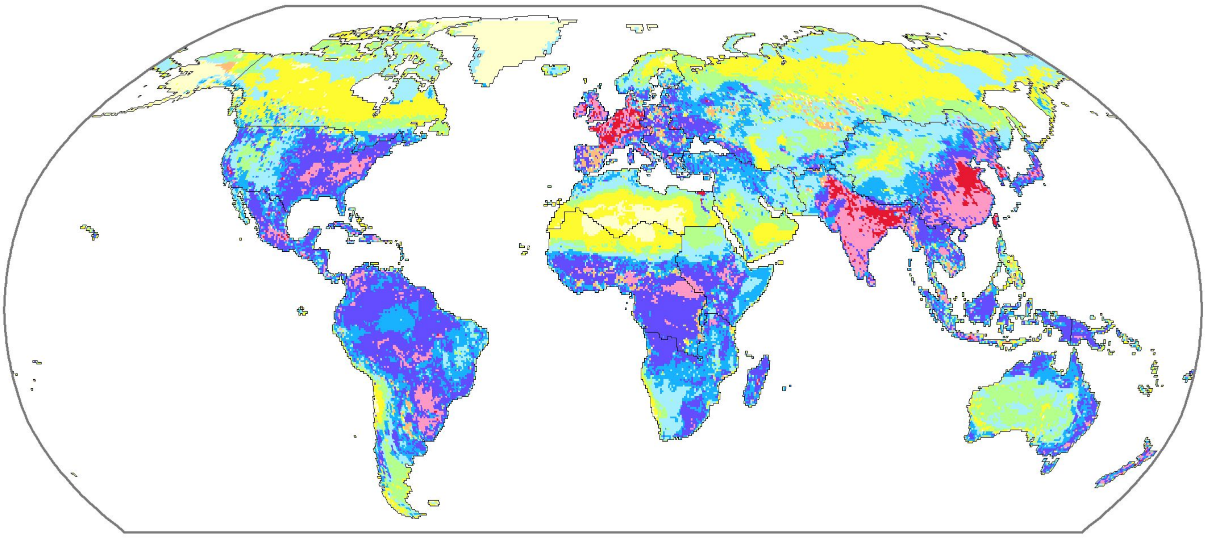
02

Global-Scale Modeling of Nitrogen Balances at the Soil Surface



Stefan Siebert

Institute of Physical Geography
Frankfurt University

January 2005

Frankfurt Hydrology Paper

JOHANN WOLFGANG GOETHE UNIVERSITÄT FRANKFURT AM MAIN

Global-Scale Modeling of Nitrogen Balances at the Soil Surface

Stefan Siebert

Institute of Physical Geography

Frankfurt University

January 2005

Frankfurt Hydrology Papers:

Institute of Physical Geography, Frankfurt University
P.O. Box 11 19 32, D-60054 Frankfurt am Main, Germany
Phone +49 (0)69 798 22393, Fax +49 (0)69 798 25058
http://www.geo.uni-frankfurt.de/ipg/ag/dl/english_version/dl/index.html

Please cite as:
Siebert, S. (2005): Global-Scale Modeling of Nitrogen Balances at the Soil Surface. *Frankfurt Hydrology Paper 02*, Institute of Physical Geography, Frankfurt University, Frankfurt am Main, Germany.

Abstract

This paper provides global terrestrial surface balances of nitrogen (N) at a resolution of 0.5 by 0.5 degree for the years 1961, 1995 and 2050 as simulated by the model WaterGAP-N. The terms livestock N excretion (N_{anm}), synthetic N fertilizer (N_{fert}), atmospheric N deposition (N_{dep}) and biological N fixation (N_{fix}) are considered as input while N export by plant uptake (N_{exp}) and ammonia volatilization (N_{vol}) are taken into account as output terms. The different terms in the balance are compared to results of other global models and uncertainties are described. Total global surface N surplus increased from 161 Tg N yr^{-1} in 1961 to 230 Tg N yr^{-1} in 1995. Using assumptions for the scenario A1B of the Special Report on Emission Scenarios (SRES) of the International Panel on Climate Change (IPCC) as quantified by the IMAGE model, total global surface N surplus is estimated to be 229 Tg N yr^{-1} in 2050. However, the implementation of these scenario assumptions leads to negative surface balances in many agricultural areas on the globe, which indicates that the assumptions about N fertilizer use and crop production changes are not consistent. Recommendations are made on how to change the assumptions about N fertilizer use to receive a more consistent scenario, which would lead to higher N surpluses in 2050 as compared to 1995.

Table of Contents

1 Introduction

As component of ammonia (NH_4^+) or nitrate (NO_3^-) nitrogen (N) plays an important role as plant nutrient. The plant biomass is being used as livestock fodder and both, vegetal and livestock products are used in human nutrition. Thus N is a component of the world's biomass which again can be transferred to soil organic matter or (fossil) biofuels. In the form of N_2 it is the major component of the atmosphere, additional N is constituent of trace gases like NO, NO_2, N_2O or NH_3. Many different pools of N in atmosphere, biosphere, hydrosphere or soils are known. Linked to these storages are processes that transfer N from one pool to another one which is often related to a change of the chemical structures (Smil, 2002). Because of the given complexity the description and quantification of pools, transport and transformation processes on a global scale is difficult and fraught with many uncertainties (Galloway et al., 2004). Therefore research usually is focusing on specific sub-systems of the global N cycle and processes related to these subsystems.

Bouwman et al. (2002), Mosier et al. (1998) and Nevison et al. (1996) presented for example models that quantify nitrogenous greenhouse gas emissions. Bouwman et al., 1997 presented an inventory of ammonia emissions. Such inventories are used in global atmospheric chemistry transport models to simulate atmospheric N depositions (e.g. Dentener and Crutzen, 1994). Other models focus on reactive Nitrogen (N_r) and in particular on anthropogenic changes of N_r (e.g. Galloway and Cowling, 2002).

Nitrogen overload is contributing to the rapid growth of oxygen-starved zones in some coastal waters (UNEP, 2004). Large parts of this overload is caused by N transport in rivers which stimulated several research teams to simulate and quantify nitrogen transport in surface waters (e.g. Galloway et al., 2004; Green et al., 2004; Van Drecht et al., 2003; Seitzinger et al., 2002). These models are based on inventories of net N inputs to terrestrial ecosystems which are, however, also a product of a modeling process.

The purpose of this report is to describe the modeling of diffuse N inputs to terrestrial ecosystems as first step in the development of a new global model called WaterGAP-N. This model focuses on the soil system and the hydrological part of the N cycle and is a further development of the global model of water availability and water use WaterGAP 2.1 (Alcamo et al., 2003). WaterGAP-N simulates the input of nitrogen from diffuse sources (synthetic fertilizer and manure, biological fixation and atmospheric deposition) to the soil and extractions from the soil by plants, denitrification and leaching to the groundwater. It will simulate N inputs to surface waters by point sources, the transport of dissolved N and its outgassing by denitrification in the groundwater as well as in surface waters (rivers, lakes and wetlands) and finally riverine N input into the world's oceans. The spatial resolution is 0.5 by 0.5 degree and the model uses monthly time steps in the period 1961-2100. The simulations for the future are based on scenario assumptions (Nakicenovic, 2000) as implemented in the IMAGE 2.2 model (RIVM, 2001).

WaterGAP-N uses a monthly soil N balance to describe and quantify N pools and N flows in the soil as:

$$\Delta N_S = N_{minz} + N_{fert} + N_{anm\_min} + N_{dep} - N_{upt} - N_{vol} - N_{denit} - N_{leach} \quad (1)$$

with:

ΔN_S	change of (mineral) soil N storage (kg N ha^{-1} month^{-1})
N_{minz}	mineral N input from mineralization of organic matter (kg N ha^{-1} month^{-1})
N_{fert}	N input from synthetic fertilizers (kg N ha^{-1} month^{-1})
N_{anm_min}	mineral N inputs from livestock excretions (kg N ha^{-1} month^{-1})
N_{dep}	mineral N inputs from atmospheric N deposition (kg N ha^{-1} month^{-1})
N_{upt}	extraction of mineral N by plant uptake (kg N ha^{-1} month^{-1})
N_{vol}	N losses by ammonia volatilization (kg N ha^{-1} month^{-1})
N_{denit}	denitrification (kg N ha^{-1} month^{-1})
N_{leach}	leaching to the ground water (kg N ha^{-1} month^{-1}).

Mineralization is being simulated as function of soil moisture, temperature and N content in an organic soil N pool that will be fed by inputs from return flows of organic matter, biological N fixation and organic parts of livestock excretions. For the purpose of this paper the soil N balance was simplified to represent a N balance at the soil surface (see next section) by assuming that the organic N inputs will become active immediately after input into the system. This removes the mineralization term from the balance; additionally denitrification and leaching are not taken into account. This simplification enabled a comparison of the terms in the balance to terms as used in other global models.

In the next section data and methods used to compute the terms in the N surface balance will be described. In section 3 results are presented while section 4 is for the discussion of the results. Finally the summary and conclusions are given in section 5.

2 Data and methods

In this section the methodology to compute the nitrogen surface balances will be described. In particular we will focus on the modeling of the distribution of nitrogen inputs and nitrogen extractions in space and time and give references to the data sets used for this purpose.

2.1 Computing nitrogen balances at the soil surface

The nitrogen balance at the soil surface is computed as the difference of the nitrogen inputs and nitrogen outputs:

$$N_{sur} = N_{anm} + N_{fert} + N_{dep} + N_{fix} - N_{exp} - N_{vol} \tag{2}$$

The inputs comprise livestock excretions (N_{anm}), synthetic fertilizer use (N_{fert}), atmospheric deposition (N_{dep}) and biological nitrogen fixation (N_{fix}) while the output terms include plant harvesting, i.e. N extraction by harvested plants (N_{exp}), and ammonia volatilization (N_{vol}). All the terms are expressed in kg N (ha * yr)$^{-1}$. The modeling of the specific terms will be described in the following sections in detail.

2.2 Modeling nitrogen inputs from livestock (N_{anm})

The modeling of nitrogen inputs from livestock comprises two steps. First, livestock numbers for dairy cattle, non-dairy cattle, buffaloes, pigs, sheep, goats, horses, camels, chicken, turkey, geese and ducks are calculated for each grid cell. Thereafter the livestock N-excretion is computed by using stock type specific excretion rates.

Modeling of livestock numbers per grid cell

Livestock numbers are computed as:

$$nstock = c_{region} * c_{country} * c_{subnational} * dens_{init} * area \quad (3)$$

whereas *area* is the land area in a specific grid cell (km²), $dens_{init}$ is an initial stock density in the specific grid cell (head km^{-2}) and c_{region}, $c_{country}$ and $c_{subnational}$ are coefficients necessary to scale the livestock sum to values given by statistics or scenario assumptions on regional, national and sub-national level. These calculations are performed on a 2.5-minute grid and later the computed livestock numbers are aggregated to a 30-minute grid by summing up 12 x 12 values. As initial densities ($dens_{init}$) best guess livestock density estimates for pigs and the groups of bovines (dairy cattle, non-dairy cattle, buffaloes), small ruminants (sheep, goats) and poultry (chicken, turkey, geese, ducks) are used (Gerber, 2004). For areas not covered by these data sets, initial densities are set to human population densities (CIESIN, 2001) because recent studies have shown that livestock densities are correlated to human population densities (Slingenbergh and Wint, 1996). Based on a land cover classification map (USGS, 2000) the following exceptions are assumed:

a) In all 2.5-minute cells completely classified as water, snow or ice, bare ground tundra, herbaceous tundra or mixed tundra initial densities for bovines and pigs were set to 0.
b) In all 2.5-minute cells completely classified as water, snow or ice or bare ground tundra initial densities for small ruminants and horses were set to 0.
c) In all 2.5-minute cells not completely classified as water, snow or ice or bare ground tundra initial densities for horses were set equally to 1.
d) Camels live only in areas classified as barren, shrubland or mixed grassland + shrubland between 55°S and 55°N. Initial densities for the related grid cells were set to 1, for all the other cells it was set to 0.

The livestock numbers computed by using the initial densities are scaled in a next step by multiplying with $c_{subnational}$ so that the livestock sums exactly meet statistics on a sub-national level, whereby $c_{subnational}$ is kept constant for all cells within the same sub-national statistical unit. These sub-national statistics are usually based on census products and were collected and provided by Jan Slingenbergh (FAO AGA) except for Australia and the United States where other inventories (ABS, 2001; Battaglin and Goolsby, 1994) have been used. After aggregation of the data to a 0.5 by 0.5 degree grid livestock numbers are scaled by using $c_{country}$ so that the livestock numbers exactly meet the FAOSTAT statistics of the livestock numbers per country for the years 1961 – 2000 (FAO, 2003a). The coefficient $c_{country}$ is kept constant for all cells within the same country, and for the years 2000 – 2100 $c_{country}$ is kept constant at the value for the year 2000. In the last step livestock numbers are scaled for all years after 2000 using the coefficient c_{region}. This coefficient was kept constant for all cells within a region and for the purpose of this paper the values were derived from scenario assumptions for 19 world-regions (RIVM, 2001).

Modeling of livestock N-excretion

Livestock N-excretion was computed by multiplying livestock numbers as computed before by an animal type–specific coefficient excr (Tab. 1, Eq. 4.1). For all animal types except of dairy cattle and non-dairy cattle the coefficients were taken from Bouwman et al. (1997) and Brandjes et al. (1996) and kept constant over time. For dairy cattle *excr* is modeled as a function of average milk yield per cow as listed in FAOSTAT (FAO, 2003a). For all years after 2000 *excr* is modified for scenario-based changes of milk-yields per world-region Eq. 4.2) as provided by the IMAGE 2.2 model (RIVM, 2001). For non-dairy cattle a N-excretion of 50 kg N per head is assumed for Canada, Mexico, United States, Japan and OECD-Europe in 1960 and an increase of *excr* by 0.25 kg N head^{-1} yr^{-1} afterwards. For all the other countries the coefficient *excr* is also limited by the computed N-excretion of dairy cattle (Eq. 4.3).

Table 1. Livestock type specific N-excretion rates *excr* as used to compute total livestock N-excretion

livestock type	N-excretion rate *excr* (kg N animal^{-1} yr^{-1})
dairy cattle	see Eq. 4.2
non-dairy cattle	see Eq. 4.3
pigs	11.0
sheep	10.0
goats	12.0
horses	50.0
buffaloes	50.0
camels	50.0
chicken	0.4
turkeys	1.4
geese	1.2
ducks	0.75

$$N_{anm} = excr_{anm} * nstock_{anm} \quad (4.1)$$

$$excr_{dairy} = \frac{c_{region} * (av\_milk\_yield + 4600)}{120} \quad (4.2)$$

$$excr_{nondairy} = \begin{cases} 50 + 0.25(year - 1960) & for \quad \text{Canada, US, Mexico, Japan or OECD - Europe} \\ MIN\begin{pmatrix} 50 + 0.25(year - 1960), \\ 0.8 * excr_{dairy} \end{pmatrix} & else \end{cases} \quad (4.3)$$

with:

N_{anm} animal-type specific livestock N-excretion (kg N yr^{-1})

$excr$	livestock N-excretion (kg N head^{-1} yr^{-1})
c_{region}	relative change of milk-yields per dairy cattle compared to milk-yield in year 2000, estimated for world-regions until 2100, c_{region} is 1.0 in years before 2000
av_milk_yield	annual milk-yield per dairy cattle averaged per country, for years later than 2000 the value of year 2000 was kept constant (kg milk head^{-1} yr^{-1})
$year$	actual simulation year.

2.3 Modeling nitrogen inputs from synthetic fertilizers (N_{fert})

Nitrogen inputs from synthetic fertilizers are simulated by multiplying crop areas by specific fertilization rates per crop. Because land use is changing over time this requires a modeling of land use first. Crop fertilization rates have also to be modeled because fertilizer use is also changing over time (FAO, 2003a).

Modeling of land use

The distribution of crops (except of grass and fodder) on agricultural land between 1970 and 2100 is similar to the distribution as simulated by the IMAGE 2.2 model (RIVM, 2001) with one exception: the share of irrigated cropland on total cell-cropland is constant over time. This exception was made because irrigated land is decreasing over time in IMAGE 2.2., while data show in most regions an increase between 1970 and 2000 (FAO, 2003a), and for 2000 to 2030 experts assume an increase of irrigated land in most regions of the world (FAO, 2002). Thus the extent of irrigated land in WaterGAP-N is approximately representative for the situation in the year 1970. IMAGE 2.2 simulates the fraction of each 0.5 degree grid cell that is covered by the following crop groups: temperate cereals (rainfed), rice (rainfed), maize (rainfed), tropical cereals (rainfed), pulses (rainfed), oil crops (rainfed), roots and tubers (rainfed), temperate cereals (irrigated), rice (irrigated), maize (irrigated), tropical cereals (irrigated), pulses (irrigated), oil crops (irrigated), roots and tubers (irrigated), maize (biofuel), sugar cane (biofuel), non-woody biofuel crops and woody biofuel crops. For years before 1970 the crop coverage as simulated for 1970 has been used.

The percentage of cell area covered by grass and fodder crops until 1992 is computed as the difference between total cropland in a recent inventory that dates back until 1700 (Ramankutty, 1999) and total cropland as computed before. The total cropland given by this inventory includes harvested grassland but excludes pasture. For all years later than 1992 changes in the fraction of cell area covered by grass and fodder crops are derived from the IMAGE 2.2 model. Only in case of an extension of cropland in grid cells almost completely covered by grassland and crops it is assumed that grassland will be converted to cropland.

The percentage of cell area covered by managed pasture in 1992 is computed as difference of total crop area and pasture area according to a global land cover map (USGS,

2000) and grass and cropping area as computed before. The area covered by natural vegetation is computed as difference between total cell land area and sum of pasture land, grassland and cropland as computed before. The ratio between pasture area and area covered by natural vegetation is kept constant for all years after 1992.

Modeling of synthetic fertilizer use

Synthetic fertilizer N application is simulated for the specific crop groups by multiplying crop area with cropping intensity and crop fertilization rate (Eq. 5.1). Cropping intensity depends on the specific simulation year and world region (RIVM, 2001). Crop-specific average fertilization rates for 101 countries were taken from an inventory provided by FAO (FAO, 2003b) and assumed to represent fertilizer use in 1995. Irrigated and non-irrigated crops are not distinguished. Average crop fertilization rates per world region were computed and thereafter used for countries not included in this inventory. Based on the computed crop fertilization rates for 1995 fertilization rates for other simulation years are computed taken into account reported or scenario based changes of total N-fertilizer use per country (FAO, 2003a; RIVM, 2001) and simulated changes of crop distribution within the countries (Eq. 5.2 – Eq. 5.4).

$$fert\_consumption_{cell,crop,year} = fert\_rate_{country,crop,year} * ci_{region,year} * crop\_area_{cell,crop,year} \quad (5.1)$$

$$fert\_rate_{country,crop,year} = fert\_rate_{country,crop,1995} * \frac{change\_tot\_fertuse_{country,year}}{change\_landuse_{country,year}} \quad (5.2)$$

$$change\_tot\_fertuse_{country,year} = \frac{c_{region,year} * FAOSTAT\_fertuse_{country,year}}{FAOSTAT\_fertuse_{country,1995}} \quad (5.3)$$

$$change\_landuse_{country,year} = \frac{fert\_consumption\_modeled_{country,1995}}{fert\_consumption\_fertrates95_{country,year}} \quad (5.4)$$

with:

$fert\_consumption_{cell,crop,year}$	N-fertilizer consumption dependent on grid cell, crop and simulation year (kg N yr^{-1})
$fert\_rate_{country,crop,year}$	fertilization rate dependent on the specific country, crop and simulation year (kg N ha^{-1} yr^{-1})
$ci_{region,year}$	cropping intensity dependent on region and year
$crop\_area_{cell,crop,year}$	cropping area for a specific crop dependent on grid cell and simulation year (ha)
$change\_tot\_fertuse_{country,year}$	relative change of total N-fertilizer use related to 1995 dependent on country and simulation year

$change\_landuse_{country,year}$	relative change of total N-fertilizer use related to 1995 due to changing crop distribution, dependent on country and simulation year
$c_{region,year}$	scenario-based relative change of total N-fertilizer use per region related to year 2000; this coefficient was derived from RIVM (2001) and was set to 1.0 for years before 2001
$FAOSTAT\_fertuse_{country,year}$	country-specific total N-fertilizer consumption as derived from FAOSTAT (FAO, 2003a) for the years 1961 – 2000 (kg N yr^{-1}); values for the year 2000 were used for years later than 2000
$fert\_consumption\_modeled_{country,1995}$	total N-fertilizer consumption per country as simulated for year 1995 (kg N yr^{-1})
$fert\_consumption\_fertrates95_{country,year}$	total N-fertilizer consumption per country as simulated by using land use in actual year and fertilization rates in 1995 (kg N yr^{-1}).

2.4 N-inputs by atmospheric deposition (N_{dep})

N-deposition data were provided by Frank Dentener for the years 1860, 1890, 1900, 1910, 1920, 1930, 1940, 1950, 1960, 1970, 1980, 1990, 1997, 2025 and 2050 as simulated by the TM3 model (Dentener and Crutzen, 1994). The dataset distinguishes NH_x and NO_y depositions and has a resolution of 1 by 1 degree (downscaled from the 3.75 x 5 degrees resolution of TM3). It was transferred to a 0.5 x 0.5 degree grid and annual values by linear interpolation. The NOx-deposition data are used as provided by F. Dentener while the NHx data were modified in order to reflect the ammonia emissions as modeled by WaterGAP-N itself. For that purpose the NHx-emissions by synthetic fertilizers and livestock manure as simulated by WaterGAP-N (see section 2.7) and all the emissions by other sources as provided by Frank Dentener were summed up to compute the total NHx-emissions. Thereafter N-deposition was computed by assuming that 30% of the total emissions are subject to short-range transport (which does not leave the grid cell), and 70% to long-range transport. The long-range transport will be transferred to other grid cells relative to the total NHx-depositions as simulated by the TM3 model.

2.5 Modeling N-inputs by biological N-fixation (N_{fix})

Biological nitrogen fixation in natural ecosystems is calculated as function of actual evapotranspiration (Cleveland et al., 1999). Because the regression equation proposed by

Cleveland et al. is based on actual evapotranspiration as simulated by the Century model, the nitrogen fixation computed by WaterGAP-N was scaled so that the average fixation rate is close to the central estimate for each natural vegetation type as given by Cleveland et al.

Non-symbiotic nitrogen fixation on agricultural lands is estimated at 5 kg N yr^{-1} in non-rice cropping systems and 25 kg N yr^{-1} in rice-based agro-ecosystems. Symbiotic N-fixation on agricultural lands is computed dependent on the actual soil nutrient balance as:

$$N_{sfix} = \begin{cases} (1.33 * N_{upt} - N_{soil}) * area & if \quad (1.33 * N_{upt}) > N_{soil} \\ 0 & otherwise \end{cases} \tag{6}$$

with:

N_{sfix}	symbiotic nitrogen fixation by leguminous crops (kg N month^{-1})
N_{upt}	nitrogen uptake by leguminous crops (kg N ha^{-1} month^{-1})
N_{soil}	plant extractable nitrogen available in the soil (kg N ha^{-1} month^{-1}), computed by soil nitrogen model
area	area planted with leguminous crops (ha).

Because this balance is carried out in monthly steps, nitrogen fixation may also be simulated if there is a nitrogen deficit only for some months but an annual surplus of nitrogen in the soil.

2.6 N-export by plant uptake (N_{exp})

Nitrogen export by plant extractions is computed as the sum of exports by crop harvest (exp_{crop}), by wood harvest (exp_{wood}) and by savanna burning (exp_{burn}):

$$N_{exp} = exp_{crop} + exp_{wood} + exp_{burn} \tag{7}$$

Crop harvests per grid cell and crop residues management per world region are used as simulated by the IMAGE 2.2 model (RIVM, 2001). Coefficients used to compute the harvested fraction of the crops and the fractions of above-ground or below-ground crop residues as well as the related nitrogen contents are documented in Table 2. It is assumed that the nitrogen content in the harvested parts of the crops will be completely removed from the fields while below-ground residues and above-ground residues that are not burned and not used as animal fodder will re-enter the soil as return flow. Grass demand of livestock is calculated following the IMAGE 2.2 model based on feed-dry matter (energy) demand per animal category and fodder preferences per world region. Grass that was harvested but not needed as fodder is assumed to be return flow to the soil. Grazing in natural grasslands takes place if there is not enough fodder available from grass crops and managed pasture.

Table 2. Coefficients used to compute N exports by crops

Crop	Fraction of total crop dry matter as residues	Above-ground fraction of crop residues	N-content in crop harvest (%)	N-content in above-ground crop residues (%)
Grass, pasture			2.5	2.0
Temp. cereals	0.60	0.55	2.0	0.6
Rice	0.55	0.67	1.2	0.6
Maize	0.65	0.55	1.4	0.6
Trop. cereals	0.65	0.55	1.5	0.6
Pulses	0.65	0.45	3.5	2.5
Roots + tubers	0.45	0.66	1.4	0.5
Oil crops	0.65	0.45	3.0	2.5
Sugar cane	0.65	0.67	0.12	0.7
Non-woody biofuels	0.65	0.55	1.8	0.6
Other crops	0.75	0.50	1.8	0.7

Table 3. Coefficients used to compute N exports by wood and savanna burning

Land cover type	Fraction of land area covered by woods	C/N ratio in harvested wood	Conversion coefficient NPP to N-uptake *	Conversion coefficient NPP to standing wood **
Tundra	0.1	150	0.070	60
Wooded tundra	0.3	150	0.088	120
Boreal forest	1.0	187	0.105	133
Cool conifer	1.0	321	0.079	140
Temp. mixed forest	1.0	217	0.100	127
Temp. deciduous forest	1.0	187	0.123	120
Warm mixed forest	1.0	217	0.150	122
Grassland, steppe	0.3		0.150	0
Hot desert	0.0			0
Scrubland	0.6	150	0.250	48
Savanna	0.5	150	0.230	61
Tropical woodland	0.9	125	0.386	85
Tropical forest	1.0	125	0.229	83

* : conversion from mg C m^{-2} (NPP) to kg N ha^{-1} (plant uptake)

** : conversion from mg C m^{-2} (NPP) to kg C ha^{-1} (wood biomass), further division by 268.8 converts kg C ha^{-1} (wood biomass) into m^3 ha^{-1} (wood).

Wood harvest is simulated by first summing up the standing wood per country and by extracting the same fraction of standing wood in each grid cell so that the sum of the extracted wood meets the wood production statistics given by FAOSTAT on a country level for the years 1961 to 2000 (FAO, 2003a). Wood production for simulation years after 2000 is on the level of the year 2000. Standing wood per grid cell is computed by multiplying NPP as simulated by the IMAGE 2.2 model (RIVM, 2001) by a land cover type specific conversion coefficient (Tab. 3). Nitrogen content in the extracted wood biomass has been computed by applying wood-type specific C:N ratios (Tab. 3) taken from the ecophysiological parameterization of the BiomeBGC model (Running and Hunt, 1993, http://www.ntsg.umt.edu/).

Nitrogen extraction by biomass burning is simulated by assuming that 5% of the nitrogen uptake of biomass in ecosystems classified as shrubland or savanna will be lost by burning. It will therefore not re-enter the soil as return flow. Plant nitrogen uptake in natural ecosystems is computed by multiplying NPP as simulated by IMAGE 2.2 (RIVM, 2001) by coefficients taken from the parameterization of the TEM model (McGuire et al., 1992) (Tab. 3).

2.7 Ammonia volatilization from synthetic fertilizers and manure (N_{vol})

Volatilization loss from stored manure, grazing and different fertilizer types is computed by applying average loss rates as reported in Bouwman et al. (1997) and documented in Tab. 4 and Tab. 5. Fertilizer mix per country was derived from FAOSTAT (FAO, 2003b) for the years 1961-2000. For years later than 2000 the fertilizer mix as reported for the year 2000 has been used. Residence times of livestock in housing units (stable) and on pasture are simulated for each grid cell to compute the fractions of manure produced in stable and during grazing based on the following rules:

a) Pigs and poultry are kept in stable the whole year.
b) Animals stay in stable if the temperature is below 2 °C.
c) If (a) and (b) do not apply and if there is enough fodder on the pasture, animals are kept outside the stable. If the fodder on pasture is limited and not enough for all animals, livestock is kept outside the stable according to the following priority list: 1) sheep and goats, 2) camels and horses, 3) buffaloes and non-dairy cattle, 4) dairy cattle.

Table 4. Ammonia loss rates for stored manure, livestock excretions on temperate pasture and livestock excretions on tropical pasture (% of N content)

Livestock type	Ammonia loss rate		
	Stable (incl. storage and manure spreading)	Temperate pasture	Tropical pasture
Dairy cattle	36	8	15
Non-dairy cattle	36	8	15
Buffalo	28	15	15
Camels	28	15	15
Horses	28	8	15
Sheep	28	4	8
Goats	28	4	8
Pigs	36	-	-
Poultry	36	-	-

Table 5. Ammonia loss rates for different fertilizer types (% of N content)

Fertilizer type	Ammonia loss rate
Ammonium sulphate	8
Ammonium nitrate, Calcium ammonium nitrate	2
Urea (temperate climate)	15
Urea (tropical climate)	25
Other fertilizers outside China	4
Other fertilizers in China (temperate climate)	20
Other fertilizers in China (tropical climate)	30

3 Results

In section 3.1 the simulated spatial distribution of N inputs, of N exports as well as of the related surface balances under current day conditions (1995) will be described. In section 3.2 the focus is on simulated temporal changes using results computed for the years 1961, 1995 and 2050.

3.1. N inputs, N exports and N surface balances in 1995

The largest nitrogen balance surplus in intensively used agricultural systems was computed for parts of China, India, Western Europe, Eastern United States and Southern America. Additionally a large nitrogen surplus was computed for tropical natural ecosystems. The simulated nitrogen surplus is low in general for arid natural ecosystems and ecosystems in the high latitudes. Areas having a nitrogen surface balance below zero (N deficiency) were simulated to be in all continents, e.g. for parts of the former USSR, Eastern Europe, South America, but also Canada and Spain (Fig. A3).

At the global scale a nitrogen surplus at the soil surface of 230 Tg N yr^{-1} was computed (Tab. 6). Nitrogen fixation (160.1 Tg N yr^{-1}) is the most important source of N inputs, followed by livestock excretions (107.7 Tg N yr^{-1}). At the regional level the highest total N surpluses as well as highest total N inputs were simulated for South America (39.4 Tg N yr^{-1}), East Asia (29.0 Tg N yr^{-1}) and South Asia (25.8 Tg N yr^{-1}). However, there are important differences regarding the sources of nitrogen. In South America most of the N inputs are from biological N fixation, in South Asia from livestock excretions and in East Asia from synthetic fertilizer use (Tab. 6).

Inputs by synthetic fertilizer use are most important in East Asia (39% of total regional N inputs), United States (29% of total N inputs) and in OECD-Europe (27% of total N inputs). N inputs by livestock excretions are in particular relevant in South Asia (38% of total regional N inputs) and in the Middle East region and Eastern Africa (38% of total regional N inputs). Atmospheric N deposition has importance in Northern Africa and in the countries of the former Soviet Union while biological N fixation is in particular important in the regions of Greenland, South Africa and Oceania (Tab. 7).

In regions of Eastern Europe, OECD-Europe and South East Asia more than 40% of all N inputs were simulated to be extracted by plant harvest or biomass burning, while in Greenland only a very small fraction of the N inputs will be extracted by these processes. Globally about one third of the considered N inputs will be extracted by plant harvest and burning (Tab. 7).

Table 6. N inputs from synthetic fertilizers (N_{fert}), livestock excretions (N_{anm}), atmospheric deposition (N_{dep}) and biological N fixation (N_{fix}); total N inputs (N_{inp}), N output by biomass extractions (N_{exp}) and ammonia volatilization (N_{vol}), total N outputs (N_{out}) and N balance at the soil surface (N_{sur}) (Tg N yr^{-1}); N balance at the soil surface (N_{surha}) (Tg N ha^{-1} yr^{-1}) for IMAGE 2.2 world regions in 1995.

Region	N_{fert}	N_{anm}	N_{dep}	N_{fix}	N_{inp}	N_{exp}	N_{vol}	N_{out}	N_{sur}	N_{surha}
Canada	1.3	0.9	1.1	4.1	*7.4*	2.1	0.4	*2.5*	***4.9***	***5.2***
United States	9.8	7.9	7.1	9.4	*34.3*	12.6	3.1	*15.7*	***18.6***	***20.1***
Central America	1.5	3.6	1.7	5.3	*12.2*	3.2	1.2	*4.5*	***7.7***	***28.5***
South America	2.6	15.5	7.7	34.5	*60.3*	16.3	4.6	*20.9*	***39.4***	***22.4***
Northern Africa	0.8	1.3	1.1	1.0	*4.3*	1.4	0.4	*1.8*	***2.5***	***4.4***
Western Africa	0.2	3.8	4.1	20.6	*28.8*	7.4	1.0	*8.4*	***20.4***	***18.1***
Eastern Africa	0.1	6.2	2.5	8.9	*17.7*	5.0	1.7	*6.6*	***11.1***	***19.0***
Southern Africa	0.7	2.8	2.7	11.9	*18.1*	6.0	0.8	*6.8*	***11.3***	***16.7***
OECD-Europe	8.8	9.0	4.8	9.6	*32.3*	15.7	2.9	*18.6*	***13.7***	***36.8***
Eastern Europe	1.8	2.5	1.8	2.1	*8.2*	4.9	0.8	*5.8*	***2.4***	***20.5***
Former USSR	4.5	7.9	6.7	9.1	*28.2*	10.9	2.7	*13.6*	***14.6***	***6.7***
Middle East	2.2	3.5	2.1	2.1	*9.9*	3.8	1.0	*4.8*	***5.1***	***8.6***
South Asia	11.8	19.8	8.5	12.0	*52.1*	19.0	7.3	*26.3*	***25.8***	***50.7***
East Asia	21.5	14.4	11.9	6.8	*54.6*	15.9	9.8	*25.6*	***29.0***	***26.2***
South East Asia	3.3	3.9	3.1	11.2	*21.6*	9.1	1.4	*10.5*	***11.1***	***25.1***
Oceania	0.6	4.0	1.2	10.4	*16.3*	4.4	1.1	*5.5*	***10.8***	***12.9***
Japan	0.6	0.6	0.4	0.8	*2.4*	0.6	0.2	*0.8*	***1.5***	***41.1***
Greenland	0.0	< 0.1	< 0.1	0.2	*0.2*	< 0.1	< 0.1	*< 0.1*	***0.2***	***0.8***
World	72.3	107.7	68.6	160.1	*408.7*	138.3	40.4	*178.7*	***230.0***	***17.3***

Table 7. Total N inputs at the soil surface (N_{inp}), fraction of N input as synthetic fertilizers (N_{fert}), livestock excretions (N_{anm}), atmospheric deposition (N_{dep}) and biological N fixation (N_{fix}); fraction of N input exported by crop harvest, grazing, wood harvest or biomass burning (N_{exp}) for world regions in 1995.

Region	N_{inp} (Tg N yr^{-1})	N_{fert} (-)	N_{anm} (-)	N_{dep} (-)	N_{fix} (-)	N_{exp} (-)
Canada	7.4	0.18	0.13	0.15	0.55	0.28
United States	34.3	0.29	0.23	0.21	0.28	0.37
Central America	12.2	0.13	0.30	0.14	0.43	0.27
South America	60.3	0.04	0.26	0.13	0.57	0.27
Northern Africa	4.3	0.20	0.30	0.26	0.24	0.33
Western Africa	28.8	0.01	0.13	0.14	0.72	0.26
Eastern Africa	17.7	0.01	0.35	0.14	0.50	0.28
Southern Africa	18.1	0.04	0.15	0.15	0.66	0.33
OECD-Europe	32.3	0.27	0.28	0.15	0.30	0.49
Eastern Europe	8.2	0.22	0.30	0.22	0.26	0.60
Former USSR	28.2	0.16	0.28	0.24	0.32	0.39
Middle East	9.9	0.23	0.35	0.21	0.21	0.38
South Asia	52.1	0.23	0.38	0.16	0.23	0.37
East Asia	54.6	0.39	0.26	0.22	0.13	0.29
South East Asia	21.6	0.15	0.18	0.14	0.52	0.42
Oceania	16.3	0.04	0.25	0.08	0.64	0.27
Japan	2.4	0.25	0.25	0.19	0.32	0.26
Greenland	0.2	0.00	< 0.01	0.17	0.83	< 0.01
World	408.7	0.18	0.26	0.17	0.39	0.34

3.2 N inputs, N exports and N surface balances in 1961 and 2050

Total global N inputs have been simulated to increase from about 283 Tg N yr^{-1} in 1961 to 409 Tg N yr^{-1} in 1995 and 698 Tg N yr^{-1} in 2050 (for the SRES A1B scenario which assumes a strongly globalized world and a focus on economic development). Total N outputs have been simulated to increase within the same period from 121 Tg N yr^{-1} to 179 Tg N yr^{-1} and 468 Tg N yr^{-1}. This leads to a surface balance N surplus of 161 Tg N yr^{-1} in 1961, 230 Tg N yr^{-1} in 1995 and 229 Tg N yr^{-1} in 2050. Synthetic fertilizer use, livestock excretions, atmospheric deposition, N export and volatilization were simulated to increase over the entire period, while symbiotic N fixation was simulated to be lower in 1995 compared to 1961 and 2050 (Tab. 6, 8, 9). Synthetic N-fertilizer use was simulated to be the largest source of N inputs in 2050, followed by biological N fixation (Tab. 9).

Surface balance N surplus was increasing between 1961 and 1995 in all regions except of Southern Africa, Japan and Greenland. In particular for South Asia and East Asia the computed increases are very large, while the balance was computed to be almost stable in Africa (Tab. 6, 8). Surface balance N surplus was computed to decrease between 1995 and 2050 for developed regions like Canada, US, OECD-Europe, Former USSR, Oceania and Japan but also for East Asia (China), South America, Southern Africa and Western Africa. Largest increases within the same period were computed for the Middle East region, North Africa, South Asia and South East Asia (Tab. 6, 9).

On the grid cell level a large N balance surplus was simulated for the year 2050 in agricultural regions of India, South East Asia, Mexico, Western Europe, North China and South Brazil. The computed N surplus for productive natural ecosystems like tropical woodland or tropical rainforest is also still large. However, the extent of areas facing an N deficiency has also increased, e.g. in North Argentina, Southern Europe, South East Africa and even in the agricultural regions of Canada, Australia, the US and South China (Fig. A4).

Table 8. N inputs from synthetic fertilizers (N_{fert}), livestock excretions (N_{anm}), atmospheric deposition (N_{dep}) and biological N fixation (N_{fix}); total N inputs (N_{inp}), N output by biomass extractions (N_{exp}) and ammonia volatilization (N_{vol}), total N outputs (N_{out}) and N balance at the soil surface (N_{sur}) (Tg N yr^{-1}); N balance at the soil surface (N_{surha}) (Tg N ha^{-1} yr^{-1}) for IMAGE 2.2 world regions in 1961.

Region	N_{fert}	N_{anm}	N_{dep}	N_{fix}	N_{inp}	N_{exp}	N_{vol}	N_{out}	N_{sur}	N_{surha}
Canada	0.1	0.7	0.6	3.9	*5.4*	1.4	0.2	*1.6*	***3.8***	***4.0***
United States	2.8	6.6	4.1	9.1	*22.7*	10.2	2.1	*12.3*	***10.3***	***11.2***
Central America	0.2	2.1	0.8	5.5	*8.6*	2.4	0.6	*3.0*	***5.6***	***20.9***
South America	0.2	8.6	4.1	33.3	*46.2*	10.6	2.1	*12.7*	***33.5***	***19.0***
Northern Africa	0.1	0.8	0.6	1.0	*2.5*	0.9	0.2	*1.1*	***1.5***	***2.5***
Western Africa	0.0	1.8	2.2	21.0	*25.0*	5.5	0.4	*5.9*	***19.1***	***16.9***
Eastern Africa	0.0	3.6	1.2	10.4	*15.2*	3.9	0.9	*4.8*	***10.4***	***17.9***
Southern Africa	0.1	2.1	1.5	14.2	*18.0*	5.2	0.5	*5.7*	***12.2***	***18.1***
OECD-Europe	3.3	7.4	2.8	9.3	*22.8*	12.1	2.0	*14.1*	***8.6***	***23.3***
Eastern Europe	0.9	2.6	1.1	2.9	*7.4*	5.0	0.7	*5.7*	***1.7***	***14.9***
Former USSR	0.9	6.5	4.0	9.7	*21.1*	10.3	1.9	*12.2*	***8.9***	***4.1***
Middle East	0.1	2.8	1.0	2.2	*6.1*	2.7	0.5	*3.2*	***2.9***	***4.8***
South Asia	0.4	13.9	4.6	9.8	*28.6*	12.9	3.0	*16.0*	***12.6***	***24.7***
East Asia	1.4	5.8	4.8	7.2	*19.2*	8.3	1.8	*10.1*	***9.1***	***8.2***
South East Asia	0.2	2.2	1.5	12.3	*16.2*	6.1	0.4	*6.6*	***9.6***	***21.7***
Oceania	0.0	3.2	0.8	9.8	*13.9*	3.6	0.8	*4.4*	***9.6***	***11.4***
Japan	0.7	0.3	0.2	2.6	*3.7*	1.7	0.1	*1.8*	***1.9***	***51.3***
Greenland	0.0	< 0.1	< 0.1	0.2	*0.2*	< 0.1	< 0.1	*< 0.1*	***0.2***	***0.8***
World	11.4	71.0	35.9	164.3	*282.7*	102.7	18.5	*121.2*	***161.4***	***12.2***

Table 9. N inputs from synthetic fertilizers (N_{fert}), livestock excretions (N_{anm}), atmospheric deposition (N_{dep}) and biological N fixation (N_{fix}); total N inputs (N_{inp}), N output by biomass extractions (N_{exp}) and ammonia volatilization (N_{vol}), total N outputs (N_{out}) and N balance at the soil surface (N_{sur}) (Tg N yr^{-1}); N balance at the soil surface (N_{surha}) (Tg N ha^{-1} yr^{-1}) for IMAGE 2.2 world regions in 2050 (SRES scenario A1B).

Region	N_{fert}	N_{anm}	N_{dep}	N_{fix}	N_{inp}	N_{exp}	N_{vol}	N_{out}	N_{sur}	N_{surha}
Canada	2.0	1.2	1.2	4.4	*8.9*	4.8	0.6	*5.4*	***3.5***	***3.6***
United States	14.7	11.9	8.0	11.9	*46.6*	33.7	4.6	*38.3*	***8.3***	***8.9***
Central America	6.9	6.2	3.9	5.1	*22.0*	10.3	2.7	*13.0*	***9.1***	***33.8***
South America	25.5	26.8	17.6	35.4	*105.3*	58.7	10.5	*69.3*	***36.1***	***20.5***
Northern Africa	2.6	4.4	3.0	1.5	*11.5*	3.6	1.6	*5.1*	***6.3***	***11.1***
Western Africa	5.5	17.9	8.8	20.7	*53.0*	33.0	5.9	*38.9*	***14.1***	***12.5***
Eastern Africa	0.8	16.0	6.0	11.1	*33.9*	13.6	4.6	*18.2*	***15.7***	***27.0***
Southern Africa	5.0	8.0	5.5	10.8	*29.4*	24.0	3.0	*26.9*	***2.5***	***3.7***
OECD-Europe	12.7	11.0	6.0	14.6	*44.2*	27.3	3.6	*31.0*	***13.3***	***35.6***
Eastern Europe	4.2	2.4	2.1	5.5	*14.1*	10.2	1.0	*11.3*	***2.8***	***24.3***
Former USSR	21.2	7.1	8.1	10.9	*47.4*	31.0	3.4	*34.4*	***13.0***	***5.9***
Middle East	10.4	8.5	6.3	3.6	*28.9*	9.7	3.8	*13.5*	***15.3***	***25.9***
South Asia	47.3	17.9	17.9	21.7	*104.8*	53.0	14.2	*67.2*	***37.5***	***73.7***
East Asia	17.5	13.5	21.4	7.9	*60.2*	31.0	8.4	*39.4*	***20.8***	***18.7***
South East Asia	31.2	10.2	7.4	17.4	*66.2*	37.7	8.3	*46.1*	***20.2***	***45.6***
Oceania	2.2	3.1	1.4	11.4	*17.9*	7.3	1.0	*8.4*	***9.6***	***11.4***
Japan	0.5	1.1	0.6	0.9	*3.2*	1.6	0.4	*2.0*	***1.2***	***32.9***
Greenland	0.0	< 0.1	< 0.1	0.2	*0.2*	< 0.1	< 0.1	*< 0.1*	***0.2***	***0.9***
World	210.2	167.2	125.3	195.0	*697.7*	390.6	77.7	*468.3*	***229.4***	***17.3***

4 Discussion

The simulation of N inputs, of N outputs and of the balance at the grid cell level involves specific problems and uncertainties. Most of the data sets used here as modeling input are also result of a modeling process itself because measurements at the used temporal and spatial resolution are not possible. The problem behind it is that point measurements of the terms included in the balance as available from the literature are only valid for the specific conditions at the specific location of the measurement. Therefore an interpolation in space and time always requires a kind of modeling. The values given as result of this report are averages for 0.5 degree grid cells and thus represent an area of 55 x 55 km at the equator. Because a measurement of the balance terms is impossible in such a large area, results presented here are compared to modeling results as published by other research groups. It should be noted that this comparison of modeling results cannot be interpreted as an estimate of uncertainty. Because the different modeling groups try to keep their modeling results close to best expert guesses, the differences between results of different models will be usually smaller than the real uncertainty. In the following sections modeling results accumulated in larger units like provinces, countries or regions are compared. For a comparison at grid cell or river basin scale the reader is referred to a companion paper (Van Drecht et. al., 2005).

4.1 Synthetic fertilizer use (N_{fert})

Synthetic fertilizer use is reported by FAO at the country scale for all years after 1960 (FAO, 2003a). Average fertilizing rates per crop are used usually to downscale these country values to smaller units like provinces, counties or grid cells (e.g. Battaglin and Goolsby, 1994; Bouwman et al., 2004). This is necessary because fertilizer use is related to the specific crop and in many countries only a few crops receive synthetic N fertilizers (FAO, 2003b, IFA, 2003). Other data sets are based on consumption (sales) statistics provided by fertilizer producing companies (e.g. NLWR Audit, 2001). Differences to the data presented in this paper are therefore mainly based on:

- different extent of specific crops (land use),
- different fertilization rates per crop,
- different scenarios of future land and fertilizer use.

Additionally, fertilization rates for one and the same crop may differ within a country because of different production intensity or availability of other fertilizers (manure). This is not considered in WaterGAP-N. In order to be able to consider the impact of future land use changes, it is necessary to use *simulated* land use also for current day conditions. The combination with fertilizing rates per crop (FAO, 2003b) leads to total fertilizer uses per country that are different from fertilizer use as reported by FAO (2003a). At the global scale we a total fertilizer use of 11.4 Tg N yr^{-1} in 1961 and 72.3 Tg N yr^{-1} in 1995 was computed, while FAO reported 11.6 Tg N yr^{-1} in 1961 and 78.4 Tg N yr^{-1} in 1995. The differences on the country level are even larger because the simulated land use was scaled only by world region to meet the reported extent of cropping areas (RIVM, 2001).

Comparisons of simulated N fertilizer use to reported fertilizer use per county of the United States (Battaglin and Goolsby, 1994) or statistical local unit of Australia (NLWR Audit, 2001) show that the spatial variability in the reported data is larger than in the values simulated by WaterGAP-N (Fig. 1, 2). Additionally, some areas that do not receive synthetic fertilizers according to WaterGAP-N are reported to receive some synthetic N fertilizer (e.g. Eastern US, areas along the border line to Mexico, Eastern coastal zone of Australia).

Global synthetic fertilizer use in 2050 was simulated to be 210 Tg N by using the SRES A1B scenario assumptions to scale fertilizer use in the future. This is within the range of 166 Tg N yr^{-1} to 343 Tg N yr^{-1} and a little bit lower than the mean projection of 236 Tg N yr^{-1} as estimated by Tilman et al. (2001). However, Galloway et al. (2004) estimate N fertilizer consumption in 2050 much lower (135 Tg N yr^{-1}) which shows the large variability inherent in projections of future N fertilizer use.

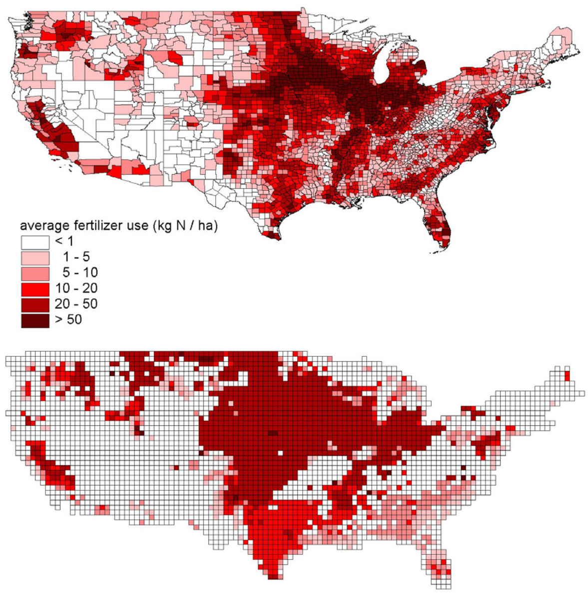


Figure 1. Average synthetic fertilizer use per county (Battaglin and Goolsby, 1994, upper figure) and synthetic fertilizer use as simulated by WaterGAP-N (bottom) for the United States in 1987 (kg N ha^{-1} yr^{-1}).

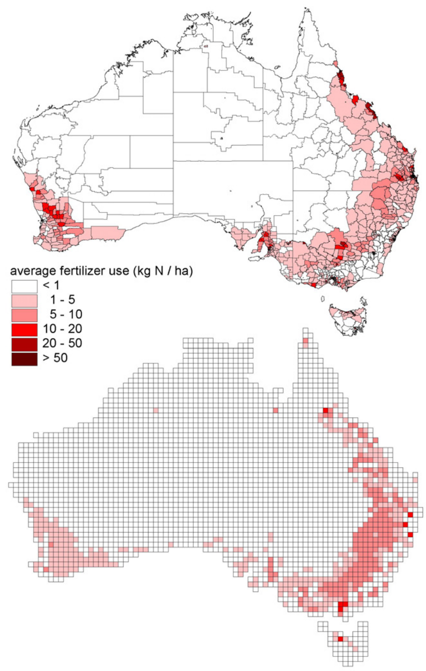


Figure 2. Average synthetic fertilizer use per statistical local unit (NLWR Audit, 2001, upper figure) and synthetic fertilizer use as simulated by WaterGAP-N (bottom) for Australia in 1995 (kg N ha^{-1} yr^{-1}).

4.2 Livestock N excretions (N_{anm})

To compute total livestock N excretion, it is necessary to know the density and excretion rates of different livestock categories. Both are changing over space and time. The modeling of livestock numbers per grid cell as presented in this paper enables that the most recent data on livestock distribution are incorporated. However, the scaling of livestock numbers computed for 1995 to compute livestock numbers in 1961 and 2050 does not account for different change rates of livestock densities relative to the average change within the countries. For example livestock density may increase in one part of a country and decrease in another part of the same country. Therefore the computed livestock numbers in 1961 have to be considered to be much more uncertain than the numbers computed for 1995.

N excretion rates are depending on various factors like animal category, weight, productivity or the used fodder types (Bouwman et al., 1997; Brandjes et al., 1996), which are however rarely known at the global scale. The simplified modeling approach used here leads therefore to differences between the simulated livestock N excretions and reported estimates, e.g. by OECD (2001). However, a comparison to the reported values for OECD member countries shows that the results computed by WaterGAP-N are reasonable for most of the countries (Tab. 10). The overestimation of excretions in many European countries can be explained by the fact that the OECD data do not include the amount of N volatilized from stored manure for many European countries. It also has to be considered that there exist estimates different from those given by OECD. Livestock N excretion for Canada, for example, was reported to be 783,000 t N in 1996 by Hofmann and Kemp (2001) while OECD estimates 1,268,980 t N for the same year. This shows the large uncertainty of those estimates.

Global livestock N excretion was simulated to increase from 71 Tg N yr^{-1} in 1961 to 108 Tg N yr^{-1} in 1995 and to 167 Tg N yr^{-1} in 2050 (SRES A1B). This means that globally the importance of manure compared to synthetic fertilizers is decreasing. The simulation results are in good agreement to Nevison et al. (1996) who computed an increase of livestock N excretion from 21 Tg N yr^{-1} to 102 Tg N yr^{-1} in the period 1860 to 1990 and Bouwman et al. (2004) who computed a livestock N excretion of 105 Tg N in 1995.

Table 10. Livestock N excretion in 1995 for OECD-member countries as estimated by OECD (2001) and simulated by WaterGAP-N (1000 kg N yr^{-1}).

Country	OECD	WaterGAP-N
United States	10,321,137	7,913,844
Mexico	2,991,806	2,521,658
Australia	2,413,324	2,942,299
France	1,506,785	1,749,229
New Zealand	1,461,886	1,004,945
Germany	1,308,483	1,515,349
Turkey	1,293,369	1,263,117
Canada	1,248,622	934,707
UK	1,008,754	1,354,063
Spain	817,136	853,956
Japan	776,076	583,014
Netherlands	652,457	560,596
Poland	621,306	771,977
Italy	616,115	806,856
Ireland	452,471	466,202

Country	OECD	WaterGAP-N
Korea, Rep.	304,250	271,462
Denmark	268,950	276,821
Greece	268,324	211,370
Belgium	264,483	298,606
Portugal	244,732	199,854
Czech Republic	170,207	225,281
Austria	166,871	207,383
Sweden	138,412	157,964
Hungary	127,204	180,767
Switzerland	117,797	149,063
Norway	101,298	102,118
Finland	86,734	104,576
Iceland	13,732	13,910
total	29,762,722	27,640,989

4.3 Biological N fixation (N_{fix})

Global terrestrial biological N fixation in natural ecosystems was estimated by Cleveland et al. (1999) to be in the range between 100 Tg N yr^{-1} and 290 Tg N yr^{-1} with a best estimate of 195 Tg N yr^{-1}. The study was based on a collection of measurements data for the different ecosystems and an estimate of the coverage of N fixing species in the different ecosystems. Galloway et al. (2004) consider the real extent of natural ecosystems on the globe and the fact that measurements of biological N fixation will usually occur more often in areas where fixation is relevant (which could lead to an overestimation of N fixation). Consequently they give lower estimates of 120 Tg N yr^{-1} (1860), 107 Tg N yr^{-1} (early 1990s) and 98 Tg N yr^{-1} (2050) for biological N fixation. WaterGAP-N simulates a biological N fixation in natural ecosystems of 132.3 Tg N yr^{-1} (1961), 125.9 Tg N yr^{-1} (1995) and 111.3 Tg N yr^{-1} (2050) and is therefore in between the two estimates mentioned above.

Biological N fixation on agricultural land in 1995 has been estimated to be in the range between 25 Tg N yr^{-1} and 41 Tg N yr^{-1} with a best estimate of 33 Tg N yr^{-1} (Smil, 1999). Galloway et al. (2004) combined the mean crop-specific fixation rates of Smil (1999) to the extent of crops as reported by FAOSTAT (FAO, 2003a) and estimate biological N fixation by cultivation to be 31.5 Tg N yr^{-1} in 1995. Van Drecht et al. (2003) estimate biological N fixation on cropland by combining fixation rates reported by Smil (1999) for non-symbiotic N fixation and harvested N-content in soy beans and pulses to be about 41 Tg N yr^{-1}. WaterGAP-N simulates a N fixation of 34.1 Tg N on agricultural land for 1995 and is therefore in between these estimates.

The modeling results of Smil (1999), Galloway et al. (2004) and WaterGAP-N agree that N fixation on agricultural land is increasing, but the amount of increase is different. While Galloway et al. estimate N fixation by cultivation to be 15 Tg N yr^{-1} in 1860 and 50 Tg N yr^{-1} in 2050, WaterGAP-N simulates amounts of 32 Tg N yr^{-1} in 1961 and 83.7 Tg N yr^{-1} in 2050. The large increase in the WaterGAP-N results for 2050 is caused by an increase of the extent of cropland on the one hand and by simulated nutrient deficiencies in many parts of the world on the other hand (see section surface balances). The simulated N deficiencies stimulate N fixation by leguminous crops and lead therefore to high N fixation rates.

4.4 Atmospheric deposition (N_{dep})

Atmospheric deposition is computed by combining emissions of nitrous oxides and ammonia as taken from global inventories and models of transformation and transport processes. The resolution of these models is much coarser than 0.5 by 0.5 degree because several vertical atmospheric layers have to be considered which makes these models computationally very expensive. To use the depositions computed by the global chemistry transport models (CTM) on the given 0.5 degree land mask it is necessary to interpolate the data. This adds additional uncertainty to the uncertainty inherent to these models itself. Another source of uncertainty is that the ammonia emission inventory used by the TM3 model (Dentener and Crutzen, 1994) to compute N depositions is different from the ammonia emissions as computed by WaterGAP-N itself. Therefore the ammonia depositions computed by TM3 were reduced by the ammonia emissions from fertilizer and manure used by TM3 and instead of it the ammonia emissions computed by WaterGAP-N have been used by assuming that 30% of the emissions is short range transport which will not leave the grid cell and 70% is long range transport that will leave the grid cell and will be deposited relative to the total deposition computed by the TM3 model. This method makes emissions and depositions more consistent on the global scale but may cause inconsistencies on the grid cell level. A major improvement could be made by using the ammonia emissions computed by WaterGAP-N directly as input in the TM3 model.

In the global summary the difference in terrestrial N depositions computed by different CTMs may be related to the fraction of N deposited on terrestrial and marine ecosystems. At the grid cell level the major sources of uncertainty should be different emission inventories, different modeling of transport and transformation processes and different interpolation errors due to the use of different resolutions in the CTMs. Total terrestrial N deposition in WaterGAP-N in 1995 (68.6 Tg N yr^{-1}) is larger than the deposition of 63.5 Tg N yr^{-1} used by Galloway et al. (2004) which may be caused by larger ammonia emissions from manure and fertilizer. The good agreement of the estimates for 2050 of 125.3 Tg N yr^{-1} (WaterGAP-N, SRES A1B scenario as implemented in RIVM, 2001) and 125.2 Tg N yr^{-1} (Galloway, 2004) indicate the use of similar scenario assumptions regarding the major driving sources of N emissions and should not be used as a measurement of uncertainty.

4.5 N export by plant uptake (N_{exp})

N export by plant extractions depends on the amount and N content of harvested (or burned) biomass. Crop harvests have been used as simulated by IMAGE 2.2 (RIVM, 2001) and are therefore scaled to reported production data in world regions. On the global and regional level past and present day crop harvests should be therefore consistent to FAOSTAT statistics. However, at the country or grid cell scale there are constraints that lead to large uncertainties in simulated crop harvests. Annual cropping intensity is equal for all cells within the same region. The coefficient used to scale simulated yields of a specific crop to reported yields on the region level is also be equal for all cells within the same region. This leads to the situation that the simulated variability of crop yields within world regions is lower than reported variability because the different specific management and intensity of crop growing is not taken into account. In general it can be expected, that crop yields are underestimated in intensive agricultural systems and overestimated in more extensive cropping areas. The used coefficients for the fraction of harvested parts and for the N content of the harvested parts are averages that do not take into account variations e.g. by different crop varieties or different management. The grouping of crops with different characteristics (e.g. oil crops, root and tubers) and using of similar coefficients for all crops within these crop groups also bears many uncertainties.

The computed extractions by savanna burning and wood harvest should be considered as very rough estimates. In particular it was not taken into account that the spatial pattern of those extractions is variable and is changing year by year depending on climate conditions (savanna burning) or new road constructions (wood extraction in tropical rain forest). At the global scale only a minor part of the plant N export is by savanna burning or wood harvest. However, at the grid cell scale it may be an important factor.

N export by plant N extractions was simulated by WaterGAP-N to be 102.7 Tg N yr^{-1} in 1961, 138.3 Tg N yr^{-1} in 1995 and 390.6 Tg N yr^{-1} in 2050. The strong increase of extractions until 2050 are the result of the scenario assumptions regarding population growth, change of human diet and use of biomass in energy production. Van Drecht et al. (2003) estimate N extractions on agricultural lands by crop harvest and grass consumption in 1995 to be 91 Tg N yr^{-1}. When reducing the simulation results of WaterGAP-N by N extractions from wood harvest, savanna burning and grazing in natural grasslands it would simulate extractions of 109 Tg N yr^{-1} for 1995. Because both models are based on the same yield model this difference indicates that the N content in harvested parts of the plants may be different or that there are different approaches to simulate return flows and crop residues management.

4.6 Ammonia volatilization from synthetic fertilizers and manure (N_{vol})

Ammonia volatilization from manure and synthetic N fertilizers depends on many things like type of fertilizer, technology used for manure storage and spreading, soil pH, cropping system and management. Based on these factors the best estimate of the mean global NH_3 loss rate was computed to be 14% for fertilizers and 23% for manure with a range of 10-19% for fertilizer and 19-29% for manure (Bouwman et al., 2002). Additional to the uncertainty regarding the loss rates there appears the uncertainty of the distribution of fertilizer application and manure production as described in the related sections above.

Total global NH_3 emission was computed to be 54 Tg N yr^{-1} for the year 1990, the amount volatilized from manure and fertilizers was given in the same study as 30.6 Tg N yr^{-1}. Van Drecht et al. (2003) computed an Ammonia-N-volatilization of about 30 Tg N yr^{-1} for 1995 while WaterGAP-N simulates 40 Tg N yr^{-1} for the same year. The difference may be caused by the fact that Van Drecht et al. (2003) did not account for NH_3 losses from stored manure in the given estimate. Galloway et al. compute total NH_3 emissions from food production of 44.3 Tg N yr^{-1} in 1993 and 106 Tg N yr^{-1} in 2050, volatilization from synthetic fertilizers and manure was computed to be 32.6 Tg N yr^{-1} in 1993 and 85.1 Tg N yr^{-1} in 2050 respectively. Ammonia volatilization as simulated by WaterGAP-N for 2050 is 77.7 Tg N yr^{-1} in thus lower than the estimates of Galloway et al. (2004).

4.7 Surface balance (N_{sur})

With WaterGAP-N, total surface balance surplus was simulated to be 161.4 Tg N yr^{-1} in 1961, 230 Tg N yr^{-1} in 1995 and 229.4 Tg N yr^{-1} in 2050. The balance cannot be compared to Van Drecht et al. (2003) because in the surface balance is given in this study only for agricultural land. Galloway et al. (2004) simulated total net inputs to the global watersheds of 230 Tg N yr^{-1} for the early 1990s. Green et al. (2004) simulated that total N load of the surface (which is similar to the surface balance used in this paper) has increased from 111 Tg N yr^{-1} in pre-industrial times to 223 Tg N yr^{-1} in the mid 1990s. Although the different approaches agree very well with respect to the present-day surface balance at the global scale there are differences at the regional, river basin and of course at the grid cell scale. For a more systematic comparison of modeled N surface balances the reader is referred to a companion paper (Van Drecht et al., 2005).

It is surprising that the various modeled N surface surpluses at the global scale are so similar despite of all the uncertainties and differences mentioned in the sections above. One reason may be that N inputs and N outputs are correlated. Lower livestock numbers, for example, will lead to a lower amount of N inputs by livestock excretions but also to lower N outputs by ammonia volatilization and fodder requirements. At the global scale livestock does not modify the amount of reactive N. and the N balance. The only importance of livestock is that N available in the fodder will be transformed to other forms (biomass, urine or faeces) and concentrated in areas of high livestock density.

Another example is the calculation of fertilizer N inputs and crop N extractions by WaterGAP-N. As already described above, crop harvest will be underestimated in productive regions and overestimated in marginal cropping areas because cropping intensity is constant in all cells of the same region. This is however also valid in almost the same manner for fertilizer N inputs and therefore both effects tend to level out in the balance. It should therefore be pointed out in general that all the approaches mentioned above were developed with the target to simulate proper balances which means that inputs and outputs have to be considered together.

There appears to exist a consensus that total surface balance surplus at the global scale has increased in the past and will increase in most of the scenarios for the future. It is therefore surprising that WaterGAP-N simulates even a small decrease of the total surface balance surplus in 2050 (229 Tg N yr^{-1}) compared to 1995 (230 Tg N yr^{-1}). The reason is to be found in the scenario assumptions about strongly increasing crop yields which lead to three times higher extractions. As consequence N_{exp} is increasing from 138.3 Tg N yr^{-1} in 1995 to 390.6 Tg N yr^{-1} in 2050. This large increase is not completely balanced out by higher N inputs. The spatial distribution of the simulated balances in 2050 (Fig. A4) indicate that the assumptions are not realistic; many agricultural areas in all parts of the globe show negative surface balances. It should be noted that N losses by denitrification and leaching are not included in the surface balance. We will therefore try to develop in the following more realistic scenario assumptions related to N-inputs in SRES A1B:

Let us assume that the reported increases of crop extractions are necessary to reflect the scenario assumptions on crop production increases as caused by population growth, change of human diet and use of biofuel crops for energy production. Then, it appears plausible that N inputs should increase much more than in the version of the A1B scenario as implemented in the IMAGE 2.2 scenarios. Because the deficits mainly appear on agricultural land, it is not plausible to increase N deposition. Biological N fixation has already doubled in the 2050 scenario as compared to 1995 because the computed N deficiency stimulated leguminous crops to fix more nitrogen. A further increase is therefore not realistic. Increase of livestock excretions is also not helpful because this would (as already mentioned above) also increase fodder demand and volatilization in the output section. The only alternative to achieve more plausible N surface balances would be to assume that more synthetic N fertilizer will be applied. We use the ratio between plant N exports (N_{exp}) and total N inputs (N_{inp}) as presented in Tab. 7 for 1995 to compute which amount of additional fertilizer N would be necessary. This ratio is close to zero in untouched natural ecosystems because the only N export is due to biomass burning. It can be larger than one for non-sustainable land use (cutting of tropical rain forest, soil mining by extreme slash and burn agriculture). The ratio will be smaller than one in common agriculture because losses by volatilization cannot be avoided and because the total surface balance should be larger than zero to account for additional losses by denitrification and leaching. At the global scale that ratio was computed by WaterGAP-N to be 0.36 in 1961, 0.34 in 1995 and 0.56 in 2050. Using a ratio of 0.34 also for 2050 and the computed N exports of 390.6 Tg N yr^{-1} leads to total N inputs of 1148.8 Tg N. By subtracting the other inputs N fertilizer use would be estimated to be 661 Tg N yr^{-1}. This would be eight times the amount of synthetic N fertilizer used in year 2000 and about three times the amount of N fertilizer used in the existing version of the scenario. The N surface surplus for 2050 would then be about 680 Tg N yr^{-1}. Of course it may be that N inputs will be used more efficiently in the future. But it should be also noted that more intensive agriculture and extension of agriculture to marginal soils could also lead to the opposite case of higher losses.

5 Summary and conclusions

Total global surface N surplus increased from 161 Tg N yr^{-1} in 1961 to 230 Tg N yr^{-1} in 1995. By implementing scenario assumptions for the scenario A1B of the Special Report on Emission Scenarios (SRES) of the International Panel on Climate Change (IPCC, total global surface N surplus was estimated to be 229 Tg N yr^{-1} in 2050. Because this would lead to negative surface balances in many agricultural regions there is a need to modify scenario assumptions to ensure a better balance between nitrogen inputs and extractions. This would lead to a higher N surplus in 2050.

In the past and under present day conditions biological N fixation provides the largest amounts of N input at the global scale. Nitrogen fixation in natural ecosystems and managed forests was simulated to decline (132.3 Tg N yr^{-1} in 1961, 125.9 Tg N yr^{-1} in 1995 and 111.3 Tg N yr^{-1} in 2050) while fixation on agricultural land was computed to increase (32 Tg N yr^{-1} in 1961, 34.1 Tg N yr^{-1} in 1995 and 83.7 Tg N yr^{-1} in 2050).

Animal manure was the most important source of N inputs on agricultural land in 1961 and with exception of North America also in 1995. However, there is a trend that synthetic fertilizer N becomes more and more dominant and replaces livestock excretions as largest input source. In 2050 livestock excretions will still be the largest N source in Africa, Japan and Oceania. Because N contained in livestock excretions has to be supplied to the animals in form of fodder before, it cannot be seen as a creation of additional nitrogen in reactive forms. The importance is more that collected manure enables a concentration and management of nutrients.

Synthetic fertilizers only played a minor role in the surface balance in 1961 (11 Tg N yr^{-1} input at the global scale). However it is the input term that shows the largest increases and is assumed to be the dominant source of N inputs to agricultural systems in 2050. To avoid environmental damages by leaching losses it will be necessary to improve the efficiency of N use in general. In particular it is recommended to introduce efficient cropping systems with low N losses in the growing biofuel crops sector.

Ammonia volatilization and atmospheric N deposition are increasing as consequence of more fertilizer consumption and more livestock excretions on the one hand and more energy production on the other hand. It should be noted that N deposition cannot be controlled by the farmers and will play therefore a minor role as crop nutrient. Nevertheless it is an important input to natural ecosystems and is altering these systems.

Export of nitrogen by crop harvest and grazing was computed to increase very strongly in the period until 2050. The trend of increasing biomass harvest is inherent also in the other IPCC scenarios published in the SRES. Synthetic fertilizers will be the major source of additional inputs to satisfy the additional nutrient demand.

It has been shown that simulated absolute values of the terms in the global surface balance are in the range given by other models published before. However, the uncertainty in particular of the input terms livestock excretions, biological N fixation and atmospheric deposition is much larger than the different model estimates indicate. On the grid cell level all terms in the balance are highly uncertain.

Major improvements of the model would be to use a better land use and crop productivity model which is also being linked to the livestock sector. This would enable consistent fertilizer input and crop extraction and dynamic livestock density changes. Besides, nitrogen deposition should be computed based on an atmospheric model which is driven by ammonia emissions as simulated by WaterGAP-N itself.

References

Alcamo, J., P. Döll, T. Henrichs, F. Kaspar, B. Lehner, T. Rösch, S. Siebert (2003): Development and testing of the WaterGAP 2 global model of water use and availability. Hydrological Sciences Journal, 48(3), 317-338.

Australian Bureau of Statistics (ABS) (2001): A spatially consistent sub-set of AgStats data 1982/83 to 1996/1997. http://adl.brs.gov.au/ADLsearch/index.cfm

Battaglin, W.A. and D.A. Goolsby (1994): Spatial data in GIS format on agri. chem. use, LU, and cropping practices in US. United States Geological Survey (USGS), http://water.usgs.gov/lookup/getspatial?ag_stock

Bouwman A.F., L.J.M. Boumans, N. Batjes (2002): Modeling global annual N_2O and NO emissions from fertilized fields. *Global Biogeochemical Cycles, 16 (2),* 1024, doi:10.1029/2000GB001389.

Bouwman, A.F., D.S. Lee, W.A.H. Asman, F.J. Dentener, K.W. Van der Hoek, J.G.J. Olivier (1997): A global high-resolution emission inventory for ammonia, *Global Biogeochemical Cycles, 11*, 561-587.

Brandjes, P.J., J.D. Wit, H.G. Van Der Meer, H. Van Keulen (1996): Livestock and the environment. Finding a balance. Environmental impact of animal manure management. Study available from the livestock, Environment and Development Initiative (LEAD) of FAO at (http://www.fao.org/DOCREP/004/X6113E/ x6113e00.htm), International Agricultural Centre (IAC), Wageningen, The Netherlands.

Center for International Earth Science Information Network (CIESIN) (2001): Gridded Population of the World, version 2. http://sedac.ciesin.columbia.edu/plue/gpw/index.html

Cleveland, C.C., A.R. Townsend, D.S. Schimel, H. Fisher, R.W. Howarth, L.O. Hedin, S.S. Perakis, E.F. Latty, J.C. von Fischer, A. Elseroad, M.F. Wasson (1999): Global patterns of terrestrial biological (N_2) fixation in natural ecosystems. *Global Biogeochemical Cycles, 13(2)*, 623-645.

Dentener, F.J. and P.J. Crutzen (1994): A three-dimensional model of the global ammonia cycle. *Journal of Atmospheric Chemistry, 19*, 331-369.

Food and Agriculture Organization of the United Nations (FAO) (2002): World agriculture towards 2015/2030 - Summary report. FAO, Rome (http://www.fao.org/documents/).

FAO (2003a): FAO Statistical Databases (FAOSTAT). http://apps.fao.org/default.htm

FAO (2003b): Fertilizer use by crop. http://www.fao.org/ag/agl/agll/oldocsp.jsp

Galloway, J.N., F.J. Dentener, D.G. Capone, E.W. Boyer, R.W. Howarth, S.P. Seitzinger, G.P. Asner, C.C. Cleveland, P.A. Green, E.A. Holland, D.M. Karl, A.F. Michaels, J.H. Porter, A.R. Townsend, C.J. Vörösmarty (2004): Nitrogen cycles: Past, present, and future. *Biogeochemistry*, *70*, 153-226.

Galloway, J.N. and E.B. Cowling (2002): Reactive nitrogen and the world: 200 years of change. *Ambio 31*, 64-71.

Gerber P., 2004. Estimated livestock densities. FAO (AGL), Rome. Several digital data sets for different regions and livestock types available from the FAO-GeoNetwork (http://www.fao.org/geonetwork/srv/en/main.search)

Green, P., C.J. Vörösmarty, M. Meybeck, J.N. Galloway, B.J. Petersen, and E.W. Boyer (2004): Pre-industrial and contemporary fluxes of nitrogen through rivers: a global assessment based on typology. *Biogeochemistry, 68*, 71-105.

Hofmann, N. and L. Kemp (2001): A geographic profile of manure production in Canada. Statistics Canada publication 16F0025XIB, Ottawa, Canada, http://www.statcan.ca:8096/bsolc/english/bsolc?catno=16F0025X

International Fertilizer Association (IFA) (2003): IFADATA statistics from 1973/74-1973 to 2001-2001/02, production, imports, exports and consumption statistics for nitrogen, phosphate and potash fertilizers. Data on CD-ROM. International Fertilizer Industry Association, Paris. (http://www.fertilizer.org/ifa/statistics/IFADATA/dataline.asp)

McGuire, A. D., J. M. Melillo, L. A. Joyce, D. W. Kicklighter, A. L. Grace, B. I. Moore, C. J. Vorosmarty (1992): Interactions between carbon and nitrogen dynamics in estimating net primary productivity for potential vegetation in North America. *Global Biogeochemical Cycles, 6(2)*, 101-124, 10.1029/92GB00219.

Mosier, A., C. Kroeze, C. Nevison, O. Oenema, S. Seitzinger, O. van Cleemput (1998): Closing the global N_2O budget: nitrous oxide emissions through the agricultural nitrogen cycle. *Nutrient Cycling in Agroecosystems 52*, 225-248.

Nakicenovic, N. (ed.) (2000): Emissions Scenarios. IPCC Special Report on Emissions Scenarios, Cambridge University Press.

National Land and Water Resources (NLWR) Audit (2001): Farm gate nutrient balance estimates for the Australian agricultural zone (1992-1996). Canberra, Australia.

Nevison, C.D., G. Esser, E.A. Holland (1996): A global model of changing N_2O emissions from natural and perturbed soils. *Climatic Change, 32*, 327-378.

Organisation for Economic Co-operation and Development (OECD) (2001): OECD Soil Surface Nitrogen Balance Database, CD-Rom publication, http://www.oecd.org/agr/env/indicators.htm.

Ramankutty, N., and J.A. Foley (1999): Estimating historical changes in global land cover: croplands from 1700 to 1992. *Global Biogeochemical Cycles, 13(4)*, 997-1027.

Rijksinstituut voor Volksgezondheid en Milieu (RIVM) (2001): The IMAGE 2.2 implementation of the SRES scenarios. A comprehensive analysis of emissions, climate change and impacts in the 21st century. RIVM CD-ROM publication 481508018, National Institute for Public Health and the Environment, Bilthoven, the Netherlands.

Running, S.W. and E.R. Hunt Jr. (1993): Generalization of a forest ecosystem process model for other biomes, BIOME-BGC, and an application for global-scale models. In: J.R. Ehleringer and C. Field (Editors), Scaling Physiological Processes: Leaf to Globe. Academic Press, San Diego, CA, pp. 141-158.

Seitzinger, S.P., C. Kroeze, A.F. Bouwman, N. Caraco, F. Dentener, R.V. Styles (2002): Global patterns of dissolved inorganic and particulate nitrogen inputs to coastal systems: Recent conditions and future projections. *Estuaries*, *25*, 640-655.

Slingenbergh, J. and W. Wint (1996): Livestock geography and land use. FAO, http://www.fao.org/WAIRDOCS/LEAD/X6148E/X6148E00.HTM

Smil, V. (2002): Nitrogen and food production: proteins for human diets. *Ambio 31*, 126-131.

Smil, V. (1999): Nitrogen in crop production: An account of global flows. *Global Biogeochemical Cycles*, *13*, 647-662.

Stevens, C.J., N.B. Dise, J.O. Mountford, D.J. Gowing (2004): Impact of nitrogen deposition on the species richness of grasslands. *Science 303*, 1876–1879.

Tilman, D., J. Fargione, B. Wolff, C. D'Antonio, A. Dobson, R. W. Howarth, D. Schindler, W. H. Schlesinger, D. Simberloff, D. Swackhamer (2001): Forecasting agriculturally driven global environmental change. *Science 292*, 281–284, DOI: 10.1126/science.1057544.

United Nations Environment Programme (UNEP) (2004): GEO Yearbook 2003. Earthprint, (http://www.unep.org/geo/yearbook/pdf.htm).

United States Geological Survey (USGS) (2000): Global Land Cover Characterization (GLCC), classified according to U.S. Geological Survey Land Use/Land Cover System. http://edcwww.cr.usgs.gov/products/landcover/glcc.html

Van Drecht, G., A.F. Bouwman, J.M. Knoop, A.H.W. Beusen, and C.R. Meinardi (2003): Global modeling of the fate of nitrogen from point and nonpoint sources in soils, groundwater and surface water. *Global Biogeochemical Cycles*, *17 (4)*, 1115, doi:10.129/2003GB002060.

Van Drecht, G., A.F. Bouwman, E.W. Boyer, P. Green and S. Siebert (2005): A comparison of global spatial distributions of nitrogen inputs for nonpoint sources and effects on river nitrogen export. *Global Biogeochemical Cycles, submitted.*

Annex - Figures

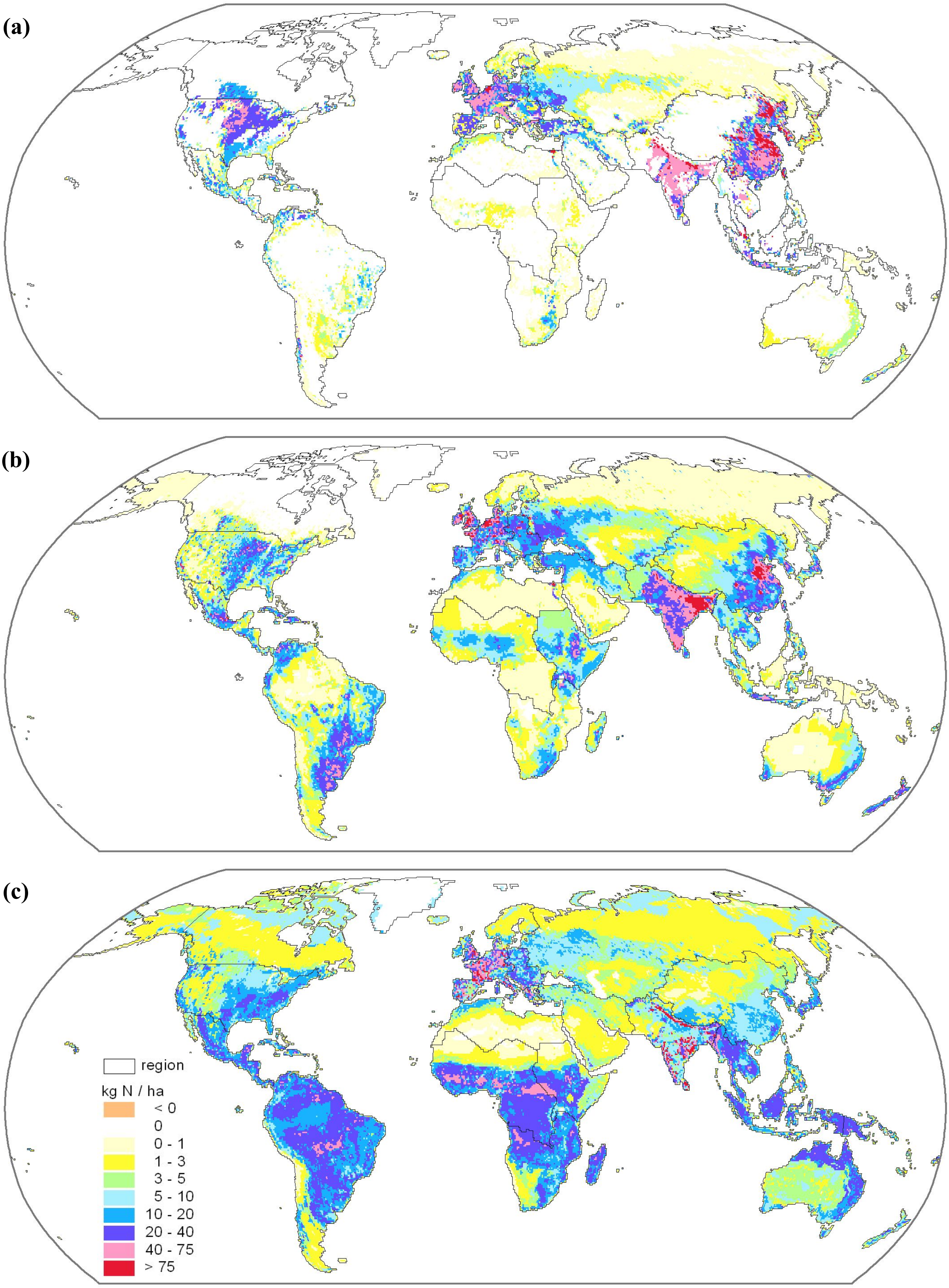


Figure A1. Simulated N inputs by synthetic fertilizers (a), livestock excretions (b) and biological N fixation (c) in 1995 (kg N ha^{-1} yr^{-1}).

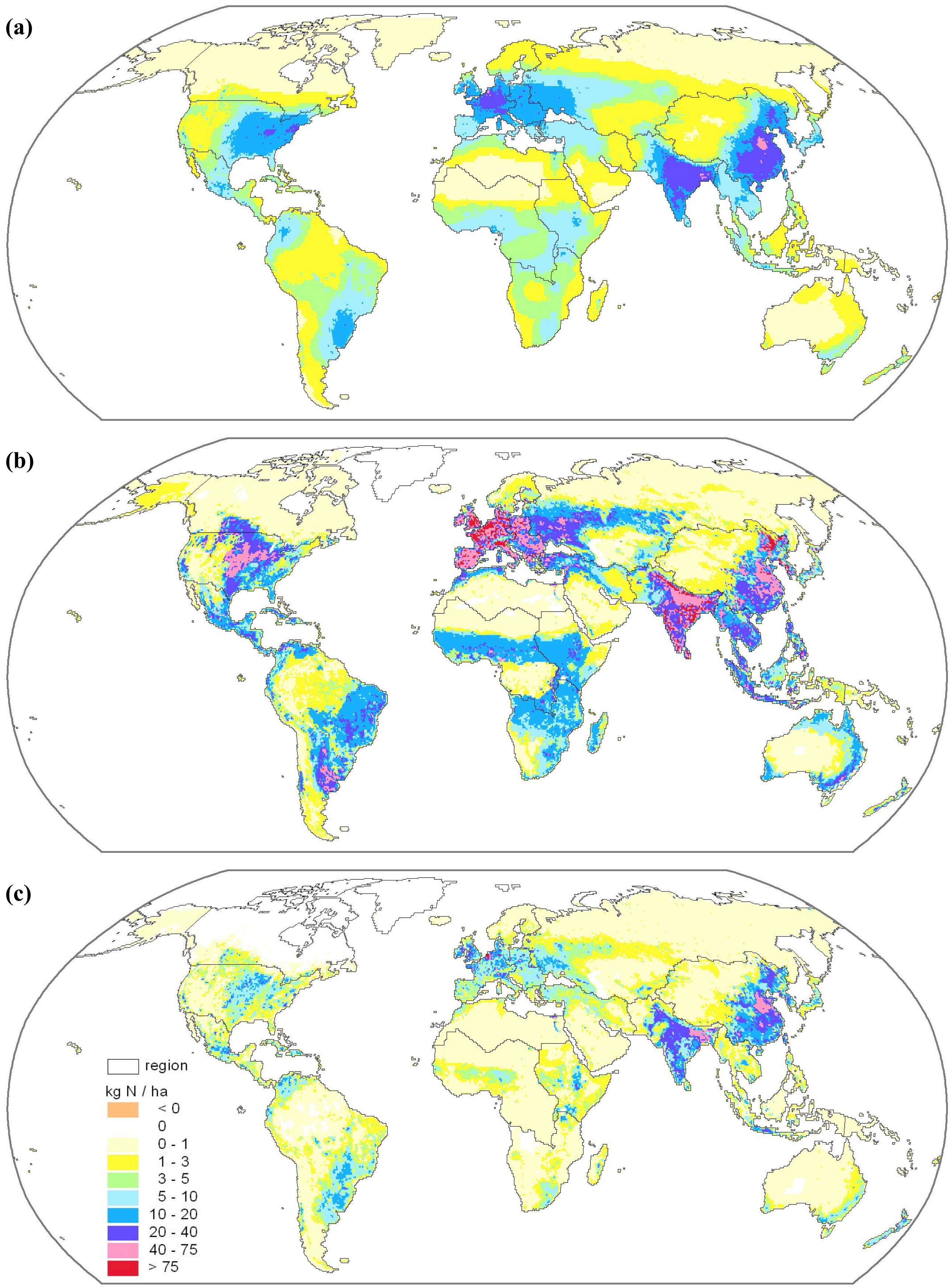


Figure A2. Simulated N inputs by atmospheric deposition (a), N exports by plant uptake (b) and ammonia volatilization (c) in 1995 (kg N ha^{-1} yr^{-1}).

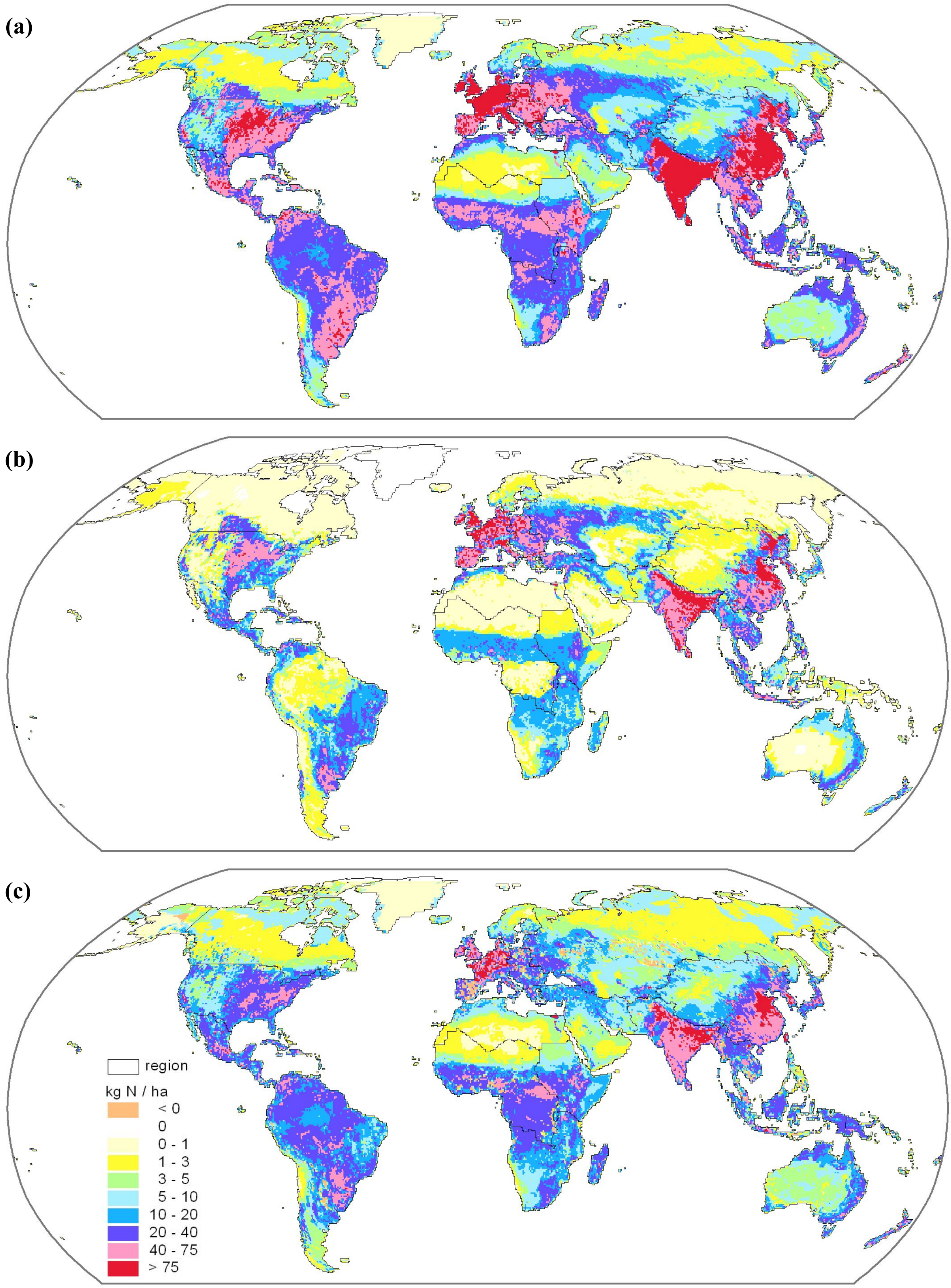


Figure A3. Simulated total N inputs (a), total N exports (b) and surface N balance (c) in 1995 (kg N ha^{-1} yr^{-1}).

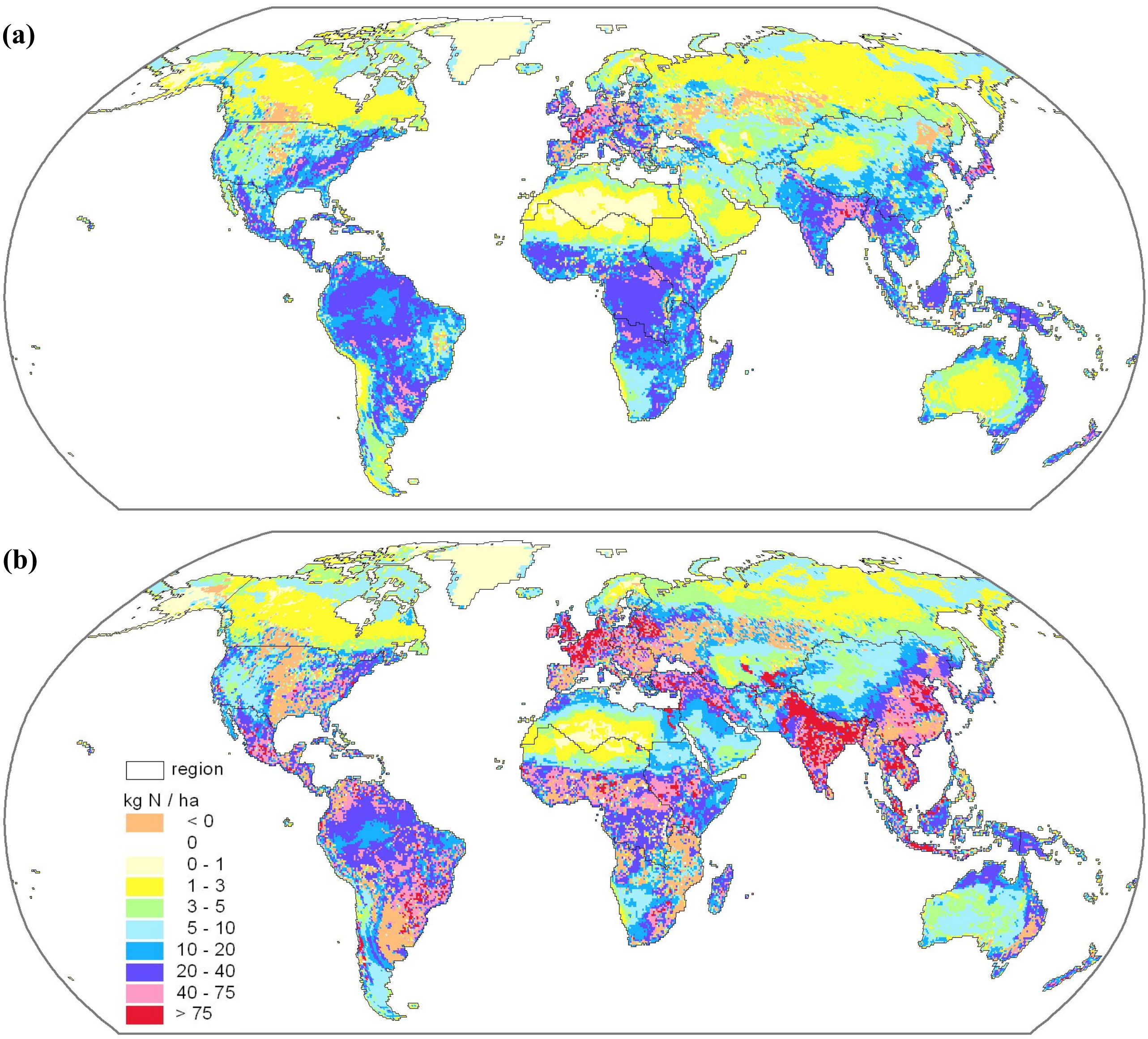


Figure A4. Simulated N balance at the soil surface in 1961 (a) and 2050 (b) (kg N ha^{-1} yr^{-1}).