Biogeochemistry **57/58:** 387–403, 2002.

Nitrogen budgets for the Republic of Korea and the Yellow Sea region

V.N. BASHKIN[1,2,*], S.U. PARK[1], M.S. CHOI[3] & C.B. LEE[3]
[1]*Department of Atmospheric Sciences, Seoul National University, Seoul, Republic of Korea;* [2]*JGSEE, School of Energy and Materials, KMUTT, 91 Pracha-uthit Rd, Rasburana, Tungkru Bangkok 10140, Thailand;* [3]*Department of Oceanography, Seoul National University, Seoul, Republic of Korea (*author for correspondence, corresponding address: Geography Faculty, Moscow State University, Vorobyovy Gory, Moscow 119899, Russia, e-mail: bashkin@rc.ru)*

Key words: anthropogenic loading, biogeochemical cycling, Korea, nitrogen deposition, Northeast Asia, regional budget

Abstract. Growing populations in northeast Asia have greatly altered the nitrogen cycle, with increases in agricultural production to feed the population, and with increases in N emissions and transboundary air pollution. For example, during the 1900's over 50% of the N deposition over Republic of Korea was imported from abroad. In this paper, we present biogeochemical budgets of N for the South Korean peninsula (the Republic of Korea) and for the Yellow Sea region. We quantify N inputs from atmospheric deposition, fertilizers, biological fixation, and imports of food, feed, and products. We quantify outputs in riverine export, crop uptake, denitrification, volatilization, runoff, sedimentation and sea water exchange. Calculations were conducted using mean values from 1994–1997. All of the nitrogen budgets were positive, with N inputs exceeding outputs. The excess N inputs gave rise to increases in N storage in landfills and in groundwater. Annual accumulation of N in the Yellow sea, including inputs from South Korea and other drainage areas, was 1229 kt yr^{-1} with a residence time for N of approximately 1.5 years, thus doubling N content in marine waters every 3 years during 1994–1997. The human derived N inputs leads to excessive eutrophication and pollution of the Yellow Sea.

Introduction

The estimation of regional fluxes of pollutants provides a powerful tool for understanding changes associated with human activities. Several examples of regional-scale N budgets include studies of N cycling in the North Atlantic Ocean and its watershed (Howarth et al. 1996) and in the Mediterranean watershed (Bashkin et al. 1997). The modification of the nitrogen cycle by humans has been well documented (e.g. Howarth et al. 1996). Nitrogen (N) is a key element of many biogeochemical processes and can be both a nutrient limiting the productivity of terrestrial and aquatic ecosystems and a pollutant where excessive accumulation in biogeochemical food chains leads to many environmental problems. The main anthropogenic sources of N pollution are related to fertilizer application, waste production and emission of gaseous species.

Modern projections suggest that large increases in emissions may occur during the next 25–50 years in East Asia associated with planned development patterns. Estimates assuming the current growth rate of energy consumption predict that N emissions in East Asia will surpass the emissions of North America and European combined by the year 2020. The primary man-made source of acidifying and greenhouse compounds in East Asia is fossil fuel of low quality, with high content of sulfur (up to 7% in Thai lignite, Chinese brown coal etc.) and heavily oil. The multiple effects of acidification and increased N deposition may cause decreases in base cations, leading to nutrient imbalances in forest vegetation which in turn increases forest vulnerability to diseases, attacks of insects and parasites. Nitrogen deposition changes natural vegetation, bacterial and mycorrhizal composition into more nitrophilic communities, with less of diversity of species, especially endemic ones. The NO_x compounds can transport to the great distance in East Asia. The spatial scale of atmospheric NH_x pollution and its effects depend on its form: gaseous NH_3 is important near sources up to 100 km; aerosol NH_4 is transported over longer distances leading to effects up to 1000 km (Carmichael et al. 1997). At present, N_2O warrants also a priority on the policy and research institutes. The increasing N_2O concentration in the atmosphere mainly results from nitrification and denitrification processes due to increasing application of mineral fertilizers in various regions of the Earth and especially in East Asia. This N species contributes to the greenhouse effect (about 6%) and to the destruction of stratospheric ozone (Erisman et al. 1999). There is agreement both nationally and internationally that long-range transboundary air pollution is not limited to the geographical limits of individual East Asian countries. It is known that during the winter the major weather patterns in East Asia facilitate the transboundary transport of air pollutants from west to east, from land to sea and the reverse in summer. Pollutants can thus be transported from country to country in the whole region of East Asia. For instance, it has been calculated that during 1990's about 50% of oxidized and about 60% of reduced N deposition over Republic of Korea were imported from abroad. It is therefore impossible for individual countries to solve the problem of air pollution and acid rain alone. There is need for regional intergovernmental cooperation. Currently, regional/sub-regional agreements on the issue of pollutant emission abatement strategy do not exist at all or are in the initial stages (Bashkin & Park 1998).

The abatement strategy for reduction of N emissions and deposition and for decreasing N losses from agroecosystems due to excessive application of fertilizers could be based on regional biogeochemical budget calculations which quantify the dominant N fluxes in terrestrial and aquatic ecosystems. The goal of this paper is to establish biogeochemical budgets for N for both the South Korean peninsula and for the Yellow Sea region.

Site description

The Republic of Korea

The Republic of Korea (or South Korea) is in the southern part of mountain Korean peninsula between 126° E–130° E and 34° N–38° N. Geographically, this is the northern temperate zone of the Eastern Hemisphere. The overall area of Republic of Korea (ROK) comprises 99,022 km^2. The dominant vegetation in ROK consists of forest trees with varying undergrowth of shrubs and small plants. The forest vegetation is divided according climate into temperate and subtropical zone forests. The secondary vegetation, which occurs in the extensive areas in the western and southern regions, consists mostly of shrubs, grasses and conifers, associated with deciduous trees. Grassland with shrubs also appears commonly as a kind of climax vegetation in the higher elevation and plateau remnants. Agricultural land uses occupy about 20% of total South Korean area.

Approximately two-thirds of the total South Korean topography is mountainous. The mountain range of Taebaeg on the Gangweon-Do runs southward along the east coast with lateral branches and spurs expending in a south westerly direction. The slopes to the east are steep while those to the west are gentle. The mountain range slopes towards the south, thus making the southern part of the country fairly level. In the contrary, the northern part is mountainous and hilly land. About 80% of the ROK lands are in regions where the altitude of the summit ranges from 300 to more than 1,000 meters. The land bears a strongly dissected relief reworked by numerous erosion cycles. The low lands include both coastal plains clayey materials and the continental alluvial plains and valley flood plans of the interior.

According to USDA Soil Taxonomy, the soils in ROK are classified as 6 orders and 14 suborders (Um 1985). The dominant soils are inceptisols with 4 suborders: Andepts, Aquepts, Ochrepts and Umbrepts (5,840,441 ha). The Entisol order consists of 4 suborder (Psamments, Aquents, Fluvents and Orthents) and occupied 2,849,102 ha. The Altisol order is presented by

Aqualfs and Udalts suborder on the area of 309,677 ha and Histosol order is devided to Saprist and Hemist suborder with total area of 384 ha.

The Yellow-Bohai Seas region

The Yellow Sea is a typical epicontinental sea surrounded by the continent of China and the Korean peninsula and connected with the East China Sea to the south and with Bohai Sea in the north (Figure 1). The mean water depth is about 44 m and the surface area is 420,000 km^2. The rivers (the Huanghe, the Aprock, the Han, the Keum, the Haihe, the Luanhe) drain freshwater of about >160 km^3 and suspended materials of 1.1×10^9 ton annually into Bohai and Yellow Sea system. Many industrial complexes and large cities are along the coastlines, from which great quantities of pollutants are discharged into rivers or directly into coastal waters. Further, the westerly and northwesterly winds, which prevail in winter and spring, deliver great amount of mineral dust and anthropogenic material. As this coastal system receives large amounts of terrestrial material produced by natural weathering and human activities, it is a suitable study site for the investigation of the biogeochemical cycle of N in the regional scale.

The Yellow Sea is a semi-enclosed basin. Wide coastal areas (<40 m water depth) are located along shorelines nearby both continents with a channel (>60 m water depth), which is developed in NW-SE direction. The southward flows in both coastal areas and northward flows of warm water in the channel are the general circulation pattern in winter, but northward flow may be disappeared in summer, which results in the formation of the Yellow sea cold water in the channel. The tidal fronts near the boundary of shallow coastal area and channel are developed during summer when thermal stratification is established in the channel and vertically homogenous water mass by strong tidal currents is sustained in shallow coastal area (Seung & Park 1990). These fronts may affect to the transport of terrestrial materials (including N) to offshore locations, and hence the biogeochemical activity.

Billions of tons of terrestrial materials are discharged annually through rivers (including the Huaghe, Aprock, Han, Keum, and others) and tens of million tons of mineral dusts (otherwise known as 'yellow sand') are deposited annually into surface seawaters from the atmosphere. Most of the particles derived from the Huanghe River are deposited in the Bohai Sea. It has been suggested that the atmospheric dust flux to the Yellow Sea may be comparable to the river input (Gao et al. 1992; Zhang et al. 1992; Choi et al. 1998).

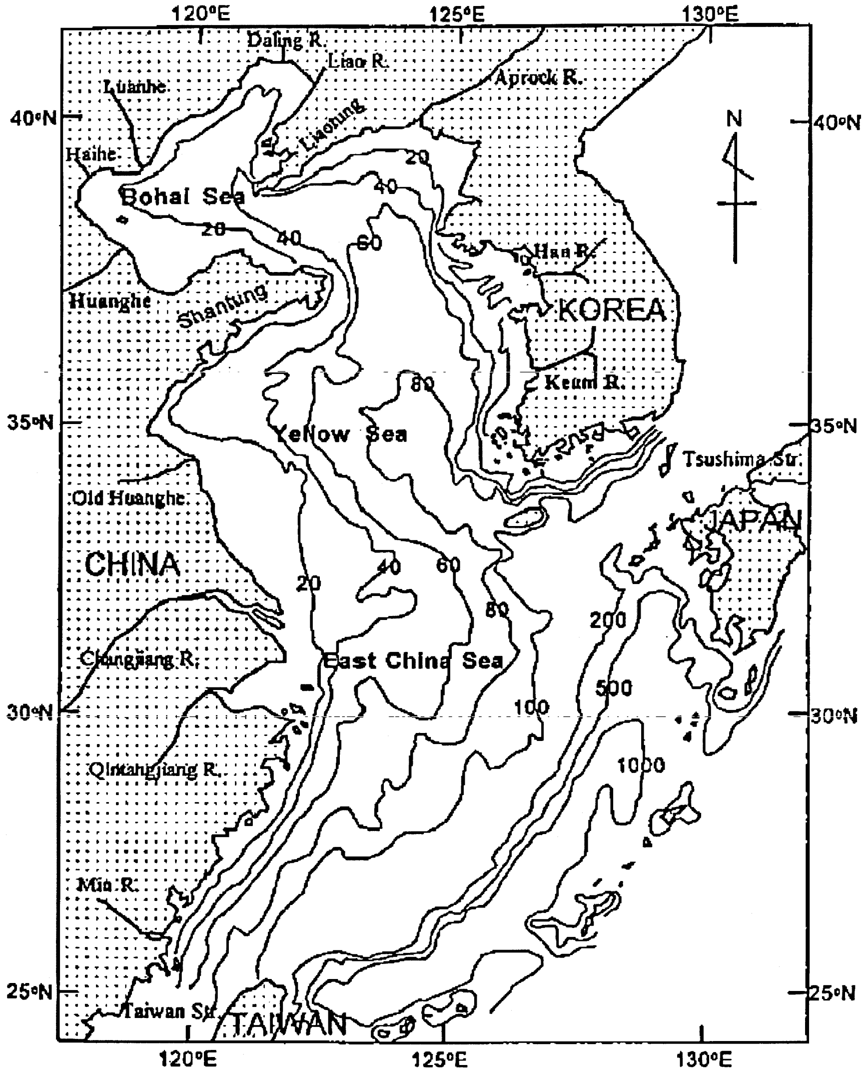

Figure 1. Bathymetry and geographic setting including the East China Sea, the Yellow Sea and Bohai Sea.

Results and discussion

Application of biogeochemical mass balance approaches to regional studies

Any type of budget for biogeochemical turnover of pollutants depends on the availability of data. The statistical characteristics for regions in East Asia were extracted from both national and international sources (e.g. Environ-

Table 1. Components of the nitrogen cycle quantified for each of the budgets presented in this paper. (+ estimated; − not estimated)

Nitrogen Budget Term	Republic of Korea, agricultural lands	Republic of Korea, entire country	Yellow & Bohai Seas region
Deposition	+	+	+
Fertilizers	+	+	–
N fixation	+	+	+
Import	–	+	–
Riverine N	–	–	+
Crops	+	–	–
Denitrification	+	+	+
Volatilization	+	+	+
Discharge	+	+	–
Sedimentation	–	–	+
Sea exchange	–	–	+

mental Statistics Yearbook 1998; UNESCO 1978; ESCAP 1998). Data on content of N species in river waters were selected both from literature studies. The specific data sources used are referenced along with the presentation of results from the individual studies below.

As is typical, more precise calculations can be made for small watersheds with homogenous (Moldan & Cerny 1994) or variable (Bashkin 1984; Gunderson & Bashkin 1994) land uses. With currently available data, it is unable to fully account for the fate of both natural and anthropogenic N added to the Yellow Sea basin. We have more complete data at smaller scales allowing us to make more detailed estimates for the agricultural ecosystems in ROK and for the total land area or the ROK. Table 1 summarizes budget terms estimated in this study, for each of the N budgets that we establish, including one for the agricultural lands in South Korea, one for the entire land area of the South Korean Peninsula within the Republic of Korea, and one for the region of the Yellow-Bohai Seas.

Quantifying N fluxes

We established a biogeochemical budget for regions in the ROK. Nitrogen input terms included atmospheric deposition, mineral and organic fertilizers, and biological fixation (Table 1). Output items considered included crop uptake, river discharge, denitrification and volatilization. All calculations were conducted for 1994–1997.

Input of N from atmospheric deposition was calculated from two models, HEMISPHERE (Sofiev 1998) and MOGUNTIA (Dentener & Crutzen 1994; Zimmerman 1998), and showed similar values (10.7–11.0 kg ha^{-1} yr^{-1}). Inputs from the application of mineral fertilizers averaged 226 kg ha^{-1} yr^{-1} in South Korean agriculture, which was the maximum input source term in the N budget for the region. Nitrogen inputs from biological fixation (nonsymbiotic only, since the area under symbiotically fixed crops was very small in ROK) was carried out using data from the Environmental Statistics Yearbook 1998; Cleveland et al. 1999; Zhu et al. 1997, as follows. In agricultural lands, the rate of fixation in the land area in rice plantations (1009560 ha) was taken to be 45 kg ha^{-1} yr^{-1}, yielding an annual flux of 45430 tons. Fixation rates in other cropland areas (966280 ha) were assumed to be 15 kg ha^{-1} yr^{-1}, yielding an annual flux of 14494 tons. In forested lands (5072600 ha) the assumed fixation rate (l kg ha^{-1} yr^{-1}) yielded an annual flux of 5072 tons. Total N inputs to agricultural and forest lands from fixation, therefore, equaled 64996 tons yr^{-1}.

N losses due to denitrification were calculated using data from Environmental Statistics Yearbook 1998; Freney 1996; Lin et al. 1996; Mosier et al. 1998; Zhu et al. 1997, as follows. Denitrification loss in the agricultural areas of rice plantation (1009560 ha) was calculated as 32% of the fertilizer use rate, yielding an annual flux of 73011 tons. Denitrification loss in upland crop areas (966280 ha) was calculated as 15% of the fertilizer use rate, yielding an annual flux of 31887 tons. Denitrification loss from manure was calculated as 13% of the manure N application rate, yielding an annual flux of 20528 tons. Denitrification losses from soils were assumed to be 3 kg ha^{-1} yr^{-1}, yielding an annual flux of 5916 tons. Agricultural recycled N was considered for regional biogeochemical budget in South Korea agroecosystems as organic fertilizer N. The values of organic fertilizer N were assessed using the statistical data on human and animal/poultry population and rates of N in excreta (Table 2). Losses from anthropogenic NH_3 emissions were estimated in an earlier study (Park 1998). The modified European calculation factors (IPCC 1997) were applied. The average total value was 142123 ton and NH_3 emission from fertilizers was predominant (35% from the total value).

In addition to the input/output items for agroecosystems, we estimated the N fluxes with river runoff for calculating the N budget for the whole South Korean area. The mean annual water discharge was 61.6×10^{12} L. In accordance with statistical data, about half of wastewater was untreated in ROK in 1994–1997. As a consequence, the content of reduced N in surface waters was almost the same as the content of oxidized N. Nitrite-N was also monitored in South Korea rivers and its mean content was 0.045 mg/L.

Table 2. Annual accumulation of nitrogen in human and animal excreta in Republic of Korea (using mean values for 1994–1997)

Items	Rate, kg per capita yr^{-1}	Population, thousand	Tons $year^{-1}$
HUMAN			
Population (adults)			
– Urban	0.44	33745.0	14848
– Rural	0.69	5494.0	3791
Subtotal			18639
LIVESTOCK			
Cattle	11.35	3267.0	37085
Horse	9.79	6.70	6552
Pig	3.22	6691.0	21525
Sheep	0.70	1.6	1
Goat	0.70	653.0	458
Poultry	1.00	85623.0	88483
Subtotal			154113
TOTAL			172752

The dissolved organic N (DON) content in the most monitored rivers and water reservoirs was negligible (<1 mg L^{-1}) due both to intensive mineralization and to algae uptake as well as the low content of organic matter in South Korean soils. The fluxes of suspended matter were significant, totaling 1.1×10^9 ton yr^{-1}, especially during summer monsoon period, with discharge-weighted mean N content of 0.085%. The total fluxes of dissolved inorganic N (DIN) and solid and particulate N (N-SPM) were 193142 tons per year in 1994–1997 (Table 3).

The quantitative parameterization of different input and output components of N biogeochemical cycle in South Korean peninsula allows us to make up the calculation of two mass balance estimates: one for South Korean agroecosystems ($\sim 2.0 \times 10^6$ ha) and one for the whole area of ROK, including input and output estimates for the components as indicated in Table 1.

Nitrogen budget for South Korean agroecosystems

The overall N budget for agroecosystems in South Korea is illustrated in Table 4. Since South Korean agriculture is characteristic of both developed countries (applying great amounts of synthetic fertilizers) and developing ones (N recycling using organic fertilizers), it was of interest to compare the

Table 3. Annual riverine fluxes of nitrogen from the area of Republic of Korea (using mean values for 1994–1997)

N species	N content, mg N L^{-1}	N fluxes, tons $year^{-1}$
N-NO_3^-	1.470	90552
N-NO_2^-	0.045	2784
N-NH_4^+	1.540	94864
N-SPM	0.085	5220
TOTAL		193142

Table 4. Nitrogen budget in agroecosystems of Republic of Korea (using mean values for 1994–1997)

N budget term	Tons $year^{-1}$	% of input
INPUT		
Fertilizers	446081	65.0
Manure	157904	23.0
Biological fixation	59924	8.7
Deposition	21692	3.3
Subtotal	685601	100.0
OUTPUT		
Crop production	259779	37.8
Denitrification	132211	19.3
NH_3 volatilization	142123	20.7
Subtotal	524113	77.8
BUDGET*	+151488	22.2

*Excess N accumulated in the landscape is distributed between surface runoff, leakage to groundwater, and increasing N content in crops (mainly vegetables).

corresponding values of N mass balance in some European countries and China with local figures (Table 5). The comparison of mass balance values between South Korean agroecosystems and those for developed European countries reveals similarities in the N budgets such as a great surplus of N (typically more than 100 kg ha^{-1} yr^{-1}). N crop uptake efficiency in Asian countries is less than in European ones and ROK is the lowest with only 38% efficiency. The large amount of surplus N in the budgets supports the idea that that an increasing non-sustainability within the agriculture, human nutrition

Table 5. Nitrogen mass balance (kg ha^{-1} yr^{-1}) and N crop uptake efficiency (% from total input) in different developed and developing countries*

Country	Agricultura 1 area, 10^6 ha	Input	Output	Surplus	Crop uptake efficiency
Denmark	2.9	217	30	187	59
Germany	12.0	215	51	164	73
U.K.	18.1	127	17	110	—
Netherlands	2.3	463	96	365	63
Norway	1.0	147	80	67	71
Sweden	3.7	121	21	100	63
S. Korea	2.0	347	51	296	38
China	94.9	294	95	199	51

*Data for European countries from Isermann (1991) and for China from Xing & Zhu (2002).

Table 6. Distribution accumulated nitrogen between various waste treatment types in the Republic of Korea (using mean values for 1994–1997)

Items	Tons $year^{-1}$	% of total
Landfill	207740	75
Incineration	13849	5
Agricultural use	5540	2
Recycling	27699	10
Damping at sea	22159	8

and waste management complex has occurred both in European and Asian countries. It has been leading to a disturbance of N biogeochemical cycle.

In order to estimate the fate of N accumulated in agroecosystems, we assessed the annual N accumulation in municipal waste for the urban area of the country (Table 6) using data from the Environmental Statistics Yearbook (1998). The annual N accumulation in sewage and wastes of 6 kg per capita was calculated from the population (46,164 thousand people) yielding an annual accumulation of 276987 tons yr^{-1}. The majority of this N was deposited in landfills with subsequent transformation, denitrification, and leaching to surface and ground water. Thus human waste leads to further pollution of drinking water, eutrophication of surface waters and increasing input of N_2O to atmosphere. The DIN contents in many South Korean water reservoirs are

Table 7. Biogeochemical budget of nitrogen for the Republic of Korea (using mean values for 1994–1997)

N budget term	Tons year^{-1}	% of input
INPUT		
Deposition	108160	13.3
Fertilizers	446081	54.8
N fixation	64996	8.0
Import		
Foods	184110	22.6
Goods	10377	1.3
Subtotal	813724	100.0
OUTPUT		
River discharge	189124	23.2
Denitrification	132211	16.2
NH_3 volatilization	142123	17.5
Sea waste damping	22159	2.7
Subtotal	485617	59.7
BUDGET	+328107	+40.3

4–10 mg N L^{-1} in summer season and most of these reservoirs are eutrophic (Environmental Statistics Yearbook 1998).

Nitrogen budget for the Republic of Korea

Taking into account the values of various input/out items of biogeochemical N cycle as well as literature data (Environmental Statistics Yearbook 1998; Park 1998; Freney 1996; Mosier et al. 1998; Zhu et al. 1997), the regional mass budget was calculated for the whole South Korean territory (Table 7). The dominant N inputs were related to the application of mineral fertilizers and import of food and goods (about 80% of total input). Deposition (including about 55% from abroad from transboundary air pollution) and non-symbiotic N fixation were responsible for the other 20% of input. N outputs were associated with N volatilization via direct NH_3 volatilization and biological denitrification (33.7% of total input) and river discharge (23.2% of total input). Total outputs were only about 60% of the inputs, indicating other storage or loss of N in the landscape. The fate of this excess N (40.3% of total N inputs) in the landscape is shown in Table 8. As it has been shown already during the analysis of N balance in agroecosystems, the main part

Table 8. Distribution of accumulated nitrogen in the Republic of Korea (using mean values for 1994–1997)

Accumulation	Ton year^{-1}	% of total
Landfill	207740	63.2
Forest uptake	16455	5.0
Groundwater leakage*	103912	31.8

*calculated by difference.

of excessive N is stored at landfills with corresponding prolonged problems of environment pollution. The values of N forest uptake were calculated on a basis of data on net primary productivity and N content in tree stems and branches. Groundwater leakage was calculated as the difference between total N accumulation and the sum of annual landfill storage and plant uptake in forest ecosystems. In general, the decomposition of waste residues in landfills lasts longer than 1 year and thus this approach to estimating groundwater leakage can be used.

Nitrogen Budget for the Yellow-Bohai Sea

In accordance with approaches shown in Table 1, the total riverine N fluxes were assessed for the Yellow-Bohai sea system (UNESCO 1978; Zhu 1997; ESCAP 1998; Choi 1998; Cha et al. 1998). These data are shown in Table 9. Previous regional analyses of the SCOPE-N Project suggest that without the influence of humans on the landscape, the flux of N from land to coastal waters would be on the order of 130 kg N km^{-2} yr^{-1} when expressed per area of watershed (Howarth et al. 1996; Lewis et al. 1999). In comparison, actual fluxes from Yellow-Bohai Seas drainage basin (areas of China and Koreas) were some 8-fold larger than this for drainages from China and 13-fold larger for the drainages from South Korean area in 1994–1997. Due to the huge amount of SPM transport in Yellow river, the N discharge from China area was dominated by solid matter (87%). The opposite pattern was true for South Korea, where only 6% of total N flux was discharged with as solid and particulates and 94% was discharged as DIN. Comparing these N budget estimates with data reported in the literature (Cha et al. 1998, Choi 1998, Park 1998, Nixon et al. 1996), we calculated the N fluxes in the entire Yellow Sea region (Table 10).

The majority of both the soluble N (53%) and particulate N (>99%) inputs to the Yellow Sea originated in China, despite the fact that only 30% of the riverine discharge was contributed from China. Total N transported to the

Table 9. Assessment of riverine fluxes of nitrogen to the Yellow-Bohai seas system

Watershed	Discharge, km^3/yr	N species	N content, mg L^{-1}	N fluxes, tons yr^{-1}
Han	25.0	NO_3^-	1.330	33188
		NH_4^-	1.310	32800
		NO_2^-	0.037	930
		N-SPM	0.064	1600
		Total		68518
Keum	6.4	NO_3^-	1.610	10317
		NH_4^+	1.540	9859
		NO_2^-	0.045	298
		N-SPM	0.056	1040
		Total		21514
Aprock	33.6	NO_3^-	0.200	6920
		NH_4^+	0.410	13840
		N-SPM	0.098	3460
		Total		24220
Liaohe	14.8	NO_3^-	0.200	2960
		NH_4^+	0.390	5920
		N-SPM	0.160	2664
		Total		11544
Haihe	22.8	NO_3^-	0.500	11400
		NH_4^+	0.650	14820
		N-SPM	0.180	4104
		Total		30324
Yellow	59.2	NO_3^-	0.870	51495
		NH_4^+	1.390	76947
		N-SPM	18.300	1083177
		Total		1211619
Yellow & Bohai seas	161.8	DIN		271614
		N-SPM		1096045
		Total		1367959

Yellow & Bohai Seas in riverine export was 52% of the total N inputs (2581 kt yr^{-1}). Both wet and dry atmospheric N deposition provided significant inputs (20 and 22%) to the region, while inputs from fixation in marine waters were small (6%). Denitrification is the major output from the Yellow & Bohai Seas systems, (37%), with similar values of sedimentation and water exchange

Table 10. Biogeochemical budget of nitrogen for the Yellow-Bohai seas system

N budget term	Tons year^{-1}	% of input
INPUT		
Wet deposition	504000	20
Dry deposition	557000	22
N fixation	152880	6
Riverine soluble N	271614	10
Riverine SPM-N	1096045	42
Subtotal	2581539	100
OUTPUT		
Denitrification	946680	37
Losses as N_2O	23520	1
Sedimentation	170000	7
Water exchange	212000	8
Subtotal	1352200	53
ACCUMULATION	+1229339	+47
N pool in marine water	1818000	
Residence time, yr	1.47	

with East China Sea (7% and 8% of total input) and with negligible values of losses as N_2O (<1%). The annual accumulation of N in Yellow sea was 1229 kt yr^{-1} (+47% of total N inputs) and the residence time of N was 1.5 years. This means that the N content in marine water was doubling every 3 years during 1994–1997.

Conclusions

We quantified N budgets for agroecosystems in South Korea; the entire landscape of the South Korea peninsula (in the borders of the Republic of Korea), and for the Yellow Sea region. The nitrogen budget for South Korean agroecosystems was positive, with N inputs exceeding outputs by about 22%. Most of the N input was from the use of fertilizers (65%). Of the N inputs to the agricultural landscape, 38% was accounted for in crop production, 19% was lost to denitrification, 21% was lost to ammonia volatilization, and the remaining 22% accumulated in the landscape.

Similarly, the N budget for the whole of the South Korea (ROK) was positive, with inputs exceeding outputs by 47%. The accumulation of N in the landscape is due to rates of fertilization, atmospheric deposition, and N imports that were not matched by output rates in river discharge, gaseous losses, and sea water damping. The excess N inputs increased N storage in landfills and in groundwater and gradually increased riverine N discharge to Yellow sea.

The majority of both soluble (53%) and particulate (>99%) N inputs to the Yellow-Sea region were contributed from Northern China, while this area contributes only 30% of the streamflow discharge to the Yellow Sea Basin. Delivery of N to the Yellow Sea region in river loads accounted for 52% of the total N inputs. Both wet and dry deposition inputs were substantial, accounting for 20% and 22% of the total inputs, respectively. Fixation in marine waters accounted for only 6% of the inputs. A substantial fraction (37%) of the N inputs to the Yellow Sea region is lost to denitrification. Sedimentation and water exchange with East China Sea were smaller, yet significant loss terms (accounting for 7% and 8% from total input, respectively). Losses of N inputs as N_2O were negligible (<1%). Therefore, the annual N accumulation of in the Yellow-Bohai seas was 1229 kt yr^{-1} (+47% of total inputs) and the residence time of N was 1.5 years, doubling the N content in marine water every 3 years during 1994–1997. The human-derived N inputs have led to excessive eutrophication and pollution of Yellow sea.

Acknowledgements

This work was initiated as part of the International SCOPE Nitrogen Project, which received support from both the Mellon Foundation and from the National Center for Ecological Analysis and Synthesis. We thank the Korean Science and Technology Federation for granting Prof. Vladimir Bashkin sabbatical leave in Seoul National University in 1998–1999, Mr. Y. Steklov (UN ESCAP, Thailand) for help in information sources and fruitful discussion of results, and Ministry of Environment of Republic of Korea for financial support of this project (G-7 grant). We thank G. Xing and an anonymous reviewer for helpful comments that improved the manuscript.

References

Bashkin VN (1984) Study of landscape-agrogeochemical balance of nutrients in agricultural regions, II: Potassium. Water, Air and Pollution 21: 97–103

Bashkin VN, Erdman LK, Abramychev AY, Sofiev MA, Priputina IV & Gusev A (1997) The input of anthropogenic airborne nitrogen to the Mediterranean Sea through its watershed. MAP Technical Reports Series No. 118, UNEP, Athens, 95 pp

Bashkin V & Park SU (Eds) (1998) Acid deposition and ecosystem sensitivity in East Asia, NovaScience Publisher, 427 pp

Carmichael GR, Hong MS, Ueda H, Chen LL, Murano K, Park JK, Lee H, Kim Y, Kang C & Shim S (1997) Aerosol composition at Cheju Island, Korea. Journal of Geophysics Research 102: 6047–6061

Cha HJ, Kim JY, Koh CH & Lee CB (1998) Temporal and spatial variation of nutrient elements in surface seawater of the west coast of Korea. The Journal of the Korean Society of Oceanography 3: 25–33

Choi MS (1998) Distribution of trace metals in the riverine, atmospheric and marine environments of the western coast of Korea. PhD thesis, Department of Oceanography, Seoul National University, 338 pp

Cleveland CC, Townsend AR, Schimel DS, Fisher H, Howarth RW, Hedin LO, Perakis SS, Latty EF, von Fischer JC, Eleseroad A & Wasson MF (1999) Global patterns of terrestrial biological nitrogen fixation in natural ecosystems. Global Biogeochemical Cycles 13: 623–646

Dentener FJ & Crutzen PJ (1994) A three dimensional model of the global ammonia cycle. Journal of Atmospheric Chemistry 19: 331–369

Environmental Statistics Yearbook (1998) Ministry of Environment, Republic of Korea, 581 pp

Erisman JW, Brydges T, Bull K, Cowling E, Grennfelt P, Nordberg L, Satake K, Scheider T, Smeulders S, van der Hoek K, Wisniewski J & Wisniewski J (1999) Summary statement. In: International Nitrogen conference, Elsevier Science

ESCAP (1998) Sources and Nature of Water Quality Problems in Asia and the Pacific, New York, United Nations, 164 pp

ESCAP (1997) Sustainable Development of Water Resources in Asia and the Pacific: an overview, New York, United Nations, 162 pp

Gao Y, Arimoto R, Duce A, Lee DS & Zhou MY (1992) Input of atmospheric trace elements and mineral matter to the Yellow Sea during the spring of a low-dust year. Journal of Geophysics Research 97: 3767–3777

Gundersen P & Gashkin VN (1994) Nitrogen cycling. In: Moldan & Cherny J (Eds) Biogeochemistry of Small Catchments. John Wiley and Sons, pp 253–277

Freney JR (1996) Control of nitrogen emission from agriculture. In: Lin HC et al. (Eds) Proceedings of SCOPE/ICSU Nitrogen Workshop: The Effect of Human Disturbance on the Nitrogen Cycle in Asia, pp 85–99

Howarth RW (Ed) (1996) Nitrogen Cycling in the North Atlantic Ocean and its Watersheds. Kluwer Academic Publishers, 304 pp

IPCC (1997) Guidelines for National Greenhouse Gas Inventories. OECD/ICDE, Paris

Iserman K (1991) Share of agriculture in nitrogen and phosphorus emission into the surface waters of Western European against the background of their eutrophication. Fertilizer Research 26: 253–269

Lewis WM, Melack JM, McDowell WH, McClain ME & Richey JE (1999) Nitrogen yields from undisturbed watershed in the Americas. Biogeochemistry 46: 149–162

Lin H-C, Yang S-S, Hung T-C & Chou C-H (Eds) (1996) The Effect of Human Disturbance on the Nitrogen Cycle in Asia, Proceedings of SCOPE/ICSU Nitrogen Workshops

Moldan B & Cherny J (Eds) (1994) Biogeochemistry of Small Catchments. John Wiley and Sons, 424 pp

Mosier A, Abrahamsen G, Bouwman L, Bockman O, Drange H, Forlking S, Howarth R, Kroeze C, Oenema O, Smith K & Bleken M (Eds) (1998) International workshop on dissipation of N from the human N cycle and its role in present and future N_2O emissions to the atmosphere. Nutrient Cycling in Agroecosystems. Kluwer Academic Publishers, 313 pp

Nixon SW, Ammerman JW, Atkinson LP, Berounsky VM, Billen G, Boicourt WC, Boynton WR, Church TM, Ditoro DM, Elmgren R, Garber JM, Giblin AE, Jahnke RA, Owens NJP, Pilson JH & Seitzinger SP (1996) The fate of nitrogen and phosphorus at the land-sea margin of the North Atlantic Ocean. In: Howarth RW (Ed) Nitrogen Cycling in the North Atlantic Ocean and its Watersheds. Kluwer Academic Publishers, pp 141–180

Park SU (Ed) (1998) Research and Development on Basic Technology for Atmospheric Environment in Global Scale: Development of Technology for Monitoring and Prediction of Acid Rain. Ministry of Environment, Republic of Korea, 602 pp

Seung YH & Park YC (1990) Physical and environmental character of the Yellow Sea. In: Park CH, Kim DH & Lee SH (Eds) The Regime of the Yellow Sea. Institute of East and West Staudies, Seoul, pp 9–38

Sofiev MA (1998) Numerical modeling for Acid deposition on Eurasian continent. In: Bashkin VN & Park SU (Eds) Acid Deposition and Ecosystem Sensitivity in East Asia. NovaScience Publishers, U.S.A., pp 5–48

Um KT (1985) Soils of Korea. Soil Survey Materials No. 11. Agricultural Science Institute, Rural Administration, Korea, 66 pp

UNESCO (1978) World Water Balance and Water Resources of the Earth. Gidrometeoizdat Publishers, Leningrad, 666 pp

Zhang J, Huang WW, Liu SM & Wang JH (1992) Transport of particulate heavy metals towards the China Sea: a preliminary study and comparison. Marine Chemistry 40: 161–178

Zhu ZL (Ed) (1997) Nitrogen Balance and Cycling in Agroecosystems of China. Kluwer Academic Publisher, 355 pp

Zimmermann PH (1998) Moguntia: A handy global tracer model. In: van Dop H (Ed) Air Pollution Modeling and its Applications VI. Plenum, New York

Xing GX & Zhu ZL (2002) Regional nitrogen budgets for China and its major watersheds. Biogeochemistry 57/58: 405–427