) and population (millions)

Year	Total area (km ²)	Agricultural land (km ²)				Forest (km ²)	Other + barren (km ²)	Number of inhabitants (millions)	Inhabitants/ agricultural area (millions km ⁻²)	
		Arable	Orchards	Meadows	Pastures					
1960	312,683	204,000	160,000	3,000	24,000	18,000	77,000	31,000	29.9	146.5
1970	312,683	195,000	151,000	2,000	25,000	17,000	84,000	31,000	32.7	167.1
1980	312,683	189,000	146,000	3,000	25,000	15,000	86,000		35.7	188.6
1990	312,683	187,000	144,000	3,000	25,000	16,000	87,000		38.2	204.0
2000	312,683	184,000	141,000	3,000	26,000	15,000	89,000		38.6	209.9

The average farm size in Poland is generally about 7 ha and the private sector manages as much as 92% of the total arable land (Ilnicki 2004). During the last 15 years there has been a tendency to polarization in the agricultural sector decreasing the number of mid-sized farms (2–15 ha) and increasing the large farms (>50 ha) (André 2003). The agricultural sector in Poland contributes to 4% of the total GNP and represents to varying degrees ~25% of total employment in Poland, which is high compared to the EU average of 5% (EUROSTAT 2005; Karaczun 2005).

Poland is a net exporter of confectionery, processed fruit and vegetables, meat, and dairy products. The process industry though often relies on imports to supplement domestic supplies of wheat, feed grains, vegetable oil, and protein meals, which are generally insufficient to meet the domestic demand. However, Poland is a leading producer in Europe of potatoes and rye and is one of the world's largest producers of sugar beets. Poland is also a significant producer of rapeseed, grains, and meat. Attempts to increase the domestic feed grain production are hampered by the constraints in the agricultural sector, e.g., farm size (Dzikiewicz 2000; FAOStat 2005; Sapek 1997). Polish agriculture can be regarded as relatively low productive in comparison to many other countries. The mean milk production per cow is for example around 3,600 kg cow⁻¹ in Poland compared to around 7,000 kg cow⁻¹ in Sweden.

Data sources and nutrient budget calculations

The N budget, presented in this paper, is a mass calculation and it consists of inputs, understood as a mass transport into the system, and outputs, understood as a mass transport from the system. The difference between N input and N output is called surplus. The total amount of N added per hectare (ha) sown area was calculated from the addition of N from four different sources, i.e., mineral fertilizers, atmospheric deposition, biological fixation, and agricultural import. The total N removed from a ha sown area was calculated as the sum of the N removed as agricultural export, human consumption, ammonia emissions (from manure, mineral fertilizers, and plants) and N runoff (Fig. 4). Most of these data were available on a regional scale, i.e., for voivodships in the Statistical yearbooks of Poland (GUS 1960–2002), but some data were only available on a

country level from the FAO database (FAOStat 2005). In order to achieve the necessary data for the budgets per watershed, the statistical data were fitted to the agricultural areas of the river catchments using GIS. Poland has been re-divided on the regional scale two times since the beginning of our study period, in 1975 and then again in 1998, thereby leading to regional data for three different sets of spatial regions (Fig. 3).

The N surplus per ha sown area was calculated as the difference between the total N added and the total N removed. The surplus N is either denitrified or accumulated in the soil, with the latter having potential to increase N runoff in the future. We did no further assumption on which part of the N is denitrified or accumulating and, hence no estimates on N₂, N₂O, and NO_x emissions are given. We also calculated the Nutrient Utilization Ratio (NUR), i.e., the N removed by human consumption and agricultural export divided by the total amount of N added. The NUR is a measure of the efficiency of the N used in the system for producing food (Table 4). All calculations were done in kilogram per ha sown area.

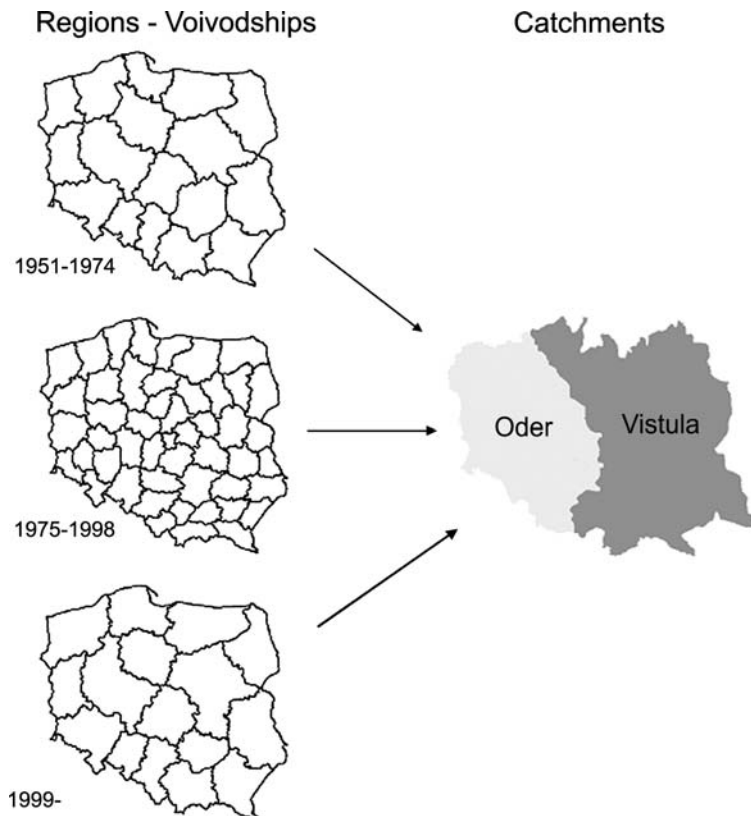
Deposition

The atmospheric N deposition (wet and dry; reduced, and oxidized N forms) used originates from the UNECE/EMEP emission database. The EMEP data on annual N deposition over the Baltic Sea catchment are available on a subcatchment scale from 1980 onwards (<http://www.mare.su.se/nest/>). The N deposition data for 1960 and 1970 were calculated after Granat (see Wulff et al. 2001) who estimated temporal trends in atmospheric deposition in the Baltic Sea area. The mean deposition of the period 1980–2000 was used as a reference period and the deposition in 1960 and 1970 was assumed to correspond to 0.4 and 0.85 times the mean deposition during the reference period.

Mineral fertilizers

The data used for the calculations were taken mainly from the Statistical Yearbooks of Poland (FAO and Fotyma 2003; GUS 1960–2002). These data are available for the whole country as well as on a regional level by province, i.e., voivodship. In order

Fig. 3 GIS fitting scheme between administrative boundaries, i.e., voivodships, in Poland from which major statistical data have been taken and the catchments of the Oder and Vistula. The voivodships have been changed two times during the study period



to obtain the data for the river catchments instead of economical regions, the regional data were assumed to be normally distributed with respect to agricultural area, then fitted and referred to the agricultural areas of the Oder and Vistula catchments using GIS (Fig. 3).

Biological fixation by plants

The biological fixation was calculated using data on harvested quantities (tonnes) and sown area (ha) of leguminous plants (pulses) and trefoil from Statistical Yearbooks of Poland (GUS 1960–2002). The biological fixation was estimated to $40 \text{ kg ha}^{-1} \text{ year}^{-1}$ for pulses and $150 \text{ kg ha}^{-1} \text{ year}^{-1}$ for trefoil (Smil 1999).

Agricultural import and export

The agricultural import and export was calculated from food balance sheets for Poland provided by the FAO (FAOStat 2005). The data were only available on country level, thus numbers for the river catchments had to be distributed with respect to distribu-

tion of animal stocks within the river catchments. The items accounted for and the respective N content in the imported and exported products (Smil 1999) used for the calculations are given in Table 2.

Human consumption

The human consumption was estimated from the utilized food estimation given in the FAO food balance sheets for Poland (FAOStat 2005). The data were only available on country level, thus the data were divided and fitted to the river catchments with respect to the distribution of the human population. The items accounted for and the respective N content (Smil 1999) used for calculations are given in Table 2.

Ammonia emissions

Ammonia emissions from manure were calculated from animal stocks. Data were available on a regional level, per voivodship, and were matched to the catchment areas using GIS (Fig. 3). The total N

Table 2 Nitrogen content in the items used in the calculation of import and export of agricultural products and in the calculation of human consumption (X = item used in calculation)

Item	Imported/ exported	Human consumption	N content (%)
Wheat	X	X	2.0
Barley	X	X	1.7
Rye	X	X	1.7
Oats	X	X	1.8
Cereals, Other		X	1.8
Soybeans	X		2.0
Potatoes		X	0.35
Maize	X		1.2
Sugar (raw equivalent)		X	0.2
Sorghum	X		2.0
Beans	X	X	2.0
Peas	X	X	3.5
Tomatoes		X	1.0
Onions		X	1.0
Vegetables, other		X	1.0
Meat	X	X	2.9
Milk and milk products	X	X	0.5
Eggs	X	X	2.0
Animal fats	X	X	2.9

excretion of the various animal types (Table 3) were estimated based on the production level (Bleken and Bakken 1997; Claesson and Steineck 1991). The relative amount of ammonia in manure varies between 25 and 50%. It was further assumed that between 7 and 12% of this ammonia is lost to the atmosphere through ventilation in stables, 15–25% during storage and 50% through spreading of manure, dependent on the animal types (Table 3) (Claesson and Steineck 1991; Ferm et al. 2005).

Table 3 Estimated losses of ammonia from animals and agricultural practice in Poland

Animal	N excretion per animal and year (kg N animal ⁻¹ year ⁻¹)	Amount NH ₃ -N of total (%)	NH ₃ -losses to the atmosphere (%)		
			Ventilation in stables	Storage	Spreading
Dairy cows	50	25	-7	-25	-50
Cattle excl dairy	35	25	-7	-25	-50
Total pigs	10	50	-12	-15	-50
Poultry	0.6	25	-10	-25	-50

Ammonia emissions from plants were estimated to 4 kg N per ha⁻¹ year⁻¹ for all years (Claesson and Steineck 1991). The emissions of ammonia to air from mineral fertilizers were estimated to increase from 0 to 2 kg N per ha⁻¹ year⁻¹ (Claesson and Steineck 1991).

Agricultural runoff

Data on agricultural runoff were estimated using monthly data on riverine TN load measured at river mouth and these data were obtained from the Baltic Environment Data Base (BED) managed by the Stockholm University (<http://www.mare.su.se/nest/>). 30% of the riverine N load in Poland was assumed to originate from point sources and diffuse sources other than agriculture (HELCOM 2004) while the remaining 70% was assumed to stem from the agricultural runoff. The load per sown area was then calculated assuming normal distribution. The data on riverine TN concentrations for 1960 were not available, therefore the N loads for this period had to be estimated by assuming a N concentration of 1 g N m⁻³, which is a typical pre-industrial concentration for agricultural dominated river systems with extensive farming (Schernewski and Neumann 2005).

Robustness of the nutrient balance calculations

The parameters in the budget calculations vary in the robustness of the estimations. The estimates of mineral fertilizers, biological fixation, and the human consumption are relatively certain, since these data are based on detailed regional annual statistics; the N deposition data derived from the EMEP model have been validated. The input and output of N through agricultural import and export are more uncertain

Table 4 Nitrogen budgets and animal density for the catchments of Oder and Vistula and Poland

Kg N ha ⁻¹ sown area year ⁻¹	Oder					Vistula					Poland				
	1960	1970	1980	1990	2000	1960	1970	1980	1990	2000	1960	1970	1980	1990	2000
N added															
Mineral fertilizers	23	61	86	87	60	21	57	63	59	44	22	58	71	68	51
Deposition	7	15	21	19	14	6	13	18	17	11	7	14	19	18	12
Biological fixation	6	7	9	8	16	6	7	9	8	16	6	7	9	8	16
Agricultural import (mainly for feed)	3.3	3.4	10.2	2.0	3.4	3.5	3.5	9.0	2.0	3.1	3.3	3.4	9.5	2.0	3.4
Total N added	40	87	126	117	94	37	81	99	86	74	38	82	109	96	83
N removed															
Agricultural exports	0.8	0.8	1.1	1.3	1.5	0.9	0.8	1.0	1.2	1.4	0.8	0.8	1.0	1.2	1.5
Human consumption	14	17	19	19	21	13	15	18	18	20	13	16	18	18	21
Ammonia emissions from															
Manure	6.9	8.5	12.0	9.8	8.5	7.2	8.5	10.6	9.5	7.4	6.9	8.2	10.5	8.9	6.5
Mineral fertilizers	0	1	2	2	2	0	1	2	2	2	0	1	2	2	2
Plants	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
N runoff	3.2	10.9	14.7	6.0	10.4	3.6	14.6	17.8	6.3	10.3	3.5	11.7	14.7	5.4	9.2
Total N removed	29	42	53	42	48	29	44	54	41	45	28	41	50	40	44
N Surplus (added-removed)	11	44	73	75	46	8	37	45	45	29	10	41	58	56	39
NUR (%)	38	21	16	17	24	37	20	19	23	29	36	20	18	20	27
Animal density (AU ha ⁻¹ sown area)	0.36	0.43	0.55	0.43	0.34	0.38	0.43	0.49	0.44	0.33	0.37	0.43	0.52	0.44	0.36

since these numbers are based purely on import and export from and to Poland and not on actual flows in and out of the catchments. We might thereby distribute these numbers in somewhat skewed way between the catchments.

The N runoff in kilograms per ha sown area is difficult to estimate exactly since there are regional differences due to variations in soil types and rainfall. Here we used the agricultural share of the river mouth output of N as a base for the calculations and thereby we believe that we get a good approximation for the entire catchments. The N runoff for 1960 is somewhat more uncertain since no measured data are available that far back in time (Table 4).

Trends in point sources and TN concentrations

Trends of the N concentrations between 1986 and 2003 from the two rivers, Oder and Vistula (<http://www.mare.su.se/nest/>), were investigated by applying locally weighted regression analysis, i.e., lowess (Cleveland 1979). This method provides a fast and robust fitting of the data, even if the spacing between

observations is not constant. In this study the fit was carried out in MINITAB 14. Two parameters have to be set, that is the number of iterations and how many points there should be included in the fitting of the regressions. The number of iterations were set to two (2) as recommended by Cleveland (Cleveland 1979) in order to filter outliers in the best possible way. The number of points was set to 0.4 (or 40% of the points).

Results

Mineral fertilizers

The use of mineral fertilizers, the most significant N input variable of the agricultural sector, increased rapidly in the catchments of the Oder and Vistula from the late 1960s to the mid-1970s (Figs. 4, 5, Table 4). In the 1970s and 1980s the annual fertilizer consumption stabilized at 85 kg N per ha sown area in the Oder catchment, and at 60 kg N per ha sown area in the Vistula catchment. The N fertilizer

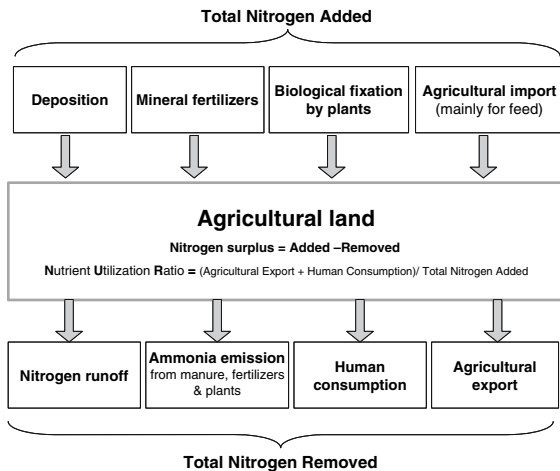


Fig. 4 Schematic presentation of the budget approach

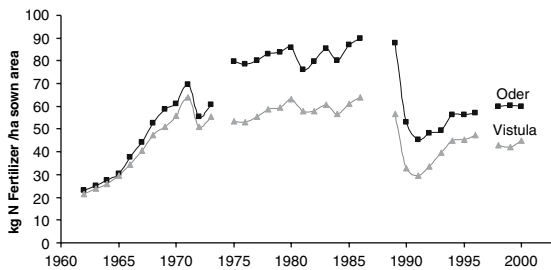


Fig. 5 The yearly consumption of nitrogenous fertilizer (kg N ha^{-1} sown area year $^{-1}$) in Oder and Vistula from 1962 to 2001

consumption was considerably higher in the Oder than in the Vistula catchment, the difference reaching even 30 kg N ha^{-1} sown area in the 1980s. The trend was the same till the present time but the difference dropped to some $15\text{--}20 \text{ kg N ha}^{-1}$ sown area over the last decade studied. Over the last decade there is a slight upward trend in fertilizer consumption but the amount of nitrogen applied in this form is still about $40\text{--}50 \text{ kg N per ha}$, thus it remains on the level of values recorded the late 1960s.

Plant and animal production

The total area used for agriculture decreased from 45.7 to 40.6% over the period 1960–2004, while the crop composition underwent some changes (Fig. 6a, b). The changes concerned in the first place the drop in the area of potato (the area halved over the period studied), but also rye. The rye area dropped consid-

erably but it was partly compensated by increasing area of wheat and by appearance of triticale in 1987.

The cattle stocks in Poland were increasing in the Oder and the Vistula catchment over the period 1960–mid-1970s, and in the 1970s production of these animals was at its peak. Thereafter, the stocks of cattle showed a decreasing trend. The pig stock in the Oder catchment showed an overall increasing trend, while in the Vistula catchment the overall increasing trend up to the 1970s was then followed by up and down tendencies (Fig. 7a, b). The animal density per ha sown area increased from 1960 to 1980 and then decreased again to 2000. The mean animal density was $0.42 (\pm 0.05)$ Animal unit (AU) ha^{-1} (Table 4).

Agricultural N runoff

The riverine load of N measured at river mouths of the Oder and the Vistula have not changed markedly since the early 1980s (Fig. 8), although lowest values have been observed within the last few years. The N output is mainly controlled by the runoff as shown in Fig. 9, where the monthly loads of N during the period 1986–2004 from the Oder and the Vistula are plotted against the runoff.

Nutrient budgets

The results of the N budget calculations for the agricultural areas within the catchments of the Oder, Vistula, and for Poland as a whole are shown in Table 4. Generally, the dominating input of N to agricultural land in Poland and in both watersheds is the fertilizer use, while the second largest addition is through atmospheric deposition. Note that in 2000 the biological fixation exceeded the inputs via atmospheric deposition due to decreasing trends in deposition and increasing use of leguminous plants and trefoil. When it comes to N removal, the largest output of N was through human consumption, ammonia emissions from manure and N runoff; agricultural export was not significant to the N budget. The annual N surplus, calculated for the entire country, ranged between 10 and 58 kg per ha-sown area. It showed an increasing trend from 1960 to 1970; in 1980 and 1990 it was highest and stable ($56\text{--}58 \text{ kg per ha}^{-1}$ sown area), and then in 2000 it decreased significantly, down to $39 \text{ kg per ha-sown}$

Fig. 6 Temporal trends in 1,000 ha of cereals (barley, wheat, rye, oats, and triticale), potatoes, sugar beets and rape and agrimony grown in the catchments of (a) the Oder and (b) the Vistula from 1962 to 2001

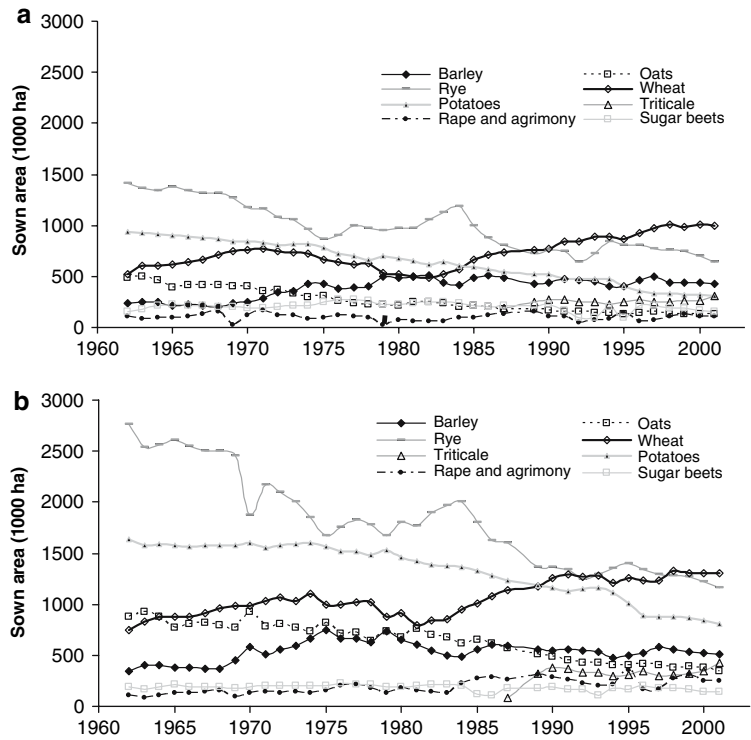
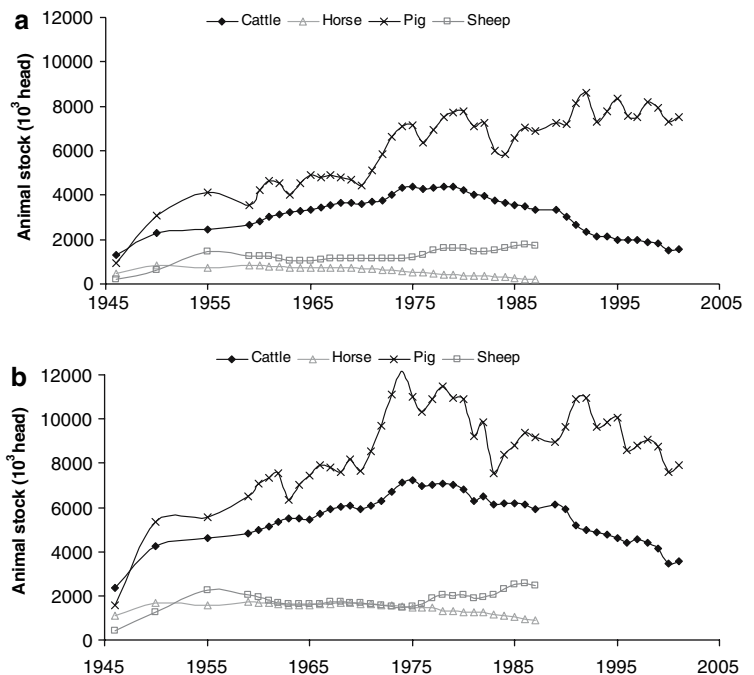


Fig. 7 Temporal trends in animal stock (in 1,000 heads) of cattle, horses, pigs, and sheep in the catchments of (a) the Oder and (b) the Vistula from 1962 to 2001



area. The overall tendency in annual N surplus was the same in the Oder and Vistula catchments, with Oder numbers being all the time higher (even by

30 kg per ha-sown area) (Table 4). NUR, calculated for the entire country, ranged between 18 and 36% during the investigated period, with the highest ratio

Fig. 8 Monthly riverine load of TN (tonnes) at the river mouth of the Oder and the Vistula 1986–2004

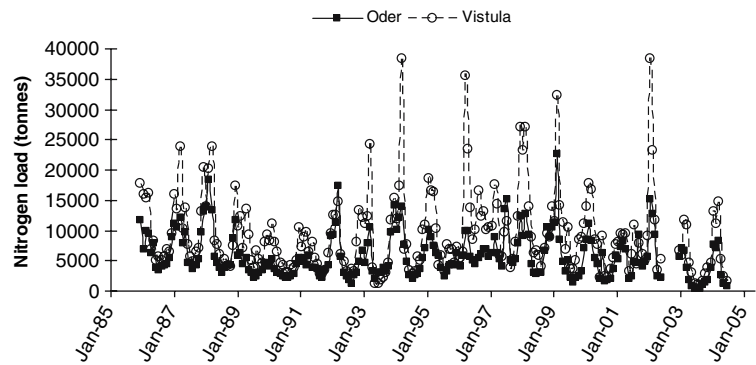
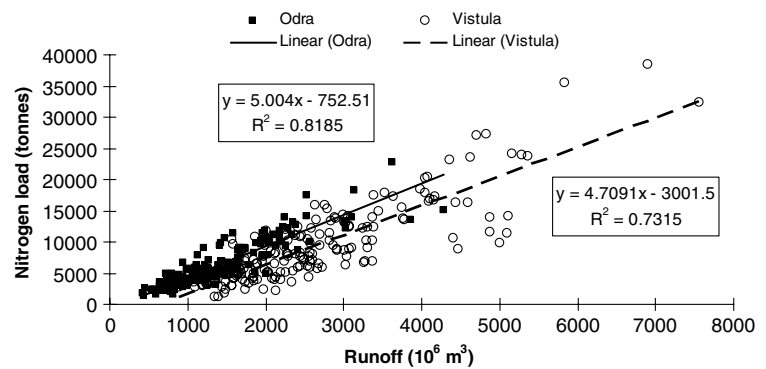


Fig. 9 Monthly riverine load of TN (tonnes) versus runoff (10^6 m^3) at the river mouth of the Oder and the Vistula 1986–2004



in 1960 and the lowest one in 1980 (Table 4). The NUR percentages, as well as tendencies in temporal NUR changes in the Oder and Vistula catchments, were similar to those for the entire country.

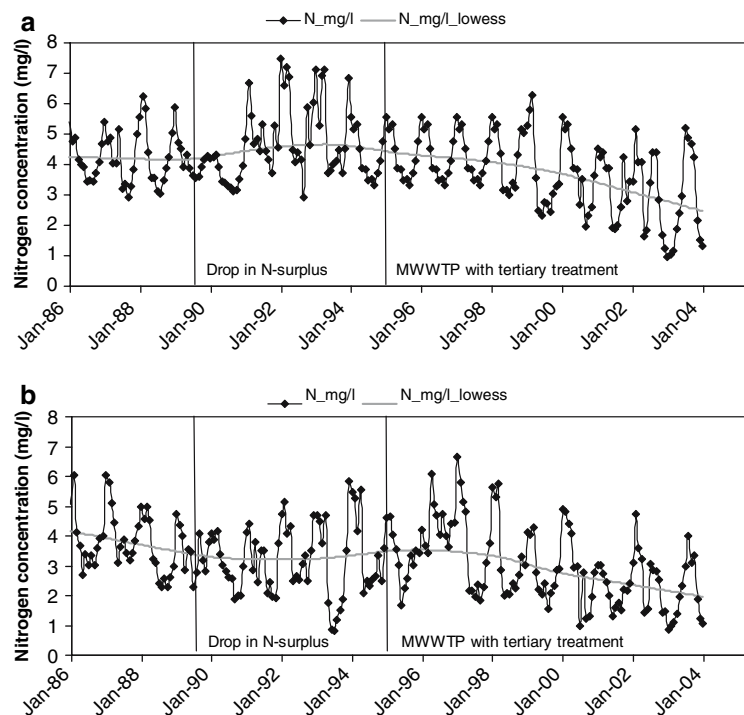
Trends in point sources and TN concentrations

Municipal waste water treatment plants with tertiary treatment were built in the 1990s in Poland and the percentage of the population connected to urban MWWTP increase gradually from 4% in 1995 to 31% in 2003. MWWTPs with secondary treatment remained relatively unchanged, whereas MWWTPs with primary treatment decreased due to modernization. N excretion per capita and year in Poland was about 6.1 kg year^{-1} , calculated from the human consumption data for Poland (FAOStat 2005). Cleaning of these human emissions from about 12 million people connected to MWWTPs by 75% (ARGE 2001) corresponds to a decrease in the order of 55,000 tonnes N year^{-1} . In 2000, about 13.7 million people lived in the catchment of the Oder and about

21.1 million people lived in the Vistula catchment. If we assume that the trends in urban emissions followed population density patterns, and if they hold also for the catchments of the Oder and the Vistula, then the decrease in N emissions to the Vistula and the Oder from MWWTPs could be of an order of 30,000 and 20,000 tonnes year^{-1} , respectively.

Before the changes in agriculture and the installation of tertiary treatment of urban sewage, the mean TN concentration in the rivers of the Vistula and Oder were 3.7 and 4.2 mg l^{-1} , respectively (Fig. 10a, b). In the period between 1990 and 1995, i.e., after the drop in N surplus of the agricultural sector, the mean TN concentrations slightly decreased in the Vistula to 3.3 mg l^{-1} or even increased to 4.5 mg l^{-1} in the Oder. After the installation of MWWTPs in 1995 the TN concentrations decreased to the lowest values recorded within the entire observation period. Between the years 1995 and 2003 the mean concentrations in the Vistula were 2.8 mg l^{-1} and in the Oder 3.6 mg l^{-1} (Fig. 10a, b).

Fig. 10 Monthly riverine TN concentration (mg l^{-1}) in (a) the Oder and (b) the Vistula 1986–1994



Discussion

N emissions from agricultural soils in Poland: a relatively constant source for decades?

Nitrogen emissions from agricultural soils is globally one of the main threats to aquatic systems (Galloway et al. 2004; Green et al. 2004) and in particular it is a major environmental variable responsible for the largest part of the riverine N loads to the Baltic Sea, which is most sensitive to cultural eutrophication. The question appears how manageable this major N source is in terms of possible reductions, which was suggested by for example Behrendt et al. 1999 and Jansson and Stålvant 2001. Our detailed N surplus analyses of the agricultural sector indicate that even drastic changes apparently did not lead to rapid reductions in N concentrations. No decrease in N concentrations or N loads has been observed in Oder or Vistula 6 years following the drop in the most significant input variable to the N budget, i.e., the use of N fertilizers. Similar results were found for 14 Estonian and four Latvian rivers 4 years after the drop in N surplus at national level from about 70 to

zero kg N per hectare sown area (Löfgren et al. 1999). It is argued here that one possible reason for the lacking riverine response might be that the N surplus in the Oder and Vistula catchments, which ranged from 8 to 75 kg N per ha sown area, similarly to what was observed in the Estonian and Latvian catchments was much lower than in many other watershed of cultivated areas of the Baltic Sea catchment with more intensive N use. It might be even inferred from our results that N emissions from agricultural soils in Poland was quite constant over time similar to something observed for the Swedish agriculture (Hoffmann et al. 2000). Thus, the contribution of diffuse N sources from agriculture to the observed deterioration trends of the Baltic Sea ecosystem might have been overestimated (Behrendt et al. 1999; HELCOM 2004; Jansson and Stålvant 2001).

It is evident though that an immediate response in N concentration as a response to a drop in N surplus has been observed in catchments where the calculated N surplus was much higher than in Poland. In the adjacent Elbe river in Germany, with similar size and geophysical settings as the catchments of the Oder

and the Vistula, the N surplus dropped from about 140 to 20 kg ha⁻¹ (Hussian et al. 2004) and in Denmark the N surplus dropped from about 130 to 80 kg ha⁻¹ (Kronvang et al. 2005). In both cases the drop in N surplus led to significant reductions in riverine N concentrations. The fertilizer use within the catchments of many small Estonian rivers in the most intensively cultivated regions was as high as 200 kg ha⁻¹ (Iital et al. 2003). After the economical changes in 1989 and 1990 it dropped to a level less than 50 kg, thus obviously changing the N surpluses of the agriculture in these catchments. N concentrations in all these rivers dropped from about 6–15 to 4–8 mg l⁻¹ (Hussian et al. 2004; Iital et al. 2003; Kronvang et al. 2005) and a significant part of these reductions can obviously be related to changes in the agriculture that lead to reduced N emissions especially from tile drainage (ARGE 2001). This was especially valid for the Estonian river catchments with low-population density of 2–30 inhabitants per km² (Iital et al. 2005) and hence low inputs from point sources. In fact, the mean N concentrations of the Oder (about 4 mg l⁻¹) and the Vistula rivers (about 3 mg l⁻¹) are low compared to other well known eutrophic rivers draining cultivated watershed within Europe with much higher fertilizer use such as the Thames, Rhine, Seine, and Elbe that all have concentrations between 5 and 8 mg (Meybeck 2001).

A much more promising way to reduce N loads appears to be the reduction of point sources. Poland has done tremendous efforts to improve cleaning of urban sewage, however, there is still a huge potential to lower emissions from point sources since some 20 million people in Poland are still not connected to modern MWWTPs. Interestingly, the drop in riverine N concentrations observed in the Vistula, from about 3.5 mg N l⁻¹ before the installation of tertiary treatment to about 2.8 mg l⁻¹ after the installation, can be entirely explained by the reductions in urban emissions. A reduction of 30,000 tonnes N annually corresponds to about 1 mg l⁻¹ decrease in TN concentrations in the Vistula River that has some 31 km³ annual discharge. The same holds for the Oder River, where the reductions due to improved MWWTPs were in the order of 20,000 tonnes. The annual mean discharge for Oder are 18 km³ leading to a theoretical reductions of 1.1 mg N l⁻¹, which can be compared with the drop in TN concentrations after the onset of tertiary cleaning of urban sewage from

about 4.4 to 3.6 mg N l⁻¹. These first large scale estimates on the role of urban point source reductions in Poland for the observed decrease in N concentrations corroborate the hypothesis that N emissions from agricultural soils have not changed significantly and that these emissions even after 14 years after the changes in agricultural practices remained unchanged.

Agricultural practices in transitional countries

Although the N surpluses in the agricultural areas within the watersheds of the Oder and Vistula and possibly in many other watershed of transitional countries are much lower compared to those in the 15 EU founder countries (Campling et al. 2005), there are still potentials to reduce the N emissions to the environment; the lower N surplus is mainly a result of lower fertilizer use in transitional countries (Fig. 2). However, one example for possible reductions of N emissions from agricultural soils is the storage and handling of manure. As argued by Iital et al. (2005), the main reason for the observed decrease in N concentrations of 20 Estonian rivers immediately after the changes in agricultural practices was the drop in organic and inorganic fertilizers. In Estonia most of the agricultural land belonged to big state owned farms and when the economy collapsed in 1989 these state owned farms were slowly being replaced by private owned farms. Simultaneously, the market for export of meat products to the former Soviet Republic collapsed in the Baltic States leading to a large decrease of animal stocks. Before the political changes, livestock contributed to the N surplus of the agriculture in the Baltic States to a much larger extent (Löfgren et al. 1999) than in Poland. Later on, Estonia introduced one of the most advanced regulations in the Baltic Sea region to prevent leakage from manure and these regulations covered the obligatory manure containers, the animal densities and the manure spreading (IEEP 2003a, b, c, d, e) Thus, the contribution of organic fertilizers (manure) could have been significant for the riverine N export of the Estonian watersheds to the Baltic Sea before the political changes, and it will be a challenge to investigate how much of the decrease in riverine N concentrations can be related to the reductions of organic versus inorganic fertilizers. In Poland, most agricultural land belonged to private landowners and,

thus, livestock was more evenly distributed over the country. The economical changes did thereby not affect the agricultural structure in the same way as it did in the Baltic States. It is estimated that 95% of livestock farms in Poland stored manure directly on the ground (Sapek 1996). Although Poland will introduce regulations on manure handling and storages in 2008 (IEEP 2003a, b, c, d, e) its effect will be probably less than in Estonia due to the lower animal density.

Outlook

Many people have argued that the transitional countries around the Baltic Sea, and especially the Polish agriculture, are responsible to a significant extent for the deterioration of the Baltic Sea (Gren et al. 1997; HELCOM 2004). Although there are potentials to decrease N emissions from agricultural soils through advanced handling of manure, the N use in agriculture is more likely to increase than decrease (Sapek 1997). The overall agricultural practices in these countries, expressed in N surplus, are not as N demanding as observed in the 15 EU founder countries or in the more intensively cultivated regions of the US where much more protein is consumed. There have been and still are hot spots of intense agricultural practices in these transitional countries; however these hot spots are not significant in terms of riverine mass fluxes to the Baltic Sea. As an example, a decrease in organic and inorganic fertilizer inputs from some intensively cultivated catchments in Estonia driven by political changes gave an immediate response and lowered the riverine N exports to the Baltic Sea. The relatively low-N surplus in the river catchments of Oder and Vistula, and its development over time, is probably more representative for a much larger part of the agriculture within transitional countries around the Baltic Sea than the development of the N surplus in the most intensively cultivated parts. N surplus as an eutrophication capacitor has probably a very limited bearing for potential reductions of riverine N exports in these regions compared with other management measures besides N fertilization. The aim for the agricultural society in Poland and other “new” member states in the EU is to make the agricultural production more efficient. This will probably be achieved by increasing the size of the farms as well

as modernizing and increasing the use of fertilizers (Sapek 1997). A more modern type agriculture will be introduced to meet the demands EU legislation and the Nitrates Directive (91/676/EEC) (Karaczun 2005) with improved manure handling and the use of catch crops to prevent N emissions. However, if these measures in conjunction with other management improvements cannot cope with the increased use of nitrogenous fertilizers, an increase in diffuse N emissions from agriculture can be foreseen for large parts of the Baltic Sea catchments. The total leakage from agriculture might though decrease through lower leakage from agricultural “point sources” such as storage of manure. Today, the largest potential to reduce N loads from Poland to the Baltic Sea appears to be the better management of urban point sources. However, these potential huge reductions may be rather quickly compensated by a much more N intensive agricultural type as found in the 15 EU founder countries or in more intensively cultivated regions of the US. Further detailed analyses are urgently needed to explore the contribution of point sources (urban emissions) versus diffusive sources (organic and inorganic fertilizers) and their future perspectives that may compensate each other in the near future in terms of N emissions into aquatic environments in many transitional countries. N concentrations in two of the most vulnerable seas for nutrient emissions, the Baltic Sea and the Black Sea, would remain unchanged for a long time perspective.

Coupled hydrological-biogeochemical models as for example the Riverstrahler model (Billen et al. 1994), the MONERIS model (Behrendt et al. 1999) or the GWLF model (Haith and Shoemaker 1987; Swaney et al. 1996) are capable to address N fluxes at a catchment scale and to estimate the role of point sources versus diffusive sources. However, these model exercises should ideally be validated by $\delta^{15}\text{N}$ stable isotope signatures (Mayer et al. 2002) that may serve as a helpful tool for the identification of different N sources and will allow to follow the path of N emissions to the sea along the aquatic continuum.

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