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N_2O emissions from the global agricultural nitrogen cycle – current state and future scenarios

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Abstract. Reactive nitrogen (N_r) is not only an important nutrient for plant growth, thereby safeguarding human alimentation, but it also heavily disturbs natural systems. To mitigate air, land, aquatic, and atmospheric pollution caused by the excessive availability of N_r, it is crucial to understand the long-term development of the global agricultural N_r cycle.

For our analysis, we combine a material flow model with a land-use optimization model. In a first step we estimate the state of the N_r cycle in 1995. In a second step we create four scenarios for the 21st century in line with the SRES storylines.

Our results indicate that in 1995 only half of the N_r applied to croplands was incorporated into plant biomass. Moreover, less than 10 per cent of all N_r in cropland plant biomass and grazed pasture was consumed by humans. In our scenarios a strong surge of the N_r cycle occurs in the first half of the 21st century, even in the environmentally oriented scenarios. Nitrous oxide (N_2O) emissions rise from 3 Tg N_2O-N in 1995 to 7–9 in 2045 and 5–12 Tg in 2095. Reinforced N_r pollution mitigation efforts are therefore required.

1 Introduction

More than half of the reactive nitrogen (N_r) fixed every year is driven by human activity (Boyer et al., 2004). The main driver of the nitrogen cycle remains agricultural production, whose ongoing growth will require ever larger amounts of N_r to provide sufficient nutrients for plant and livestock production in the future.

The industrial fixation of the once scarce nutrient contributed to an unrivaled green revolution of production in the second half of the 20th century. Yet, only 35 to 65 % of the N_r applied to global croplands is taken up by plants (Smil, 1999). The remaining share may interfere with natural systems: The affluent availability of N_r leads to biodiversity losses and to the destruction of balanced ecosystems (Vitousek et al., 1997). In the form of nitrous oxide (N_2O), N_r contributes to global warming (Forster et al., 2007) and is the single most important ozone depleting substance (Ravishankara et al., 2009). Finally, it contributes to soil (Velthof et al., 2011), water (Grizzetti et al., 2011), and air pollution (Moldanova et al., 2011). Brink et al. (2011) estimate that the damage caused by nitrogen pollution adds up to 70–320 billion Euro in Europe alone, equivalent to 1–4 % of total income.

Therefore, much effort has been dedicated to improving our knowledge about the global agricultural N_r cycle. Smil (1999) pioneered the creation of the first comprehensive global N_r budget, and determined the key N_r flows in agriculture, most importantly fertilizer application, biological nitrogen fixation, manure application, crop residue management, leaching, and volatilisation. Sheldrick et al. (2002) extended the nutrient budgets to phosphorus and potash. Galloway et al. (2004) included natural terrestrial and aquatic systems in the N_r cycle. Liu et al. (2010a) broke up the global agricultural nutrient flows to a spatially explicit level. Bouwman et al. (2005, 2009, 2011) were the first, and so far the only, to have simulated the future development of the N_r cycle with detailed regional N_r flows.

However, the description of the current state of the N_r cycle was often incomprehensive. Belowground residues were so far not considered explicitly by other global studies, even though they withdraw large amounts of N_r from soils, and their decay on fields contributes to N_r losses and emissions. Similarly, not all past studies included fodder crops in their

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budgets, although they make up a considerable share of total cropland production. Furthermore, no bottom-up estimate for N_r release by the loss of soil organic matter exists so far. Regarding future projections, substitution effects between different N_r inputs are usually not considered.

In this paper, we create new estimates for the state of the agricultural N_r cycle in 1995 and four future scenarios until 2095 based on the SRES storylines. Our study presents a comprehensive description of the N_r cycle and covers N_r flows that have not been regarded by other studies so far. We create detailed cropland N_r budgets, but also track N_r flows upstream towards the processing sector, the livestock system and final consumption. This unmasks the low N_r efficiency in agricultural production. We use an independent parametrisation of the relevant N_r flows, concerning for example N_r in crop residues or biological N_r fixation. This allows for the identification of uncertainties in current estimates. For future projections we use a closed budget approach that allows for substitution between cropland N_r inputs (like fertilizer, manure or crop residues) and for an endogenous calculation of livestock N_r excretion. The budget approach is also used to estimate total nitrogen losses from fertilization and manure management (the sum of N_2, NO_x, NH_y and N_2O volatilisation as well as N_r leaching). As N_2O emissions play a crucial role in a global context, our model estimates them explicitly. For this purpose, our study uses the emission parameters of the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (Eggleston et al., 2006).

The paper is set up as follows: In the methods section, we first describe the Model of Agricultural Production and its Impact on the Environment (MAgPIE) that delivers the framework for our analysis. Then we give an overview on the implementation of crop residues, conversion byproducts and manure in the model. The description of all major N_r flows is followed by a summary of the scenario designs. In the results section, we present our simulation outputs for the state of the N_r cycle in 1995 and our projections for inorganic fertilizer consumption, N_2O emissions and other important N_r flows. In the discussion section, we compare our estimates to other studies and integrate the findings to a comprehensive cropland N_r budget for 1995, highlighting the largest uncertainties. We also compare our scenarios for the rise of the N_r cycle in the 21st century to estimates of other studies. As it is a key driver of the N_r cycle, we examine the livestock sector in more detail. Finally, the implications of our findings on the threat of N_r pollution are followed by our conclusions and an outlook on the opportunities for mitigation.

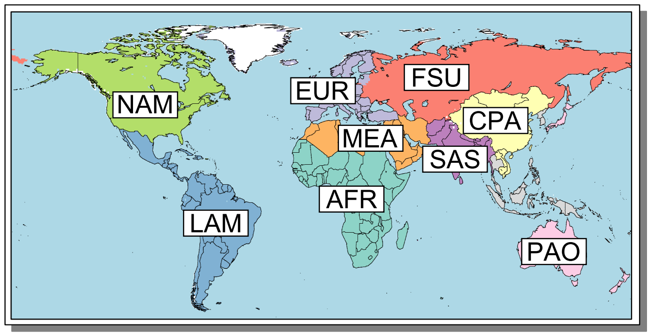

Fig. 1. The ten MAgPIE world regions. Sub-Sahara Africa (AFR), Centrally Planned Asia (CPA), Europe (including Turkey) (EUR), Former Soviet Union (FSU), Latin America (LAM), Middle East and North Africa (MEA), North America (NAM), Pacific OECD (Australia, Japan and New Zealand) (PAO), Pacific Asia (PAS), and South Asia (SAS).

2 Materials and methods

2.1 General model description

MAgPIE (Lotze-Campen et al., 2008; Popp et al., 2010, 2012; Schmitz et al., 2012) is a model well suited to performing assessments of agriculture on a global scale and to simulating long-term scenarios. It is comprehensive concerning the spatial dimension and covers all major crop and livestock sectors. Moreover, it features the major dynamics of the agricultural sector, like trade, technological progress or land allocation according to the scarcity of suitable soil, water and financial resources. As it treats agricultural production not only as economic value but also as physical good, it can easily perform analysis of material flows.

MAgPIE optimizes global land-use patterns to settle a global food demand at minimal production costs. Food demand is exogenous to the model and differentiated into 18 crop groups and 5 livestock production types. The demand for feed depends on the livestock production quantity with individual feed baskets for each livestock category (Weindl et al., 2010). The demand for material consumption and the production waste are assumed to grow in proportion to food demand, while the production for seed is a fixed share of crop production. All demand categories are estimated separately for 10 world regions (Fig. 1) and have to be met by the world crop production. Additionally, the regions have to produce a certain share of their demand domestically to account for trade barriers (Schmitz et al., 2012). The production of crops requires financial resources as well as land and irrigation water. Production costs per area are derived from GTAP cost-of-firm data (Schmitz et al., 2010). Land requirements depend on the yield-level of the region, which are calibrated to meet 1995 FAO data. Higher production can either be reached by land expansion or by the purchase of yield-increasing technological change (Dietrich, 2011; Popp et al., 2011). Water availability and water requirements per crop are derived from the LPJmL model (Bondeau et al., 2007; Gerten et al., 2004). MAgPIE is solved for each 10-yr timestep between 1995 and 2095, whereby the cropland area and the level of technology are passed on from one timestep as input data to the consecutive timestep.

The existing model (as described in the Supplement) has been extended by a number of features in order to describe the dynamics of the N_r cycle. Crop residues and conversion byproducts from crop processing make up a major share of total biomass and were therefore integrated into the model (Sect. 2.2). Moreover, all dry matter flows were transformed into N_r flows. N_r flows in manure management, cropland fertilization and the transformation of N_r losses into emissions were included (Sect. 2.3). Finally, the scenario setup is described in Sect. 2.4. Detailed documentation as well as a mathematical description of all model-extensions can be found in Appendix A.

2.2 Crop residues and conversion byproducts

As official global statistics exist only for crop production and not for crop residue production, we obtain the biomass of residues by using crop-type specific plant growth functions based on crop production and area harvested. Plant biomass is divided into three components: the harvested organ as listed in FAO, the aboveground (AG) and the belowground (BG) residues. For AG residues of cereals, leguminous crops, potatoes and grasses, we use linear growth functions (Eggleston et al., 2006) with a positive intercept which accounts for the decreasing harvest index with increasing yield. For crops without a good matching to the categories of Eggleston et al. (2006), we use constant harvest indices (Wirsenius, 2000; Lal, 2005; Feller et al., 2007).

Based on Smil (1999), we assume that 15 % of AG crop residues in developed and 25 % in developing regions are burned in the field. Furthermore, developing regions use 10 % of the residues to settle their demand for building materials and household fuel. The demand for crop residues for feed is calculated based on crop residues in regional livestock specific feed baskets from Weindl et al. (2010). The remaining residues are assumed to be left on the field. We estimate BG residue production by multiplying total AG biomass (harvest + residue) with a crop-specific AG to BG ratio (Eggleston et al., 2006; Khalid et al., 2000; Mauney et al., 1994). All BG crop residues are assumed to be left on the field.

Conversion byproducts like brans, molasses or oil cakes occur during the processing of crops into refined food. We link the production of conversion byproducts to the domestic supply of the associated crops using a fixed regional conversion ratio. Feed demand for conversion byproducts is based on feed baskets from Weindl et al. (2010) and rises with livestock production in the region. All values are calibrated to meet the production and demand for conversion byproducts of FAO in 1995 (FAOSTAT, 2011). In case the future demand for feed residues or crop byproducts exceeds the production, they can be replaced by feedstock crops of the same nutritional value.

2.3 N_r flows

2.3.1 N_r content of plant biomass, conversion byproducts and food

The biomass flows of the MAgPIE model are transformed into N_r flows, using product-specific N_r contents. We compile the values for harvested crops, conversion byproducts, AG and BG residues from Wirsenius (2000); Fritsch (2007); FAO (2004); Roy et al. (2006); Eggleston et al. (2006) and Khalid et al. (2000). The N_r in vegetal food supply is estimated by subtracting the N_r in conversion byproducts from N_r in harvest dedicated for food. N_r in livestock food supply is calculated by multiplying the regional protein supply from each commodity group of FAOSTAT (2011) with protein to N_r ratios of Sosulski and Imafidon (1990) and Heidelbaugh et al. (1975). As food supply does not account for waste on the household-level, we use regional intake to supply shares from Wirsenius (2000).

2.3.2 Manure management

The quantity of N_r in livestock excreta is calculated endogenously from N_r in feed intake (consisting of feedstock crops, conversion byproducts, crop residues and pasture) and livestock productivity. The N_r in feed minus the amount of N_r in the slaughtered animals, milk and eggs equals the amount of N_r in manure. To estimate the mass of slaughtered animals, we multiply the FAO meat production with livestock-specific carcass to whole body weight ratios from Wirsenius (2000). N_r contents of slaughtered animals, milk and eggs are obtained from Poulsen and Kristensen (1998).

Manure from grazing animals on pasture is assumed to be returned to pasture soils except a fraction of manure being collected for household fuel in some developing regions (Eggleston et al., 2006). Manure from feedstock crops and conversion byproducts are assumed to be excreted in animal houses. We estimate that one quarter of the N_r in crop residues used as feed in developing regions stems from stubble grazing on croplands, while the rest is assigned to animal houses. Finally, we distribute all manure in animal houses between 9 different animal waste management systems according to regional and livestock-type specific shares in Eggleston et al. (2006).

2.3.3 Cropland N_r inputs

In our model, cropland N_r inputs include manure, crop residues left in the field, biological N_r fixation, soil organic matter loss, atmospheric deposition, seed and inorganic fertilizer.

For the manure managed in animal houses, recycling shares for each animal waste management system are adopted from Eggleston et al. (2006). The manure collected for recycling in developing regions is assigned fully to cropland soils, while it is split between cropland and pasture soils in developed regions. Additionally, all N_r excreted during stubble grazing is returned to cropland soils.

For crop residues left in the field, we assume that all N_r is recycled to the soils, while 80–90 % of the residues burned in the field are lost in combustion (Eggleston et al., 2006).

N_r fixation by free living bacteria in cropland soils and rice paddies is taken into account by assuming fixation rates of 5 kg per ha for non-legumes and 33 kg per ha for rice (Smil, 1999). The N_r fixed by leguminous crops and sugar cane is estimated by multiplying N_r in plant biomass (harvested organ, AG and BG residue) with regional plant-specific percentages of plant N_r derived from N_2 fixation (Herridge et al., 2008).

N_r release by the loss of soil organic matter after the conversion of pasture land or natural vegetation to cropland is estimated based on the methodology of Eggleston et al. (2006). Our estimates for 1995 use a dataset of soil carbon under natural vegetation from the LPJmL model (Sitch et al., 2003; Gerten et al., 2004; Bondeau et al., 2007). For 1995, we use historical land expansion from the HYDE-database (Klein Goldewijk et al., 2011a), while the land expansion in the future is estimated endogenously by MAgPIE.

The regional amount of atmospheric deposition on croplands for 1995 is taken from Dentener (2006). For future scenarios, we assume that the atmospheric deposition per cropland area grows with the same growth rate as the average regional agricultural NO_x and NH_y emissions.

The amount of harvest used for seed is obtained from FAOSTAT (2011). We multiply the seed with the N_r share of the harvested organ to estimate N_r in seed returned to the field.

Regional inorganic fertilizer consumption in 1995 is obtained from IFADATA (2011). For the scenarios, we use a closed budget approach. For this purpose, we define cropland soil N_r uptake efficiency (SNUpE) as the share of N_r inputs to soils (fertilizer, manure, residues, atmospheric deposition, soil organic matter loss and free-living N_r fixers) that is withdrawn from the soil by the plant. These withdrawals from the soil are calculated by subtracting N_r derived not from the soil (seed and internal biological fixation by legumes and sugarcane) from N_r in plant biomass. SNUpE is calculated on a regional level for the year 1995 and becomes an exogenous scenario parameter for future estimates. Its future development is determined by the scenario storyline (see Sect. 2.4).

In future scenarios, the soil withdrawals and the exogenous SNUpE determine the requirements for soil N_r inputs. If the amount of organic fertilizers is not sufficient, the model has to apply as much nitrogen fertilizer as it requires to balance out the budget. In our model, the N_r inputs to crops have no influence on the yield. We assume in reverse that a given crop yield can only be reached with sufficient N_r inputs. An eventual N_r limitation is already reflected in the height of the crop yield.

2.3.4 Emissions

Emission calculations are in line with the 2006 IPCC Guidelines of National Greenhouse Gas Emissions (Eggleston et al., 2006), accounting for NO_x, NH_y as well as direct and indirect N_2O emissions from managed soils, grazed soils and animal waste. Our estimates neither cover agricultural N_2O emissions from savannah fires, agricultural waste burning or cultivation of histosols, nor emissions from waste disposal, forestry or fertilizer production. Emission factors are connected directly to the corresponding N_r flows of inorganic fertilizer application, as well as residue burning and decay on field, manure management, manure application, direct excretion during grazing, and soil organic matter loss. We use a Monte Carlo analysis to estimate the effect of the uncertainty of the IPCC emission parameters on global N_2O emissions.

2.4 Future scenarios

For future projections, we analyse four scenarios based on the SRES storylines (Nakicenovic et al., 2000), varying in two dimensions: economy versus ecology and globalisation versus heterogeneous development of the world regions. The parametrisation of these scenarios differs in several aspects, which try to cover the largest uncertainties for the future development of the N_r cycle (Table 1). In the following, the scenario settings are shortly described, while a detailed description and an explanation of the model implementation is provided in Appendix A4.

Food demand projections and the share of calories from livestock products are calculated based on regressions between income and per-capita calorie demand (intake and household waste), as well as regressions between income and the share of livestock calories in total demand. The regressions are based on a panel dataset (5889 data points) from FAOSTAT (2011) and WORLDBANK (2011) for 162 countries from 1961 to 2007. In the environmentally oriented scenarios, we used different functional forms for the regressions that result in lower values for plant and livestock demand. The future projections are driven by population and GDP scenarios from the SRES marker scenarios (CIESIN, 2002a,b).

Trade in MAgPIE is oriented along historical trade patterns, fixing the share of products a region has imported or exported in the year 1995. To account for trade liberalisation, an increasing share of products can be traded according to comparative advantages in production costs instead of historical patterns. We use two different trade scenarios based on Schmitz et al. (2012), assuming faster trade liberalisation in the globalised scenarios.

The livestock production systems in the 10 MAgPIE regions differ in 1995 both regarding their productivity and the animal feed baskets. To account for the increasing industrialisation of livestock production, we assume an increasing convergence of the livestock systems from the current mix towards the industrialised European system. This highly

Table 1. Scenario definitions, based on the IPCC SRES scenarios.

	1995	2045				2095			
		A1	A2	B1	B2	A1	A2	B1	B2
GDP (10^{12} US$)	34	222	106	170	138	674	314	453	319
Population (10^9 heads)	5.7	8.6	10.8	8.6	9.2	7.4	14.8	7.4	10.4
Food demand (10^{18} J)	23	46	50	42	43	47	81	41	53
– Thereof livestock products	16 %	24 %	17 %	22 %	22 %	22 %	17 %	16 %	18 %
Trade patterns									
– Historical	100 %	60 %	88 %	60 %	88 %	37 %	78 %	37 %	78 %
– Comparative advantage	0 %	40 %	12 %	40 %	12 %	65 %	22 %	65 %	22 %
Livestock systems									
– Current mix	100 %	20 %	50 %	20 %	50 %	0 %	20 %	0 %	20 %
– Industrialised	0 %	80 %	50 %	80 %	50 %	100 %	80 %	100 %	80 %
Animal waste[1]									
– Current mix	100 %	30 %	80 %	40 %	80 %	0 %	50 %	20 %	50 %
– Daily spread	0 %	0 %	0 %	30 %	20 %	0 %	0 %	40 %	50 %
– Anaerobic digester	0 %	70 %	20 %	30 %	0 %	100 %	50 %	40 %	0 %
Soil N_r uptake efficiency (SNUpE)	51 %[2]	60 %	55 %	65 %	65 %	60 %	60 %	70 %	70 %
Intact and frontier forest protection		no	no	yes	yes	no	no	yes	yes

[1] Only for waste in animal houses.
[2] Global average.

productive system has a large proportion of feedstock crops and conversion byproducts in the feed baskets. In the globalised scenarios, convergence is assumed to be faster than in the regionalised scenarios.

Currently, regional animal waste management systems are diverse and their future development is highly uncertain. We assume two major future trends. Firstly, due to the scarcity of fossil fuels and the transformation of the energy system towards renewables, the use of animal manure as fuel for bioenergy will become increasingly important. Secondly, in the environmental scenarios, we also assume that an increasing share of manure is spread to soils in a timely manner. We therefore shift the current mix of animal waste management systems gradually towards anaerobic digesters and daily spread.

Improvements in the cropland soil N_r uptake efficiency may occur in the future due to increasing environmental awareness or to save input costs. The regional efficiencies have been calculated for 1995, and we assume that they gradually increase in all scenarios, with the environmental scenarios reaching the highest efficiencies.

Finally, the expansion of agricultural area into unprotected intact and frontier forests is restricted gradually until 2045 in the environmental oriented scenarios, as described in Schmitz (2012).

The scenarios start in the calibration year 1995 and continue until 2095. The base year 1995 facilitates the comparison with other studies (Smil, 1999; Sheldrick et al., 2002; Liu et al., 2010a) and allows for a consistency check and benchmarking between the scenarios and the real development since 1995.

3 Results

Detailed global and regional results of the current state of the agricultural N_r cycle and the four scenarios can be found in the Supplement. In the following, the most important results are summarised.

3.1 Global nitrogen cycle

3.1.1 State in 1995

According to our calculations for the year 1995, 205 Tg N_r are applied to or fixed on global cropland, of which 115 is taken up by cropland plant biomass. Thereof, 50 Tg are fed to animals in the form of feedstock crops, crop residues, or conversion byproducts, plus an additional 72 Tg from grazed pasture, to produce animal products which contain 8 Tg N_r. In total, plant and animal food at whole market level contains 24 Tg N_r, of which finally only 17 Tg N_r are consumed. Figure 2 shows an in-depth analysis of N_r flows in 1995 on a global level.

3.1.2 Scenarios

In our four scenarios, the throughput of the N_r cycle rises considerably within the 21st century. Total N_r in cropland plant biomass reaches 244 (B2)–323 (A1) Tg N_r in 2045 and 251 (B1)–434 (A2) Tg N_r in 2095. Also, the range of soil inputs increases throughout the century, starting with 185 Tg in 1995 to 286 (B2)–412 (A1) Tg N_r in 2045 and 286 (B1)–553 (A2) Tg N_r in 2095. Inorganic fertilizer consumption in the B scenarios show a modest increase to 121 (B2) and 145

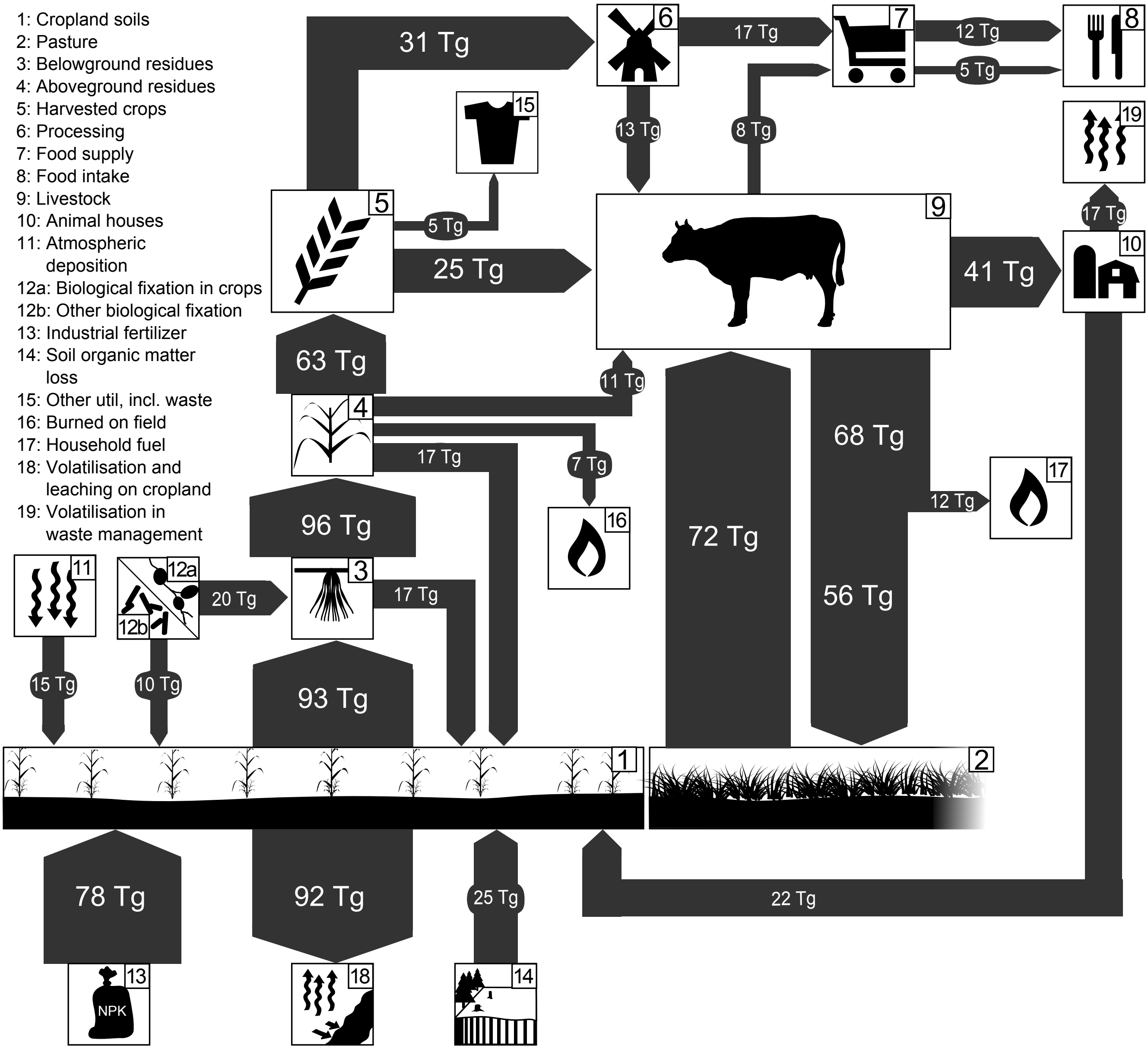

Fig. 2. Agricultural N_r cycle in Tg N_r in the year 1995. Flows below 5 Tg N_r are not depicted. No estimates were made for N_r inputs to pasture soils by atmospheric deposition and biological fixation.

(A1) Tg N_r until 2045 and a stagnating or even declining consumption thereafter, while the A scenarios exhibit a much stronger and continuous increase to 173 (A1) and 177 (A2) Tg N_r in 2045, and 214 (A1) and 260 (A2) Tg N_r in 2095 (Fig. 3). Despite these wide ranges, the differences of N_2O emissions between the scenarios is in the first half of the century rather narrow. They start with 3.9 Tg N_2O-N in 1995, with a range of 3.0 to 4.9 Tg N_2O-N being the 90 % confidence interval for uncertainty of the underlying emission parameters of Eggleston et al. (2006). Up to 2045, they rise to 7.2 (5.4 to 9.0) Tg N_2O-N in the B1 scenario and 8.6 (6.6 to 10.5) Tg N_2O-N in the A2 scenario, and widen towards the end of the century to 4.9 (3.5 to 6.4) Tg N_2O-N in the B1 scenario and 11.6 (8.8 to 14.2) Tg N_2O-N in the A2 scenario (Fig. 4).

3.2 Regional budgets

While the surge of the N_r cycle can be observed in all regions, the speed and characteristics are very different between regions (Table 2). Sub-Saharan Africa (AFR), South Asia (SAS), and Australia and Japan (PAO) show the strongest relative increases in harvested N_r, while in Europe (EUR) and North America (NAM) the increases are more modest. The

Table 2. Regional estimates of N_r flows for the state in 1995 and for the four scenarios $\frac{A1|B1}{A2|B2}$ in Tg N_r per year. Losses consist of losses from cropland soils and animal waste management.

N_r flow	Year	World		AFR		CPA		EUR		FSU		LAM		MEA		NAM		PAO		PAS		SAS	
				Regions																					
Harvest	1995	63		3		12		10		5		6		2		13		2		3		7	
	2045	182	160	15	14	30	28	15	14	10	9	29	21	10	10	20	19	17	11	6	5	30	29
		153	143	12	12	26	28	15	14	9	9	22	19	8	7	23	20	10	7	6	5	21	22
	2095	196	137	20	9	33	27	16	13	11	8	26	13	14	12	21	17	18	7	5	3	33	29
		260	169	24	19	38	30	19	15	13	11	50	22	13	9	32	21	25	9	10	6	35	29
Residues	1995	35		3		6		4		3		4		1		6		1		2		5	
	2045	94	85	10	9	15	15	7	7	7	7	16	13	4	4	10	9	9	6	4	4	12	12
		73	67	8	7	12	13	6	6	4	4	11	9	3	2	10	8	5	3	4	3	11	10
	2095	98	76	11	7	17	15	7	6	8	7	15	9	5	5	11	9	8	3	4	3	13	12
		114	76	12	10	19	14	8	6	5	4	21	9	5	3	13	9	11	4	6	3	15	12
Fertilizer	1995	78		1		24		13		2		4		3		13		1		4		13	
	2045	173	145	9	7	40	36	13	13	11	9	6	7	15	14	23	21	33	19	5	3	20	15
		177	122	14	8	41	30	21	16	8	5	7	10	11	8	30	20	18	9	6	4	22	11
	2095	214	128	0	0	50	39	21	16	12	8	23	0	23	17	19	15	32	12	4	4	24	17
		260	131	19	10	59	35	22	15	10	7	20	5	12	9	37	20	46	12	7	5	27	12
Manure	1995	111		15		12		13		7		21		3		10		4		3		22	
	2045	241	217	65	60	28	22	20	15	8	7	63	55	7	7	9	6	3	2	6	5	32	39
		250	262	51	56	26	37	17	13	10	9	58	52	11	8	14	9	5	3	9	9	49	65
	2095	205	131	105	44	16	12	6	2	7	5	23	36	5	3	17	8	2	1	4	2	19	18
		332	240	69	69	34	26	21	10	11	5	92	51	20	11	17	5	5	1	12	7	50	55
Biol. N_r	1995	27		2		4		2		2		4		0		5		1		2		4	
	2045	72	61	8	7	8	7	5	4	4	4	17	11	1	1	8	7	2	2	4	2	17	16
		57	56	6	6	6	8	4	3	4	4	13	11	1	1	8	8	2	2	3	2	10	11
	2095	75	46	11	4	9	5	4	3	5	3	15	6	1	1	7	6	3	0	1	1	20	17
		95	64	12	8	7	7	4	4	5	6	30	12	3	2	11	8	3	2	4	2	17	14
Trade	1995	0		0		-1		-2		-1		2		-2		4		0		-1		0	
	2045	0	0	-8	-8	-1	3	-6	-3	1	1	-11	-14	-2	-1	10	11	14	8	-3	-2	9	6
		0	0	-3	-6	-4	-7	-1	1	1	2	1	3	-7	-4	10	11	7	4	-4	-4	1	0
	2095	0	0	-51	-21	16	14	6	7	1	0	4	-21	0	1	0	6	14	5	-3	-3	14	11
		0	0	-5	-15	-6	1	-2	4	1	6	-3	-8	-19	-6	15	14	20	8	-6	-3	4	-2
Losses	1995	109		5		27		15		9		8		3		18		3		7		15	
	2045	180	146	17	16	32	27	15	13	11	10	28	23	10	9	18	14	19	10	7	6	21	19
		201	137	18	14	37	31	21	14	11	8	27	16	10	7	27	16	13	6	10	7	25	18
	2095	197	103	39	11	31	20	14	8	12	7	23	14	14	8	19	11	18	5	6	3	21	15
		257	131	25	19	45	25	21	11	12	6	43	19	14	8	30	12	26	6	12	5	29	19
N_2O	1995	3.9		0.4		0.7		0.5		0.3		0.7		0.1		0.6		0.1		0.2		0.4	
	2045	8.1	7.2	1.4	1.3	1.1	1	0.6	0.5	0.4	0.3	1.8	1.6	0.4	0.4	0.6	0.5	0.6	0.4	0.3	0.2	0.9	0.9
		8.6	7.5	1.3	1.3	1.2	1.3	0.7	0.5	0.4	0.3	2	1.6	0.4	0.3	0.9	0.6	0.4	0.2	0.3	0.3	1	1
	2095	7.2	4.9	1.8	0.8	1	0.8	0.5	0.3	0.4	0.3	0.8	0.8	0.5	0.4	0.7	0.5	0.6	0.2	0.2	0.1	0.7	0.6
		11.6	7.2	1.7	1.5	1.5	1	0.8	0.5	0.4	0.3	2.9	1.5	0.6	0.4	1.1	0.5	0.9	0.3	0.4	0.2	1.2	1.1

increase in production in AFR is not sufficient to settle domestic demand, such that large amounts of N_r have to be imported from other regions. Also the Middle East and Northern Africa (MEA) have to import large amounts of N_r due to the unsuitable production conditions and high population growth. At the same time, AFR requires only low amounts of inorganic fertilizer, as the domestic livestock production fed with imported N_r provides sufficient nutrients for production. In the globalised scenarios A1 and B1, the overspill of manure even reduces the actual soil nutrient uptake efficiency (SNUpE) in 2095 with 0.41 (A1) and 0.67 (B1), below the potential scenario value of 0.6 or 0.7.

Despite its large increase in consumption, SAS does not require large imports, as it can also settle its N_r requirements with a balanced mix of biological fixation, manure, crop residues and inorganic fertilizer. Similarly, Latin America can cover large parts of its N_r demand with biological fixation and manure. In comparison with this, the large exporters North America (NAM) and Pacific OECD (PAO) have a much stronger focus on fertilization with inorganic fertilizers.

In the globalised scenarios, these characteristics tend to be more pronounced than in the regionalised scenarios, as each region specialises in its relative advantages. The structural differences between the economical and ecological oriented scenarios are less distinct, yet it can be observed that the reduced livestock consumption in developed regions leads to a lower importance of manure and a generally lower harvest of N_r in these regions.

4 Discussion

This study aims to create new estimates for the current state and the future development of the agricultural N_r cycle. For this purpose, we adapted the land-use model MAgPIE to calculate major agricultural N_r flows. As will be discussed in the following, the current size of the N_r cycle is much higher than previously estimated. The future development of the N_r cycle depends largely on the scenario assumptions, which we based on the SRES storylines (Nakicenovic et al., 2000). We expect the future rise of the N_r cycle to be higher than suggested by most other studies. Thereby, the livestock sector dominates both the current state and future developments. The surge of the N_r cycle will most likely be accompanied by higher N_r pollution.

4.1 The current state of the agricultural N_r cycle

Data availability for N_r flows is poor. Beside the consumption of inorganic fertilizer, no N_r flow occurs in official statistics. Even the underlying material flows, like production and use of crop residues or animal manure are usually not recorded in international statistics. Therefore, independent model assessments are required, using different methodologies and parametrisations to identify major uncertainties. In the following we compare our results mainly with estimates of Smil (1999), Sheldrick et al. (2002) and Liu et al. (2010a), as summarised in Table 3.

The estimates for N_r withdrawals by crops and aboveground residues are relatively certain. They have now been estimated by several studies using different parametrisations. The scope between the studies is still large with 50 to 63 Tg N_r for harvested crops and 25 to 38 Tg N_r for residues, whereby the estimate of Sheldrick et al. (2002) may be too high due to the missing correction for dry matter when estimating nitrogen contents (Liu et al., 2010b).

Large uncertainties can be attributed to the cultivation of fodder and cover crops. They represent a substantial share of total agricultural biomass production, and they are rich in N_r and often N_r fixers. Yet, the production area, the species composition and the production quantity are highly uncertain, and no reliable global statistics exist. The estimate from FAOSTAT (2005) used by our study has been withdrawn without replacement in newer FAOSTAT releases. It counts 2900 Tg fresh matter fodder production on 190 million ha (Mha). Smil (1999) appraises the statistical yearbooks of 20 large countries and provides a lower estimate of only 2500 Tg that are produced on 100–120 Mha.

Estimates for N_r in animal excreta diverge largely in the literature. Using bottom-up approaches based on typical excretion rates and N_r content of manure, Mosier et al. (1998) and Bouwman et al. (2011) calculate total excretion to be above 100 Tg N_r. Smil (1999) assumes total excretion to be significantly lower with only 75 Tg N_r. Our top-down approach, using the fairly reliable feed data of the FAOSTAT database, can support the higher estimates of Mosier et al. (1998) and Bouwman et al. (2011), with an estimate of 111 Tg N_r. The same global total of 111 Tg N_r can be obtained bottom-up if one multiplies typical animal excretion rates taken from Eggleston et al. (2006) with the number of living animals (FAOSTAT, 2011). Yet, regional excretion rates diverge significantly; the top-down approach leads to considerably higher rates in Africa and the Middle East and lower rates in South and Pacific Asia.

Biological N_r fixation is another flow of high uncertainty and most studies still use the per ha fixation rates of Smil (1999) for legumes, sugarcane and free-living bacteria. Currently no better estimate exists for free-living bacteria (Herridge et al., 2008). However, they contribute only a minor input to the overall N_r budget with little impacts on our model results. To estimate the fixation by legumes and sugarcane, we use a new approach based on percentages of plant N_r derived from fixation, similar to Herridge et al. (2008). This, in combination with total above- and belowground N_r content of a plant, can predict N_r fixation more accurately. However, the parametrisation of Herridge et al. (2008) probably overestimates N_r fixation, especially for soybeans. Most importantly, the N_r content of the belowground residues as well as the shoot : root ratio seem too high when comparing them with Eggleston et al. (2006), Sivakumar et al. (1977) or Dogan et al. (2011). Also the N_r content of the shoot seems too high given that soybean residues have a much lower N_r content than the beans (Fritsch, 2007; Wirsenius, 2000; Eggleston et al., 2006). Correcting the estimates of Herridge et al. (2008) for the water content of the harvested crops further reduces their estimate. If one finally accounts for the difference in base year between the two estimates, with global soybean production increasing by 69 % between 1995 and 2005, we come to a global total fixation from legumes and sugarcane of 9 Tg N_r in 1995 as opposed to 21 Tg N_r in 2005 in the case of Herridge et al. (2008). Our estimate is in between the estimates of Smil (1999) and Sheldrick et al. (2002), even though we used a different approach.

Accumulation or depletion of N_r in soils has so far been neglected in future scenarios (Bouwman et al., 2009, 2011), assuming that soil organic matter is stable and all excessive N_r will volatilise or leach. However, the assumption of a steady state for soil organic matter should not be valid for land conversion or for the cultivation of histosols. Our rough bottom-up calculations estimate that the depletion of soil organic matter after transformation of natural vegetation or pasture to cropland releases 25 Tg N_r per year. With a yearly global average release of 122 kg N_r per ha newly converted cropland, the amount of N_r released may exceed the nutrients actually required by the crops, especially in temperate, carbon rich soils. Vitousek et al. (1997) estimates that the cultivation of histosols and the drainage of wetlands releases another 10 Tg N_r per year, although it is unclear how much thereof enters agricultural systems.

The total size of the cropland N_r budget is larger than estimated by previous studies. This can be attributed less to a correction of previous estimates than to the fact that past studies did not cover all relevant flows. In Table 3 we summarise cropland input and withdrawals mentioned by previous studies. The sum of all withdrawals (Total OUT) ranges between 81 and 115 Tg N_r. However, if the unconsidered flows are filled with estimates from other studies, the corrected withdrawals (Total OUT*) shifts to 105–134 Tg N_r. The same applies to inputs, where the range shifts and narrows down from 137–205 Tg N_r total inputs (Total IN) to 198–232 Tg N_r total inputs when all data gaps are filled (Total IN*). The N_r uptake efficiency (NUpE*), defined as the fraction of IN* which is incorporated into OUT* remains within the plausible global range of 0.35–0.65 defined by Smil (1999) for all studies. In our study, this holds even for every MAgPIE world region. SNUpE and SNUpE* are slightly higher, with 49 % and 51 % of N_r applied to soils being taken up by the roots of crops. The corrected estimates for total losses (Losses*) is, with 84–112 Tg N_r, significantly higher than previously estimated.

Table 3. Comparison of global cropland soil balances.

	This study	Smil (1999b)	Sheldrick (1996)	Liu (2010)
Base year	1995	1995	1996	2000
OUT				
Crops	50	50	63	52
Crop residues	31	25	38	29
Fodder	13	10	–	–
Fodder residues	4	–	–	–
BG residues	17	–	–	–
IN				
Residues	12	14	23	11
Fodder residues	4	–	–	–
BG residues	17	–	–	–
Legume fixation	9	10	8	22
Other fixation	10	11	–	
Fixation fodder	11	12	–	–
Atm. deposition	15	20	22	14
Manure on field	24	18	25	17
Seed	2	2	–	–
Irrigation water	–	4	–	3
Sewage	–	–	3	–
Soil organic matter loss	25	–	–	–
Fertilizer	78	78	78	68
Histosols	–	–	–	–
BALANCE				
Total OUT	115	85	101	81
Total OUT*	115	105	134	114
Total IN	205	169	159	137
Total IN*	212	217	232	198
Losses	91	80	75	67
Losses*	98	112	97	84
NUpE	0.56	0.50	0.64	0.59
NUpE*	0.54	0.48	0.58	0.58
SNUpE	0.51	0.42	0.62	0.51
SNUpE*	0.49	0.42	0.54	0.48

*Data gaps are filled with estimates from other studies. We use estimates by this study if available; for irrigation we use Smil (1999), for sewage Sheldrick et al. (2002), and for histosols no estimate exists.

4.2 Scenario assumptions

The simulation of the widely used SRES storylines (Nakicenovic et al., 2000) facilitates the comparison with other studies like Bouwman et al. (2009) or Erisman et al. (2008) and allows for the integration of our results into other assessments. However, the SRES storylines provide only a qualitative description of the future. In the following, the key assumptions underlying our parametrisation and model structure shall be discussed.

All SRES storylines tend to assume a continuation of current trends, without external shocks or abrupt changes of dynamics. They merely diverge in the interpretation of past dynamics or the magnitude of change assigned to certain trends. Population grows at least until the mid of the 21st century, and declines first in developed regions. Per-capita income grows throughout the century in all scenarios and all world regions, and developing regions tend to have higher growth rates than developed regions. This has strong implications on the food demand, which is driven by both population and income growth. As food demand is a concave function of income, it depends mostly on the income growth in low-income regions. In the first half of the century, the pressure from food demand is therefore highest in the high-income A1 scenario. In the second half, the A2 scenario also reaches a medium income and therefore a relatively high per capita food demand. Additionally, the population growth diverges between the scenarios in the second half of the century, with the A2 scenario reaching the highest world population and as a consequence the highest food demand. As food demand is exogenous to our model, price effects on consumption are not captured by the model. However, even in the A2 scenario the shadow prices (Lagrange multipliers) of our demand constraints increase globally by 0.5 % per year until 2045, with no region showing higher rates than 1.1 %. This indicates only modest price pressure, lagging far behind income growth.

Concerning the productivity of the livestock sector, we assume that the feed required to produce one ton of livestock product is decreasing in all scenarios, even though at different rates. Starting from a global level of 0.62 kg N in feed per ton livestock product dry matter, the ratio decreases to 0.4 (A1) or 0.52 (B2) in 2095 (see Supplement). A critical aspect is that as all regions converge towards the European feed baskets, no productivity improvements beyond the European level take place. Beside the improvement of feed baskets, the amount of feed is also determined by the mix of livestock products, with milk and eggs requiring less N_r in feed than meat. As we could not find a historical trend in the mix of products (FAOSTAT, 2011), we assumed that current shares remain constant in the future. This causes continuing high feeding efficiencies in Europe and North America, where the share of milk and non-ruminant meat is high.

As we calculate our livestock excretion rates based on the feed mix, the increased feeding efficiency also translates into lower manure production per ton livestock product. At the same time, our scenario assumptions of an increasing share of either anaerobic digesters or daily spread in manure management also lead to higher recycling rates of manure excreted in confinement. Even though with increasing development an increasing share of collected manure is applied also to pastureland as opposed to cropland, the amount of applied manure N_r per unit crop biomass remains rather constant. Due to the increasing N_r efficiency, its ratio relative to other N_r inputs like inorganic fertilizers increases.

Our closed budget approach to calculate future inorganic fertilizer consumption is based on the concept of cropland soil N_r uptake efficiency (SNUpE). Other indicators of N_r efficiency relate N_r inputs to crop biomass. They include for example N_r use efficiency (NUE), defined as grain dry matter divided by N_r inputs (Dawson et al., 2008), and agronomic efficiency of applied N_r (AE_N), defined as grain dry matter increase divided by N_r fertilizer (Dobermann, 2005). Compared to these indicators, N_r uptake efficiency (NUpE) indicates the share of all N_r inputs that is incorporated into plant biomass (Dawson et al., 2008). Under the condition that all N_r inputs (including the release of soil N_r) are accounted for, this share has the advantage of an upper physical limit of 1. N_r withdrawals cannot exceed N_r inputs. At the same time, this indicator reveals the fraction of losses connected to the application of N_r inputs. SNUpE is similar to NUpE, but regards only soil inputs and withdrawals and excludes seed N_r as well as internal biological fixation from legumes and sugarcane. Prior to the uptake by the plant, these inputs are not subject to leaching and volatilisation losses (Eggleston et al., 2006), and denitrification losses are also inconsiderable (Rochette and Janzen, 2005). Therefore, one regional value of SNUpE suffices to simulate that NUpE of N_r fixing crops is higher compared to the NUpE of normal crops (Peoples and Herridge, 1990).

The level of SNUpE is in our model an exogenous scenario parameter for future simulations which has a large impact on the estimates of inorganic fertilizer consumption and N_2O emissions. If SNUpE would be 5 percentage points lower, fertilizer consumption would increase by 8 to 10 % in 2045, depending on the scenario. At the same time, total agricultural N_2O emissions would increase by 11 to 15 %. If fertilizer efficiency would increase by 5 percentage points, fertilizer consumption would fall by 7 to 8 % and emissions would decrease by 9 to 13 %. As the magnitude of N_r flows is higher in some scenarios, a ±5 % variation of SNUpE translates in the A1 scenario into a change of fertilizer consumption of −32 to +37 Tg N_r and a change of −1.1 to +1.3 Tg N_2O-N of emissions in 2045, while in the B2 scenario fertilizer changes only by −20 to +24 Tg N_r and emissions by −0.7 to +0.8 Tg N_2O-N.

The future development of SNUpE is highly uncertain. It depends on numerous factors, most importantly on the management practices like timing placing and dosing of fertilizers and the use of nutrient trap crops. Also, a general improvement of agricultural practices like providing adequate moisture and sufficient macro- and micronutrients, pest control and avoiding soil erosion can contribute their parts. Finally, climate, soils, crop varieties and the type of nutrient inputs also influence N_r uptake efficiency. The complexity of these dynamics and the numerous drivers involved still do not allow making long-term model estimates for N_r efficiencies, but this should be a target for future research.

Meanwhile, we use SNUpE as an explicitly defined scenario parameter. As it descriptively indicates the share of losses, and as the theoretical upper limit of 1 is clearly fixed, it makes our model assumptions transparent and easily communicable. Our assumptions concerning the development of SNUpE are rather optimistic. In 1995, none of the 10 world regions reached a SNUpE of 60 %, and four regions (CPU, FSU, PAS, SAS) were even below 50 %. The current difference between the region with the lowest SNUpE (CPA with 43 %) and the region with the highest SNUpE (EUR with 57 %) is thereby still lower than the difference of EUR and our scenario parameter of 70 % for the environmentally oriented scenarios.

We assumed that trade liberalisation continues in all scenarios, even though at different paces. The trade patterns diverge strongly between the scenarios, even though certain dynamics persist. Sub-Saharan Africa, Europe and Latin America tend to become livestock exporting regions, while South, Central and Southeast Asia as well as the Middle East and Northern Africa become importers of livestock products. On the other hand, sub-Saharan Africa and Pacific Asia become importers of crop products, while the former Soviet Union and Australia become exporters of crops. Trade dynamics in MAgPIE are determined partly on the basis of historical trade patterns, partly by competitiveness. However, certain other dynamics that are of great importance in reality, most importantly political decisions like tariffs or export subsidies, are not represented explicitly in the model. Due to the uncertainty regarding trade patterns, regional production estimates are therefore of higher uncertainty than global estimates. Trade patterns have strong implications on the N_r cycle. As soon as two regions are trading, the fertilizer consumption also shifts from the importing to the exporting region. Even more, sub-Saharan Africa currently imports crops and exports livestock products. Livestock fed with imported crops contributes in the form of manure to the cropland soil budgets and facilitates sub-Saharan Africa to use little inorganic fertilizer. Also in our future scenarios, the African livestock sector is very competitive and the inorganic fertilizer consumption does not increase until the mid of the century. A similar dynamic can be observed in Latin America, where inorganic fertilizer consumption also stays rather low.

In our environmentally oriented scenarios B1 and B2, vulnerable ecosystems are protected from land expansion. However, these protection schemes are assumed to be implemented gradually until 2045 and include only some of the most vulnerable forest areas. Large forest areas are still cleared in the beginning of the century, most importantly in the Congo river basin and the southern part of the Amazonian rainforest. Due to the land restrictions in the B scenarios, crop yields have to increase faster to be able to settle the demand with the available cropland area.

4.3 The future expansion of the N_r cycle

The size of the agricultural N_r cycle has increased tremendously since the industrial revolution. While in 1860 agriculture fixed only 15 Tg N_r (Galloway et al., 2004), in 1995 the Haber–Bosch synthesis, biological fixation and soil organic matter loss injected 133 Tg new N_r into the N_r cycle. Our scenarios suggest that this surge will persist into the future, and will not stop before the middle of this century. The development is driven by a growing population and a rising demand for food with increasing incomes, along with a higher share of livestock products within the diet. The N_r in harvested crops may more than triple. Fixation by inorganic fertilizers and legumes as well as recycling in the form of crop residues and manure may also increase by a factor of 2–3.

Our top-down estimates of future animal excreta are higher than the bottom-up estimates by Bouwman et al. (2011). In our scenarios, N_r excretion rises from 111 Tg N_r in 1995 to 217 Tg N_r (B1)–262 Tg N_r (A1) in 2045. Bouwman et al. (2011) estimate that N_r excretion increases from 102 Tg N_r in 2000 to 154 Tg N_r in 2050. These differences are caused by diverging assumptions. Firstly, while Bouwman et al. (2011) assume an increase of global meat demand by 115 % within 50 yr, our study estimates an increase by 136 % (A2)–200 % (A1). Secondly, Bouwman et al. (2011) assume rising N_r excretion rates per animal for the past, but constant rates for the future, such that weight gains of animals are not connected to higher excretion rates. As the current excretion rates in developing regions are still lower than in developed regions (IPCC, 1996), this assumption will underestimate the growth of excretion rates in developing regions. Our implementation calculates excretion rates based on the feed baskets and the N_r in livestock products. Under the assumption that developing regions increasingly adopt the feeding practices of Europe, this top-down approach results in increasing excretion rates per animal in developing regions. However, as we assume no productivity improvements in developed regions, we tend to overestimate future manure excretion in developed regions.

N_r release from soil organic matter (SOM) loss contributes to the N_r budget also in the future, yet with lower rates. In the environmentally oriented B scenarios, cropland expansion and therefore also SOM loss almost ceases due to forest protection, while in the economically oriented scenarios, the loss of SOM still contributes 10 (A1) and 18 (A2) Tg N_r per year. In the A2 scenario the loss even continues at low rates until the end of the century. The reduced inputs of soil organic matter loss have to be replaced by inorganic fertilizers.

Our estimates of inorganic fertilizer consumption are within the range of previous estimates. Figure 3 compares our results to estimates by Daberkow et al. (2000), Davidson (2012), Erisman et al. (2008), Tilman et al. (2001), Tubiello and Fischer (2007) and Bouwman et al. (2009). The differences in estimates is enormous, ranging in 2050 from 68 (Bouwman et al., 2009) to 236 Tg N_r (Tilman et al., 2001). In contrast to Bouwman et al. (2009) and Erisman et al. (2008), who also created scenarios based on the SRES storylines, our highest estimate is the A2 scenario, while the other two models have the A1 scenario as highest scenario. Also, our scenarios have in general a higher fertilizer consumption, especially compared to Bouwman et al. (2009). This may be

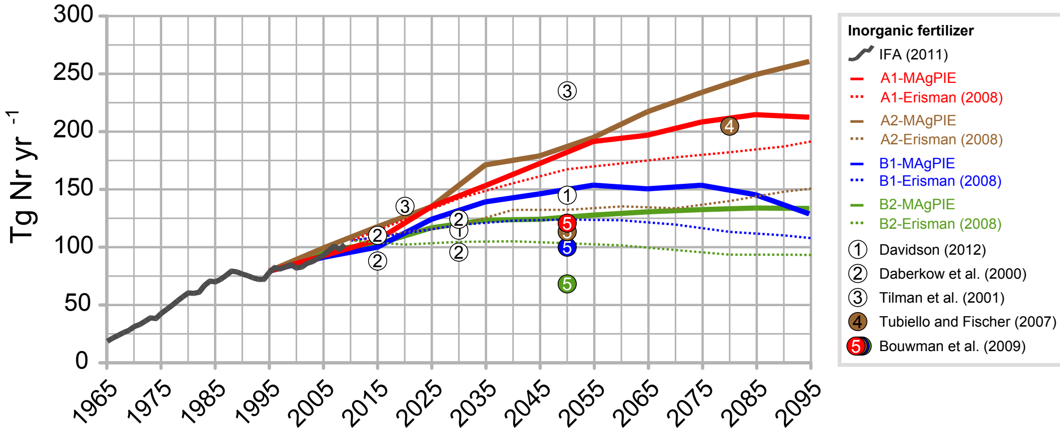

Fig. 3. Fertilizer consumption: historic dataset of IFADATA (2011), SRES scenario estimates by Erisman et al. (2008), Bouwman et al. (2009), Tubiello and Fischer (2007) and our study, as well as other estimates by Davidson (2012), Daberkow et al. (2000) and Tilman et al. (2001).

rooted in a different scenario parametrisation and a different methodological approach: Our scenarios assume a strong demand increase also for relatively low income growth as we explained in Sect. 4.2. At the same time, low income growth goes along with slow efficiency improvements in production. The combined effects explain the strong rise of inorganic fertilizer consumption in the A2 scenario. At the same time, our estimates are based on a top-down approach, compared to the bottom-up approach of Bouwman et al. (2009, 2011) or Daberkow et al. (2000). Both approaches have advantages and disadvantages. Data availability for bottom-up estimates of fertilizer application is currently poor, and may be biased by crop-rotations and different manure application rates. Our top-down approach has the disadvantage that it has to rely on an exogenous path for the development of N_r uptake efficiency. Also, as the closing entry of the budget, it accumulates the errors of other estimated N_r flows. But the top-down approach has the advantage that it can consistently simulate substitution effects between different N_r sources or a change in crop composition. This is of special importance if one simulates large structural shifts in the agricultural system like an increasing importance of the livestock sector.

Data on historic fertilizer consumption is provided by IFADATA (2011) and FAOSTAT (2011). Both estimates diverge, as they use different data sources and calendar years. On a regional level, differences can be substantial. FAO's estimate for fertilizer consumption in China in the year 2002 is 13 % higher than the estimate by IFA. As IFADATA (2011) provides longer continuous time series, we will refer to this dataset in the following. Fertilizer consumption between 1995 and 2009 (IFADATA, 2011) grows by +1.8 % per year. The estimates of Daberkow et al. (2000) and Bouwman et al. (2009, 2011) show lower growth rates of −0.4 % to +1.7 % over the regarded period of 20 to 50 yr. Our 50 yr average growth rate also stays with +0.9 % (B1) to +1.7 % (A2) below the observations. Yet, our short-term growth rate from 1995 to 2005 captures the observed development with a range of +1.5 % (B1) to +2.4 % (A2) between the scenarios. Due to trade our regional fertilizer projections are more uncertain than the global ones (see Sect. 4.2). Our results still meet the actual consumption trends of the last decades for most regions. However, fertilizer consumption in India rises slower than in the past or even stagnates, while the Pacific OECD region shows a strong increase in fertilizer consumption.

The range of our scenario outcomes is large for all N_r flows, and continues to become larger over time. It can be observed that the assumptions on which the globalised and environmentally oriented scenarios are based lead to a substantially lower turnover of the N_r cycle than the regional fragmented and economically oriented scenarios.

4.4 The importance of the livestock sector

The agricultural N_r cycle is dominated by the livestock sector. According to our calculations, livestock feeding appropriates 40 % (25 Tg) of N_r in global crop harvests and one third (11 Tg) of N_r in aboveground crop residues. Conversion byproducts add another 13 Tg N_r to the global feed mix. Moreover, 70 Tg N_r may be grazed by ruminants on pasture land, even though this estimate is very uncertain due to poor data availability on grazed biomass and N_r content of grazed pasture. The feed intake of 123 Tg results in solely 8 Tg N_r in livestock products.

In developed countries, the relative share of animal calories in total consumption already declined in the last decades. However, developing and transition countries still feature a massive increase in livestock consumption (FAOSTAT, 2011). According to our food demand projections, the rising global demand for livestock products will not end before the middle of the century. In the second half of the century, both an upward or a downward trend is possible.

More efficient livestock feeding will not necessarily relieve the pressure from the N_r cycle. Although the trend towards energy efficient industrial livestock feeding may reduce the demand for feed, this also implies a shift from pasture grazing, crop residues and conversion byproducts towards feedstock crops. Pasture grazing and crop residues do not have the required nutrient-density for highly productive livestock systems (Wirsenius, 2000). According to our calculations, conversion byproducts today provide one fourth of the proteins fed to animals in developed regions. Latin America exports twice as much N_r in conversion byproducts as in crops. At the same time, Europe cannot settle its conversion byproduct demand domestically. Conversion byproducts will not be sufficiently available if current industrialised feeding practices are adopted by other regions. The feedstock crops required to substitute conversion byproducts, pasture and crop residues will put additional pressure on the cropland N_r flows. The pressure on pasture however will most likely be only modest.

4.5 The future expansion of N_r pollution

All N_r that is not recycled within the agricultural sector is a potential environmental threat. Bouwman et al. (2009) estimate that over the next 50 yr, only 40–60 % of the lost N_r will be directly denitrified. The remaining N_r will either volatilise in the form of N_2O, NO_x and NH_y or leach to water bodies. With the surge of the N_r cycle, air, water and atmospheric pollution will severely increase, which has strong negative consequences for human health, ecosystem services and the stability of ecosystems.

Along with local and regional impacts, it is still under debate whether a continuous accumulation of N_r could destabilize the earth system as a whole (Rockström et al., 2009a,b). While there is little evidence supporting abrupt changes on a global level, N_r pollution contributes gradually to global phenomena such as biodiversity loss, ozone depletion and global warming. For the latter two, N_2O emissions play a crucial role. N_2O, is currently the single most important ozone depleting substance, as it catalyses the destruction of stratospheric ozone (Ravishankara et al., 2009). In addition, N_2O has an extraordinarily long atmospheric lifetime and absorbs infrared radiation in spectral windows not covered by other greenhouse gases (Vitousek et al., 1997). Fortunately, the greenhouse effect of N_2O might be offset by NO_x and NH_y emissions. By reducing the atmospheric lifetime of CH_4, scattering light and increasing biospheric carbon sinks, these emissions have a cooling effect (Butterbach-Bahl et al., 2011).

According to our calculations, N_2O emissions from managed soils and manure contributed 3.9 Tg N_2O-N, or approximately half of total anthropogenic N_2O emissions (Vuuren et al., 2011). However, the uncertainty involved is high. The result of our Monte Carlo variation of the emission parameters suggests that the emissions may lie with a 90 % probability in the range of 3.0 to 4.9 Tg N_2O-N. This only covers parts of the uncertainty, as the underlying activity data is also uncertain. Finally, actual agricultural emissions should be slightly higher than our estimate, as we do not cover all agricultural N_2O emission sources of the National Greenhouse Gas Inventories (Eggleston et al., 2006) and as also these inventories have no full coverage. Crutzen et al. (2008), using a top-down approach, estimate total agricultural N_2O emissions in 2000 to be in the range of 4.3 to 5.8 Tg N_2O-N, which is modestly higher than our estimate of 3.4 to 5.5 (90 % confidence, mean: 4.4) Tg N_2O-N in the year 2000.

Compared to the SRES marker scenarios (Nakicenovic et al., 2000), our results suggest that emissions will increase with substantially higher growth rates in the first half of the century. Especially in the case of the A1 and B2 scenarios, we come to 66 % (A1) and 36 % (B2) higher cumulative emissions over the century. In scenario A2 our estimates are continuously approximately 20 % lower (A2), while in the B1 scenario cumulative emissions are 6 % higher (B1) but occur later in the century (Fig. 3). None of our agricultural N_2O emission scenarios would be compatible with the RCP2.6 scenario, which keeps the radiative forcing below 2.6 $\frac{W}{m^2}$ in 2100 (Moss et al., 1998). To reach a sustainable climate target, explicit GHG mitigation efforts would therefore be required even in optimistic scenarios. If the non-agricultural N_2O emissions grow in similar pace than agricultural N_2O emissions, the A2 scenario might even outpace the RCP8.5 scenario.

In the beginning of the century, the uncertainty of emission parameters is much larger than the spread of scenario mean values. Only in the second half of the century, the differences of the scenarios are of similar magnitude to the emission parameter uncertainty. While the scenarios are just representative pathways and have no pretension to cover a specific probability space, this still indicates that a better representation of the underlying biophysical processes would largely improve our emission estimates.

5 Conclusions

The current state of the global agricultural N_r cycle is highly inefficient. Only around half of the N_r applied to cropland soils is taken up by plants. Furthermore, only one tenth of the N_r in cropland plant biomass and grazed pasture is actually consumed by humans. During the 21st century, our scenarios indicate a strong growth of all major flows of the N_r cycle. In the materialistic, unequal and fragmented A2 scenario, inorganic fertilizer consumption more than triples due to a strong population growth and slow improvement in N_r efficiencies in livestock and crop production. In the prosperous and materialistic A1 scenario, the strong increase of livestock consumption in the first half of the century and the industrialisation of livestock production quadruple the demand for N_r in feed crops already in 2045. In the heterogeneous,

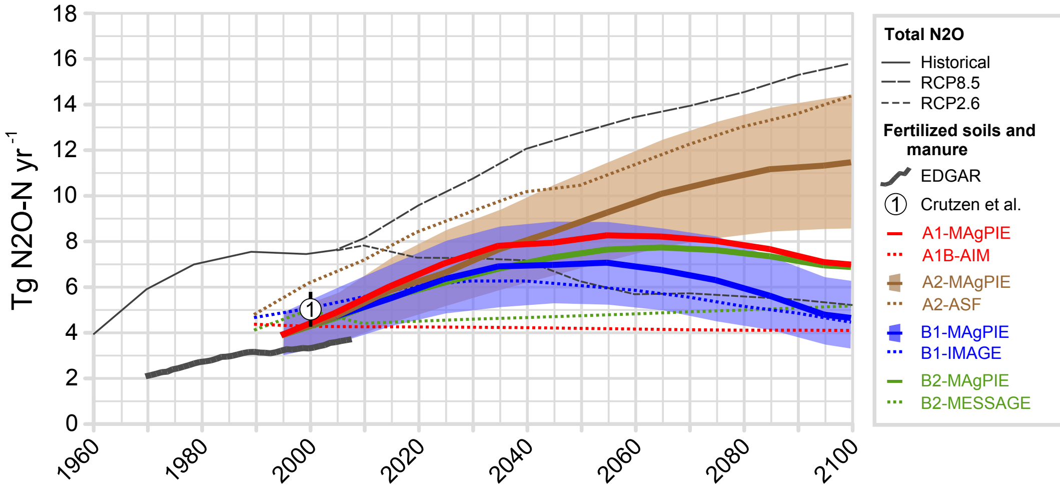

Fig. 4. Total anthropogenic N_2O emissions: historic emissions, highest and lowest RCP scenarios (Vuuren et al., 2011). N_2O emissions from soils and manure: historic estimates for 1970–2008 of the EDGAR 4.2 database (EC-JRC/PBL, 2011), a top-down estimate by Crutzen et al. (2008) for the year 2000, the SRES marker scenarios (Nakicenovic et al., 2000) for 1990–2100 and our scenarios for the SRES storylines for 1995–2095. The shaded areas represent a 90 % probability range in respect to the uncertainty of emission parameters of our A2 and B1 scenarios. Our A1 and B2 scenarios have a similar relative uncertainty range.

environmentally oriented B2 scenario, food demand is lower, especially in the first half of the century. However, the livestock sector productivity is improving only slowly and requires high amounts of N_r in feed. Finally, even in the globalised, equitable, environmental B1 scenario, N_r in harvested crops more than doubles and fertilizer consumption increases by 60 % and emissions by 23 % until the end of the century, with a peak in the middle of the century. In this scenario, the low meat consumption and large N_r efficiency improvements both in livestock and crop production are outbalanced by population growth and the catch-up of the less developed regions with the living standard of the rich regions.

Losses to natural systems will also continuously increase. This has negative consequences on both human health and local ecosystems. Moreover, it threatens the earth system as a whole by contributing to climate change, ozone depletion and loss of biodiversity. N_r mitigation is therefore one of the key global environmental challenges of this century.

Our model of the agricultural sector as a complex interrelated system shows that a large variety of dynamics influence N_r pollution. Each process offers a possibility of change, such that mitigation activities can take place not only where pollution occurs physically, but on different levels of the agricultural system: (a) already at the household level, the consumer has the choice to lower his N_r footprint by replacing animal with plant calories and reducing household waste (Popp et al., 2010; Leach et al., 2012); (b) substantial wastage during storage and processing could be avoided (Gustavsson et al., 2011); (c) information and price signals on the environmental footprint are lost within trade and retailing, such that sustainable products do not necessarily have a market advantage (Schmitz et al., 2012); (d) livestock products have potential to be produced more efficiently, both concerning the amount of N_r required for one ton of output and the composition of feed with different N_r footprints; (e) higher shares of animal manure and human sewage could be returned to farmlands (Wolf and Snyder, 2003); (f) nutrient uptake efficiency of plants could be improved by better fertilizer selection, timing and placing, as well as enhanced inoculation of legumes (Herridge et al., 2008; Roberts, 2007); (g) finally, unavoidable losses to natural systems could be directed or retained to protect vulnerable ecosystems (Jansson et al., 1994).

Appendix A

Extended methodology

A1 Model of Agricultural Production and its Impact on the Environment (MAgPIE): general description

MAgPIE is a global land-use allocation model which is linked with a grid-based dynamic vegetation model (LPJmL) (Bondeau et al., 2007; Sitch et al., 2003; Gerten et al., 2004; Waha et al., 2012). It takes into account regional economic conditions as well as spatially explicit data on potential crop yields and land and water constraints, and derives specific land-use patterns, yields and total costs of agricultural production for each grid cell. The following will provide only a brief overview of MAgPIE, as its implementation and validation is presented in detail elsewhere (Lotze-Campen et al., 2008; Popp et al., 2010, 2012; Schmitz et al., 2012).

The MAgPIE model works on three different levels of disaggregation: global, regional, and cluster cells. For the model-runs of this paper, the lowest disaggregation level contains 500 cluster cells, which are aggregated from 0.5 grid cells based on an hierarchical cluster algorithm (Dietrich, 2011). Each cell has individual attributes concerning the available agricultural area and the potential yields for 18 different cropping activities derived from the LPJmL model. The geographic grid cells are grouped into ten economic world regions (Fig. 1). Each economic region has specific costs of production for the different farming activities derived from the GTAP model (Schmitz et al., 2010).

Food demand is inelastic and exogenous to the model, as described in further detail in the Sect. A4. Demand distinguishes between livestock and plant demand. Each calorie demand can be satisfied by a basket of crop or livestock products with fixed shares based on the historic consumption patterns. There is no substitution elasticity between the consumption of different crop products.

The demand for livestock calories requires the cultivation of feed crops. Weindl et al. (2010) uses a top-down approach to estimate feed baskets from the energy requirements of livestock, dividing the feed use from FAOSTAT (2011) between the five MAgPIE livestock categories.

Two virtual trading pools are implemented in MAgPIE which allocate the demand to the different supply regions. The first pool reflects the situation of no further trade liberalisation in the future and minimum self-sufficiency ratios derived from FAOSTAT (2011) are used for the allocation. Self-sufficiency ratios describe how much of the regional agricultural demand quantity is produced within a region. The second pool allocates the demand according to comparative advantage criteria to the supply regions. Assuming full liberalisation, the regions with the lowest production costs per ton will be preferred. More on the methodology can be found in Schmitz et al. (2012).

The non-linear objective function of the land-use model is to minimise the global costs of production for the given amount of agricultural demand. For this purpose, the optimization process can choose endogenously the share of each cell to be assigned to a mix of agricultural activities, the share of arable land left out of production, the share of non-arable land converted into cropland at exogenous land conversion costs and the regional distribution of livestock production. Furthermore, it can endogenously acquire yield-increasing technological change at additional costs (Dietrich, 2011). For future projections, the model works in time steps of 10 yr in a recursive dynamic mode, whereby the technology level of crop production and the cropland area is handed over to the next time step.

The calculations in this paper are created with the model-revision 4857 of MAgPIE. While a mathematical description of the core model can be found in the Supplement, the following Sects. A2, A3 and A4 explain the model extensions which are implemented for this study. The interface between the core model and the nutrient module consists of cropland area ($X^{\text{area}}_{t,j,v,w}$), crop and livestock dry-matter production ($\mathrm{P}(x_t)^{\text{prod}}_{t,i,k}$) and its use ($\mathrm{P}(x_t)^{\text{ds}}_{t,i,k,u}$). All parameters are described in Table A2. The superscripts are no exponents, but part of the parameter name. The arguments in the subscripts of the parameters include most importantly time (t), regions (i), crop types (v) and livestock types (l) (Table A1).

A2 Crop residues and conversion byproducts

A2.1 Crop residues

Eggleston et al. (2006) offer one of the few consistent datasets to estimate both aboveground (AG) and belowground (BG) residues. Also, by providing crop-growth functions (CGF) instead of fixed harvest indices, it can well describe current international differences of harvest indices and also their development in the future. The methodology is thus well eligible for global long-term modelling. Eggleston et al. (2006) provide linear CGFs with positive intercept for cereals, leguminous crops, potatoes and grasses. As no values are available for the oilcrops rapeseed, sunflower, and oilpalms as well as sugar crops, tropical roots, cotton and others, we use fixed harvest indices for these crops based on (Wirsenius, 2000; Lal, 2005; Feller et al., 2007). If different CGFs are available for crops within a crop group, we build a weighted average based on the production in 1995. The resulting parameters $r_v^{\text{cgf\_i}}$, $r_v^{\text{cgf\_s}}$ and $r_v^{\text{cgf\_r}}$ are displayed in Table A3. The AG crop residue production $\mathrm{P}(x_t)^{\text{prod\_ag}}_{t,i,v}$ is calculated as a function of harvested production $\mathrm{P}(x_t)^{\text{prod}}_{t,i,v}$ and the physical area $X^{\text{area}}_{t,j,v,w}$, and BG crop production as a function of total aboveground biomass.

$$\mathrm{P}(x_t)^{\text{prod\_ag}}_{t,i,v} := \sum_{j\in I_i,w} X^{\text{area}}_{t,j,v,w} \cdot r_v^{\text{cgf\_i}} + \mathrm{P}(x_t)^{\text{prod}}_{t,i,v} \cdot r_v^{\text{cgf\_s}} \tag{A1}$$

$$\mathrm{P}(x_t)^{\text{prod\_bg}}_{t,i,v} := (\mathrm{P}(x_t)^{\text{prod}}_{t,i,v} + \mathrm{P}(x_t)^{\text{prod\_ag}}_{t,i,v}) \cdot r_v^{\text{cgf\_r}} \tag{A2}$$

While it is assumed that all BG crop residues remain on the field, the AG residues are assigned to four different categories: feed, on-field burning, recycling and other uses. Residues fed to livestock ($\mathrm{P}(x_t)^{\text{ds\_ag}}_{t,i,v,\text{feed}}$) are calculated based on livestock production and livestock and regional specific residue feed baskets $r^{\text{fb\_ag}}_{t,i,l,v}$ from Weindl et al. (2010). The demand rises with the increase in livestock production $\mathrm{P}(x_t)^{\text{prod}}_{t,i,l}$ and can be settled either by residues $\mathrm{P}(x_t)^{\text{ds\_ag}}_{t,i,v,\text{feed}}$ or by additional feedstock crops $\mathrm{P}(x_t)^{\text{ds}}_{t,i,l,v,\text{sag}}$. The latter prevents that crops are produced just for their residues.

$$\sum_v \mathrm{P}(x_t)^{\text{ds\_ag}}_{t,i,v,\text{feed}} = \sum_{l,v} (\mathrm{P}(x_t)^{\text{prod}}_{t,i,l} \cdot r^{\text{fb\_ag}}_{t,i,l,v} - \mathrm{P}(x_t)^{\text{ds}}_{t,i,l,v,\text{sag}}) \tag{A3}$$

Residue burning ($\mathrm{P}(x_t)^{\text{ds\_ag}}_{t,i,v,\text{burn}}$) is fixed to 15 % of total AG crop residue dry matter in developed and 25 % in developing

Table A1. Attributes.

Set	Description	Elements
t	timesteps	y1995 (1), y2005 (2) .. y2095 (11)
i	economic world regions	AFR, CPA, EUR, FSU, LAM, MEA, NAM, PAO, PAS, SAS (Fig. 1)
j	cells, each assigned to a region i ($I_{AFR}=\{1..30\}$,...)	1:300
w	irrigation	irrigated, rainfed
v	crops	temperate cereals, maize, tropical cereals, rice, soybeans, rapeseed, groundnut, sunflower, oilpalm, pulses, potatoes, tropical roots, sugar cane, sugar beet, fodder crops, fibres, others
l	livestock	ruminant livestock, non-ruminant livestock, poultry, eggs, milk
k	products	$v \cup l$
f	feeding systems	grazing on cropland (grazc), grazing on pasture (grazp), animal houses (house)
c	animal waste management systems	anaerobic lagoons, liquid/slurry, solid storage, daily spread, anaerobic digester, chicken layers, pit storage < 1 month, pit storage > 1 month, others
u	product use	food (food), feed (feed), seed (seed), other use (other), substitution for byproducts (sby), substitution for aboveground crop residues (sag)
r	AG residue use	feed (feed), recycling to soils (rec), burning in the field (burn), other use (other)
b	conversion byproduct use	feed (feed), other use (other)

regions for each crop. Other removals ($P(x_t)^{\text{ds\_ag}}_{t,i,l,v,\text{other}}$) are assumed to be only in developing regions of major importance and is set in these regions to 10 % of total residue dry matter production (Smil, 1999). All residues not assigned to feed, food, burning or other removals are assumed to remain in the field ($P(x_t)^{\text{ds\_ag}}_{t,i,v,\text{rec}}$). Trade of residues between regions is not considered.

$$P(x_t)^{\text{prod\_ag}}_{t,i,v} = \sum_r P(x_t)^{\text{ds\_ag}}_{t,i,v,r} \tag{A4}$$

A2.2 Conversion byproducts

Conversion byproducts are generated in the manufacturing of harvested crops into processed food. Of major importance are press cakes from oil production, molasses and bagasses from sugar refinement and brans from cereal milling. While they are also consumed as food, used for bioenergy production or as fertilizer, their most important usage lies currently in livestock feeding. Until recently, they were also reported in FAOSTAT. As the feed baskets used by MAgPIE from Weindl et al. (2010) are not in line with the then unpublished but probably more accurate statistics of FAOSTAT (2011), we decided to use the latter estimates on production and use (for feed or other purposes). We distributed the byproducts between the different livestock production types proportional to their energy in the feed baskets from Weindl et al. (2010) to create livestock-specific feed baskets for conversion byproducts $r^{\text{fb\_by}}_{t,i,l,v}$.

In the model, the production of 8 different conversion byproducts $P(x_t)^{\text{prod\_by}}_{t,i,v}$ (brans, molasses and 6 types of oilcakes) is linked to the total domestic supply $\sum_u P(x_t)^{\text{ds}}_{t,i,v,u}$ of their belonging crop groups (Table A3.1) by a factor $r^{\text{by\_conv}}_{\text{i,v}}$ fixed to the ratio of conversion byproduct production to their belonging crop domestic supply in 1995 (FAOSTAT, 2011). If the demand for byproducts is higher than the production, byproducts from other regions can be imported or the model can also feed feedstock crops $P(x_t)^{\text{ds}}_{t,i,l,v,\text{sby}}$.

$$P(x_t)^{\text{prod\_by}}_{t,i,v} := \sum_u P(x_t)^{\text{ds}}_{t,i,v,u} \cdot r^{\text{by\_conv}}_{\text{i,v}} \tag{A5}$$

$$P(x_t)^{\text{ds\_by}}_{t,i,v,\text{feed}} = \sum_l (P(x_t)^{\text{prod}}_{t,i,l} \cdot r^{\text{fb\_by}}_{t,i,l,v} - P(x_t)^{\text{ds}}_{t,i,l,v,\text{sby}}) \tag{A6}$$

$$\sum_i P(x_t)^{\text{prod\_by}}_{t,i,v} = \sum_{i,b} P(x_t)^{\text{ds\_by}}_{t,i,v,b} \tag{A7}$$

A3 N_r flows

A3.1 Attributes of plant biomass, conversion byproducts and food

The parametrisation of the goods represented in the model is a core task in a material flow model. From the literature, we derived N_r content of dry matter of harvested organs r^{Nharvest}_v (Wirsenius, 2000; Fritsch, 2007; FAO, 2004; Roy et al., 2006), aboveground crop residues r^{Nag}_v (Wirsenius, 2000; Fritsch, 2007; FAO, 2004; Eggleston et al., 2006; Chan and Lim, 1980), belowground crop residues r^{Nbg}_v(Eggleston et al., 2006; Fritsch, 2007; Wirsenius, 2000; Khalid et al., 2000) and conversion byproducts r^{Nby}_v(Wirsenius, 2000; Roy et al., 2006) (Table A3.1). For the aggregation to MAgPIE crop groups, we weighted the parameters of each crop group with its global dry matter biomass in 1995. In the case of missing values for a specific FAO crop, we adopted the parametrisation of a selected representative crop of its crop group (e.g. we assign the value of wheat, being the representative crop of *temperate cereals*, to the FAO item *mixed grain*). The N_r in crop and residue production and its subsequent use is thus

Table A2. Parameters, descriptions and units (all units per year). The name of the equivalent parameter in Eggleston et al. (2006) is indicated in brackets.

Parameter	Description	Unit
Area		
$X_{t,j,v,w}^{\text{area}}$	Cropland area under cultivation	Mha
$\mathrm{P}(x_t)_{t,j}^{\text{landconv}}$	Land conversion	Mha
Production		
$\mathrm{P}(x_t)_{t,i,k}^{\text{prod}}$ $\mathrm{N}(x_t)_{t,i,k}^{\text{prod}}$	Crop production	TgDM $\mathrm{TgN_r}$
$\mathrm{P}(x_t)_{t,i,v}^{\text{prod\_ag}}$ $\mathrm{N}(x_t)_{t,i,v}^{\text{prod\_ag}}$	AG residue production	TgDM $\mathrm{TgN_r}$
$\mathrm{P}(x_t)_{t,i,v}^{\text{prod\_bg}}$ $\mathrm{N}(x_t)_{t,i,v}^{\text{prod\_bg}}$	BG residue production	TgDM $\mathrm{TgN_r}$
$\mathrm{P}(x_t)_{t,i,v}^{\text{prod\_by}}$ $\mathrm{N}(x_t)_{t,i,v}^{\text{prod\_by}}$	Conversion byproduct production	TgDM $\mathrm{TgN_r}$
Domestic supply and its use		
$\mathrm{P}(x_t)_{t,i,v,u}^{\text{ds}}$ $\mathrm{N}(x_t)_{t,i,v,u}^{\text{ds}}$	Crop use	TgDM $\mathrm{TgN_r}$
$\mathrm{P}(x_t)_{t,i,v,r}^{\text{ds\_ag}}$ $\mathrm{N}(x_t)_{t,i,v,r}^{\text{ds\_ag}}$	AG residues use	TgDM $\mathrm{TgN_r}$
$\mathrm{P}(x_t)_{t,i,v,b}^{\text{ds\_by}}$ $\mathrm{N}(x_t)_{t,i,v,b}^{\text{ds\_by}}$	Conversion byproduct use	TgDM $\mathrm{TgN_r}$
$\mathrm{N}(x_t)_{t,i,k}^{\text{fs}}$	Food supply	$\mathrm{TgN_r}$
$r_{t,i,k}^{\text{int}}$	Intake share of food supply	$\frac{\mathrm{TgN_r}}{\mathrm{TgDM}}$
$\mathrm{N}(x_t)_{t,i,k}^{\text{int}}$	Intake	$\mathrm{TgN_r}$
P_t^{tb}	Trade balance reduction	1
Crop growth functions, processing rates and biological fixation		
$r_v^{\text{cgf\_i}}$	AG residues intercept	$\frac{\mathrm{TgDM}}{\mathrm{Mha}}$
$r_v^{\text{cgf\_s}}$	AG residues slope	$\frac{\mathrm{TgDM}}{\mathrm{TgDM}}$
$r_v^{\text{cgf\_r}}$	AG to BG biomass ratio	$\frac{\mathrm{TgDM}}{\mathrm{TgDM}}$
$r_{\mathrm{i,v}}^{\text{by\_conv}}$	Conversion byproducts generated per unit of crop production	$\frac{\mathrm{TgDM}}{\mathrm{TgDM}}$
r_v^{ndfa}	Plant $\mathrm{N_r}$ derived from atmospheric fixation	$\frac{\mathrm{TgN_r}}{\mathrm{TgN_r}}$
r_v^{Nfix}	Fixation of free-living bacteria	$\frac{\mathrm{TgN_r}}{\mathrm{TgMha}}$
Products		
r_v^{Nharvest}	$\mathrm{N_r}$ content of harvested crops	$\frac{\mathrm{TgN_r}}{\mathrm{TgDM}}$
r_v^{Nag}	$\mathrm{N_r}$ content of AG residues	$\frac{\mathrm{TgN_r}}{\mathrm{TgDM}}$
r_v^{Nbg}	$\mathrm{N_r}$ content of BG residues	$\frac{\mathrm{TgN_r}}{\mathrm{TgDM}}$
r^{Npast}	$\mathrm{N_r}$ content of grazed pasture	$\frac{\mathrm{TgN_r}}{\mathrm{TgDM}}$
r_v^{Nby}	$\mathrm{N_r}$ content of conversion byproducts	$\frac{\mathrm{TgN_r}}{\mathrm{TgDM}}$
r_l^{PR}	Protein content of livestock products	$\frac{\mathrm{TgPr}}{\mathrm{TgDM}}$
r_l^{NtoPR}	Protein to $\mathrm{N_r}$ content ratios	$\frac{\mathrm{TgN_r}}{\mathrm{TgPr}}$

obtained as follows:

$$\mathrm{N}(x_t)_{t,i,v}^{\text{prod}} := \mathrm{P}(x_t)_{t,i,v}^{\text{prod}} \cdot r_v^{\text{Nharvest}} \tag{A8}$$

$$\mathrm{N}(x_t)_{t,i,v}^{\text{prod\_ag}} := \mathrm{P}(x_t)_{t,i,v}^{\text{prod\_ag}} \cdot r_v^{\text{Nag}} \tag{A9}$$

$$\mathrm{N}(x_t)_{t,i,v}^{\text{prod\_bg}} := \mathrm{P}(x_t)_{t,i,v}^{\text{prod\_bg}} \cdot r_v^{\text{Nbg}} \tag{A10}$$

$$\mathrm{N}(x_t)_{t,i,v,u}^{\text{ds}} := \mathrm{P}(x_t)_{t,i,v,u}^{\text{ds}} \cdot r_v^{\text{Nharvest}} \tag{A11}$$

$$\mathrm{N}(x_t)_{t,i,v,r}^{\text{ds\_ag}} := \mathrm{P}(x_t)_{t,i,v,r}^{\text{ds\_ag}} \cdot r_v^{\text{Nag}} \tag{A12}$$

.

A3.2 Manure management

Feed $\mathrm{N_r}$ is assigned to three feeding systems (f): pasture grazing (grazp), cropland grazing (grazc) and animal houses (house). All $\mathrm{N_r}$ from pasture was assigned to grazp. $\mathrm{N_r}$ in feedstock crops and conversion byproducts is assumed to be eaten in confinement houses. Crop residues in developed regions are fully assigned to house, while in developing regions we assume that 25 % of the $\mathrm{N_r}$ in residues are consumed directly on croplands during stubble grazing ($r_{t,i}^{\text{grazC}}$).

$$\mathrm{N}(x_t)_{t,i,l,\text{grazp}}^{\text{feed}} := r_{t,i,l}^{\text{fb\_past}} \cdot \mathrm{P}(x_t)_{t,i,l}^{\text{prod}} \cdot r^{\text{Npast}} \tag{A13}$$

$$\mathrm{N}(x_t)_{t,i,l,\text{grazc}}^{\text{feed}} := \sum_v r_{t,i,l,v}^{\text{fb\_ag}} \cdot \mathrm{P}(x_t)_{t,i,l}^{\text{prod}} \cdot r_v^{\text{Nag}} \cdot r_{t,i}^{\text{grazC}} \tag{A14}$$

$$\begin{aligned}\mathrm{N}(x_t)_{t,i,l,\text{house}}^{\text{feed}} := & \sum_v \Big(r_{t,i,l,v}^{\text{fb\_by}} \cdot \mathrm{P}(x_t)_{t,i,l}^{\text{prod}} \cdot r_v^{\text{Nby}} \\ & + r_v^{\text{Nharvest}} \cdot (r_{t,i,l,v}^{\text{fb\_conc}} \cdot \mathrm{P}(x_t)_{t,i,l}^{\text{prod}} \\ & + \mathrm{P}(x_t)_{t,i,l,v,\text{sby}}^{\text{ds}} + \mathrm{P}(x_t)_{t,i,l,v,\text{sag}}^{\text{ds}}) \\ & + r_{t,i,l,v}^{\text{fb\_ag}} \cdot \mathrm{P}(x_t)_{t,i,l}^{\text{prod}} \cdot r_v^{\text{Nag}} \cdot (1 - r_{t,i}^{\text{grazC}}) \Big)\end{aligned} \tag{A15}$$

In a second step, we use a top-down approach to estimate regional livestock specific annual average $\mathrm{N_r}$ excretion rates, rooted in the Tier 2 methodology of Eggleston et al. (2006). From the feed in all feeding systems (f) we subtract the amount of $\mathrm{N_r}$ which is integrated into animal biomass

Table A2. Continued.

Parameter	Description	Unit
Livestock		
$r^{\mathrm{fb\_conc}}_{t,i,l,v}$	Feedstock crops in feed basket	$\frac{\mathrm{TgDM}}{\mathrm{TgDM}}$
$r^{\mathrm{fb\_ag}}_{t,i,l,v}$	AG residues in feed basket	$\frac{\mathrm{TgDM}}{\mathrm{TgDM}}$
$r^{\mathrm{fb\_past}}_{t,i,l}$	Grazed pasture in feed basket	$\frac{\mathrm{TgDM}}{\mathrm{TgDM}}$
$r^{\mathrm{fb\_by}}_{t,i,l,v}$	Byproducts in feed basket	$\frac{\mathrm{TgDM}}{\mathrm{TgDM}}$
$r^{\mathrm{grazC}}_{t,i}$	Fraction of feed residues consumed during stubble grazing	$\frac{\mathrm{TgDM}}{\mathrm{TgDM}}$
$\mathrm{N}(x_t)^{\mathrm{feed}}_{t,i,l,f}$	Feed N_r distributed to livestock types in feeding systems	$\frac{\mathrm{TgN_r}}{\mathrm{TgN_r}}$
r^{sl}_{l}	Ratio between marketable product and whole body weight	$\frac{\mathrm{TgDM}}{\mathrm{TgDM}}$
r^{Nl}_{l}	Whole body N_r content	$\frac{\mathrm{TgN_r}}{\mathrm{TgDM}}$
$\mathrm{N}(x_t)^{\mathrm{sl}}_{t,i,l}$	N_r in whole animal bodies	$\mathrm{TgN_r}$
$r^{\mathrm{fs}}_{t,i,l,f}$	Fraction of manure in feeding system (based on $\mathrm{MS_{(T,S)}}$)	$\frac{\mathrm{TgN_r}}{\mathrm{TgN_r}}$
$r^{\mathrm{cs}}_{t,i,l,c}$	Fraction of manure managed in animal waste management systems (based on $\mathrm{MS_{(T,S)}}$)	$\frac{\mathrm{TgN_r}}{\mathrm{TgN_r}}$
$\mathrm{N}(x_t)^{\mathrm{ex}}_{t,i,l,f}$	N_r in excretion ($\mathrm{Nex_{(T)}}$)	$\mathrm{TgN_r}$
$r^{\mathrm{fuel}}_{t,i,l}$	Fraction of manure collected for fuel	$\frac{\mathrm{TgN_r}}{\mathrm{TgN_r}}$
$\mathrm{N}(x_t)^{\mathrm{closs}}_{t,i}$	Manure N_r lost in animal houses and waste management	$\mathrm{TgN_r}$

$\mathrm{N}(x_t)^{\mathrm{sl}}_{t,i,l}$ and assume that the remaining N_r is excreted as manure. For meat products, we calculate the N_r in the whole animal body $\mathrm{N}(x_t)^{\mathrm{sl}}_{t,i,l}$ using livestock product to whole body ratios r^{sl}_{l} from Wirsenius (2000), and whole body N_r content r^{Nl}_{l} based on Poulsen and Kristensen (1998) (Table A5). For milk and eggs, we calculate $\mathrm{N}(x_t)^{\mathrm{sl}}_{t,i,l}$ by the N_r content in milk and eggs (Poulsen and Kristensen, 1998) (Table A5). $\mathrm{N}(x_t)^{\mathrm{sl}}_{t,i,l}$ is assigned to one of the three feeding systems by the parameter $r^{\mathrm{fs}}_{t,i,l,f}$, which is based on Eggleston et al. (2006).

$$\mathrm{N}(x_t)^{\mathrm{sl}}_{t,i,l} := \mathrm{P}(x_t)^{\mathrm{prod}}_{t,i,l}\frac{r^{\mathrm{Nl}}_{l}}{r^{\mathrm{sl}}_{l}} \quad \text{(A16)}$$

$$\mathrm{N}(x_t)^{\mathrm{ex}}_{t,i,l,f} := \mathrm{N}(x_t)^{\mathrm{feed}}_{t,i,l,f} - r^{\mathrm{fs}}_{t,i,l,f}\cdot \mathrm{N}(x_t)^{\mathrm{sl}}_{t,i,l} \quad \text{(A17)}$$

In a third step, the N_r excreted in animal houses is divided between 9 animal waste management systems (c) using the parameter $r^{\mathrm{cs}}_{t,i,l,c}$. When available, we used the regional and livestock specific shares from Eggleston et al. (2006); for

Table A2. Continued.

Parameter	Description	Unit
Soil Budget		
$\mathrm{N}(x_t)^{\mathrm{withd}}_{t,i}$	Soil N_r withdrawals	$\mathrm{TgN_r}$
$\mathrm{N}(x_t)^{\mathrm{inp}}_{t,i}$	Soil N_r inputs	$\mathrm{TgN_r}$
$\mathrm{N}(x_t)^{\mathrm{loss}}_{t,i}$	Soil N_r losses	$\mathrm{TgN_r}$
$r^{\mathrm{SNUpE}}_{t,i}$	Cropland soil N_r uptake efficiency	$\frac{\mathrm{TgN_r}}{\mathrm{TgN_r}}$
$\mathrm{N}(x_t)^{\mathrm{dep}}_{t,i}$	Atmospheric deposition of N_r	$\mathrm{TgN_r}$
$\mathrm{N}(x_t)^{\mathrm{volat}}_{t,i}$	Volatilisation of NO_x and NH_y	$\mathrm{TgNO_xNH_y}$
$\mathrm{N}^{\mathrm{som}}_{t,i}$	N_r release by soil organic matter loss (F_{SOM})	$\mathrm{TgN_r}$
$r^{\mathrm{som}}_{t,j}$	N_r release by soil organic matter loss	$\frac{\mathrm{TgN_r}}{\mathrm{Mha}}$
$\mathrm{N}(x_t)^{\mathrm{fert}}_{t,i}$	Inorganic N_r fertilizer (F_{SN})	$\mathrm{TgN_r}$
$\mathrm{N}(x_t)^{\mathrm{res}}_{t,i}$	N_r in recycled AG and BG residues (F_{CR})	$\mathrm{TgN_r}$
$\mathrm{N}(x_t)^{\mathrm{FixFree}}_{t,i}$	N_r fixed by free-living microorganisms (F_{CR})	$\mathrm{TgN_r}$
$\mathrm{N}(x_t)^{\mathrm{m}}_{t,i}$	N_r in manure excreted in animal houses and applied to agricultural soils (F_{AM})	$\mathrm{TgN_r}$
$r^{\mathrm{msplit}}_{t,i}$	Fraction of manure in animal houses applied to cropland soils	$\frac{\mathrm{TgN_r}}{\mathrm{TgN_r}}$
$\mathrm{N}(x_t)^{\mathrm{m\_cs}}_{t,i}$	N_r in manure applied or excreted on cropland soils	$\mathrm{TgN_r}$
$\mathrm{N}(x_t)^{\mathrm{m\_ps}}_{t,i}$	N_r in manure applied or excreted on pasture soils	$\mathrm{TgN_r}$
Emissions		
$r^{\mathrm{gas\_fert}}$	Fraction of industrial fertilizer N_r that volatises as NO_x and NH_y ($\mathrm{Frac_{GasF}}$)	$\frac{\mathrm{TgNO_xNH_y}}{\mathrm{TgN_r}}$
$r^{\mathrm{gas\_awms}}_{l,c}$	Fraction of manure N_r that volatises in waste management facilities as NO_x and NH_y ($\mathrm{Frac_{GasMS}}$)	$\frac{\mathrm{TgNO_xNH_y}}{\mathrm{TgN_r}}$
$r^{\mathrm{loss\_awms}}_{l,c}$	Fraction of manure N_r that is lost in waste management ($\mathrm{Frac_{LossMS}}$)	$\frac{\mathrm{TgNO_xNH_y}}{\mathrm{TgN_r}}$

chicken, sheep, goats and other animals, we used the default parameters of IPCC (1996). The category *others* for chicken is assumed to be *poultry with litter*.

Not all the manure excreted in animal houses is recycled within the agricultural system, but large fractions are lost to volatilisation and leaching or is simply not brought out to the farmland. We use animal waste management system specific

Table A2. Continued.

Parameter	Description	Unit
$r^{\mathrm{gas\_m}}$	Fraction of manure N_r that volatises during application as NO_x and NH_y ($\mathrm{Frac_{GasM}}$)	$\frac{\mathrm{TgNO_xNH_y}}{\mathrm{TgN_r}}$
r^{leach}	Fraction of N_r that leaches to water bodies ($\mathrm{Frac_{Leach-H}}$)	$\frac{\mathrm{TgN_r}}{\mathrm{TgN_r}}$
$\mathrm{r_v^{CF}}$	Combustion factor for on-field residue burning (C_f)	$\frac{\mathrm{TgN_r}}{\mathrm{TgN_r}}$
r^{dir}	Direct emission factor for N inputs to managed soils ($\mathrm{EF_1}$)	$\frac{\mathrm{TgN_2O-N}}{\mathrm{TgN_r}}$
$r^{\mathrm{dir\_rice}}$	Direct emission factor for N inputs to flooded rice fields ($\mathrm{EF_{1fr}}$)	$\frac{\mathrm{TgN_2O-N}}{\mathrm{TgN_r}}$
$r_c^{\mathrm{dir\_house}}$	Direct emission factor for manure excreted in animal houses ($\mathrm{EF}_{3(S)}$)	$\frac{\mathrm{TgN_2O-N}}{\mathrm{TgN_r}}$
$r_l^{\mathrm{dir\_graz}}$	Direct emissions from manure excreted on pasture, range and paddock ($\mathrm{EF_{3PRP}}$)	$\frac{\mathrm{TgN_2O-N}}{\mathrm{TgN_r}}$
$r^{\mathrm{indir\_gas}}$	N_2O emission factor for volatised N_r ($\mathrm{EF_{iv}}$)	$\frac{\mathrm{TgN_2O-N}}{\mathrm{TgNO_xNH_y}}$
$r^{\mathrm{indir\_leach}}$	N_2O emission factor for leached N_r ($\mathrm{EF_v}$)	$\frac{\mathrm{TgN_2O-N}}{\mathrm{TgN_r}}$
$\mathrm{N_2O}(x_t)_{t,i}^{\mathrm{fert}}$	N_2O from industrial fertilizer	$\mathrm{TgN_2O-N}$
$\mathrm{N_2O}(x_t)_{t,i}^{\mathrm{res}}$	N_2O from crop residues	$\mathrm{TgN_2O-N}$
$\mathrm{N_2O}(x_t)_{t,i}^{\mathrm{m}}$	N_2O from animal manure applied to croplands	$\mathrm{TgN_2O-N}$
$\mathrm{N_2O}(x_t)_{t,i}^{\mathrm{past}}$	N_2O from pasture range and paddock	$\mathrm{TgN_2O-N}$
$\mathrm{N_2O}(x_t)_{t,i}^{\mathrm{house}}$	N_2O from animal waste management systems	$\mathrm{TgN_2O-N}$
$\mathrm{N_2O}(x_t)_{t,i}^{\mathrm{som}}$	N_2O from soil organic matter loss	$\mathrm{TgN_2O-N}$

shares of the total amount of managed manure $r_{l,c}^{\mathrm{loss\_awms}}$ not being recycled, including a fraction $r_{l,c}^{\mathrm{gas\_awms}}$ that is lost in the form of volatilisation in the form of NO_x and NH_y. Because default parameters for $r_{l,c}^{\mathrm{gas\_awms}}$ and $r_{l,c}^{\mathrm{loss\_awms}}$ are not available for all animal waste management systems, we made the following assumptions: For pit storage <1 month of swine manure, we used the lower value of the proposed range (0.15), and the upper value (0.3) for pit storage >1 month. If no estimates are available, drylots and solid storage received the same emission factor, as was done in the old methodology (IPCC, 1996). Based on Marchaim (1992), we assumed that losses for manure managed in *anaerobic digesters* are negligible. In the absence of default parameters for $r_{t,i,l,c}^{\mathrm{cs}}$ for chicken, sheep, goats and other animals, we used the default parameters of Eggleston et al. (2006). *Others*

Table A3. Estimates of crop growth functions: AG residues intercept ($r_v^{\mathrm{cgf\_i}}$), slope ($r_v^{\mathrm{cgf\_s}}$) and AG to BG biomass ratio ($r_v^{\mathrm{cgf\_r}}$) (for sources see text).

Crop type (kcr)	$r_v^{\mathrm{cgf\_i}}$	$r_v^{\mathrm{cgf\_s}}$	$r_v^{\mathrm{cgf\_r}}$
Temperate cereals	0.58	1.36	0.24
Tropical cereals	0.61	1.03	0.22
Maize	0.79	1.06	0.22
Rice	2.46	0.95	0.16
Soybeans	1.35	0.93	0.19
Rapeseed	0	1.86	0.22
Groudnut	1.54	1.07	0.19
Sunflower	0	1.86	0.22
Oilpalm	0	1.86	0.24
Pulses	0.79	0.89	0.19
Potatoes	1.06	0.10	0.20
Tropical roots	0	0.85	0.20
Sugar cane	0	0.67	0.07
Sugar beet	0	0.54	0.20
Others	0	0.39	0.22
Fodder	0.26	0.28	0.45
Fibres	0	1.48	0.13

Table A4. N_r contents of harvested crops (r_v^{Nharvest}), aboveground crop residues (r_v^{Nag}), belowground crop residues (r_v^{Nbg}) and conversion byproducts (r_v^{Nby}) for the MAgPIE crop types. All N_r contents are in % of dry matter biomass. Collected and aggregated from Wirsenius (2000), Fritsch (2007), Eggleston et al. (2006), FAO (2004), Roy et al. (2006), Chan and Lim (1980) and Khalid et al. (2000).

Crop type (v)	r_v^{Nharvest}	r_v^{Nag}	r_v^{Nbg}	r_v^{Nby}
Temperate cereals	2.17	0.74	0.98	2.93 (Temperate cereals, Maize, Tropical cereals, Rice)
Maize	1.60	0.88	0.70	
Tropical cereals	1.63	0.70	0.60	
Rice	1.28	0.70	0.90	
Soybeans	5.12	0.80	0.80	7.90
Rapeseed	3.68	0.81	0.81	6.43
Groudnut	2.99	2.24	0.80	7.28
Sunflower	2.16	0.80	0.80	5.92
Oilpalm	0.57	0.52	0.53	6.43
Pulses	4.21	1.05	0.80	
Potatoes	1.44	1.33	1.40	
Tropical roots	0.53	0.86	1.40	
Sugar cane	0.24	0.80	0.80	1.36 (Sugar cane, Sugar beet)
Sugar beet	0.56	1.76	1.40	
Others	2.85	0.81	0.70	5.72
Fodder	2.01	1.91	1.41	
Fibres	2.39	0.93	0.70	
Pasture	1.60			
Pasture	r^{Npast}			
Past	1.60			

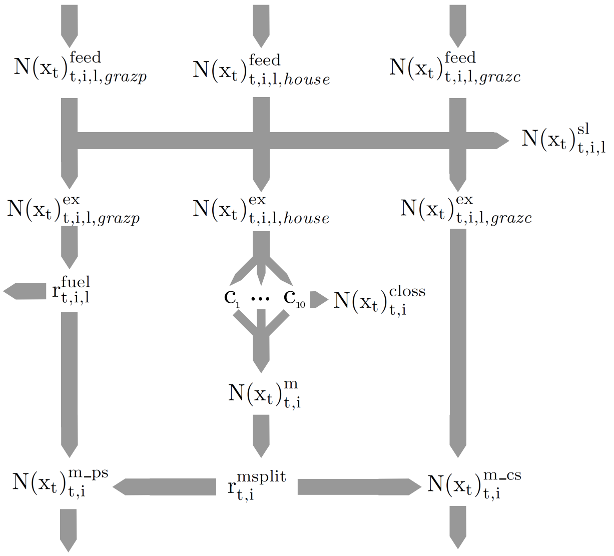

Fig. A1. Modelling N_r flows in the livestock sector.

Table A5. Estimates of whole body N_r content (r_l^{Nl}) in % of dry matter, and estimates of the ratio between marketable product and whole body weight (r_l^{sl}).

	r_l^{Nl}	r_l^{sl}
Ruminant livestock	6.3[a]	0.66[c]
Non-ruminant livestock	6.0[a]	0.81[c]
Poultry	7.1[a]	0.76[c]
Eggs	5.6[a]	1
Milk	4.6[b]	1

[a]Based on cows, market pigs, chicken and chicken eggs in Poulsen and Kristensen (1998).
[b]Based on milk with 3.5 % proteins in line with Smil (2002).
[c]Based on medium quality cows, swine and broilers from Wirsenius (2000).

is assumed to be *deep bedding* for pigs, cattle and others. All remaining gaps in the loss factors are filled with the values for cattle of the respective animal waste management system.

While all remaining manure in animal houses is fully applied to cropland soils in developing regions, we assume that in NAM and EUR only a fraction $r_{t,i}^{msplit}$ of 87 % and 66 % is returned on cropland soils (Liu et al., 2010b), while the rest is applied to pasture soils. Furthermore, in developing regions, a certain share of manure excreted on pasture is dedicated for household fuel and does not return to pasture soils (Eggleston et al., 2006). Because the N_r in fuel is leaving the agricultural sector, it is not further considered in this study, while the N_r from pasture grazing is assumed to be returned to pasture soils.

Losses of N_r in animal houses and waste handling ($N(x_t)_{t,i}^{closs}$), recycled manure ($N(x_t)_{t,i}^{m}$) and manure arriving on cropland soils ($N(x_t)_{t,i}^{m\_cs}$) and pasture soils ($N(x_t)_{t,i}^{m\_ps}$) are calculated as follows:

$$N(x_t)_{t,i}^{closs} := \sum_c N(x_t)_{t,i,l,\text{house}}^{ex} \cdot r_{t,i,l,c}^{cs} \cdot r_{l,c}^{loss\_awms} \tag{A18}$$

$$N(x_t)_{t,i}^{m} := \sum_c N(x_t)_{t,i,l,\text{house}}^{ex} \cdot r_{t,i,l,c}^{cs} \cdot (1 - r_{l,c}^{loss\_awms}) \tag{A19}$$

$$N(x_t)_{t,i}^{m\_cs} := N(x_t)_{t,i}^{m} \cdot r_{t,i}^{msplit} + \sum_l N(x_t)_{t,i,l,\text{grazc}}^{ex} \tag{A20}$$

$$N(x_t)_{t,i}^{m\_ps} := N(x_t)_{t,i}^{m} \cdot (1 - r_{t,i}^{msplit}) + \sum_l N(x_t)_{t,i,l,\text{grazp}}^{ex} \cdot (1 - r_{t,i,l}^{fuel}) \tag{A21}$$

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A3.3 Cropland N_r inputs

Inorganic fertilizer is the only N_r flow appearing in international statistics. We aggregate the values of IFADATA (2011) for all N_r fertilizer products to the 10 MAgPIE regions to determine $N(x_t)_{t,i}^{fert}$ in 1995. For the scenario analysis, inorganic fertilizer consumption is determined endogenously as described in Sect. A3.4.

The amount of crop residues left in the field is estimated as described in Sect. A2 as the remainder of the produced residues which are not used for feed, construction, fuel or burned in the field. While the nutrients of these residues are fully returned to cropland soils, the largest part of the N_r in the crop residues burned in the field (r_v^{CF}) is combusted; only a fraction of 10 % for temperate cereal residues and 20 % for all other residues (Eggleston et al., 2006) remains uncombusted and returns to cropland soils.

$$N(x_t)_{t,i}^{res} := \sum_v \Big(N(x_t)_{t,i,v}^{prod\_bg} + N(x_t)_{t,i,v,\text{rec}}^{ds\_ag} + N(x_t)_{t,i,v,\text{burn}}^{ds\_ag} \cdot (1 - r_v^{CF}) \Big) \tag{A22}$$

A major part of the N_r lost from field in the form of NO_x and NH_y as well as other N_r compounds from the combustion of fossil fuels are later on deposited from the atmosphere on cropland area. Based on spatial datasets for atmospheric deposition rates (Dentener, 2006) and cropland area (Klein Goldewijk et al., 2011a), we derive the regional atmospheric deposition on croplands $N(x_t)_{t=1,i}^{dep}$. As a large part of volatilised N_r will be deposited close to the emission source, the largest part of cropland atmospheric deposition probably stems from agricultural NO_x and NH_y. For the future we therefore assume that the deposition rates grow with the same growth rate as the agricultural NO_x and NH_y emissions $N(x_t)_{t,i}^{volat}$ (see Eq. (A38) in Sect. A3.5).

$$N(x_t)_{t,i}^{dep} := \frac{N(x_t)_{t,i}^{volat}}{N(x_t)_{t=1,i}^{volat}} \cdot N(x_t)_{t=1,i}^{dep} \tag{A23}$$

Table A6. Estimates of N_r fixation rates per area (r_v^{Nfix}) or as percentage of plant N_r (r_v^{ndfa}), based on Herridge et al. (2008) and aggregated to MAgPIE crop types.

Crop type	r_v^{Nfix} $\frac{\mathrm{TgN_r}}{\mathrm{Mha}}$	r_v^{ndfa} $\frac{\mathrm{TgN_r}}{\mathrm{TgN_r}}$
Temperate Cereals	0.005	–
Maize	0.005	–
Tropical Cereals	0.005	–
Rice	0.033	–
Soybeans	–	0.5[a], 0.6 [b], 0.8 [c], 0.68[d]
Rapeseed	0.005	–
Groudnut	–	0.5[a], 0.6 [b], 0.8 [c], 0.68[d]
Sunflower	0.005	–
Oilpalm	0.005	–
Pulses	–	0.53
Potatoes	0.005	–
Tropical roots	0.005	–
Sugar Cane	–	0.2[b], 0.1[d]
Sugar Beet	0.005	–
Others	0.005	–
Fodder	0.004	0.31
Fibres	0.005	–

[a] For the region CPA
[b] For the region LAM
[c] For the region NAM
[d] For all other regions

While plants are unable to fix nitrogen from N_2 in the atmosphere, some microorganisms are able to do this. These microorganisms either live free in soils, or in symbiosis with certain crops or cover crops. The symbiosis is typical mainly for leguminous crops (beans, groundnuts, soybean, pulses, chickpeas, alfalfa), which possess special root nodules in which the microorganisms live. Also, sugar cane can fix N_r in symbiosis with endophytic bacteria. In the case of rice paddies, free-living cyanobacteria and cyanobacteria living in symbiosis with the water-fern Azolla can also fix substantial amounts of N_r. While N_r fixation by leguminous plants has been well investigated, estimates for N_r fixation by sugar cane and free-living bacteria is much more uncertain or even speculative.

For legumes and sugar cane, where N_r fixation is the direct product of a symbiosis of the microorganisms with the crop, we assumed that fixation rates are proportional to the N_r in the plant biomass. The percentage of fixation-derived N_r is taken from Herridge et al. (2008). In the case of soybeans, groundnuts and sugarcane, fixation rates vary between regions to account for differences in management practices like fertilization or inoculation.

For legumes and sugar cane, where N_r fixation is the direct product of a symbiosis of the microorganisms with the crop, we assumed that fixation rates are proportional to the N_r in the plant biomass. The percentage of fixation-derived N_r is taken from Herridge et al. (2008). In the case of soybeans, groundnuts and sugarcane, fixation rates vary between regions to account for differences in management practices like fertilization or inoculation. N_r fixation by free-living bacteria in cropland soils and rice paddies does not necessarily depend on the biomass production of the harvested crop, so we used fixation rates per area r_v^{Nfix}. In the case of the MAgPIE crop types fodder and pulses, which contain crop species with different rates of N_r fixation, a weighted mean is calculated based on the relative share of biomass production in 1995 for r_v^{ndfa} or on the relative share of harvested area in 1995 for r_v^{Nfix} (Table A6). Our model does not cover that the fixation rates might change in the future due to the change of management practices. Improved inoculation of root nodules could increase fixation rates, while fertilization of legumes could reduce the biological fixation.

$$\mathrm{N}(x_t)^{\mathrm{FixFree}}_{t,i} := \sum_{j\in I_i,v,w} X^{\mathrm{area}}_{t,j,v,w} \cdot r_v^{\mathrm{Nfix}}) \tag{A24}$$

A certain share of the N_r in a plant is already incorporated in the seed. The amount of seed required for production $\mathrm{P}(x_t)^{\mathrm{ds}}_{t,i,v,\mathrm{seed}}$ is estimated crop and region specific using seed shares from FAOSTAT (2011).

$$\mathrm{N}(x_t)^{\mathrm{ds}}_{t,i,v,\mathrm{seed}} := \mathrm{P}(x_t)^{\mathrm{ds}}_{t,i,v,\mathrm{seed}} \cdot r_v^{\mathrm{Nharvest}} \tag{A25}$$

When pastureland or natural vegetation is transformed to cropland, soil organic matter (SOM) is lost. This also releases N_r for agricultural production. Total N_r release by SOM loss $\mathrm{N}^{\mathrm{som}}_{t,i}$ is estimated by multiplying the land conversion $\mathrm{P}(x_t)^{\mathrm{landconv}}_{t,j}$ in each grid cell with the yearly N_r losses per ha $r^{\mathrm{som}}_{t,j}$.

$$\mathrm{N}^{\mathrm{som}}_{t,i} = \sum_{j\in I_i} \left(\mathrm{P}(x_t)^{\mathrm{landconv}}_{t,j} \cdot r^{\mathrm{som}}_{t,j} \right) \tag{A26}$$

Land conversion $\mathrm{P}(x_t)^{\mathrm{landconv}}_{t,j}$ is calculated as the increase of $X^{\mathrm{area}}_{t,j,v,w}$ into area that has previously not been used as cropland. As pastureland and natural vegetation have a similar level of SOM (Eggleston et al., 2006), we can calculate the N_r inputs from SOM loss $\mathrm{N}^{\mathrm{som}}_{t,i}$ on the basis of land conversion for cropland, independent of whether the expansion occurs into natural vegetation or pastureland. After the conversion of cropland, we assume that cropland management releases 20 to 52 % of the original soil carbon, depending on the climatic region (Eggleston et al., 2006), plus the full litter carbon stock of the cell. Soil and litter carbon were estimated using the natural vegetation carbon pools of LPJmL. N_r losses per hectare converted cropland $r^{\mathrm{som}}_{t,j}$ are then estimated on a cellular basis from the carbon losses, using a fixed C : N ratio of 15 for the conversion of forest or grassland to cropland. In reality, the soil carbon is released over a period of 20 yr until the carbon stock arrives in the new equilibrium (Eggleston et al., 2006). For simplification, we assume that all N_r

is released in the timestep of conversion (10 yr). To derive the yearly N_r release per ha $r^{som}_{t,j}$, we divide N_r losses per hectare by 10 and assume no delayed release in the subsequent decade.

As MAgPIE is calibrated to the cropland area in 1995, no land conversion occurs in this timestep. To estimate $P(x_t)^{landconv}_{t=1,j}$, we use the HYDE database with a 5 arcminutes resolution (Klein Goldewijk et al., 2011a). We define land conversion as the sum of (positive) cropland expansion in each geographic grid cell into land which was not used as cropland since the year 1900. In the case that cropland area first shrinks and then increases again, it is assumed that the same cropland area is taken into management that was abandoned before, so that no new SOM loss takes place. The high spatial resolution of Klein Goldewijk et al. (2011a) is of importance, because with higher aggregation (e.g. country-level estimates by FAOSTAT, 2011) expansion and contraction of cropland area within the same aggregation unit cancel out and land conversion is underestimated. The results for the historical estimates can be found in Table A7. The estimates for 1990–2000 are too high. The HYDE estimates are based on an older release of FAOSTAT data, while more recent FAOSTAT data corrected cropland expansion significantly downwards, reaching even a negative net expansion for the period 1990–2000 (Klein Goldewijk , 2011b). To estimate the contribution of N_r released by SOM loss to the N_r budget in 1995, we therefore only used the period 1980–1990.

A3.4 Losses and inorganic fertilizer

We calculate regional soil nitrogen uptake efficiency (SNUpE) $r^{SNUpE}_{t=1,i}$ in 1995 by dividing total soil withdrawals $N(x_t)^{withd}_{t=1,i}$ by total soil inputs $N(x_t)^{inp}_{t=1,i}$.

$$r^{SNUpE}_{t=1,i} = \frac{N(x_t)^{withd}_{t=1,i}}{N(x_t)^{inp}_{t=1,i}} \tag{A27}$$

The soil inputs include inorganic fertilizer, manure, N_r released from soil organic matter loss, recycled crop residues, atmospheric deposition and N_r fixation by free-living bacteria and algae. N_r in seed as well as N_r fixation by legumes and sugarcane are not counted as soil inputs, as they reach the plant not via the soil. Soil withdrawals are calculated by subtracting from the N_r in plant biomass (harvested organ, above- and belowground biomass) the amount of N_r that is not taken up from the soil and therefore not subject to losses prior to uptake. The latter includes again seed N_r as well as the N_r fixed from the atmosphere by legumes and sugarcane.

$$N(x_t)^{withd}_{t,i} := \sum_v \Big((1 - r^{ndfa}_v) \cdot (N(x_t)^{prod}_{t,i,v} + N(x_t)^{prod\_ag}_{t,i,v} + N(x_t)^{prod\_bg}_{t,i,v}) - N(x_t)^{ds}_{t,i,v,seed} \Big) \tag{A28}$$

$$N(x_t)^{inp}_{t,i} := N(x_t)^{fert}_{t,i} + N(x_t)^{res}_{t,i} + N(x_t)^{m\_cs}_{t,i} + N^{som}_{t,i} + N(x_t)^{dep}_{t,i} + N(x_t)^{FixFree}_{t,i} \tag{A29}$$

The loss of N_r from cropland soils $N(x_t)^{loss}_{t,i}$ is defined as the surplus of soil inputs over soil withdrawals.

$$N(x_t)^{loss}_{t,i} := N(x_t)^{inp}_{t,i} - \sum_v N(x_t)^{withd}_{t,i} \tag{A30}$$

For the year 1995, we use historical data on regional fertilizer consumption based on (IFADATA, 2011) to estimate $r^{SNUpE}_{t=1,i}$. In the following timesteps, $r^{SNUpE}_{t,i}$ is fixed on an exogenous level (see Sect. A4), while the model balances out the regional budget by endogenously determining the amount of required inorganic fertilizer $N(x_t)^{fert}_{t,i}$.

$$N(x_t)^{inp}_{t,i} \geq \frac{N(x_t)^{withd}_{t,i}}{r^{SNUpE}_{t,i}} \tag{A31}$$

A3.5 Emissions

We distinguish into emissions from inorganic fertilizer ($N_2O(x_t)^{fert}_{t,i}$), crop residues ($N_2O(x_t)^{res}_{t,i}$), animal manure excreted or applied on cropland ($N_2O(x_t)^{m}_{t,i}$), manure excreted on pasture range and paddock ($N_2O(x_t)^{past}_{t,i}$), animal waste management ($N_2O(x_t)^{house}_{t,i}$) and soil organic matter loss ($N_2O(x_t)^{som}_{t,i}$). Each emission category has direct N_2O emissions plus eventually indirect emissions from volatilisation and leaching.

Direct N_2O emissions from soils are calculated as a fraction r^{dir} of the inputs from manure, fertilizer, crop residues and soil organic matter loss. According to Eggleston et al. (2006), paddy rice has lower direct emissions (r^{dir_rice} instead of r^{dir}) from fertilization with inorganic fertilizers. As our methodology is unable to estimate the amount of inorganic fertilizer which is used specifically for rice production, we use EF_{1FR} for all N_r inputs of rice. The direct emission factor for emissions from N_r excreted during pasture range and paddock $r^{dir\_graz}_l$ diverges between different animal types. For our livestock categories "ruminant meat" and "ruminant milk", containing animals of different types, we used weighted averages according to net excretion rates in 1995.

N_2O emissions from volatilisation occur when inorganic fertilizer or manure is applied to fields. The fraction volatilising in the form of NO_x or NH_y is different between the excretion or application of manure (r^{gas_m}), the application of inorganic fertilizer (r^{gas_fert}) and the management of animal

Table A7. Land conversion due to cropland expansion and release of N_r from subsequent soil organic matter (SOM) loss. For sources see text.

		Net expansion[a]	Land conversion[b]	SOM loss from land conversion			
		10^6 ha	10^6 ha	Tg C	Tg N_r	$\frac{\text{kgN}_r}{\text{ha}}$	$\frac{\text{kgN}_r}{\text{ha}\cdot\text{yr}}$ [c]
World	1960–1970	53	77	2574	172	2226	111
World	1970–1980	30	66	2464	164	2486	124
World	1980–1990	69	103	3754	250	2432	122
– AFR	1980–1990	13	17	529	35	2137	107
– CPA	1980–1990	33	25	848	57	2237	112
– EUR	1980–1990	−3	3	115	8	2885	144
– FSU	1980–1990	−2	9	542	36	4019	201
– LAM	1980–1990	8	12	489	33	2708	135
– MEA	1980–1990	5	4	48	3	738	37
– NAM	1980–1990	−1	13	614	41	3045	152
– PAO	1980–1990	4	5	108	7	1342	67
– PAS	1980–1990	10	10	359	24	2441	122
– SAS	1980–1990	2	5	103	7	1505	75
World	1990–2000[d]	22	325	12 370	825	2535	127

[a] Net expansion counts the aggregated change in regional or global cropland, and thus the difference of expansion and contraction.
[b] Land conversion sums up the expansion of each geographic grid cell into land which was not used as cropland since the year 1900. Contracting cropland is not substracted.
[c] Assuming that the soil organic matter is lost over 20 yr.
[d] Estimates for 1990–2000 are too high and should not be used (see text).

waste($r^{\text{gas\_awms}}_{l,c}$). A fraction $r^{\text{indir\_gas}}$ of these NO_x and NH_y gases transforms later on into N_2O.

Leaching is relevant for inorganic fertilizer application, residue management as well as the excretion or application of animal manure to agricultural soils. We assume, that a fraction r^{leach} of the applied N_r leaches into water bodies. According to Eggleston et al. (2006), r^{leach} is only relevant on croplands where runoff exceeds water holding capacity or where irrigation is employed, while for this model we made the simplification that leaching occurs everywhere. This assumption is also used in IPCC (1996). Of all N_r leaching into water bodies, a fraction $r^{\text{indir\_leach}}$ is assumed to transform later on into N_2O.

The following equations sum up the calculations according to the emission sources:

$$\mathrm{N_2O}(x_t)^{\text{fert}}_{t,i} := \mathrm{N}(x_t)^{\text{fert}}_{t,i} \cdot (r^{\text{dir}} + r^{\text{gas\_fert}} \cdot r^{\text{indir\_gas}} + r^{\text{leach}} \cdot r^{\text{indir\_leach}}) \tag{A32}$$

$$\mathrm{N_2O}(x_t)^{\text{res}}_{t,i} := \mathrm{N}(x_t)^{\text{res}}_{t,i} \cdot (r^{\text{dir}} + r^{\text{leach}} \cdot r^{\text{indir\_leach}}) \tag{A33}$$

$$\mathrm{N_2O}(x_t)^{\text{m}}_{t,i} := \mathrm{N}(x_t)^{\text{m}}_{t,i} \cdot (r^{\text{dir}} + r^{\text{gas\_m}} \cdot r^{\text{indir\_gas}} + r^{\text{leach}} \cdot r^{\text{indir\_leach}}) \tag{A34}$$

$$\mathrm{N_2O}(x_t)^{\text{past}}_{t,i} := \sum_{l} \Big(\mathrm{N}(x_t)^{\text{ex}}_{t,i,l,\text{grazp}} + \mathrm{N}(x_t)^{\text{ex}}_{t,i,l,\text{grazc}} \Big) \cdot \Big(r^{\text{dir\_graz}}_{l} + r^{\text{gas\_m}} \cdot r^{\text{indir\_gas}} + r^{\text{leach}} \cdot r^{\text{indir\_leach}} \Big) \tag{A35}$$

$$\mathrm{N_2O}(x_t)^{\text{house}}_{t,i} := \sum_{l,c} \left(\mathrm{N}(x_t)^{\text{ex}}_{t,i,l,\text{house}} \cdot r^{\text{cs}}_{t,i,l,c} \cdot (r^{\text{gas\_awms}}_{l,c} \cdot r^{\text{indir\_gas}} + r^{\text{dir\_house}}_{c}) \right) \tag{A36}$$

$$\mathrm{N_2O}(x_t)^{\text{som}}_{t,i} := \mathrm{N}^{\text{som}}_{t,i} \cdot (r^{\text{dir}} + r^{\text{leach}} \cdot r^{\text{indir\_leach}}) \,. \tag{A37}$$

The NO_x and NH_y volatilisation on cropland area $\mathrm{N}(x_t)^{\text{volat}}_{t,i}$, which is required for the calculation of atmospheric deposition in Eq. A23, is calculated as follows:

$$\mathrm{N}(x_t)^{\text{volat}}_{t,i} := \mathrm{N}(x_t)^{\text{fert}}_{t,i} \cdot r^{\text{gas\_fert}} + (\mathrm{N}(x_t)^{\text{m}}_{t,i} + \mathrm{N}(x_t)^{\text{ex}}_{t,i,l,\text{grazp}} + \mathrm{N}(x_t)^{\text{ex}}_{t,i,l,\text{grazc}}) \cdot r^{\text{gas\_m}} + \sum_{l,c} (\mathrm{N}(x_t)^{\text{ex}}_{t,i,l,\text{house}} \cdot r^{\text{cs}}_{t,i,l,c} \cdot r^{\text{gas\_awms}}_{l,c}) \,. \tag{A38}$$

The 2006 guidelines differ from the widely used 1996 guidelines (IPCC, 1996) most importantly in two aspects. Firstly, the N_r fixed by legumes and other N_r-fixing plants is not considered to have significant N_2O emissions. Only their comparably N_r-rich crop residues contribute to the N_2O emissions if they are left on the field. Secondly, the emission factor from leached N_r (EF_5, in our case $r^{\text{indir\_leach}}$) was lowered considerably from 2.5 % to 0.75 %.

To estimate the sensitivity of our results in regard to the uncertainty of the emission parameters, we carried out a Monte Carlo analysis with the software @Risk. We used a log-logistic probability density function (PDF) for the emission parameters r^{dir}, $r^{\text{dir\_house}}_{c}$, $r^{\text{dir\_graz}}_{l}$, $r^{\text{indir\_gas}}$, $r^{\text{indir\_leach}}$, r^{leach}, $r^{\text{gas\_fert}}$, $r^{\text{gas\_m}}$, and $r^{\text{gas\_awms}}_{l,c}$. We chose this PDF, because it is non-negative, and because the median and the quantiles can be defined freely. We used the default value as mean and the uncertainty range from Eggleston et al. (2006) as 2.5 % and 97.5 % confidence intervals. We assumed that emission factors are non-correlated between each other. As the uncertainty range of the emission parameters in Eggleston et al. (2006) were estimated for country inventories, it is questionable whether they should be regarded as correlated between countries or not. We decided to regard the parameters as not correlated between regions, but as fully correlated for all countries within a region. As a consequence, regional uncertainties partly cancel out, and our global emission estimates have a lower relative uncertainty range. To simplify our calculation, we did not differentiate between waste management systems for animals kept in confinement, and simply assumed an error range of −50 % to +100 % for the aggregated mean of $r_c^{\text{dir\_house}}$ and $r_{l,c}^{\text{gas\_awms}}$.

We express the resulting uncertainty range for the emissions as a 90 % confidence interval, as the uncertainty distribution becomes very flat for higher significance levels.

A3.6 Food supply and intake

N_r in food supply is not equal to the N_r in harvested crops and slaughtered animals assigned for food, because the food products are processed. For food supply of crop products $N(x_t)_{t,i,v}^{\text{fs}}$, we therefore subtracted the N_r in conversion byproducts from the N_r in harvest assigned for food. Also, in the case of livestock products, the amount of N_r in the final products is not equal to the amount of N_r in the slaughtered animals, as only certain parts of the slaughtered animal are marketed, while the fifth quarter (often including head, feet, intestines and blood) is not used for food. Therefore, we calculated protein content per food product r_l^{PR} based on FAOSTAT (2011) and multiplied them with product specific protein–N_r ratios r_l^{NtoPR} from Sosulski and Imafidon (1990) and Heidelbaugh et al. (1975) to estimate the amount of N_r in livestock food supply ($N(x_t)_{t,i,l}^{\text{fs}}$).

Finally, the food supply is significantly higher than actual intake $N(x_t)_{t,i,k}^{\text{int}}$ because of significant waste rates on household level or in catering. We used regional intake to supply shares $r_{t,i,k}^{\text{int}}$ from Wirsenius (2000). As these shares will change with rising income, we estimated actual intake only for the year 1995.

$$N(x_t)_{t,i,v}^{\text{fs}} := N(x_t)_{t,i,v,\text{food}}^{\text{ds}} - N(x_t)_{t,i,v}^{\text{prod\_by}} \tag{A39}$$

$$N(x_t)_{t,i,l}^{\text{fs}} := N(x_t)_{t,i,l}^{\text{prod}} \cdot r_l^{\text{PR}} \cdot r_l^{\text{NtoPR}} \tag{A40}$$

$$N(x_t)_{t,i,k}^{\text{int}} := N(x_t)_{t,i,k}^{\text{fs}} \cdot r_{t,i,k}^{\text{int}} \tag{A41}$$

A4 Scenarios

For future projections, we created scenarios based on the SRES storylines (Nakicenovic et al., 2000). Quantitative interpretations of these storylines have been done by various integrated assessment models, whereof marker scenarios were selected. We use downscaled projections of population and per capita income of these marker scenarios as main drivers of the MAgPIE model (CIESIN, 2002a,b).

Bodirsky et al. (2012) create food demand scenarios for plant and livestock products based on the SRES population and GDP marker scenarios. To account for materialistic and non-materialistic lifestyles, they use different regressional forms for the A and B scenarios. In the A scenarios, they apply a log–log regression with a positive continuous time-trend for total caloric intake, and a multiple linear regression model for the livestock demand share. For the sustainable B scenarios, they use a log–log regression with positive declining time trend for total caloric intake, and an inverted u-shape regression model for livestock demand. In the latter, the share of animal products is increasing for low and medium incomes, but decreases for high incomes. The functional forms of the B scenarios tend to result in lower demand than the regression in the A scenarios. Yet, all four regressions are consistent with past observations (Table A8). The calculations are carried out on country level and are subsequently aggregated to the 10 MAgPIE regions. The scenarios are calibrated to meet the food demand in 1995 (FAOSTAT, 2011), the initial year of the MAgPIE model. Afterwards, they converge linearly towards the regression values throughout the 21st century to account for a globalisation of diets.

In all scenarios, the global food demand more than doubles from 1990 to 2070 (Fig. A2), while towards the end of the 21st century, the globalised scenarios A1 and B1 have a slightly declining food demand. Demand for livestock products (Fig. A3) is rising disproportionally strong, yet declines in all but the A2 scenario towards the end of the century.

The food demand projections are based on population and income growth of the SRES scenarios, starting in 1990. As can be seen in figure A2 and A3, the historical data of food demand is met more or less precisely depending on the scenario. Global food calorie demand diverges in 2005 by 98 PJ (+0.4 %) (B1) to 452 PJ (1.7 %) (B1), while meat demand diverges by −244 PJ (−5.2 %) (A2) to +60 PJ (1.2 %) (B2). The largest differences can be observed in the estimates for meat demand in CPA, where the A2 scenario diverges by −422 PJ (−31.5 %) while the B2 scenario almost matches the observed data with 15 PJ (+1.1 %). Large parts of these variations in estimates are determined by the uncertainty of the original SRES projections for population and GDP.

A parameter which is subject to large uncertainty is the development of future trade liberalisation policies. For 1995, we fix the share of domestic demand settled by imported products at their actual level in 1995. For the subsequent timesteps, we assume that an increasing share can be traded according to comparative advantages in production costs. The share of products traded according to historical trade patterns decreases in turn by 10 % per decade in the two globalised scenarios A1 and B1. These scenarios are equivalent to the policy scenario of Schmitz et al. (2012), extended

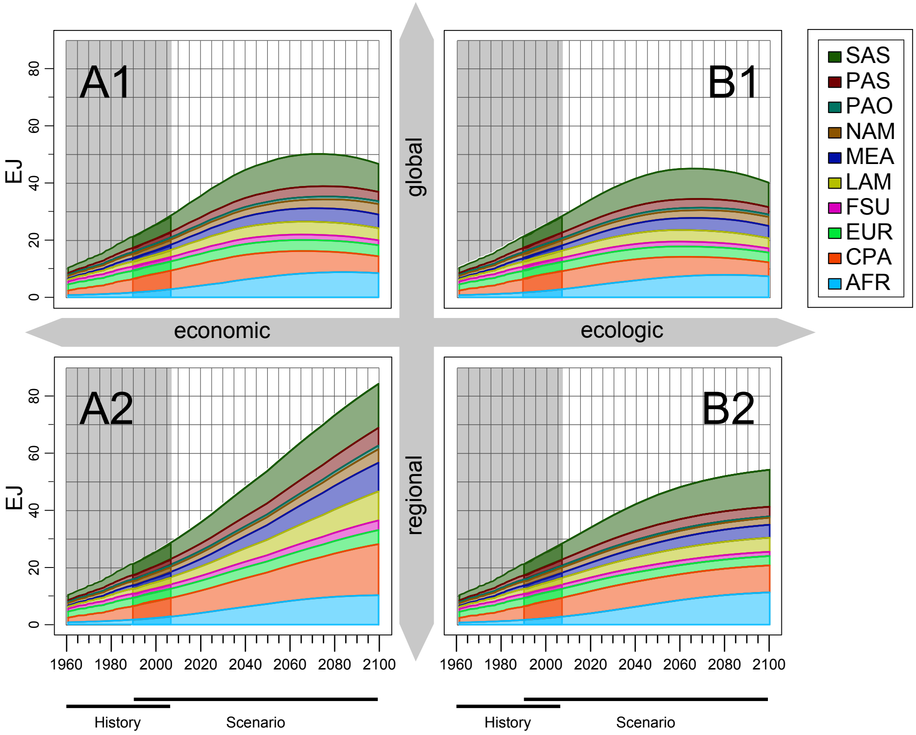

Fig. A2. Total food energy demand in the 10 MAgPIE world regions. History and future developments for the four SRES scenarios (Bodirsky et al., 2012).

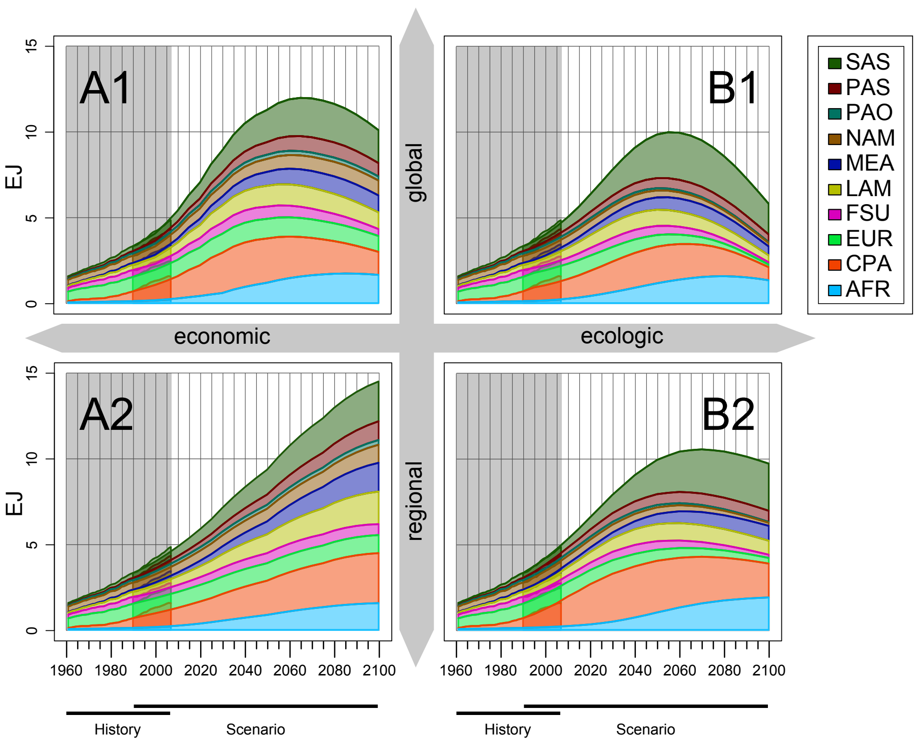

Fig. A3. Demand for energy from livestock products in the 10 MAgPIE world regions. History and future developments for the four SRES scenarios (Bodirsky et al., 2012).

Table A8. Regression models for total calories C_T in kcal and the share of livestock calories in total demand C_S, depending on income I in 2005 US Dollar in market exchange rate.

SRES	Model	Formulae	Parameter	Slope	r^2	p-value	F-statistics
A	Calories	$C_T = a \cdot (I)^b$	$a = \exp(2.825 + 2.131 \times 10^{-3} \cdot \text{year})$, $b = 0.162 - 3.124 \times 10^{-5} \cdot \text{year}$	0.658	0.65	<0.001 (***)	11060
	Livestock share	$C_S = \exp(k + l \cdot \ln(I) + m \cdot \text{year} + n \cdot \ln(I) \cdot \text{year})$	$k = -36.733, l = 4.497$, $m = 0.016, n = -0.002$	0.705	0.63	<0.001 (***)	9913
B	Calories	$C_T = a \cdot (I)^b$	$a = 933.89 + \frac{387.47 \cdot (\text{year}-1960)}{\text{year}-1960+9.77}$, $b = 0.0894 + \frac{0.008445 \cdot (\text{year}-1960)}{\text{year}-1960-0.75569}$	0.678	0.64	<0.001 (***)	10551
	Livestock share	$C_S = p \cdot \sqrt{I} \cdot \exp(-q \cdot I)$	$p = 0.00932 - 3.087 \times 10^{-6} \cdot \text{year}$, $q = -2.654 \times 10^{-4} + 1.420 \times 10^{-7}$	0.706	0.62	<0.001 (***)	9685

to 2095. For the regionalised scenarios, we assume a slower rate of market integration with a reduction of only 2.5 % per decade.

The efficiency of nutrient uptake on croplands is a parameter which has strong impact on the results of the model. While we estimate this parameter for the base year 1995, its development into the future is rather uncertain. Policies like the nitrate directive in Europe seemed to have a large impact in the past (Oenema et al., 2011), so the environmental awareness seems to be a key driver of N_r efficiency. To differentiate the economically orientated from the environmentally orientated scenarios, we adjust the cropland nutrient uptake efficiency $r_{t,i}^{\text{SNUpE}}$ for future scenarios. The starting points for $r_{t=1,i}^{\text{SNUpE}}$ are calculated endogenously in the model, and converge linearly over n timesteps to their scenario values $r_{n,i}^{\text{SNUpE}}$ (Table 1).

$$r_{t,i}^{\text{SNUpE}} := (1 - \frac{t}{n}) \cdot r_{t=1,i}^{\text{SNUpE}} + \frac{t}{n} \cdot r_{n,i}^{\text{SNUpE}} \quad \text{(A42)}$$

We chose to have high efficiency values in the B scenario due to high awareness for local environmental damages. The most efficient agricultural systems currently absorb around 70 % of applied N (Smil, 1999), and Vuuren et al. (2011) estimate that "in practice, recovery rates of 60–70 % seem to be the maximum achievable". So we adopted this value for the environmentally oriented B scenarios. In the A1 scenario, we assumed that $r_{t,i}^{\text{SNUpE}}$ increases due to widespread use of efficient technologies (e.g. precision farming), which saves costs but also resources. Yet, no improvements beyond cost efficiency are made, thus $r_{t,i}^{\text{SNUpE}}$ stays behind the B scenarios towards the end of the century. Finally, the A2 scenario stagnates slightly above the current mean, and only improves towards the end of the century.

A further scenario parameter is the development of livestock production systems. Feed baskets and livestock productivity diverge significantly in different world regions, with some systems being more industrialised and consuming mainly feedstock crops, others being pastoral or mixed systems. While the development of the livestock system is highly uncertain, a trend towards industrialised systems can be observed (Delgado, 1999). For future scenarios, we converge the feed baskets and livestock productivity linearly towards the European livestock system, a system with rather low share of pastoral and traditional systems and a high share of industrialised livestock production. We assume a fast convergence in the globalised systems A1 and B1, while the regional scenarios keep more of their current regional feed mixes (Table 1). To implement this into the model, we converged the parameters $r_{t,i,l,v}^{\text{fb\_conc}}$, $r_{t,i,l}^{\text{fb\_past}}$, $r_{t,i,l,v}^{\text{fb\_ag}}$, $r_{t,i,l,v}^{\text{fb\_by}}$ and $r_{t,i,l,f}^{\text{fs}}$ similar to Eq. (A42) to the European values in 1995. To account for an increasing modernization of the agricultural sector, the same type of convergence is applied to $r_{t,i}^{\text{msplit}}$ and $r_{t,i,l}^{\text{fuel}}$ and the fractions of byproducts and crop residues burned or used for other purposes.

Even more uncertain is the development of the animal waste management. Even for the present, little information exists on the differences of animal waste management around the world, and there is no clear pattern as to which of the systems is dominating with increasing modernization. Similarly, we assumed that manure management for housed animals is changing over time. For the economically orientated scenarios and the B1 scenario, we assumed that bioenergy plants using anaerobic digesters increase in importance, while the B scenarios also have an increasing share of manure being directly brought back on fields as daily spread. The convergence towards these systems is higher in globalised scenarios, while the current regional animal waste management mix partly prevails in the A2 and B2 scenarios. In the model, we implemented the convergence for the parameter $r_{t,i,l,c}^{\text{cs}}$ similar to Eq. (A42).

Supplementary material related to this article is available online at: http://www.biogeosciences.net/9/4169/2012/bg-9-4169-2012-supplement.zip.

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