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Current state and future scenarios of the global agricultural nitrogen cycle

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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 cropland biomass. Moreover, less than 10 per cent of all N_r in cropland 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 5–15 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 allowed for 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 threatens 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

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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 this to phosphorus and potash, Galloway et al. (2004) included natural terrestrial and aquatic systems into 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, who 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. Above all, most studies do not consider fodder crops and belowground residues as major N_r withdrawals from cropland soils. 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

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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 N_r 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 pioneers integrating the emission parameters of the recent 2006 IPCC Guidelines for National Greenhouse Gas Inventories (Eggleston et al., 2006) into the model.

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 into 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.

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 is 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 technological change are passed on from one timestep as input data to the consecutive timestep.

The existing model (as described in the Supplement) must be 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 have so far not been covered by the model, yet they make up a major share of total biomass and should therefore be considered by a

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material-flow model (Sect. 2.2). Moreover, all dry matter flows have to be transformed into N_r flows. N_r flows in manure management, cropland fertilization and the transformation of N_r losses into emissions need to be included (Sect. 2.3). Finally, the scenario setup is described in Sect. 2.4. A 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. Crop 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 countries are burned in the field. Furthermore, developing countries 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)

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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).

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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 countries (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 countries stems from stubble grazing on croplands, while the rest is also 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 countries is assigned fully to cropland soils, while it is split between cropland and pasture soils in developed countries. 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 total plant biomass (harvested organ, AG and BG residue) with 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

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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) and historical land-expansion from the HYDE-database (Klein Goldewijk et al., 2011).

The amount of atmospheric deposition is taken from Dentener (2006) and depends on the physical cropland area.

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.

Inorganic fertilizer consumption in 1995 is obtained from IFADATA (2011). For the projections, we use a closed budget approach. The cropland soil nitrogen use efficiency, defined as the ratio between N_r soil inputs (fertilizer, manure, residues, atmospheric deposition, soil organic matter loss and free-living N_r fixers) and soil withdrawals (harvest and crop residues minus seed and biological fixation by legumes and sugarcane), has been calculated for 1995 and becomes an exogenous scenario parameter for future projections. To balance out the budget at fixed N_r use efficiency, the model can purchase as much nitrogen fertilizer as it requires.

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 histosoils, 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.

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, 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); 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 industrialization of livestock production, we assume an increasing convergence of the livestock systems from the current mix towards the industrialised European system. This high productive system has a large proportion of feedstock crops and conversion

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byproducts in the feed baskets. In the globalised scenarios, convergence is assumed to be faster than in the regionalised scenarios.

Currently, animal waste management systems are highly diverse between regions and their future development is highly uncertain. We assume two major future trends. Firstly, that 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 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, we do not allow the model to expand agricultural area into intact and frontier forest in the environmental oriented scenarios, as described in Popp et al. (2012). Similarly, we assume that conversion of natural vegetation and pasture into cropland, leading to soil organic matter loss, will come to rest for the environmentally oriented scenarios, whilst remaining constant in the economic oriented scenarios.

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.

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3 Results

3.1 Global nitrogen cycle

3.1.1 State in 1995

According to our calculations for the year 1995, 183 Tg N_r are applied to or fixed on global cropland, of which 113 is taken up by total plant biomass. Thereof, 46 Tg are fed to animals in the form of feedstock crops, crop residues, or conversion byproducts, plus additional 70 Tg from grazed pasture, to produce animal products which contain 7 Tg N_r. In total, plant and animal food at whole market level contains 23 Tg N_r, of which finally only 16 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 biomass reaches 271 (B2)–365 (A1) Tg N_r in 2045 and 243 (B1)–562 (A2) Tg N_r in 2095. Also the range of soil inputs increases throughout the century, starting with 184 Tg in 1995 to 330 (B2)–461 (A1) Tg N_r in 2045 and 264 (B1)–724 (A2) Tg N_r in 2095. In the case of inorganic fertilizer consumption, the trends between scenarios are contradictory (Fig. 3). The A1, B1 and B2 scenarios show a modest increase to 118 (B1)–133 (A1) Tg N_r until 2045 and a stagnating or even declining consumption thereafter, while the A2 scenario exhibits a much stronger and continuous increase to 167 Tg N_r in 2045 and 288 Tg N_r in 2095. Despite these wide ranges, the differences of N_2O emissions between the scenarios is in the first half of the century rather narrow, rising from 3.2 Tg N_2O-N in 1995 to 7.0 (B1)–9.2 (A2) in 2045 and widening towards the end of the century to 4.6 (B1)–14.7 (A2) Tg N_2O-N (Fig. 2).

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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) and South Asia (SAS) show the strongest relative increases in harvested N_r, while in developed regions like Europe (EUR) or North America (NAM) the increase is more modest. The 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. At the same time, these regions require only low amounts of inorganic fertilizer, as the domestic livestock production fed with imported N_r provides sufficient nutrients for production. Latin America (LAM) is the largest exporter in all scenarios, and is able to settle a large fraction of its fertilization requirements with biological fixation. 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. In comparison with this, China (CPA) has 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 countries 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 state and the future development of the agricultural N_r cycle. For this purpose, we adapted the landuse model MAgPIE to calculate major agricultural N_r flows. The simulation of the widely used SRES scenarios

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facilitates the comparison with other studies like Bouwman et al. (2009) and allows for the integration of our results into other assessments.

As will be discussed in the following, the current size of the N_r cycle is much higher than previously estimated. Moreover, we expect the future rise of the N_r cycle to be higher than suggested by 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 parametrisation to identify major uncertainties. In the following we compare our results 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 parametrisation. The scope between the studies is still large with 49–63 Tg N_r and 25–38, 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, 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.

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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 has the advantages that it can build on comparably reliable feed data of the FAOstat database, and that changing feed baskets in future scenarios also lead to altered excretion rates. Our results for 1995 can support the higher estimates of Mosier et al. (1998) and Bouwman et al. (2011), with an estimate of 109 Tg N_r. A similar 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 considerable 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). While we also use these expert-guesses on N_r fixation by free-living bacteria, we are able to use a diverging methodology for estimating legume and sugarcane fixation. Our methodology uses the percentage of plant N_r derived from fixation. This, in combination with total above-and belowground N_r content of a plant, can predict N_r fixation more accurately. Despite the same fixation rates, we come to substantially lower estimates of N_r fixation than Herridge et al. (2008). This is caused by a different base year along with different estimates for the underlying plant growth functions and N_r contents.

N_r accumulation in soils has so far been neglected for future projections, assuming that soil organic matter is stable and all excessive N_r will volatilize or leach (Bouwman et al., 2009, 2011). However, the assumption of a steady state for soil organic matter should not be valid for land conversion and cultivation of histosoils. Our rough bottom-up calculations estimate that the transformation of natural vegetation or pasture to cropland has released 28 Tg N_r in 1995. The cultivation of histosoils and the drainage

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of wetlands may release another 10 Tg N_r per year (Vitousek et al., 1997), 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 113 Tg N_r. However, if the unconsidered flows are filled with estimates from other studies, the corrected withdrawals (Total OUT*) shifts to 106–135 Tg N_r. The same applies to inputs, where the range shifts and narrows down from 137–204 Tg N_r total inputs (Total IN) to 211–231 Tg N_r total inputs when all data gaps are filled (Total IN*). 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. At the same time, the corrected estimates for total losses is with 83–115 Tg N_r significantly higher than previously estimated.

4.2 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 factor 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 109 Tg N_r in 1995 to 243 Tg N_r (B1)–291 Tg N_r (A1) in 2045. Bouwman et al. (2011) estimate that

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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. Ensuring the consistency between feed mix, livestock productivity and excretion rates, our top-down approach results in increasing excretion rates per animal in developing countries.

Our inorganic fertilizer projections are also higher than previous estimates, with annual growth rates of 0.9 % (B1) to 1.8 % (A2) until 2045. Estimates from Daberkow et al. (2000) have growth rates of only 0.6 to 1.4 % for the next decades. According to Bouwman et al. (2009, 2011), N_r fertilizer consumption might even shrink with −0.4 (B2) to 0.8 % (A1) annual change until 2050. The differences can be partly attributed to our higher livestock and thus feed demand, and partly to the different methodology. Our results are based on a top-down approach, compared to the bottom-up approach of Bouwman et al. (2009, 2011) and Daberkow et al. (2000). Data availability for bottom-up estimates of fertilizer application is currently poor, and may be biased by crop-rotations and different manure application rates. While our top-down approach has to rely on an exogenous path for the development of N_r uptake efficiency, 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.

Observed fertilizer consumption between 1995 and 2005 (IFADATA, 2011) is significantly higher than model projections by Bouwman et al. (2009, 2011) and Daberkow et al. (2000), and exceeds with a growth rate of 2.1 % even our estimates. Our results meet the trend of actual consumption on a regional level. Only in South and East Asia, we tend to underestimate the real developments, while we overestimate inorganic fertilizer consumption in Europe. The latter may be attributed to the ambitious environmental regulation introduced in the recent past (Jensen et al., 2011).

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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.

4.3 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 almost 25 % (8 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 116 Tg results in solely 7 Tg N_r in livestock products.

In developed countries, the relative share of animal calories in total consumption already has 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 and 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 countries. 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 industrialized feeding practices are adopted

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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.

4.4 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.

Air pollution is caused directly by N_2O and indirectly by the formation of ground-level ozone and secondary particulate matter. The impacts include respiratory diseases, damages to vegetation and odeur (Moldanova et al., 2011). Our results show that pollution will increase particularly in densely populated and intensively managed regions like China and India, which are today already heavily exposed. Air pollution by NO_x and NH_y may become a new problem in the intensively managed parts of Africa, Pacific Asia or the Middle East. Emissions rise only modestly in developed regions like Europe and North America, where current pollution is already high.

Leaching of N_r into water bodies may pollute drinking water which increases the risk of colon cancer. N_r leaching may also lead to abrupt and non-linear changes in lakes, estuaries, and marine ecosystems with sufficient phosphorus. This causes a restraint of their ecosystem services and a loss of biodiversity (Vitousek et al., 1997; Grizzetti et al., 2011). Again, our results indicate that emerging economies are subject to the highest increase in N_r pollution. Leaching in developed regions with a high level of current contamination also continues to rise.

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., 2009b; **?**). 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 has an extraordinarily long atmospheric lifetime and absorbs infrared radiation in spectral windows not covered by other greenhouse gases (Vitousek et al., 1997). In addition, N_2O, is currently the major ozone depleting substance, as it catalyses the destruction of stratospheric ozone (Ravishankara et al., 2009). In 1995, N_2O emissions from managed soils and manure contributed 3.3 Tg N_2O-N, or approximately half of total anthropogenic N_2O emissions. As a result of the corrected emission factors of Eggleston et al. (2006) compared to IPCC (1996) (see Appendix A3.5), our estimates are approximately one-third lower than estimtated by the SRES marker scenarios. Our results also indicate that emissions will increase with substantially higher growth rates in the first half of the century, offsetting the lower starting level. Especially in the case of the A1 and B2 scenarios, we come to 70 % (A1) and 40 % (B2) higher cumulative emissions over the century. In scenarios A2 and B1, our estimates are 10 % lower (A2) or equal (B1) to the cumulative emissions in the marker scenarios, despite occuring later in the century (Fig. 4). Fortunately, the greenhouse effect of N_2O might be offset by NO_x and NH_y emissions. By reducing the atmospheric lifetime of CH4, scattering light and increasing biospheric carbon sinks, these emissions have a cooling effect (Butterbach-Bahl et al., 2011).

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 produced cropland biomass and grazed pasture is actually consumed by humans. If the N_r cycle expand as expected to double or triple its size during the 21st century, the 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

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biodiversity. N_r mitigation is therefore one of the key global environmental challenges of this century.

Current scientific examination of N_r mitigation options is concentrated mainly on the farm level. However, a comprehensive analysis of the whole agricultural system, as demonstrated in this study, suggests that mitigation could take place at several levels: (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 signal 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 agriculture 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 300 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 calory 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

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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 nutrient branch of MAgPIE, model-revision 3606. 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 ($\text{P}(x_t)^{\text{prod}}_{t,i,k}$) and its use ($\text{P}(x_t)^{\text{ds}}_{t,i,k,u}$). 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

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(CGF) instead of fixed harvest indices, it can well describe current international differences of harvest indices and also their development into 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, 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 $r_v^{\mathrm{cgf\_i}}$, $r_v^{\mathrm{cgf\_s}}$ and $r_v^{\mathrm{cgf\_r}}$ are displayed in Table A3. The AG crop residue production $\mathrm{P}(x_t)_{t,i,v}^{\mathrm{prod\_ag}}$ is calculated as a function of harvested production $\mathrm{P}(x_t)_{t,i,v}^{\mathrm{prod}}$ and the physical area $X_{t,j,v,w}^{\mathrm{area}}$, BG crop production as a function of total aboveground biomass.

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

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

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 ($\mathrm{P}(x_t)_{t,i,v,\mathrm{feed}}^{\mathrm{ds\_ag}}$) are calculated based on livestock production and livestock and regional specific residue feed baskets $r_{t,i,l,v}^{\mathrm{fb\_ag}}$ from Weindl et al. (2010). The demand rises with the increase in livestock production $\mathrm{P}(x_t)_{t,i,l}^{\mathrm{prod}}$ and can be settled either by residues $\mathrm{P}(x_t)_{t,i,v,\mathrm{feed}}^{\mathrm{ds\_ag}}$ or by additional feedstock crops $\mathrm{P}(x_t)_{t,i,l,v,\mathrm{sag}}^{\mathrm{ds}}$.

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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 countries for each crop. Other removals ($\mathrm{P}(x_t)^{\text{ds\_ag}}_{t,i,l,v,\text{other}}$) are assumed to be only in developing countries 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 ($\mathrm{P}(x_t)^{\text{ds\_ag}}_{t,i,v,\text{rec}}$). Trade of residues between regions is not considered.

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

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 fertiliser, their most important usage lies currently in livestock feeding. So far, they have not been accounted for in most global material flow analysis, an exception being Wirsenius (2000) and Weindl et al. (2010). Until recently, they were also not 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

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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 $\text{P}(x_t)^{\text{prod\_by}}_{t,i,v}$ (brans, molasses and 6 types of oilcakes) is linked to the total domestic supply $\sum_u \text{P}(x_t)^{\text{ds}}_{t,i,v,u}$ of their belonging crop groups (Table A) 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 $\text{P}(x_t)^{\text{ds}}_{t,i,l,v,\text{sby}}$.

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

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

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

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,

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2000; Roy et al., 2006) (Table A). 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 obtained as follows:

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

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

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

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

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

A3.2 Manure management

Feed N_r is assigned to three feeding systems (f): pasture grazing (grazp), cropland grazing (grazc) and animal houses (house). The N_r related to the pasture grazing system is calculated on the basis of regional livestock specific feed baskets $r^{fb\_past}_{t,i,l}$ from Weindl et al. (2010). N_r in feedstock crops and conversion byproducts is fully assigned to house. Crop residues in developed countries are fully assigned to house, while in developing countries we assume that 25 % of the N_r in residues are consumed directly

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on croplands during *stubble grazing* ($r^{\mathrm{grazC}}_{\mathrm{t,i}}$).

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

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

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

In a second step, we use a top-down approach to estimate regional livestock specific annual average 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 N_r which is integrated into animal biomass $N(x_t)^{\mathrm{sl}}_{t,i,l}$ and assume that the remaining N_r is excreted as manure. For meat products, we calculate the N_r in the whole animal body $N(x_t)^{\mathrm{sl}}_{t,i,l}$ 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 $N(x_t)^{\mathrm{sl}}_{t,i,l}$ by the N_r content in milk and eggs (Poulsen and Kristensen, 1998) (Table A5). $N(x_t)^{\mathrm{sl}}_{t,i,l}$ 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).

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

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

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In a third step, the N_r excreted in animal houses is divided between 9 animal waste management systems (c) using the parameter $r^{\text{cs}}_{t,i,l,c}$. When available, we used the regional and livestock specific shares from Eggleston et al. (2006); for 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 shares of the total amount of managed manure $r^{\text{loss\_awms}}_{l,c}$ not being recycled, including a fraction $r^{\text{gas\_awms}}_{l,c}$ that is lost in the form of volatilization in the form of NO_x and NH_y. Because default parameters for $r^{\text{gas\_awms}}_{l,c}$ and $r^{\text{loss\_awms}}_{l,c}$ 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* is neglectable. In the absence of default parameters for $r^{\text{cs}}_{t,i,l,c}$ for chicken, sheep, goats and other animals, we used the default parameters of Eggleston et al. (2006). *Others* 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 countries, we assume that in NAM and EUR only a fraction $r^{\text{msplit}}_{t,i}$ of 87 % and 66 % is returned on cropland soils (Liu et al., 2010b), while the rest is applied to pasture soils. Furthermore, in developing countries, 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.

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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:

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

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

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

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

A3.3 Cropland N_r inputs

Inorganic fertiliser is the only N_r flow appearing in international statistics. We aggregate the values of IFADATA (2011) for all N_r-fertiliser products to the 10 MAgPIE regions to determine $N(x_t)_{t,i}^{fert}$ in 1995. For the scenario analysis, inorganic fertiliser consumption is determined endogenously as described in Sect. A4.

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

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residues (Eggleston et al., 2006) remains uncombusted and returns to cropland soils.

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

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 lateron deposited from the atmosphere on cropland area. Based on spatial datasets for atmospheric deposition rates (Dentener, 2006) and cropland area (Klein Goldewijk et al., 2011), we derive average deposition rates per area for each region ($r^{\text{dep}}_{t,i}$). As the dataset of Dentener (2006) only exists for the years 2000 and 2050, we interpolated the other timesteps linearly and left the values constant at 2050 level thereafter.

$$N(x_t)^{\text{dep}}_{t,i} := \sum_{j \in I_i, v, w} X^{\text{area}}_{t,j,v,w} \cdot r^{\text{dep}}_{t,i} \tag{A23}$$

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. Management practices like inoculation of root nodules can increase the rates of N_r fixation. Also, sugar cane can fix N_r in symbiosis with endophytic bacteria, and some trees like the alder tree are also able to fix N_r. 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 be 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

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to the N_r in the plant biomass. The percentage of fixation-derived N_r is taken from Herridge et al. (2008) for legumes and sugar cane and from Galloway et al. (2004) for pasture. 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-crops 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).

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

When pastureland or natural vegetation is transformed to cropland, soil organic matter is lost, which also releases N_r for agricultural production. To calculate the N_r inputs from soil organic matter loss $\mathrm{N}_{t,i}^{\mathrm{som}}$, we first estimate the area converted from natural vegetation or pasture to cropland. For this purpose, we use the HYDE database with a 5′ resolution (Klein Goldewijk et al., 2011). The increase of cropland area in a grid-cell is considered as expansion into natural vegetation, if the cropland area exceeds the maximum historical cropland area. 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 soil organic matter loss takes place. For our estimates, the cropland expansion in the period 1980–1990 is multiplied with the soil and litter carbon in the cell. Assuming full tillage practices, cropland management releases 20–52 % of the original carbon, depending on the climatic region (Eggleston et al., 2006). N_r losses are estimated using a fixed C:N ratio of 15 for the conversion of forest or grassland to cropland. The results are ggregated to the regional level of the 10 MAgPIE regions. Its future development is fixed exogenously according to the scenario assumptions.

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

A3.4 Losses and inorganic fertiliser

In the timestep 1995, the model uses historical data on regional fertiliser consumption based on (IFADATA, 2011) to calculate regional NR efficiencies $r^{Neff}_{t,i}$. If biofixation takes place within the plant, we assume that no losses from the internally fixed N_r occurs, while the N_r fixed by free-living bacteria or in symbiosis with algae in rice paddies is assumed to underly the same proportion of losses as the other N_r inputs.

$$N(x_t)^{withd}_{t,i} = N(x_t)^{inp}_{t,i} \cdot r^{Neff}_{t,i} \tag{A25}$$

$$N(x_t)^{withd}_{t,i} := \sum_v \Big((1 - r^{ndfa}_v) \cdot (N(x_t)^{prod}_{t,i,v} + N(x_t)^{prod\_ag}_{t,i,v} + N(x_t)^{prod\_bg}_{t,i,v}) - N(x_t)^{ds}_{t,i,v,seed} \Big) \tag{A26}$$

$$N(x_t)^{inp}_{t,i} := N(x_t)^{fert}_{t,i} + N(x_t)^{res}_{t,i} + N(x_t)^{m\_cs}_{t,i} + N^{som}_{t,i} + N(x_t)^{dep}_{t,i} + N(x_t)^{FixFree}_{t,i} \tag{A27}$$

In the following timesteps, $r^{Neff}_{t,i}$ is fixed on an exogenous level (see Sect. A4), while fertiliser consumption becomes endogenous. The loss of N_r from cropland soils $N(x_t)^{loss}_{t,i}$ is defined as:

$$N(x_t)^{loss}_{t,i} := N(x_t)^{inp}_{t,i} - \sum_v N(x_t)^{withd}_{t,i} \tag{A28}$$

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A3.5 Emissions

We distinguish into emissions from inorganic fertiliser ($N_2O(x_t)_{t,i}^{\text{fert}}$), crop residues ($N_2O(x_t)_{t,i}^{\text{res}}$), animal manure excreted or applied on cropland ($N_2O(x_t)_{t,i}^{\text{m}}$), manure excreted on pasture range and paddock ($N_2O(x_t)_{t,i}^{\text{past}}$), animal waste management ($N_2O(x_t)_{t,i}^{\text{house}}$) and soil organic matter loss ($N_2O(x_t)_{t,i}^{\text{som}}$). 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, fertiliser, crop residues and soil organic matter loss. According to Eggleston et al. (2006), paddy rice has lower direct emissions ($r^{\text{dir\_rice}}$ instead of r^{dir}) from fertilization with inorganic fertilisers. As our methodology is unable to estimate the amount of inorganic fertiliser 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 $r_l^{\text{dir\_graz}}$ 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 fertiliser or manure is applied to fields. The fraction volatilizing in the form of NO_x or NH_y is different between the excretion or application of manure ($r^{\text{gas\_m}}$), the application of inorganic fertiliser ($r^{\text{gas\_fert}}$) and the management of animal waste($r_{l,c}^{\text{gas\_awms}}$). A fraction $r^{\text{indir\_gas}}$ of these NO_x and NH_y gases transforms lateron into N_2O.

Leaching is relevant for inorganic fertiliser 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

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N_r leaching into water bodies, a fraction $r^{\text{indir\_leach}}$ is assumed to transform lateron into N_2O.

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

$$N_2O(x_t)^{\text{fert}}_{t,i} := N(x_t)^{\text{fert}}_{t,i} \cdot (r^{\text{dir}} + r^{\text{gas\_fert}} \cdot r^{\text{indir\_gas}} + r^{\text{leach}} \cdot r^{\text{indir\_leach}}) \tag{A29}$$

$$N_2O(x_t)^{\text{res}}_{t,i} := N(x_t)^{\text{res}}_{t,i} \cdot (r^{\text{dir}} + r^{\text{leach}} \cdot r^{\text{indir\_leach}}) \tag{A30}$$

$$N_2O(x_t)^{\text{m}}_{t,i} := N(x_t)^{\text{m}}_{t,i} \cdot (r^{\text{dir}} + r^{\text{gas\_m}} \cdot r^{\text{indir\_gas}} + r^{\text{leach}} \cdot r^{\text{indir\_leach}}) \tag{A31}$$

$$N_2O(x_t)^{\text{past}}_{t,i} := \sum_l (N(x_t)^{\text{ex}}_{t,i,l,\text{grazp}} + N(x_t)^{\text{ex}}_{t,i,l,\text{grazc}}) \cdot (r^{\text{dir\_graz}}_l + r^{\text{gas\_m}} \cdot r^{\text{indir\_gas}} + r^{\text{leach}} \cdot r^{\text{indir\_leach}}) \Big) \tag{A32}$$

$$N_2O(x_t)^{\text{house}}_{t,i} := \sum_{l,c} \Big(N(x_t)^{\text{ex}}_{t,i,l,\text{house}} \cdot r^{\text{cs}}_{t,i,l,c} \cdot (r^{\text{gas\_awms}}_{l,c} \cdot r^{\text{indir\_gas}} + r^{\text{dir\_house}}_c) \Big) \tag{A33}$$

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

The 2006 guidelines differ from the widely used 1996 guidelines (IPCC, 1996) most importantly in three 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 for direct emissions from managed soils (EF_1, in our case r^{dir}) was

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lowered considerably from 1.25 to 1 % of N_r inputs, with indications that an even lower value of 0.9 % would be appropriate. Thirdly, the emission factor from leached N_r (EF_5, in our case $r^{\mathrm{indir\_leach}}$) was lowered considerably from 2.5 % to 0.75 %.

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 $N(x_t)^{\mathrm{fs}}_{t,i,v}$, 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 or blood) is not used for food. Therefore we calculated protein content per food product r^{PR}_l based on (FAOSTAT, 2011) and multiplied them with product specific protein-N_r ratios r^{NtoPR}_l from (Sosulski and Imafidon, 1990; Heidelbaugh et al., 1975) to estimate the amount of N_r in livestock food supply ($N(x_t)^{\mathrm{fs}}_{t,i,l}$).

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

$$N(x_t)^{\mathrm{fs}}_{t,i,v} := N(x_t)^{\mathrm{ds}}_{t,i,v,\mathrm{food}} - N(x_t)^{\mathrm{prod\_by}}_{t,i,v} \tag{A35}$$

$$N(x_t)^{\mathrm{fs}}_{t,i,l} := N(x_t)^{\mathrm{prod}}_{t,i,l} \cdot r^{\mathrm{PR}}_l \cdot r^{\mathrm{NtoPR}}_l \tag{A36}$$

$$N(x_t)^{\mathrm{int}}_{t,i,k} := N(x_t)^{\mathrm{fs}}_{t,i,k} \cdot r^{\mathrm{int}}_{t,i,k} \tag{A37}$$

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

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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).

Rolinski 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 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 time-invariant log-log regression 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 A7). 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 globalization 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.

A parameter which is subject to large uncertainty is the development of future trade liberalization 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 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 baseyear 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 the nitrogen use efficiency. To differentiate the economically orientated from the environmentally orientated scenarios, we adjust the cropland nutrient uptake efficiency $r^{\text{Neff}}_{t,i}$ for future scenarios. The starting points for $r^{\text{Neff}}_{t=1,i}$ are calculated endogenously in the model, and converge linearly over n timesteps to their scenario values $r^{\text{Neff}}_{n,i}$ (Table 1).

$$r^{\text{Neff}}_{t,i} := (1 - \frac{t}{n}) \cdot r^{\text{Neff}}_{t=1,i} + \frac{t}{n} \cdot r^{\text{Neff}}_{n,i} \tag{A38}$$

We chose to have high efficiency values in the B scenario due to high awareness for environmental damages. In the A1 scenario, $r^{\text{Neff}}_{t,i}$ also increases due to widespread use of efficient technologies (like e.g. precision farming), which saves costs but also resources. Yet, no improvements beyond cost efficiency are made, thus $r^{\text{Neff}}_{t,i}$ stays behind the B scenarios towards the end of the century. Finally, the A1 scenario stagnates around the current mean, and only improves towards the end of the century. The most efficient agricultural systems currently absorb around 70 % of applied N (Smil, 1999), so we used this value for high efficient scenarios.

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 pastural 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

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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 $r^{\mathrm{fb\_conc}}_{t,i,l,v}$, $r^{\mathrm{fb\_past}}_{t,i,l}$, $r^{\mathrm{fb\_ag}}_{t,i,l,v}$, $r^{\mathrm{fb\_by}}_{t,i,l,v}$ and $r^{\mathrm{fs}}_{t,i,l,f}$ similar to Eq. (A38) to the European values in 1995. To account for an increasing modernization of the agricultural sector, the same type of convergence is applied to $r^{\mathrm{msplit}}_{t,i}$ and $r^{\mathrm{fuel}}_{t,i,l}$ 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, few information exists on the differences of animal waste management around the world, and there is no clear pattern 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 $r^{\mathrm{cs}}_{t,i,l,c}$ similar to Eq. (A38).

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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$)	33	223	107	173	135	675	315	454	320
Population (10^9 heads)	5.6	8.6	10.8	8.6	9.1	7.4	14.8	7.4	10.3
Food demand (10^{18} J)	23	46	51	40	42	48	81	38	50
– thereof livestock products	16 %	24 %	17 %	22 %	21 %	22 %	17 %	13 %	17 %
Trade patterns									
– Historical	100 %	59 %	88 %	59 %	88 %	35 %	77 %	35 %	77 %
– Comparative advantage	0 %	41 %	12 %	41 %	12 %	65 %	23 %	65 %	23 %
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 %
N_r uptake efficiency	53 %[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.

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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	226	188	20	17	36	31	21	21	17	15	36	27	7	6	27	23	3	2	12	7	48	40
		184	164	17	17	33	30	19	18	11	10	32	28	7	5	28	21	3	2	8	7	26	27
	2095	267	153	30	22	30	18	29	21	19	8	26	13	12	6	50	14	4	1	14	6	53	44
		348	215	43	39	52	30	26	21	22	12	67	31	15	8	50	26	5	2	19	7	50	39
Residues	1995	34		2		6		5		3		3		1		6		1		2		5	
	2045	87	73	9	7	16	14	9	8	6	6	11	8	4	3	10	9	1	1	4	3	15	13
		78	69	8	8	15	14	8	8	5	4	11	9	3	2	11	8	1	1	4	3	12	12
	2095	89	59	11	9	9	11	11	9	6	3	8	4	8	3	17	5	1	0	5	2	13	11
		133	82	17	15	23	15	11	8	8	5	21	9	7	4	17	9	2	1	7	3	18	14
Fertilizer	1995	78		1		24		13		2		4		3		13		1		4		13	
	2045	138	121	0	0	40	36	29	27	9	10	15	13	0	0	24	25	0	1	0	0	21	9
		194	133	12	10	50	33	31	25	7	7	27	18	4	1	33	22	3	2	4	2	23	13
	2095	161	85	0	0	16	21	39	27	14	6	6	7	0	0	69	14	0	1	4	0	17	10
		288	131	25	11	73	33	40	26	16	9	46	17	0	0	49	23	2	2	6	0	29	10
Manure	1995	109		12		12		13		7		21		3		10		4		4		22	
	2045	291	243	53	51	38	30	19	10	16	12	39	26	27	23	17	9	9	4	24	17	49	62
		268	261	48	50	33	43	17	10	13	11	42	35	21	15	17	8	8	4	16	16	53	68
	2095	299	148	78	55	18	9	16	2	16	4	26	9	41	17	21	4	10	1	29	13	44	34
		411	261	80	89	37	24	21	5	18	5	61	20	60	28	25	4	12	1	35	18	63	68
Biol. N_r	1995	22		1		3		2		2		3		0		4		1		1		4	
fixation	2045	83	68	7	7	5	4	3	4	7	7	19	14	1	1	10	8	1	0	5	3	25	21
		59	55	6	6	5	6	3	3	4	4	16	14	1	1	10	8	1	1	3	2	10	10
	2095	89	55	5	6	12	3	6	4	7	2	14	7	2	1	8	5	0	0	4	2	30	25
		116	76	14	13	6	4	2	4	8	5	33	17	3	1	19	11	1	0	7	3	22	17
Trade	1995	0		0		-1		-2		-1		2		-2		4		-1		-1		0	
	2045	0	0	-22	-22	-5	-1	9	12	4	5	38	29	-23	-19	11	14	-5	-2	-14	-11	8	-5
		0	0	-11	-11	-1	-9	7	11	0	1	26	24	-17	-12	12	12	-3	-1	-9	-9	-4	-7
	2095	0	0	-48	-31	5	5	17	16	6	3	42	19	-41	-20	31	8	-6	-1	-18	-9	10	10
		0	0	-18	-29	-1	1	11	15	5	7	56	31	-53	-23	26	21	-5	0	-19	-12	-2	-11
Losses	1995	104		4		26		14		9		7		3		17		3		7		14	
	2045	209	162	22	20	41	31	23	18	15	12	24	17	12	10	23	17	4	2	13	9	32	27
		247	167	26	21	49	37	26	17	14	9	33	20	13	8	32	16	6	3	14	10	33	27
	2095	201	99	27	21	20	14	27	13	15	5	14	6	14	6	43	8	3	1	12	6	26	19
		347	169	49	40	60	26	30	14	19	7	50	16	27	12	40	12	7	1	23	10	42	30
N_2O	1995	3.2		0.2		0.7		0.5		0.3		0.3		0.1		0.5		0.1		0.2		0.4	
	2045	8.5	7.0	1.1	1.0	1.6	1.2	0.8	0.7	0.6	0.5	1.0	0.8	0.7	0.6	0.8	0.6	0.2	0.1	0.6	0.4	1.2	1.2
		9.2	7.5	1.2	1.1	1.7	1.5	0.9	0.7	0.5	0.4	1.3	1.0	0.7	0.5	1.0	0.6	0.2	0.1	0.5	0.4	1.2	1.2
	2095	8.0	4.6	1.3	1.1	0.7	0.6	1.0	0.6	0.5	0.2	0.6	0.3	0.7	0.3	1.5	0.3	0.2	0.0	0.6	0.3	1.0	0.8
		14.7	8.0	2.2	2.0	2.4	1.3	1.2	0.6	0.8	0.3	1.9	0.7	1.6	0.7	1.4	0.5	0.3	0.1	1.1	0.5	1.8	1.4

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Table 3. Comparison of global cropland soil balances.

	This study	Smil (1999b)	Sheldrick (1996)	Liu (2010)
baseyear	*1995*	*1995*	*1996*	*2000*
OUT				
Crops	50	50	63	52
Crop residues	30	25	38	29
Fodder	13	10	–	–
Fodder residues	5	–	–	–
BG residues	16	–	–	–
IN				
Residues	14	14	23	11
Fodder residues	5	–	–	–
BG residues	16	–	–	–
Legume fixation	7	10	8	} 22
Other fixation	10	11	–	
Fixation fodder	8	12	–	–
Atm. deposition	13	20	22	14
Manure on field	24	18	25	17
Seed	2	2	–	–
Irrigation water	–	4	–	3
Sewage	–	–	3	–
Soil organic matter loss	28	–	–	–
Fertilizer	78	78	78	68
Histosoils	–	–	–	–
BALANCE				
Total OUT	*113*	*85*	*101*	*81*
*Total OUT**	*113*	*106*	*135*	*115*
Total IN	*204*	*169*	*159*	*137*
*Total IN**	*211*	*221*	*231*	*198*
Losses	*91*	*80*	*75*	*67*
Losses*	98	115	96	83
OUT/IN	*0.55*	*0.50*	*0.64*	*0.59*
OUT*/IN*	*0.54*	*0.48*	*0.58*	*0.58*

* 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), for histosoils no estimate exists.

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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)

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

Parameter	Description	Unit
Production		
$X_{t,j,v,w}^{\mathrm{area}}$	Cropland area under cultivation	Mha
$\mathrm{P}(x_t)_{t,i,k}^{\mathrm{prod}}$ $\mathrm{N}(x_t)_{t,i,k}^{\mathrm{prod}}$	Crop production	TgDM $\mathrm{TgN_r}$
$\mathrm{P}(x_t)_{t,i,v}^{\mathrm{prod\_ag}}$ $\mathrm{N}(x_t)_{t,i,v}^{\mathrm{prod\_ag}}$	AG residue production	TgDM $\mathrm{TgN_r}$
$\mathrm{P}(x_t)_{t,i,v}^{\mathrm{prod\_bg}}$ $\mathrm{N}(x_t)_{t,i,v}^{\mathrm{prod\_bg}}$	BG residue production	TgDM $\mathrm{TgN_r}$
$\mathrm{P}(x_t)_{t,i,v}^{\mathrm{prod\_by}}$ $\mathrm{N}(x_t)_{t,i,v}^{\mathrm{prod\_by}}$	Conversion byproduct production	TgDM $\mathrm{TgN_r}$
Domestic supply and its use		
$\mathrm{P}(x_t)_{t,i,v,u}^{\mathrm{ds}}$ $\mathrm{N}(x_t)_{t,i,v,u}^{\mathrm{ds}}$	Crop use	TgDM $\mathrm{TgN_r}$
$\mathrm{P}(x_t)_{t,i,v,r}^{\mathrm{ds\_ag}}$ $\mathrm{N}(x_t)_{t,i,v,r}^{\mathrm{ds\_ag}}$	AG residues use	TgDM $\mathrm{TgN_r}$
$\mathrm{P}(x_t)_{t,i,v,b}^{\mathrm{ds\_by}}$ $\mathrm{N}(x_t)_{t,i,v,b}^{\mathrm{ds\_by}}$	Conversion byproduct use	TgDM $\mathrm{TgN_r}$
$\mathrm{N}(x_t)_{t,i,k}^{\mathrm{fs}}$	Food supply	$\mathrm{TgN_r}$
$r_{t,i,k}^{\mathrm{int}}$	Intake share of food supply	$\frac{\mathrm{TgN_r}}{\mathrm{TgDM}}$
$\mathrm{N}(x_t)_{t,i,k}^{\mathrm{int}}$	Intake	$\mathrm{TgN_r}$
P_t^{tb}	Trade Balance reduction	1

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Table A2. Continued.

Parameter	Description	Unit
Crop growth functions, processing rates and biological fixation		
$r_v^{cgf\_i}$	AG residues intercept	$\frac{TgDM}{Mha}$
$r_v^{cgf\_s}$	AG residues slope	$\frac{TgDM}{TgDM}$
$r_v^{cgf\_r}$	AG to BG biomass ratio	$\frac{TgDM}{TgDM}$
$r_{i,v}^{by\_conv}$	Conversion byproducts generated per unit of crop production	$\frac{TgDM}{TgDM}$
r_v^{ndfa}	Plant N_r derived from atmospheric fixation	$\frac{TgN_r}{TgN_r}$
r_v^{Nfix}	Fixation of free-living bacteria	$\frac{TgN_r}{TgMha}$
Products		
$r_v^{Nharvest}$	N_r content of harvested crops	$\frac{TgN_r}{TgDM}$
r_v^{Nag}	N_r content of AG residues	$\frac{TgN_r}{TgDM}$
r_v^{Nbg}	N_r content of BG residues	$\frac{TgN_r}{TgDM}$
r_{past}^{Npast}	N_r content of grazed pasture	$\frac{TgN_r}{TgDM}$
r_v^{Nby}	N_r content of conversion byproducts	$\frac{TgN_r}{TgDM}$
r_l^{PR}	Protein content of livestock products	$\frac{TgPr}{TgDM}$
r_l^{NtoPR}	Protein to N_r content ratios	$\frac{TgN_r}{TgPr}$

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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	$\frac{\mathrm{TgDM}}{\mathrm{TgDM}}$
$r^{\mathrm{grazC}}_{\mathrm{t,i}}$	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	$\mathrm{TgN_r}$

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Table A2. Continued.

Parameter	Description	Unit
Soil Inputs		
$N(x_t)_{t,i}^{dep}$	Atmospheric deposition of N_r	TgN_r
$r_{t,i}^{dep}$	Atmospheric deposition rates	$\frac{TgN_r}{Mha}$
$N_{t,i}^{som}$	Soil organic matter loss (F_{SOM})	TgN_r
$N(x_t)_{t,i}^{fert}$	Inorganic N_r fertiliser (F_{SN})	TgN_r
$N(x_t)_{t,i}^{res}$	N_r in crop residues (F_{CR})	TgN_r
$N(x_t)_{t,i}^{FixFree}$	N_r fixed by free-living microorganisms (F_{CR})	TgN_r
$N(x_t)_{t,i}^{m}$	N_r in manure excreted in animal houses and applied to agricultural soils (F_{AM})	TgN_r
$r_{t,i}^{msplit}$	Fraction of manure in animal houses applied to cropland soils	$\frac{TgN_r}{TgN_r}$
$N(x_t)_{t,i}^{m\_cs}$	N_r in manure applied or excreted on cropland soils	TgN_r
$N(x_t)_{t,i}^{m\_ps}$	N_r in manure applied or excreted on pasture soils	TgN_r
Emissions		
r^{gas_fert}	Fraction of industrial fertiliser N_r that volatises as NO_x and NH_y ($Frac_{GasF}$)	$\frac{TgNO_xNH_y}{TgN_r}$
$r_{l,c}^{gas\_awms}$	Fraction of manure N_r that volatises in waste management facilities as NO_x and NH_y ($Frac_{GasMS}$)	$\frac{TgNO_xNH_y}{TgN_r}$
$r_{l,c}^{loss\_awms}$	Fraction of manure N_r that is lost in waste management ($Frac_{LossMS}$)	$\frac{TgNO_xNH_y}{TgN_r}$

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Table A2. Continued.

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

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Table A3. Estimates of crop growth functions (sources see text).

Crop type (kcr)	$r_v^{cgf\_i}$	$r_v^{cgf\_s}$	$r_v^{cgf\_r}$
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
Groudnnut	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

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Table A4. N_r contents of harvested crops, aboveground crop residues, belowground crop residues and conversion byproducts for the MAgPIE crop types. Collected and aggregated from Wirsenius (2000); Fritsch (2007); Eggleston et al. (2006); FAO (2004); Roy et al. (2006); Chan and Lim (1980); Khalid et al. (2000).

<table>
<tr><th>Crop type (v)</th><th>$r_v^{Nharvest}$</th><th>r_v^{Nag}</th><th>r_v^{Nbg}</th><th>r_v^{Nby}</th></tr>
<tr><td>Temperate cereals</td><td>2.17</td><td>0.74</td><td>0.98</td><td rowspan="4">2.93</td></tr>
<tr><td>Maize</td><td>1.60</td><td>0.88</td><td>0.70</td></tr>
<tr><td>Tropical cereals</td><td>1.63</td><td>0.70</td><td>0.60</td></tr>
<tr><td>Rice</td><td>1.28</td><td>0.70</td><td>0.90</td></tr>
<tr><td>Soybeans</td><td>5.12</td><td>0.80</td><td>0.80</td><td>7.90</td></tr>
<tr><td>Rapeseed</td><td>3.68</td><td>0.81</td><td>0.81</td><td>6.43</td></tr>
<tr><td>Groudnnut</td><td>2.99</td><td>2.24</td><td>0.80</td><td>7.28</td></tr>
<tr><td>Sunflower</td><td>2.16</td><td>0.80</td><td>0.80</td><td>5.92</td></tr>
<tr><td>Oilpalm</td><td>0.57</td><td>0.52</td><td>0.53</td><td>6.43</td></tr>
<tr><td>Pulses</td><td>4.21</td><td>1.05</td><td>0.80</td><td></td></tr>
<tr><td>Potatoes</td><td>1.44</td><td>1.33</td><td>1.40</td><td></td></tr>
<tr><td>Tropical roots</td><td>0.53</td><td>0.86</td><td>1.40</td><td></td></tr>
<tr><td>Sugar cane</td><td>0.24</td><td>0.80</td><td>0.80</td><td rowspan="2">1.36</td></tr>
<tr><td>Sugar beet</td><td>0.56</td><td>1.76</td><td>1.40</td></tr>
<tr><td>Others</td><td>2.85</td><td>0.81</td><td>0.70</td><td>5.72</td></tr>
<tr><td>Fodder</td><td>2.01</td><td>1.91</td><td>1.41</td><td></td></tr>
<tr><td>Fibres</td><td>2.39</td><td>0.93</td><td>0.70</td><td></td></tr>
<tr><td>Pasture</td><td>1.60</td><td></td><td></td><td></td></tr>
<tr><th>Pasture</th><th>r_{past}^{Npast}</th><th></th><th></th><th></th></tr>
<tr><td>past</td><td>1.60</td><td></td><td></td><td></td></tr>
</table>

Table A5. Estimates of whole body N_r content r_l^{Nl} in % of dry matter (DM), 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).

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Table A6. Estimates of N_r fixation rates per area or as percentage of plant N_r (% Ndfa), based on Herridge et al. (2008) and aggregated to MAgPIE crop types.

Crop type	r_v^{Nfix} $\frac{TgN_r}{Mha}$	r_v^{ndfa} $\frac{TgN_r}{TgN_r}$
Temperate Cereals	0.005	–
Maize	0.005	–
Tropical Cereals	0.005	–
Rice	0.033	–
Soybeans	–	0.58
Rapeseed	0.005	–
Groudnut	–	0.58
Sunflower	0.005	–
Oilpalm	0.005	–
Pulses	–	0.53
Potatoes	0.005	–
Tropical roots	0.005	–
Sugar Cane	–	0.13
Sugar Beet	0.005	–
Others	0.005	–
Fodder	0.004	0.31
Fibres	0.005	–

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Table A7. 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	$C_T = a \cdot (I)^b$	$a = 7.074$, $b = 0.0993$	1.004	0.63	<0.001 (***)	5887
	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

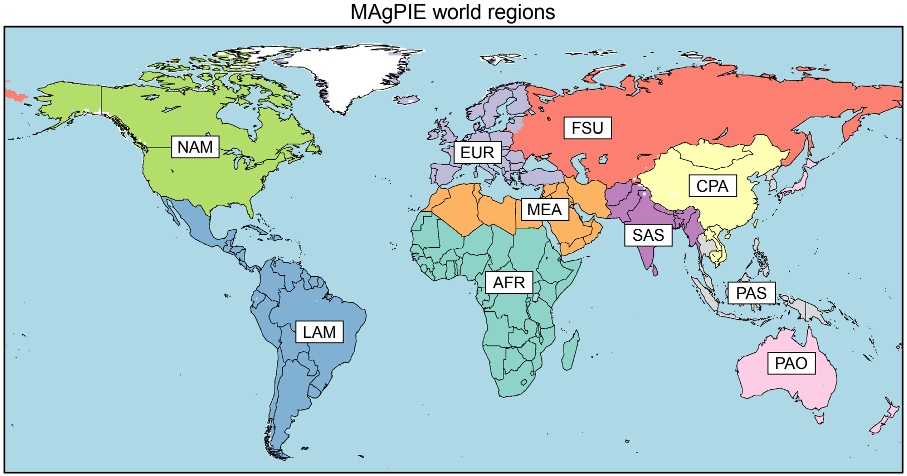

Fig. 1. The ten MAgPIE world regions. Sub-Sahara Africa (AFR), Centrally Planned Asia (CPA), Europe (incl. Turkey) (EUR), Former Soviet Union (FSU), Latin America (LAM), Middle East and North Africa (MEA), North America (NAM), Pacific OECD (Australia, Japan and New Zealand) (PAO), Pacific Asia (PAS),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

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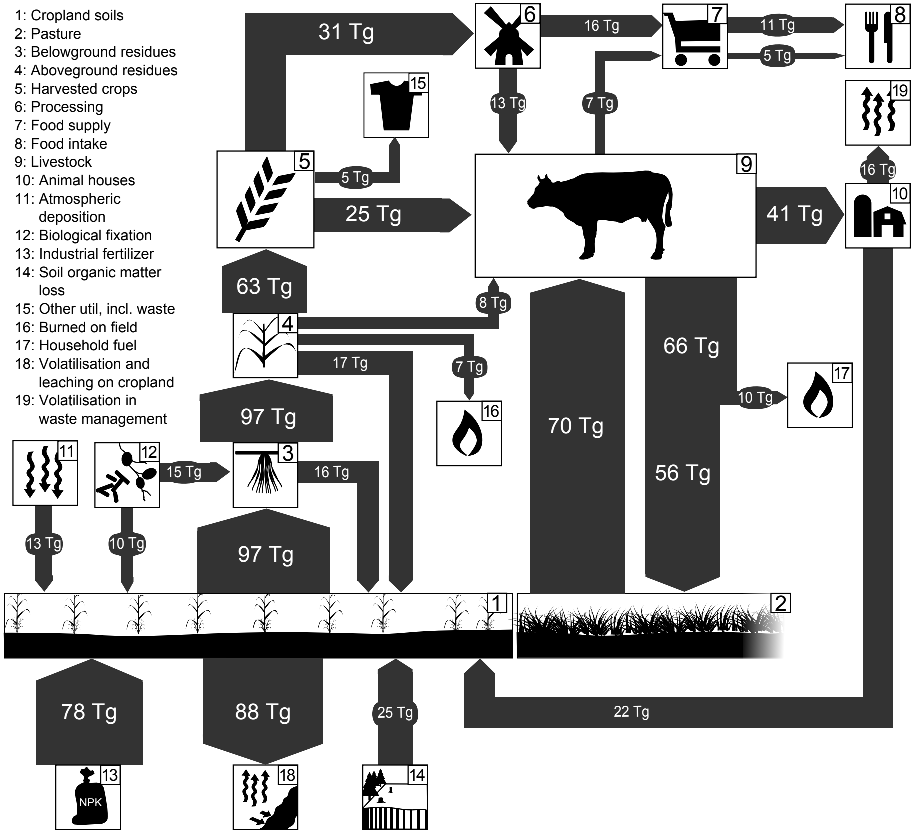

Fig. 2. Agricultural N_r cycle in Tg N_r in the year 1995. Flows below 5 Tg N_r are not depicted. N_r inputs to pasture soils by atmospheric deposition and biological fixation were not considered, as they depend largely on the definition of pasture land.

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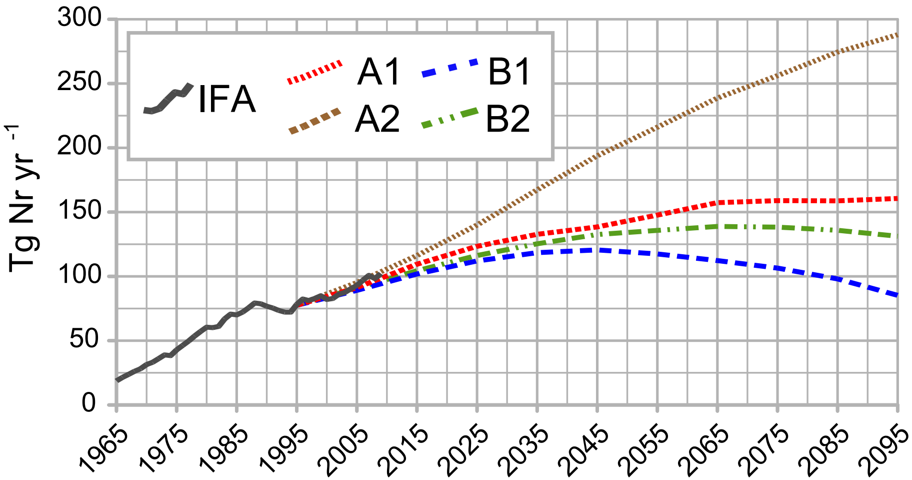

Fig. 3. Fertilizer consumption, historic dataset of the IFADATA database (IFADATA, 2011) and our scenarios for the 4 SRES storylines for 1995–2095.

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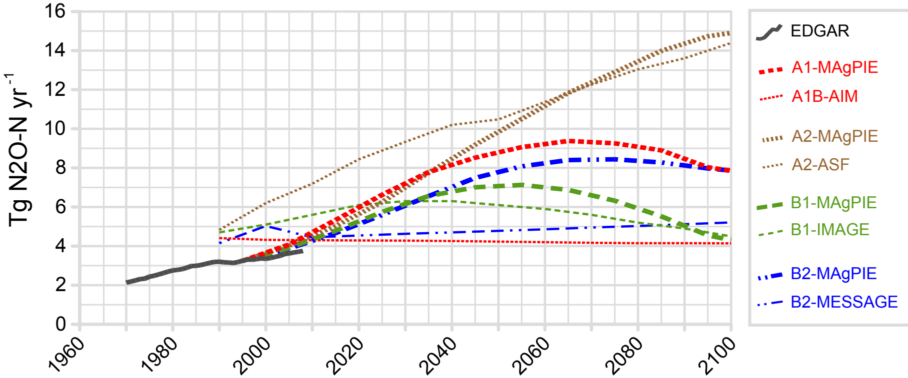

Fig. 4. N_2O emissions from soils and manure, historic estimates for 1970–2008 of the EDGAR 4.2 database (EC-JRC/PBL, 2011), the SRES marker scenarios (Nakicenovic et al., 2000) for 1990–2100 and our scenarios for the SRES storylines for 1995–2095.

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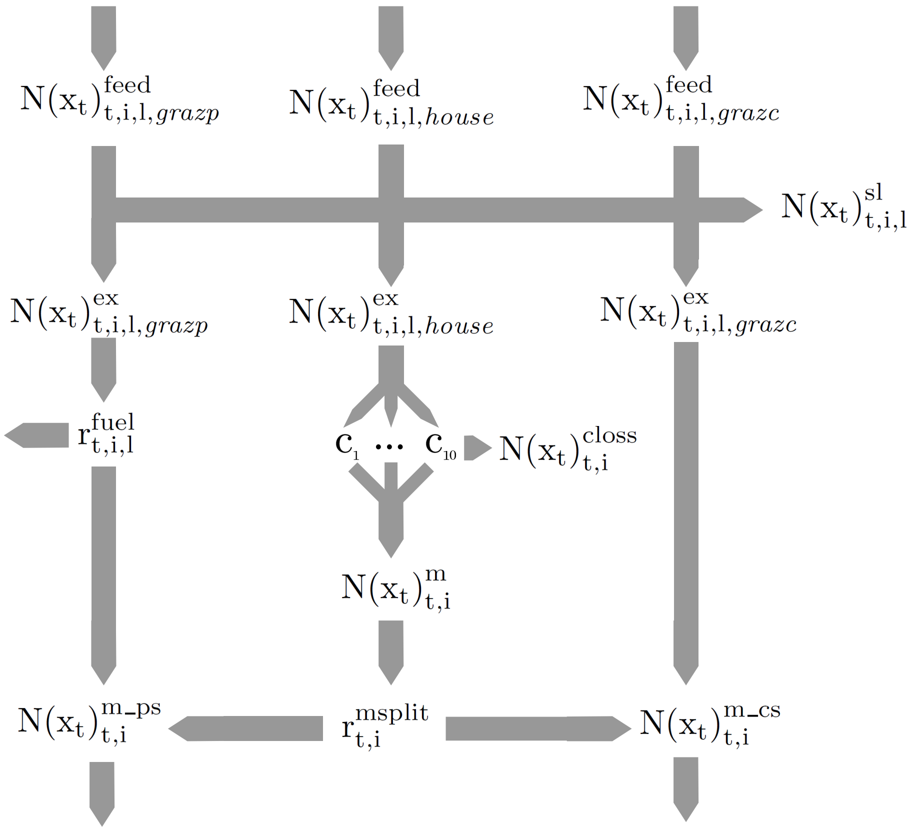

Fig. A1. Modelling N_r flows in the livestock sector.

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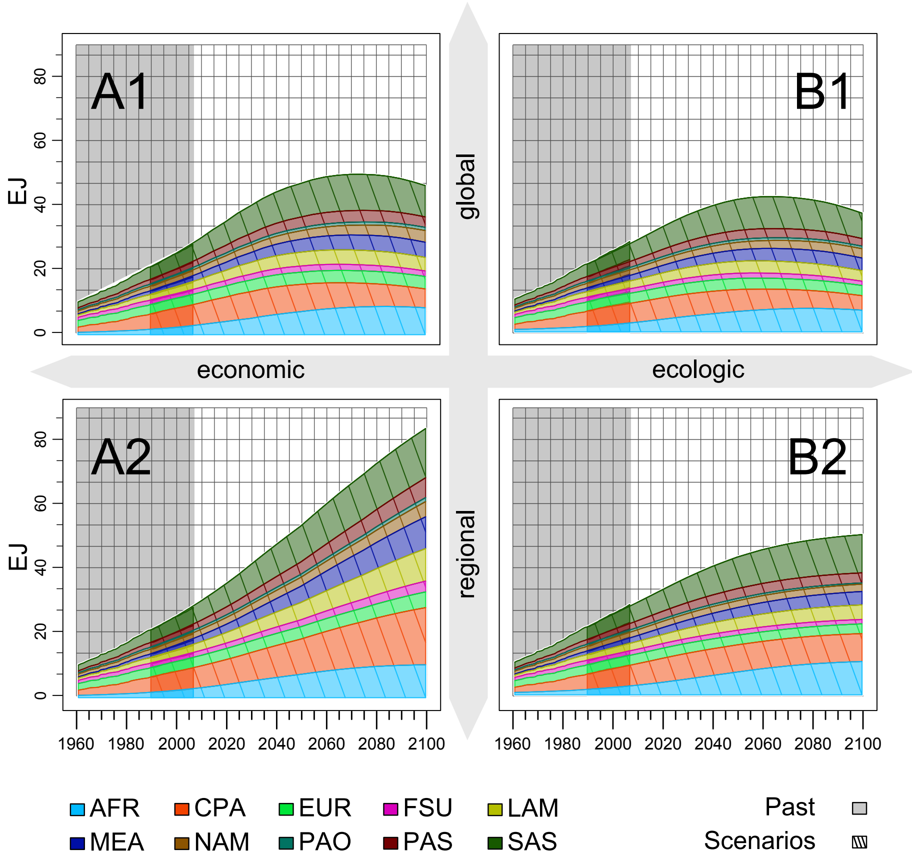

Fig. A2. Total food energy demand in the 10 MAgPIE world regions. History and future developments for the four SRES scenarios (Rolinski et al., 2012).

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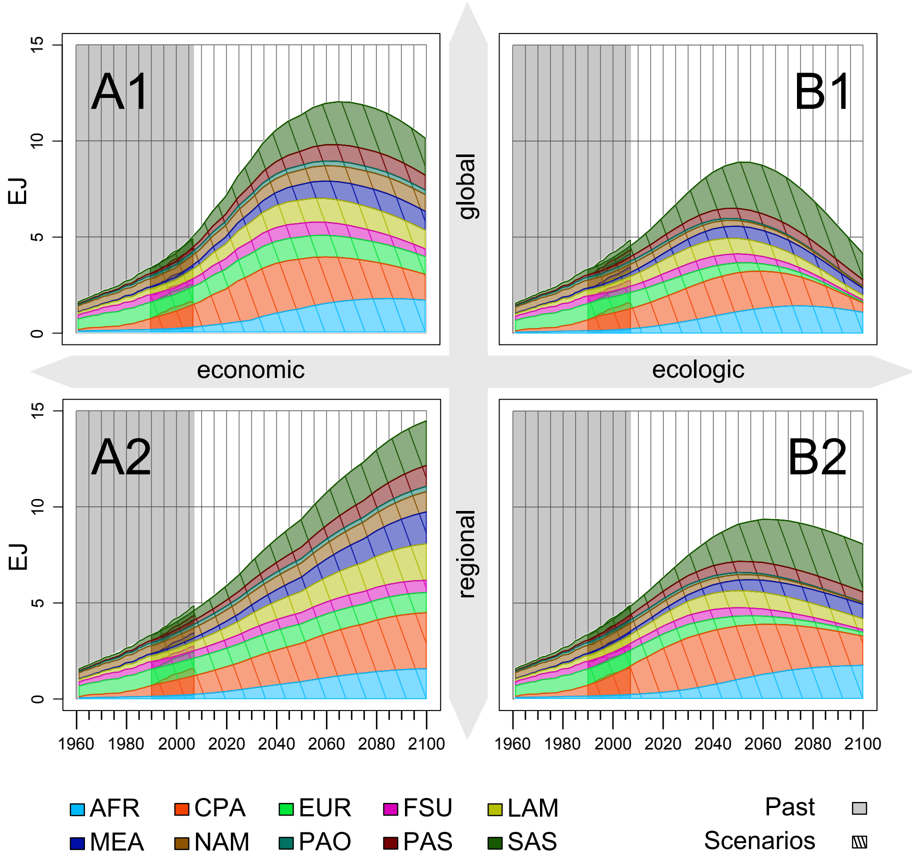

Fig. A3. Demand for energy from livestock products in the 10 MAgPIE world regions. History and future developments for the four SRES scenarios (Rolinski et al., 2012).