Biogeosciences Discuss., 9, C2459–C2485, 2012
www.biogeosciences-discuss.net/9/C2459/2012/

Biogeosciences
Discussions

Interactive comment on "Current state and future scenarios of the global agricultural nitrogen cycle" *by* B. L. Bodirsky et al.

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Received and published: 17 July 2012

In a revised version, the authors should (*) be more explicit in what their scenario assumptions entail, (*) validate their model results against other existing scientific material and (*) be more wary regarding the uncertainties and correct some errors. Such an improved paper would be very helpful to understand (and intervene into) possible future developments, and I would like to see it published.

Taking up the structure of your comments, our reply will be structured as follows: In section 1, we will present more model parameters and discuss some of the underlying model-dynamics that determine the outputs. Section 2 will extend the validation of our results. Section 3 will discuss some of the uncertainty issues. Finally Section 4 will reply to your minor comments.

1 Scenario Parameters and underlying model dynamics

We strongly agree with your comment to include more model parameters into our paper.

We now included an additional table, including key model outputs. This table includes the outputs suggested by reviewer 1 and a large set of additional outputs. All estimates are given for all 4 scenarios, 10 regions + global, and three time slices (1995,2045,2095). Because of its great detail (>1000 rows, 11 columns), we add the table to the supplementary material. As a .xls file, it also facilitates other researchers to analyse and use our data.

In the text, we refer to this table as follows:
p. 2766 line 1
"Detailed global and regional results of the current state of the agricultural Nr cycle and the four scenarios can be found in the supplementary material. The following chapter sums up the most important findings."

We also include a new chapter into the discussion, Chapter 4.2 "Critical assessment of scenario assumptions"
In this chapter, which follows the discussion of the current state of the Nr cycle, the parametrisation of our SRES scenarios shall be discussed, before chapter 4.3 then concentrates on the outcome of our simulations.

"4.2. Critical assessment of scenario assumptions
The simulation of the widely used SRES storylines (Nakicenovic et al., 2000) facilitates the comparison with other studies like Bouwman et al. (2009) or Erisman et al. (2008) and allows for the integration of our results into other assessments. However, the SRES storylines provide only a qualitative description of the future. In the following, the key assumptions underlying our parametrisation shall be discussed.
All SRES storylines tend to assume a continuation of current trends, without exter-

nal shocks or abrupt changes of dynamics. They merely diverge in the interpretation of past dynamics or the magnitude of change assigned to certain trends. Population grows at least until the mid of the 21st century, and declines first in developed countries. Per-capita income grows throughout the century in all scenarios and all world regions, and developing regions tend to have higher growth rates than developed regions. This has strong implication on the food demand, which is driven by both population and income growth. Due to the Engels-shaped demand curve for food, the development of total food demand depends mostly on the income growth of low-income regions. The same holds for the share of animal calories. In the first half of the century population growth does not differ much in most regions. The pressure from food demand is therefore highest in the high-income A1 scenario, while in the second half, the A2 scenario also reaches a medium income and therefore a relatively high per capita-demand. This, combined with a high population growth leads to a very high total food demand in the A2 scenario. As food demand is exogenous to our model, price effects on consumption are not captured by the model. However, even in the A2 scenario the shadow prices (Lagrange multipliers) of our demand constraints increase globaly by 0.5% per year until 2045, with no region showing higher rates than 1.1%. This indicates only modest price pressure, lagging far behind income growth.

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

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

Our closed budget approach to calculate future inorganic fertilizer consumption is based on the concept of Soil Nr Uptake Efficiency (SNUE). Compared to other indicators of Nr efficiency that relate Nr inputs to crop biomass like Nr use efficiency (grain dry matter divided by Nr inputs, not to be confused with Nr Uptake Efficiency), SNUE has the advantage of an upper physical limit, as Nr withdrawals cannot exceed Nr inputs. At the same time, it indicates the fraction of losses connected to the application of Nr inputs. As it includes a large number of Nr inputs, substitution effects can be represented well. Finally, compared to Nitrogen Uptake Efficiency (NUE), one regional value of SNUE suffices to simulate higher NUE of Nr fixing crops compared to normal crops.

The level of SNUE is in our model an exogenous scenario parameter for future simulations, which has enormous impact on the estimates of inorganic fertilizer consumption and N2O emissions. If SNUE would be 5 percentage points lower, fertilizer consumption would increase by 8 to 10% in 2045, depending on the scenario. At the same time, total agricultural N2O emissions would increase by 11 to 15%. If fertilizer efficiency would increase by 5 percentage points, fertilizer consumption would fall by 7 to 8% and emissions would decrease by 9 to 13%. As the magnitude of Nr flows is higher in some scenarios, a +-5% variation of SNUE translates in the A1 scenario into a change of fertilizer consumption of -32 to +37 Tg Nr and a change of -1.06 to +1.26 Tg N2O-N of emissions in 2045, while in the B2 scenario fertilizer changes only by -20 to +24 Tg Nr and emissions by -0.7 to +0.8 Tg N2O-N.

The future development of SNUE is highly uncertain. It depends on numerous factors: most importantly on the management practices like timing placing and dosing of fertilizers and the use of nutrient trap crops. Also a general improvement of agricultural practices like providing adequate moisture and sufficient macro- and micronutrients, pest control and avoiding soil erosion can contribute their parts. Finally, climate, soils, crop varieties and the type of nutrient inputs also influence Nr uptake efficiency. The complexity of these dynamics and the numerous drivers involved still do not allow to make long-term model estimates for Nr efficiencies, but should be target for future research. Meanwhile, we use SNUE as an explicitly defined scenario parameter. As it descriptively indicates the share of losses, and as the theoretical upper limit of 1 is clearly fixed, it makes our model assumptions transparent and easily communicable.

Our assumptions concerning the development of SNUE are rather optimistic. In 1995, none of the 10 world regions reached a SNUE of 60%, and four regions (CPU, FSU, PAS, SAS) were even below 50%. The current difference between the region with the lowest SNUE (CPA with 43%) and the region with the highest SNUE (EUR with 57%) is thereby still lower than the difference of EUR and our scenario parameter of 70% for the environmentally oriented scenarios.

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

In the environementally oriented scenarios B1 and B2, we restricted the expansion of cropland into intact and frontier forest. However, these protected areas only include some of the most vulnerable forest areas, and its implementation is assumed to take place gradually until 2045. Large forest areas are still cleared, most importantly in the Congo river basin and the southern part of the Amazonian rainforest. Due to the land restrictions, crop yields have to increase faster to be able to settle the demand with the available cropland area. Also, the area-dependent Nr inputs from soil organic matter loss, atmospheric deposition and free-living bacteria are lower. "

2 Validation of our Results

In addition to the papers mentioned (Bouwman et al.), the authors may wish to support their case by consulting other N scenarios like those presented by Erisman et al. (2008), Nat.Geosci 1:636-639 and van Vuuren et al (2011), Current Opinion in Environmental Sustainability 3:359–369.

Our validation in the original article included

- A comparison of different estimates for the current state of the Nr budget. We systematically compared estimates by Smil (1999b), Sheldrick (1996) and Liu (2010) with our study in table 3. These estimates were completed by comparison with estimates for single flows by Mosier et al.(1998), Bouwman et al. (2009, 2011), Herridge et al (2008) and Vitousek et al (1997).
- A comparison for future scenarios of the Nr cycle. Here we compared our estimates with Bouwman et al. (2009, 2011), Daberkov et al. (2000) and IFADATA (2011). We mostly compared inorganic fertilizer, but also manure excretion.
- N2O emissions were compared to Nakicenovic et al. (2000).

We believe that we have a good validation of the current state of the Nr cycle. But we agree, that more comparison of our future scenarios both concerning the Nr cycle and emissions would be desirable. We will do this as explained in the following two sections:

The former publication, also focusing on SRES scenarios, provides a much simpler estimate of future developments of N pollution – discrepancies or agreement with a more complex model as the one presented by Bodirsky et al. will however strongly enhance the explanatory value of the complex model.

Based on the suggestion of reviewer 1 we now include additional comparisons. The study by Erisman et al (2008) was very helpfull, and we integrated their simulations of inorganic fertilizer consumption into our figure 3. Curiously, we did not find any information about the methodology (I assume its a decomposition analysis) or even the name of the model used in the text of the article. This makes a qualitative discussion difficult.
Next to Erisman et al. (2008), we now also include Davidson (2012), Tubiello and Fischer (2007) and Tilman et al (2001) into our comparison in Figure 3.

An updated version of figure 3 is attached to this document.

The figure has the following subtitle:

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

Also we exchange the last 2 paragraphs on page 2771 line 9ff by the following

"Our estimates of inorganic fertilizer consumption are within the range of previous estimates. Figure 3 compares our results to estimates by Daberkow et al. (2000), Davidson (2012), Erisman (2008), Tilman et al. (2001), Tubiello and Fischer (2007) and Bouwman et al. (2009). The differences in estimates is enormous, ranging in 2050 from 68 (Bouwman et al, 2009) to 236 Tg Nr (Tilman et al, 2001). In contrast to Bouwman (2009) and Erisman (2008), who also created scenarios based on the SRES storylines, our highest estimate is the A2 scenario, while the other two models have the A1 scenario as highest scenario. Also, our scenarios have in general a higher fertilizer consumption, especially compared to Bouwman (2009). The origins of the differences are difficult to identify as we have little insight into the other models. Different methodologcial approaches may contribute one part to differing dynamics. Our estimates are based on a top-down approach, compared to the bottom-up approach of Bouwman et al. (2009, 2011) or Daberkow et al. (2000). 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 Nr uptake efficiency, it can consistently simulate substitution effects between different Nr 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. Another reason for our high fertilizer consumption estimates may be, that we estimate a strong demand increase also in scenarios with relatively low income growth as we explained in section 4.2 [note: the newly included chapter 4.2]. At the same time, low income growth goes along with slow effiency improvements in production. The combined effect explain the strong rise

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

The latter (note also the references within) refers to quite detailed results – even with respect to N2O emissions, though limitations as discussed below apply here too – from the RCP exercise. While I understand the motivation of the authors to use in their work SRES instead of RCP, I wonder if it is a good idea to ignore RCP developments.

We agree that the RCP scenarios represent currently the newest stage of N2O scenarios created by integrated assessment models. Unfortunately, they do not provide much insight into the underlying socio-economic drivers of the emissions.
The RCPs, to our knowledge, do not provide a sectoral breakdown of N2O emissions. We did find agricultural N2O emissions neither reported in the Van Vuuren et al (2011) paper nor in the RCP database (http://www.iiasa.ac.at/web-apps/tnt/RcpDb) or else-

where. Therefore it is not possible to isolate agricultural N2O emissions which would be comparable to our estimates.
We integrate the total emissions into the update figure 4, which is attached to this document. The subtitle of figure 4 is:

"Fig. 4. Total anthropogenic N2O emissions: Historical emissions, highest and lowest RCP scenario (van Vuuren et al., 2011). N2O emissions from soils and manure: Historic estimates for 1970–2008 of the EDGAR 4.2 database (EC-JRC/PBL, 2011), a top-down estimate by Crutzen et al. (2007) for the year 2000, the SRES marker scenarios (Nakicenovic et al., 2000) for 1990–2100 and our scenarios for the SRES storylines for 1995–2095. The shaded areas represent a 90% probability range in respect to the uncertainty of emission parameters of the A2 and B1 scenario. A1 and B2 have a similar relative uncertainty range."

We also add the following text in section 4.4. of the discussion (p.2773,2774): "None of our agricultural N2O emission scenarios would be compatible with the RCP2.6 scenario, that keeps the radiative forcing below 2.6 W per m^2 in 2100. To reach a sustainable climate target, explicit GHG mitigation efforts are therefore required even in optimistic scenarios. If the non-agricultural N2O emissions grow in similar pace than agricultural N2O emissions, the A2 scenario might even outpass the RCP8.5 scenario."

3 Discussing the uncertainty

It seems perfectly acceptable to focus on one "problem area" associated with Nr, with N2O emissions, to provide insight into the model's abilities. In an uncertainty analysis (this is missing: the authors focus instead on the spread of the SRES scenarios as the overall uncertainty margin), also the uncertainty of applying the 2006 IPCC guidelines (the authors refer to it as Eggleston 2006) needs consideration. IPCC 2006 (in their volume 4, table 11.1) suggest an uncertainty

range of one order of magnitude – clearly indicating the difficulties involved in quantifying N2O release.

We agree, that the IPCC methodology is subject to large uncertainties, especially for N2O emissions from agriculture. We therefore took up the comment of the reviewer and performed an uncertainty analysis to the Emission factors of the 2006 Guidelines. Due to the large uncertainty ranges and due to the assymetric probability density functions involved, we could not use the propagation of error method described in Eggleston et al. (2006) chapter 3.2.3.1. Instead, we had to use a Monte Carlo Analysis. According to this analysis, our cumulated global emissions have a range of 3.0 to 4.9 Tg N2O-N in 1995, and a range of 5.2 to 10.5 for our 4 scenarios in 2045.

We will include this into the description of our methodology in the main text and in the appendix as well as the results and discussion sections:

Methods:
p.2763 line 27:
"We use a Monte Carlo Analysis to estimate the effect of the uncertainty of the IPCC emission parameters on global N2O emissions."

Appendix p.2790 end of chapter 3.5
"To estimate the sensitivity of our results in regard to the uncertainty of the emission parameters, we carried out a Monte Carlo Analysis with the software @Risk. We used a log-logistic probability density function (pdf) for the emission parameters EF_1, EF_3, $EF3_{PRP,CPP}$, $EF3_{PRP,SO}$,EF$_4$, EF_5, $frac_{leach}$, $frac_{gasf}$, $frac_{gasm}$, and $frac_{gasms}$. The advantage of this pdf is, that it is non-negative, and that the median and the quantiles can be defined freely. We used the default value as mean and the uncertainty range from Eggleston et al (2006) as 2.5% and 97.5% confidence intervals. We assumed that emission factors are non-correlated between each other. As the uncertainty range of the emission parameters in Eggleston et al. (2006) were estimated for country inventories, it is questionable whether they should be regarded as correlated between

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countries or not. We decided to regard the parameters as not correlated between regions, but as fully correlated for all countries within a region. As a consequence, regional uncertainties partly cancel out, and our global emission estimates have a lower relative uncertainty range. To simplify our calculation, we did not differentiate between waste management systems for animals kept in confinement, and simply assumed an error range of -50% to +100% for the aggregated mean of EF_3 and $frac_{gasms}$."

Results:
p. 2766 we add a new sentence to the end of the paragraph
"... . Despite these wide ranges, the differences of N2O emissions between the scenarios is in the first half of the century rather narrow. They start in 1995 with 3.9 Tg N2O-N in 1995, with a range of 3.0 to 4.9 Tg N2O-N being the 90% confidence interval for uncertainty of the underlying emission parameters of Eggleston et al (2006). Up to 2045, they rise to 7.2 (5.4 – 9.0) Tg N2O-N in the B1 scenario and 8.6 (6.6 to 10.5) Tg N2O-N in the A2 scenario, and widen towards the end of the century to 4.9 (3.5 to 6.4) in the B1 scenario and 11.6 (8.8 to 14.2) in the A2 scenario."

Discussion:
p. 2774 line 5
"According to our calculations, N2O emissions from managed soils and manure contributed 3.9 Tg N2O-N, or approximately half of total anthropogenic N2O emissions (van Vuuren et al., 2011). However, the uncertainty involved is high. The result of our Monte-Carlo variation of the emission parameters suggest that the emissions may lie with a 90% probability in the range of 3.0 to 4.9 Tg N2O-N. This only covers parts of the uncertainty, as the underlying activity data is also uncertain. Finally, actual agricultural emissions should be slightly higher than our estimate, as we do not cover all agricultural N2O emission sources of the National Greenhouse Gas Inventories (Eggleston, 2006) and as also these inventories have no full coverage. Crutzen et al (2007), using a top-down approach, estimate total agricultural N2O emissions in 2000 to be in the range of 4.3 to 5.8 Tg N2O-N, which is modestly higher than our estimate of 3.4 to 5.5

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(90% confidence, mean: 4.4) Tg N2O-N in the year 2000.
Compared to the SRES marker scenarios (Nakicenovic et al., 2000), our results suggest that emissions will increase with substantially higher growth rates in the first half of the century. Especially in the case of the A1 and B2 scenarios, we come to 66% (A1) and 36% (B2) higher cumulative emissions over the century. In scenario A2 our estimates are continuously approximately 20% lower (A2), while in the B1 scenario cumulative emissions are 6% higher (B1), but occur later in the century (Fig. 4). None of our agricultural N2O emission scenarios would be compatible with the RCP2.6 scenario, that keeps the radiative forcing below 2.6 W per m^2 in 2100. To reach a sustainable climate target, explicit GHG mitigation efforts are therefore required even in optimistic scenarios. If the non-agricultural N2O emissions grow in similar pace than agricultural N2O emissions, the A2 scenario might even outpass the RCP8.5 scenario.
In the beginning of the century, the uncertainty of emission parameters is much larger than the spread of scenario mean values. Only in the second half of the century, the differences of the scenarios is of similar magnitude than the emission parameter uncertainty. While the scenarios are just representative pathways and have no pretension to cover a specific probaility space, this still indicates that a better representation of the underlying biophysical processes would largely improve our emission estimates."

We also change figure 4 as follows: the 90% confidence interval of the A2 and B1 scenarios is included into the picture as shaded area. The A1 and B2 scenarios have a similar range, however if we include them into the graphic, the picture becomes very confusing as the ranges of 4 scenarios overlap.
The new figure 4 is attached to this document. It has the following subtitle:

"Fig. 4. Total anthropogenic N2O emissions: Historical emissions, highest and lowest RCP scenario (van Vuuren et al., 2011). N2O emissions from soils and manure: Historic estimates for 1970–2008 of the EDGAR 4.2 database (EC-JRC/PBL, 2011), a top-down estimate by Crutzen et al. (2007) for the year 2000, the SRES marker scenarios (Nakicenovic et al., 2000) for 1990–2100 and our scenarios for the SRES storylines for 1995–2095. The shaded areas represent a 90% probability range in respect to the uncertainty of emission parameters of the A2 and B1 scenario. A1 and B2 have a similar relative uncertainty range."

Thus the authors may wish to be a little bit more cautious in their wording (p. 2758, line 6 "our study ... pioneers integrating ... recent ..."), and instead acknowledge that IPCC (2006) is a good technical guidance for operative country level assessments, but does not attempt to mimic the soil processes and is also quite uncertain.

We will change the sentence as follows:
"For this purpose, our study uses the emission parameters of the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (Eggleston et al., 2006).

Also note that IPCC very generally assigns emissions to a certain source – subsequent emissions (even if "indirect" is included here) not necessarily cover the full life cycle.

We took this point up, by confronting our estimates with a top-down estimate of Crutzen et al (2007) , resulting in a total of 4.3-5.8 Tg N2O-N that can be considered an upper estimate of N2O-N emissions in agriculture. We entered this estimate into figure 4 as well as into the text:

"Finally, actual agricultural emissions should be slightly higher than our estimate, as we do not cover all agricultural N2O emission sources of the National Greenhouse Gas Inventories (Eggleston, 2006) and as also these inventories have no full coverage. Crutzen et al (2007), using a top-down approach, estimate emissions in 2000 to be in the range of 4.3 to 5.8 Tg N2O-N, which is modestly higher than our estimate of 3.4 to 5.5 (90% confidence, mean: 4.4) Tg N2O-N in the year 2000."

4 Further Comments

P. 2774 line 8: One striking methodological difference between the 1996 IPCC inventory guidelines (IPCC, 1997) and the 2006 guidelines is often overlooked. The 1996 guidelines operate in stages, such that NH3 release (default 10-20%) from soil N input is subtracted before N2O emissions are calculated (1.25% of N remaining in soil after subtracting gaseous emissions) while the 2006 guidelines base their estimate of 1% emissions on the total N-input, part of which evaporates as NH3. In consequence, direct emissions of both approaches are very similar – a difference is only to be seen on indirect emissions from leaching, much smaller than the authors claim.

We thank you very much for your comment on the changed emission factors. Indeed, we misunderstood the guidelines in this respect. Checking why our results were lower led me to finding an important bug in my model-code. I did an error in the distribution of manure between different animal waste management systems, weighting the relative shares of AWM systems with the animal number instead of the amount of excretion. This led to a significant altering of our results. Especially in the ruminant category with a large number of sheeps and goats, that are not kept in similar animal waste management systems but have much smaller excretion rates per animal, this made a big difference. Also, we forgot to include leaching emissions from pastureland into our estimate.

Our results are now higher with 3.9 Tg Nr in 1995.

We delete the following sentence:
"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."

and in the Appendix A3.5 p.2789, we shorten the last paragraph:

"The 2006 guidelines differ from the widely used 1996 guidelines (IPCC, 1996) most importantly in two aspects. Firstly, the Nr fixed by legumes and other Nr-fixing plants is not considered to have significant N2O emissions. Only their comparably Nr-rich crop residues contribute to the N2O emissions if they are left on the field. Secondly, the emission factor from leached Nr (EF5, in our case r^{indir_leach}) was lowered considerably from 2.5% to 0.75%. "

Also note that SRES, to my knowledge, would not offer N2O emission data. If the authors know some subsequent work doing so, it would be worthwhile to compare their results.

The SRES N2O emission data from the integrated assesment modelling groups was published in Nakicenovic et al. (2000), chapter 5.4.2.. We took our comparison data from table 5-6.

P. 2773 line 10: direct air pollution from NO2 (not N2O) – but also note that soils typically emit NO which first needs to be oxidized in the atmosphere.

This is right, we correct our error:
"Air pollution is caused by NO2, which is formed by the oxidation of NO in the atmosphere, as well as indirectly by the formation of ground-level ozone and secondary particulate matter."

P. 2757 and elsewhere: For the time being, the classical ODS (namely, CFC's) covered in the Montreal protocol are the prime ozone depleters – see also Ravishankara et al. (2009)

Our formulation was misleading ("N2O is currently the major ozone depleting substance").
We wanted to say, that N2O is the single most important ozone depleting substance, not that it is contributing >50% of the total emissions. This is also what Ravishankara et al (2009) write: "we show that N2O emission currently is the single most important

ozone-depleting emission" (2nd line of the abstract).

We therefore exchange the word "major" by "single most important" on page 2774, line 4.

P. 2760 and elsewhere: Smil (1999) provides excellent overview data – as a model input such information however needs some critical assessment (uncertainty analysis, at least quantitatively, to understand how much the model results are influenced).

We use Smil's estimates for two model parameters (Nr fixation by free-living bacteria and crop residues burned or used as material) and for one scenario parameter (Nr efficiency in the SRES B scenarios). A variation of the two model parameters has no notable effect on the overall model outcomes. We explain this in detail in the following:

A: Share of crop residues burned or used for construction and household fuel

There are few estimates concerning the global use of crop-residues. Apart from Smil, we are only aware of the estimate by IPCC (1996), who estimate the share of burned residues to be lower in developed countries (10% instead of 15%) and who do not consider other uses of crop residues.

However, the influence of this model parameter on the dynamics can be considered to be fairly low. Firstly, 20% of the nutrients in burned residues are still returned to soils, and secondly, if these residues were recycled instead, they would be a rather low contribution to the total sum of Nr inputs. Doubling or halfing the amount of residues burned or used for construction would only change the NUE by +-1 percentage point. In the future, the impact of this parameter is even lower, as fewer crop residues are used for other purposes, and as the shift in harvest index reduces the amount of residues relative to the harvest.

Due to the little importance of this parameter on the model dynamics, we will not discuss the sensitivity in the manuscript.

B:Nr fixation of free-living bacteria and in rice paddies
Smils estimates for Nr fixation in rice paddies have been approved by Herridge et al (2008). However, the amount fixed by free-living bacteria in cropland not used for legumes, rice or sugarcane is extremely uncertain or even speculative. Herridge et al (2008) deliver a large literature overview, but come to the conclusion that Smil's estimate can currently neither be approved or disaproved, but are eventually lower than 5 Tg.
In our model, these free-living bacteria contribute only 5 Tg Nr to the total inputs of 207 Tg Nr in 1995. Again, this process is not large enough to have a notable effect on the results. In our future scenarios, free fixation almost stagnates and therefore has also no noticeable effect.

We make this more clear in the discussion, p. 2769 line 14:
"Biological Nr fixation is another flow of high uncertainty and most studies still use the per ha fixation rates of Smil (1999) for legumes, sugarcane and free-living bacteria. For the latter, currently no better estimate exists. However, free-living bacteria contribute only a minor input to the overall Nr budget with little impacts on our model results."

C:Scenario parameter for high-end efficiencies
The last parameter we use from Smil is an estimate for NUE under good agricultural practice. Smils estimate of 65-70% is also confirmed by van Vuuren et al (2011), who write that "in practice, recovery rates of 60-70% seem to be the maximum achievable".

SNUE is a key model parameter, and has large influence on our results. This, and the large uncertainty connected to this parameter, was the reason why we made it a scenario parameter, varying in future scenarios from 0.55 (A2 2045) to 0.7 (B1 2045, B1 2095, B2 2095).
However, we agree with the reviewer, that the uncertainty connected to this parameter should be made more clear, and also that the large impacts of a variation of this

parameter require a critical assesment in our discussion.

We do this now in detail in the section 4.2.:
"The level of soil nutrient uptake efficiency (SNUE) is in our model an exogenous scenario parameter for future simulations, which has a strong impact on the estimates of inorganic fertilizer consumption and N2O emissions. If SNUE would be 5 percentage points lower, fertilizer consumption would increase by roughly one fifth in 2045 or 2095 throughout all scenarios. At the same time, total agricultural N2O emissions would increase by 6-8%. If fertilizer efficiency would increase by 5 percentage points, fertilizer consumption would fall by one sixth and emissions would decrease by 5-6%. As the magnitude of Nr flows is higher in some scenarios, a +-5% variation of SNUE translates in the A2 scenario into a change of fertilizer consumption of -53 to +63 Tg Nr and -0.75 to +0.88 Tg N2O-N less emissions in 2095, while in the B1 scenario fertilizer changes only back by -25 to +29 Tg Nr and emissions by -0.36 to +0.41 Tg N2O-N.
The actual development of SNUE is highly uncertain. It depends on numerous factors: most importantly on the management practices like timing placing and dosing of fertilizers and the use of nutrient trap crops. Also a general improvement of agricultural practices like providing adequate moisture and sufficient macro- and micronutrients, pest control and avoiding soil erosion can contribute their parts. Finally, climate, soils, crop varieties and the type of nutrient inputs also influence Nr uptake efficiency. The complexity of these dynamics and the numerous drivers involved still do not allow to make long-term model estimates for Nr efficiencies, but should be target for future research. Meanwhile, we use SNUE as an explicitly defined scenario parameter. As it descriptively indicates the share of losses, and as the theoretical upper limit of 1 is clearly fixed, it makes our model assumptions transparent.
Our assumptions concerning the development of SNUE are rather optimistic. In 1995, none of the 10 world regions reached a SNUE of 60%, and four regions (CPU, FSU, PAS, SAS) were even below 50%. The current difference between the region with the lowest SNUE (CPA with 43%) and the region with the highest SNUE (EUR with 57%)

is thereby still lower than the difference of EUR and our scenario parameter of 70% for the environmentally oriented scenarios."

We also chose to rewrite the section in the appendix (p. 2792 line 14), which makes the text better readable:
"We chose to have high efficiency values in the B scenario due to high awareness for local environmental damages. The most efficient agricultural systems currently absorb around 70% of applied N (Smil, 1999), and van Vuuren (2011) estimates that "in practice, recovery rates of 60-70% seem to be the maximum achievable". So we adopted this value for the environmentally oriented B scenarios. In the A1 scenario, we assumed that $r_{t,i}^{Neff}$ 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 $r_{t,i}^{Neff}$ stays behind the B scenarios towards the end of the century. Finally, the A2 scenario stagnates around the current mean, and only improves towards the end of the century."

P. 2778, appendix A states that "all BG crop residues remain on the field", but P. 2757, line 17 mentions a feature of the approach of this paper, that "most [other?] studies do not consider ... belowground residues as major Nr withdrawals ..." – so what?

It is true, that in our model the nitrogen withdrawals from BG biomass equal the Nr inputs from BG biomass. However, in our approach, the uptake is subject to losses. In this way, only a part of the BG crop residues will be taken up by the subsequent rotation, while the rest is lost. This assumption is supported by IPCC 2006, where BG residues are an emission source.

We make this point more clear on p. 2757, line 18:
"However, the description of the current state of the Nr cycle was often incomprehensive. Belowground residues were so far not considered explicitly by other global studies, even though they withdraw large amounts of Nr from soils, and their decay on

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fields contributes to Nr losses and emissions. Similary, not all past studies included fodder crops into their budgets, although they make up a considerable share of total cropland production."

P. 2774, "Conclusions" actually are no conclusions (new thoughts and discussion, mainly) – may be considered "Outlook" instead.

P. 2774 We agree, that outlook would be more fitting. If the editor agrees, we would change the title to "Conclusions and Outlook". To strengthen the conclusion part of this section, we include more results as the reviewer proposed in his last comment.

Also note that a statement such as "current scientific examination of Nr mitigation options is concentrated mainly on the farm level" (P. 2775) is ignoring work like the "European Nitrogen Assessment", as well as many global studies which the authors are very well aware of.

We delete this sentence and rewrite the beginning of the paragraph as follows:

"Our model of the agricultural sector as a complex interrelated system shows that a large variety of dynamics influence Nr pollution. Each process offers a possibility of change, such that mitigation activities can take place not only where pollution occurs physically, but on different levels of the agricultural system: (a) .."

P. 2774, first paragraph: I would like to see results as indicated here shorthand in more details, by scenario! It does make a difference if N efficiencies are assumed to increase or decrease, how animal husbandry and crop production releases N (on the global level) in order to devise interventions.

We take up the valuable reviewer comment, and change the first paragraph of the conclusion as follows:
"The current state of the global agricultural Nr cycle is highly inefficient. Only around half of the Nr applied to cropland soils is taken up by plants. Furthermore, only one tenth of the Nr in produced cropland biomass and grazed pasture is actually consumed

by humans. During the 21st century, our scenarios indicate a strong growth of all major flows of the Nr cycle. In the materialistic, unequal and fragmented A2 scenario, inorganic fertilizer consumption more than triples due to a strong population growth and slow improvement in Nr efficiencies in livestock and crop production. In the prosper and materialistic A1 scenario, the strong increase of livestock consumption in the first half of the century and the industrialization of livestock production quadruples the demand for Nr in feed crops already in 2045. In the heterogenous, environmentally oriented B2 scenario, the slow improvements in feeding efficiency lead to a doubling of manure production. Finally, even in the globalized, equitable, environmental B1 scenario, Nr in harvested crops more than doubles, fertilizer consumption increases by 60% and emissions by 23% until the end of the century with a peak in the midlle of the century. The low meat consumption and large Nr efficiency improvements both in livestock and crop production are outbalanced by population growth and the catch-up of the less developed regions with the living standard of the rich regions.
Losses to natural systems will also continuously increase. ..."

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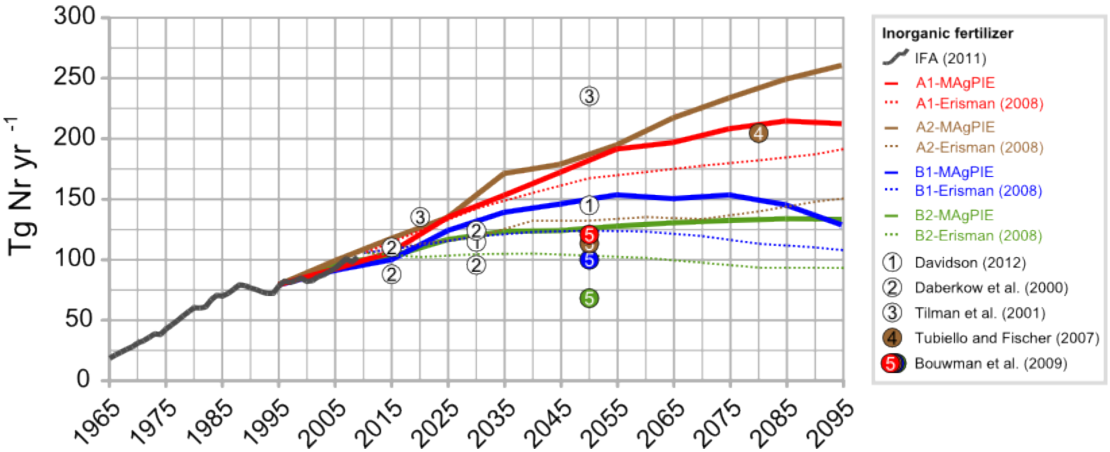

Fig. 1. Fig. 3: Fertilizer consumption ...

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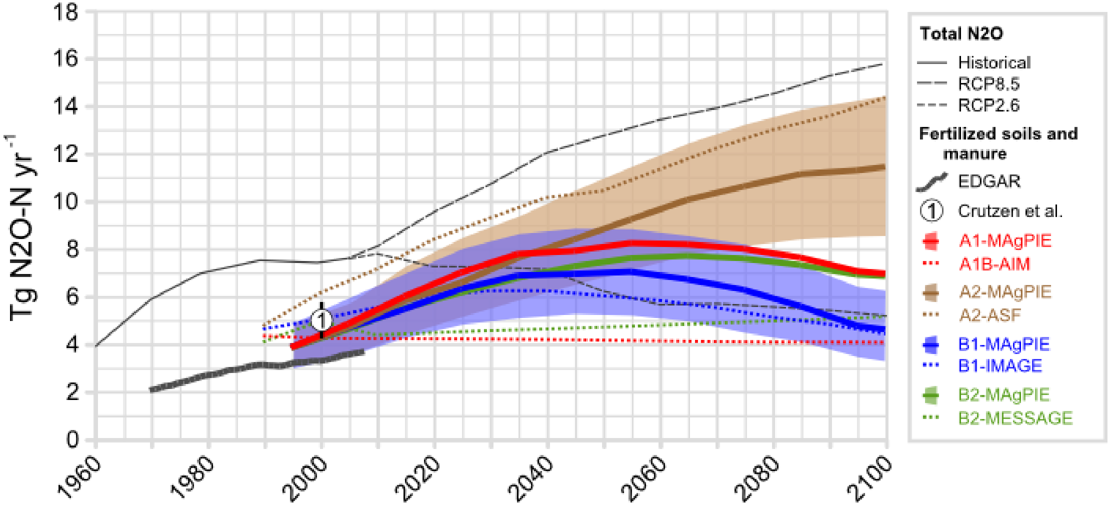

Fig. 2. Fig 4: N2O ...

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