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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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1) My first suggestion is to change the world agriculture into cropland, since the model used does not cover the role of grasslands.

We agree that our model only covers grassland partially (only grazing from grasslands and excretion of manure on grasslands). However, "cropland" would also fall short of the actual model, because large parts of the model describe the livestock sector as well as the up-stream processing and consumption of products.
Missing flows are mainly nitrogen fixation on pastures, and atmospheric deposition on pastures. We chose deliberately not to cover these flows as they are mostly depending on the definition of pastureland and therefore of little use.

We would therefore prefer to stick with the current title.

In addition, there are some important questions regarding the approach to compute the nitrogen inputs in crop production systems, and the efficiency of nitrogen use.
2. A second suggestion is to add a discussion of the nitrogen use efficiency as used in agronomy. There are various definitions. The definition used in this paper is completely different from what is generally used, and a comparison and discussion is needed of the advantage of the definition used compared to others.

Based on the suggestion of the reviewer we now use two definitions for nitrogen efficiency in our article:

- Nr uptake efficiency (NUE) as defined by Dawson et al. (2008) as the ratio between Total N in plant and N supply. This definition is used to compare our results to other studies.
- Soil Nr uptake efficiency (SNUE), defined as the share of the Nr inputs to soils taken up by the plant. This definition is used within in the model to estimate inorganic fertilizer requirements. The reason for including this new type of definition is, that nitrogen fixed from the atmosphere by legumes as well as seed are not subject to losses prior to uptake. (In this context, please also have a look also on our reponse to your comments 3,4 and 12.)

We will make the definitions clear on page 2763 line 10:

"Regional inorganic fertilizer consumption in 1995 is obtained from IFADATA (2011). For the scenarios, we use a closed budget approach. For this purpose, we define cropland soil Nr uptake efficiency (SNUE) as the ratio between Nr soil inputs (fertilizer, manure, residues, atmospheric deposition, soil organic matter loss and free-living Nr fixers) and soil withdrawals (harvest and crop residues minus seed and minus biological

fixation by legumes and sugarcane). The definition of SNUE diverges from the widely used Nr uptake efficiency (NUE) (Dawson et al., 2008) in the aspect that it regards only Nr that is taken up from the soil. Seed Nr is already part of the plant biomass, and biological fixation of Nr from the atmosphere takes place within the organism. The reason for the differentiation is that these Nr inputs should not subject to leaching, volatilisation or denitrification prior to the uptake by the plant. This implies also, that legumes and sugarcane have a higher NUE than other crops. SNUE is calculated on a regional level for the year 1995 and becomes an exogenous scenario parameter for future estimates. Its future development is determined by the scenario storyline (see chapter 2.4.).
In future scenarios, the soil withdrawals and the fixed SNUE determine the requirements for soil Nr inputs. If the amount of organic fertilizers is not sufficient, the model can apply as much nitrogen fertilizer as it requires to balance out the budget. In our model, the Nr inputs to crops have no influence on the yield. We assume in reverse that a given crop yield can only be reached with sufficient Nr inputs. An eventual Nr limitation is already reflected in the height of the crop-yield."

We will also discuss our definition in the new section 4.2 (see end of this manuscript for a full version of the new chapter 4.2):
"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."

We will also replace the words Nr efficiency by the appropriate term (NUE or SNUE) throughout the text.

In the following, we will answer to your comments 12 and 13, as they are on the same topic.

12. On page 2763 the soil nitrogen use efficiency is defined as the ratio between Nr soil inputs (fertilizer, manure, residues, atmospheric deposition, soil organic matter loss and free-living Nr fixers) and soil withdrawals (harvest and crop residues minus seed and biological fixation by legumes and sugarcane). It is not clear if biological N fixation by legumes and sugarcane is part of the withdrawal or not. I would argue that it is added to both the withdrawal AND to the inputs.

For the purpose of the model – to estimate the requirement of inorganic fertilizer and the amount of Nr lost on the field – we think that biological fixation that takes place within in the plant should be counter neither to soil inputs, nor to withdrawals.

We agree, that our definition of Soil Nr Uptake Efficiency (SNUE) diverges from the commonly used definition of Nr Uptake Efficiency (NUE). We believe, that our definition is better suited to estimate losses and can simulate the future dynamics of losses more correctly.

The main reasoning behind our new definition is, that Nr fixed from the atmosphere is not subject to losses prior to the uptake by the plant. While e.g. fertilizer leaches, volatilizes or denitrifies when it is applied to fields, this is not the case for biologically fixed Nr. Also Eggleston et al. (2006) assume, that Nr fixation itself has no significant direct impact on losses and thus emissions, but only via the decay of residues.
The decay of residues contributes to losses also in our model. Straw and roots (from both legumes and non-legumes) which remain on the field after harvest enter the soil inputs $N(x_t)^{inp}_{(t,i)}$. All soil inputs exceeding the withdrawals are considered as losses (eq. 28). Therefore, also Nr fixed biologically in straw and roots contributes to losses when it decays on fields.

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If biological fixation within the plant is not subject to losses, this also has implications on the model dynamics. Assuming a SNUE of 50%, replacing one ton of biologically fixed Nr requires two tons of other Nr inputs. Legumes and sugarcane therfore have a higher NUE compared to normal crops. This was also observed in reality, see for example Smil (1999).

We made this point more clear in the text on page 2763, as we already described in the answer to question 2.

13. The way the efficiency is calculated implies that any deficit is compensated for by fertilizer nitrogen. In other words, deficits are assumed not to exist?

Deficits may well exist in our model.

The crop yields in MagPIE reflect the actual yield. If a yield is low, this may have its origin in several climatic or management shortcomings, including the lack of nitrogen fertilizers. It may therefore well be, that the crop yield is so low, because the plant is Nr-deficient.
However, it would not be possible to reach these (even deficient) yields without sufficient Nr supply for these low yields. Nr requirements thus reflect Nr deficits, but Nr deficits do not explicetly determine crop yields.

We made this point clear in the text on page 2763
"In future scenarios, the soil withdrawals and the fixed SNUE determine the requirements for soil Nr inputs. If the amount of organic fertilizers is not sufficient, the model can apply as much nitrogen fertilizer as it requires to balance out the budget. In our model, the Nr inputs to crops have no influence on the yield. We assume in reverse that a given crop yield can only be reached with sufficient Nr inputs. An eventual Nr limitation is already reflected in the height of the crop-yield.“

3. On page 2787 it is assumed that “no losses from the internally fixed Nr occurs, while the Nr 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 Nr inputs". It is absolutely unclear what is meant here. Is N fixation by free-living bacteria lost? And is the N fixed by legumes not part of the soil-plant system, where the straw and roots are decomposed after harvest and subject to losses? But losses like surface runoff, denitrification and leaching are not computed directly.

Chapter A.3.4 is indeed confusing. We rewrite this chapter, concentrating on the technical implemention:
"We calculate regional soil nitrogen uptake efficiency (SNUE) $r_{(t,i)}^{Neff}$ by dividing total soil withdrawals $N(x_t)_{(t,i)}^{withd}$ by total soil inputs $N(x_t)_{(t,i)}^{inp}$.
eq A25
The soil inputs include inorganic fertilizer, manure, Nr released from soil organic matter loss, recycled crop residues, atmospheric deposition and Nr fixation by free-living bacteria and algae. Nr in seed as well as Nr fixation by legumes and sugarcane are not counted as soil inputs, as they reach the plant not via the soil. Soil withdrawals are calculated by subtracting from the Nr in total plant biomass (harvested organ, above- and belowground biomass) the amount of Nr that is not taken up from the soil and therefore not subject to losses prior to uptake. The latter includes again seed Nr as well as the Nr fixed from the atmosphere by legumes and sugarcane.
Eq A26 + A27
The loss of Nr from cropland soils $N(x_t)_{(t,i)}^{loss}$ is defined as the surpluss of soil inputs over soil withdrawals.
eq A28
As Nr from seed and biological fixation by legumes and sugarcane is integrated directly into plant biomass, we assume that these inputs do not contribute to losses.
For the year 1995, we use historical data on regional fertilizer consumption based on IFADATA (2011) to estimate $r_{(t,i)}^{Neff}$. In the following timesteps, $r_{(t,i)}^{Neff}$ is fixed on an exogenous level (see Sect. A4), while fertilizer consumption $N(x_t)_{(t,i)}^{fert}$ becomes en-

dogenously calculated by the model."

4. In figure 2, N fixation is 25 Tg, of which 15 in belowground tissue. So I wonder why this is not considered as being subject to losses, just like all other input terms. Or is this amount from free-living bacteria and the fixation in rice paddies?

The fixation of 15 Tg Nr does not refer to free-living bacteria or fixation in rice paddies. It is the Nr fixed in leguminous plants and sugarcane. To make this point more clear, we changed the legend of figure 2 and seperate between "Biol. fixation by crops" and "Other biol. fixation".
The N fixed within the plant is not subject to losses prior to decay, as we explained in our answer to comment 3+12.

5. The difference between the N fixation in the harvested parts in this study and other recent papers needs more attention (different base year, plant growth functions and N content of the grains), It is not clear what the reason is for this large difference. How can plant growth functions be of influence, because it is the production and N content that determine the result, and production is (hopefully) equal to the data from statistics. If the N content is different, why is that? And why not take the N content of Herridge in order to be consistent with that inventory?

Our estimate for legume fixation (7 Tg) is similar to the estimate of Sheldrick et al. (1996) (8 Tg) or Smil (1999) (10 Tg). However, it largely diverges from Herridge et al. (2008), who estimated fixation by legumes to contribute 21 Tg Nr (not including fodder or sugarcane).
There are several reasons, why we had lower total biological Nr fixation than Herridge et al (2008). Their estimate is based on the following formula

Fix = prod · hi · %Nr · crop:shoot · %ndfa

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with:

- Fix: Nr fixation
- prod: production
- hi: harvest index as ratio of shoot biomass to crop biomass
- %Nr: Nr content of shoot
- crop:shoot: Ratio of total Nr (shoot + root) to shoot Nr.
- %ndfa: Percent of crop Nr derived by fixation from the atmosphere.

Because we think that the parameterization of Herridge overestimates Nr fixation, we used an own parameterization for all of these factors, which mostly lead to lower estimates. We will explain this in the following on the example of soybean. Soybean makes up more than 75% (16.44 Tg Nr) of total crop legume fixation in the estimate of Herridge et al (2008), and is also responsible for the large difference in estimates.

- prod
  There are two differences concerning the production.
  Firstly, Herridge et al (2008) use a different base year (2005 instead of 1995). During this time period, global soybean production increased by 69%. Shifting the baseyear to 1995 reduces the estimate of Herridge et al by roughly 40%. Secondly, Herridge et al. (2008) did not correct for dry matter when applying their harvest index (they define it as dry matter grain to dry matter shoot ratio, but seem to apply it to wet matter grain production if I compare their number to FAOSTAT numbers). Correcting this error reduces their estimate of Nr fixation by another 10%.

- hi We use different aboveground harvest indices to estimate total plant biomass. Calculating our harvest index in 1995 in the same way as they do (dm grain to dm shoot ratio), our global harvest index is 0.36 as opposed to 0.4 by Herridge et al. (2008). The difference in harvest index actually decreases the difference in the estimates from Herridge et al (2008) and our estimate. With our harvest index the fixation rates are higher, as our shoot biomass is 2.75 times the grain mass, while it is only 2.5 times in the case of Herridge et al (2008). This increases our Nr fixation by 10% compared to their estimate.

- %Nr We use a different Nr content of the shoot: 2.4% as opposed to 3% by Herridge (2008). Our estimate is based on a relatively high value for soybean grains (5.12%) based on Fritsch (2007) and a value of only 0.8% for soybean residues (both Wirsenius 2000 and Eggleston 2006). This again results in 20% lower Nr fixation compared to Herridge et al (2008).

- crop:shoot For belowground biomass our assumptions are strikingly different. Again, we have a look at the prime fixation legume, soybean. We assume a DM root to shoot ratio of 0.19:1 and a Nr-content of 0.8%, both in accordance with Eggleston et al. (2006). Based on these assumptions, the global N root-to-shoot ratio in 1995 is in our case 6.4%. Herridge et al assume it to be 50%. Unfortunately, Herridge et al. (2008) provides no citation or argument for his assumption on the N root-to-shoot ratio. Stephen A. Williams, who carried out the literature review for Eggleston et al. (2006), provides several citations for his estimate of DM root to shoot ratio. I also tried to find some support for this ratio, finding for example Sivakumar (1977), whose field observations showed with 0.11:1 a even lower rootshoot ratio. Similarily, Dogan (2011) observed in field experiments ratios of 0.1:1 to 0.15:1. If we assume that the 0.19:1 DM root to shoot ratio is correct, the belowground biomass of Herridge would require to have an N content of 8%. This value is definetly too high. We used Egglestons (2007) estimate of 0.8% Nr per ton dry matter. This estimate is only based on a citation from the

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year 1925. However, Dogan et al (2011) come in a recent study to similar results, indicating N contents of 0.6 to 0.7%. We therefore believe that belowground N estimates from Herridge et al are significantly too high, and remain with Egglestons estimates for root:shoot ratio and N contents of belowground biomass. The differences in assumptions concerning the belowground biomass have a large effect and reduce Nr fixation of soybeans by 30%. .

- %ndfa Sixthly, used the rates of Nr derived from fixation from the atmosphere (%ndfa) estimates from farm observations (Peoples et al 2008 quoted in Herridge), while Herridget et al (2008) used values from experimental sites. The farm observations were actually not based on Herridge et al. (2008), but only quoted by Herridge and taken from Peoples et al (2008). For soybean, the main fixer, these values were 0.58 instead of 0.68. This results in a 15% lower fixation.

Aggregating the individual correction factors results in a reduction of Nr fixation from soybeans from 16.44 Tg Nr to 4.6 Tg Nr.
16.44 Tg Nr $\cdot 0.6 \cdot 0.9 \cdot 1.1 \cdot 0.8 \cdot 0.7 \cdot 0.85 = 4.6$ Tg Nr
This explains the large divergence of our estimates.

The reviewer proposed we should consider to use the N-content of Herridge also for our estimates. Unfortunately, this is not possible as Herridge et al (2006) only considers the Nr content of the total AG shoot biomass, while we need a seperation into harvested organ and crop residues.
However, for consistency reasons, we now changed our parameters to the values from experimental sights that were also taken by Herridge et al. (2008). This also allow to distinguish them regionally (see answer to question 6)
We now come to fixation by soybeans of 5.4 Tg Nr and a total Nr fixation by legumes and sugarcane of 9.3 Tg Nr.

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To point the differences in estimates more out, we change the discussion on page 2769 as follows:

"To estimate the fixation by legumes and sugarcane, we use a new approach based on percentages of plant Nr derived from fixation, similar to Herridge et al (2008). This, in combination with total above-and belowground Nr content of a plant, can predict Nr fixation more accurately. However, we think that the parametrisation of Herridge et al (2008) overestimates Nr fixation, especially for soybeans. Most importantly the Nr content of the belowground residues as well as the shoot:root ratio seem too high when comparing them with Eggleston et al (2006), Sivakumar et al (1977) or Dogan et al (2011). But also the Nr content of the shoot seems too high given that soybean residues have a much lower Nr content than the beans (Fritsch 2007, Wirsenius 2000 and Eggleston 2006). Correcting the estimates of Herridge et al (2008) for the water content further reduces their estimate. If one finally accounts for the difference in baseyear between the two estimates, with global soybean production increasing by 69% between 1995 and 2005, we come to a global total fixation from legume and sugarcane of 9 Tg Nr in 1995 as opposed to 21 Tg Nr in 2005 in the case of Herridge et al. (2008). Our estimate is inbetween the estimates of Smil (1999b) and Sheldrick (1996), even though using a different approach."

6. The N fixed by legumes is thus assumed to be in the harvested parts only. This is not correct, since the N fixed is also in the straw and root tissue.

We do not assume that fixed Nr is only in the harvested parts.

We state this in several parts of the manuscript:

- In the methodology (p. 2762)
  "The Nr fixed by leguminous crops and sugar cane is estimated by multiplying Nr in total plant biomass (harvested organ, AG and BG residue) with plant specific percentages of plant Nr derived from N2 fixation (Herridge et al., 2008)."

- in the discussion p2769
  old version: "Our methodology uses the percentage of plant Nr derived from fixation. This, in combination with total above- and belowground Nr content of a plant, can predict Nr fixation more accurately."
  new version: "To estimate the fixatio by legumes and sugarcane, we use a new approach based on percentages of plant Nr derived from fixation, similar to Herridge et al (2008). This, in combination with total above-and belowground Nr content of a plant, can predict Nr fixation more accurately."
- in the Appendix (p. 2785, 2786, 2787).

We do not know to which part of the text the Reviewer is referring. If there is a misleading formulation in the text, please indicate the page and line number so we can correct this error.

Another problem is the nitrogen fertilizer applied to leguminous crops, which may be considerable in some countries like Egypt. This means that the fractions of nitrogen in the harvested parts which is assumed to be from nitrogen fixation, is actually from fertilizer, so nitrogen fixation needs to be corrected for this.

We agree, that different management can lead to different rates of Nr fixation. Most importantly, if root nodules are not inocculated properly, or if too much inorganic fertilizer is applied, Nr fixation rates can be reduced significantly. To account for the regional variations in management, we change the model accordingly.
Management practices may vary considerably between regions. To account for this, we use again the approach of Herridge et al (2008). The differentiation of soybean as the largest single legume fixer is again of the largest importance. Of global soybean production, four countries make up more than 85% of the producion: United States, Brazil, Argentina and China (FAOSTAT 2012). We assume, based on Herridge, that the percentage of crop Nr derived from biological fixation from the atmosphere (%ndfa) in North America is 60%, in Latin America 80%, in Centrally planned Asia 50%. In

all other regions we assume the world average of 68%. The same values were also applied to groundnuts, which have according to Herridge the same fixation rates. Similarily, we now distinguish fixation rates of sugarcane to 20% ndfa in Latin America and 10% ndfa in the rest of the world.

We make this change in methodology clear in the following parts of the paper: p.2762 line 26:
"The Nr fixed by leguminous crops and sugar cane is estimated by multiplying Nr in total plant biomass (harvested organ, AG and BG residue) with regional plant specific percentages of plant Nr derived from N2 fixation (Herridge et al., 2008)."

p. 2785
"For legumes and sugar cane, where Nr fixation is the direct product of a symbiosis of the microorganisms with the crop, we assumed that fixation rates are proportional to the Nr in the plant biomass. The percentage of fixation-derived Nr is taken from Herridge et al (2008). In the case of soybeans, groundnuts and sugarcane, fixation rates vary between regions to account for differences in management practices like fertilization or inocculation."

Finally, we change the table A.6 to include the regional values.

7.-9.
Comments 7-9 all refer to soil organic matter loss. We will answer each question individually. However, since the whole description of the methodology in the appendix on page 2786 line 10-25 changed, we will present the whole revised version of the text in the end of question 9.
Also, a new table A7 (see attachment) will be included into the appendix, giving details on the calculation of soil organic matter loss.

7. A further question is about the contribution from soil organic matter loss. The authors state that they considered the conversion of forest and grassland to cropland for the period 1980-1990. It is peculiar that 1980-1990 data is used

for 1995, since the cropland expansion for 1990-2000 is much less than in the decade before.

According to Eggleston et al. (2006), the time of soil organic matter loss after conversion is approximately 20 years. Ideally, the period to estimate Nr release from soil organic matter loss in 1995 would be 1975-1995.
If we use the HYDE data for 1990-2000 for the calculation of soil organic matter loss, we come to very high numbers for soil organic matter loss (see new table below). This is very surprising, because (as the reviewer mentioned), the land-expansion from 1990-2000 was rather low. The HYDE database in contrast has much higher rates of land-expansion in this period. When we noticed this we asked Mr Kees Klein Goldewijk for the reason. He answered us by email that FAO made an update of its database in 2011 and reduced its cropland area dramatically compared to the FAOSTAT estimate in 2008. A corrected version of the HYDE database is not yet available.
We therefore decided not to use the period from 1990-2000.

We make this point clear in the rewritten part of the appendix, page 2786
"The results for the historical estimates can be found in Table A7. The estimates for 1990-2000 are too high. The HYDE estimates are based on an older release of FAOSTAT data, while more recent FAOSTAT data corrected the land-expansion significantly downwards, reaching even a negative net-expansion for the period 1990-2000 (Klein-Goldewijk, personal communication). For our estimate of Nr released by soil organic matter, we used the estimates for the period 1980-1990."

In addition, FAO does not provide the conversion of grassland to cropland, so I wonder where this information is coming from.

In our methodology, it is not important whether pasture or natural vegetation is converted to cropland. According to Eggleston et al. (2006), soil carbon in pastureland does not significantly differ from soil carbon in natural vegetation. Only after conversion to cropland, a significant reduction takes place. It does therefore not matter whether the cropland expansion goes into pasture or natural vegetation.

Our formulation in the Appendix, p.2786 is misleading. We change the paragraph as follows: "When pastureland or natural vegetation is transformed to cropland, soil organic matter is lost. This also releases Nr for agricultural production. As pastureland and natural vegetation have a similar level of soil organic matter (Eggleston 2006), we can calculate the Nr inputs from soil organic matter loss ($N^{som}_{(t,i)}$) on the basis of cropland expansion, independent of whether this expansion occurs into natural vegetation or pastureland.“

The expansion of cropland according to HYDE is 69 million hectare for 1980-1990.

We used the HYDE database instead of FAOSTAT because this allows us to estimate not only the net expansion of cropland, but the total land-expansion. If one hectar is deforested in one cell and abandoned in a different cell of the same country, the net-land expansion (thus the one captured by FAOSTAT) is zero. The brutto land-expansion, which is important for the release of soil organic matter, however is 1 ha. This process is rather important: In the HYDE database, the net-expansion in the period 1980-1990 is 69 ha, while the brutto land-expansion is 103 ha. As described in our article (p.2786), we only counted the brutto-expansion that went into land that was historically not used as cropland.

We change the text on p.2786 as follows
"As MAgPIE is calibrated to the cropland area in 1995, no land expansion occurs in this timestep. Instead, we use the HYDE database with a 5’ resolution (Klein Goldewijk et al., 2011) to estimate historical land expansion per grid-cell and the initial contribution of soil organic matter loss to the cropland budget. The cropland area as covered by FAOSTAT (2011) only allows to estimate the net-change of cropland area; expansion

and contraction of cropland area within the same country cancel out. The spatial explicit HYDE database allows to estimate actual land conversion, defined as the sum of (positive) cropland expansion in each geographic grid-cell into land which was not used as cropland since the year 1900. In the case that cropland area first shrinks and then increases again, it is assumed that the same cropland area is taken into management that was abandoned before, so that no new soil organic matter loss takes place. The results for the historical estimates can be found in Table A7."

To make this point more clear, we add an extra column in the new table A7 (see attachment) indicating both net expansion and land conversion.

With a soil N loss of 28 Tg in 1995,

We made a mistake when we copied the value from our calculations into the paper. The actual values was 25 Tg Nr (we used the correct value in the model for the projections). We correct this value in our paper.

this means that 400 kg of N is lost per year and per hectare, or 4 tonnes of nitrogen for a 10-year period. I assume that the soil organic matter loss after the conversion to cropland takes 10 years. The soil organic carbon loss would thus be 6100 kg C, or 12 tonnes of soil organic matter, or 120 tonnes of soil organic matter over a 10-year period. As a global average this sounds like a large amount, and this important term in the global cropland nitrogen balance needs more explanation for readers to understand.

We agree that the amount of Nr released by soil organic matter loss is enormous. However the numbers of Nr release per ha and year are lower.
Firstly, the brutto area expanded is – as we noticed above – higher and reaches 103 Mha in the period 1980-1990. Therefore, the average amount released by land-expansion in the 10-year period 1980-1990 is 36 t C per ha or 2.4 t Nr per ha.
Secondly, this amount of Nr is not instantly released , but over a period of approximately 20 years (Eggleston 2006 Chapter 2 page 2.30). The annual release per ha

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land-expansion is therefore in average 1.8 t C or 122 kg Nr per ha per year.

These calculations will be published in a new table A7 in the appendix. You find the table attached to this document.

8. The inclusion of this soil loss term in the global nitrogen balance is fine, but it needs to be stressed that this term does not add to the nitrogen to all croplands, but only in those areas where recently forest has been cleared for cropland expansion. And since it is such a large amount that cannot be taken up by the crops, most of it is probably lost by surface runoff, leaching and denitrification and does not contribute to crop uptake. This will occur if this term is used in the regional nitrogen budgets.

We agree with the reviewer, that the Nr release might surpass the amount of Nr that can be taken up by crops. Also, it may distort the regional nitrogen efficiencies if the amount of Nr that cannot be taken up by crops is significantly higher than in the case of other Nr inputs like manure or fertilizers.
We therefore analyzed not only the regional average of Nr release, but also the variance between grid-cells. If we limited the amount of Nr input per ha to 150 kg per ha and year, the contribution of soil organic matter loss to the cropland budget was reduced from 25.0 Tg to 21.9 Tg Nr per year. The reduction took mainly part region FSU, which has very carbon-rich soils.
It is difficult to judge, whether the amount of losses is higher in the case of soil organic matter loss than for other inputs. Inorganic fertilizer is also often applied in far too high rates. In China, for example, average inorganic fertilizer application is 200 kg per ha, with some regions exceeding 400 kg per ha (Smil 2002). Also, in regions with a strong livestock sector , manure is applied in excessive rates because it cannot be transported cheaply to where it is needed.
We therefore decided to keep the full amount of Nr from soil organic matter loss in our budget, but to critically assess this point in our discussion:

p 2769 line 29
"...cropland has released 25 TgNr in 1995. With a yearly global average release of 122 kg Nr per ha newly converted cropland, the amount of Nr released will often exceed the nutrients actually required by the crops, especially in temperate, carbon rich soils. The cultivation of histosoils..."

9. For the future, this term is fixed exogenously according to the scenario assumptions. This sounds strange, because the model simulates land transformations, so can calculate forest conversion and thus the nitrogen from soil organic matter loss, instead of the assumptions on page 2765. For example, the assumption that in the B1 and B2 scenarios, forest clearing will be halted may not be correct if biofuel production will increase rapidly in future (which could be in B1 and B2).

We agree that an endogenous calculation of soil organic matter loss would be a large model-improvement. We therefore take up the reviewer comment, and change the model accordingly. Future soil organic matter loss is now determined by cropland expansion in MAgPIE.

We describe our implementation in the manuscript and in the appendix:

We delete on P. 2765 the lines 17-19
"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."

and insert instead on page 2763
"Nr release by the loss of soil organic matter after the conversion of pasture land or natural vegetation to cropland is estimated based on the methodology of Eggleston et al. (2006). Our estimates for 1995 use a dataset of soil carbon under natural vegetation from the LPJmL model (Sitch et al., 2003; Gerten et al., 2004; Bondeau et al., 2007). For 1995, we use historical land-expansion from the HYDE-database (Klein Goldewijk

et al., 2011), while the land-expansion in the future is estimated endogenously by MAgPIE."

In the appendix, we change the paragraph on page 2786 line 10 as follows:

"When pastureland or natural vegetation is transformed to cropland, soil organic matter is lost. This also releases Nr for agricultural production. As pastureland and natural vegetation have a similar level of soil organic matter (Eggleston 2006), we can calculate the Nr inputs from soil organic matter loss ($N^{som}_{(t,i)}$) on the basis of cropland expansion, independent of whether this expansion occurs into natural vegetation or pastureland. Cropland expansion $X(x_t)^{areaexp}_{(t,j)}$ is calculated as the increase of $X(x_t)^{area}_{(t,j,v,w)}$ into area that has previously not been used as cropland. After the conversion of cropland, we assume that cropland management releases 20–52% of the original soil carbon, depending on the climatic region (Eggleston et al., 2006), plus the full litter carbon stock of the cell. Soil and litter carbon were estimated using the natural vegetation carbon pools of LPJml. Yearly Nr losses after the potential conversion of an hectare cropland ($r^{som}_{(t,j)}$) are then estimated on a cellular basis from the carbon losses, using a fixed C:N ratio of 15 for the conversion of forest or grassland to cropland and dividing the result by 20 years, which is the time assumed until the cabon stock arrives in the new equilibrium (Eggleston 2006). Soil organic matter loss is finally estimated by multiplying the cropland expansion in each grid-cell with the yearly Nr losses per ha. For simplification, we assume that instead of releasing the Nr in two consecutive timesteps (20 years), the Nr is fully released in the timestep of conversion, and therefore multiply with 2.

$$N^{som}_{(t,i)} = X(x_t)^{areaexp}_{(t,j)} \cdot r^{som}_{(t,j)} \cdot 2$$

As MAgPIE is calibrated to the cropland area in 1995, no land expansion occurs in this timestep. Instead, we use the HYDE database with a 5' resolution (Klein Goldewijk et al., 2011) to estimate historical land expansion per grid-cell and the initial contribution of soil organic matter loss to the cropland budget. The cropland area as covered by FAOSTAT (2011) only allows to estimate the net-change of cropland area; expansion and contraction of cropland area within the same country cancel out. The spatial explicit HYDE database allows to estimate actual land conversion, defined as the sum of (positive) cropland expansion in each geographic grid-cell into land which was not used as cropland since the year 1900. In the case that cropland area first shrinks and then increases again, it is assumed that the same cropland area is taken into management that was abandoned before, so that no new soil organic matter loss takes place. The results for the historical estimates can be found in Table A6. The estimates for 1990-2000 are too high. The HYDE estimates are based on an older release of FAOSTAT data, while more recent FAOSTAT data corrected the land-expansion significantly downwards, reaching even a negative net-expansion for the period 1990-2000 (Klein-Goldewijk, personal communication). For our estimate of Nr released by soil organic matter, we used the estimates for the period 1980-1990."

Estimates for future soil organic matter loss are included into the new parameter overview table in the supplementary material.

Finally, we add a sentence to page 2771 line 9
“Nr release from soil organic matter (SOM) loss contributes to the Nr budget also in the future, yet with lower rates. In the environmentally B oriented scenarios, cropland expansion and therefore also SOM loss almost ceases due to forest protection, while in the economically oriented scenarios, the loss of SOM still contributes 10 (A1) and 18 (A2) Tg Nr per year. In the A2 scenario the loss even continues at low rates until the end of the century. The reduced inputs of soil organic matter loss have to be replaced by inorganic fertilizers.”

10. Regarding the scale of the calculations, it is not clear if the nitrogen balances are calculated on a regional basis, or spatially explicit. I assume that it is on a regional basis, but this needs to be stated more clearly.

We agree with the reviewer that the scale of calculations for nitrogen balances has to be more clearly described. We therefore will change the manuscript on p. 2763, line 10 (please note the changes made in response to your second comment) to:

“Regional inorganic fertilizer consumption in 1995 is obtained from IFADATA (2011). [...] SNUE is calculated on a regional level for the year 1995 and becomes an exogenous scenario parameter for future estimates.“

and page 2878 line 16
"In the following timesteps, $r^{Neff}_{(t,i)}$ is fixed on an exogenous level (see Sect. A4), while the model can balance out the regional budget with inorganic fertiliser."

11. If this is so, the nitrogen use efficiency is lumped at the scale of the 10 MagPie regions. This is another problem. If the crop mix changes, for example if the share of nitrogen fixing crops increases, or the share of rice, the use of the nitrogen use efficiency as a scenario variable is not correct.

It is one advantage of our definition of SNUE, that the different NUE of legumes and non-legumes can be accounted for.
Assume the biomass of a lentil plant to contain 100 kg Nr. It receives approximately 50%, thus 50kg of its Nr from biological fixation. The remaining 50kg have to stem from external sources. With a SNUE of 50% this requires fertilizers with 100kg Nr. The NUE is thus 100/(50+100) = 75%, much higher than the average crop where it is 50%. These higher NUE of legumes and forages have also been observed in realitiy. Smil (1999) estimates that normal crops have a NUE of 0.35-0.55, while legumes and forages have uptake efficiencies of 0.65 and 0.75 respectively.

Nevertheless, we agree that many other processes that determine SNUE are not covered within the model. Different crop species have a different ability taking up available soil Nr. Similarily, different types of Nr fertilizers (Manure, residues, inorganic fertilizer) can be taken up better or worse. Thus a change in composition of crop species or Nr inputs should have an influence on Nr efficiency. Besides, there are numerous other factors influencing SNUE like management or climate.
Our approach, assuming that every Nr input will be taken up with the same Nr efficiency is thus a simplification. However, the processes that determine Nr uptake efficiency are

very complex. This is one reason, why we made it an exogenous scenario parameter. This makes our underlying assumptions clear.

We will discuss this in the new chapter 4.2. which critically assesses our scenario assumptions (see end of this manuscript for a full version of the new chapter 4.2).

"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.“

Comment 12 and 13 were answered earlier (see above)

14. Although the Appendix presents many details about the methods, data and model, it is not possible to understand how the model works and how scenarios were constructed. For example, the food demand is expressed as EJ (figure A2). Readers would be grateful to see the actual regional domestic production in tonnes, and also the cropland areas, yield development and fertilizer use. That would also clarify a bit more why fertilizer use increases so rapidly under A1 assumptions, and decreases so rapidly in B2 and not in B1.

In response to this valuable comment we now want to include a large list of model outputs into the supplementary material, including domestic production in tons and Nr, cropland areas, yield development and fertilizer use.
The table also includes the distribution of production to food, feed, material demand,

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seed, exports. It also includes all cropland inputs and withdrawals, such that model dynamics can be easily traced back.

Also, the new section of the discussion 4.2 will assess the implications of our scenario assumptions (see end of this manuscript for a full version of the new chapter 4.2)

15. In the A1 scenario fertilizer use increases very rapidly. This is peculiar, because at present fertilizer use efficiency is increasing in industrialized countries, and one could expect that the same will happen in developing countries. China and India are currently the major consumers of fertilizer nitrogen, determining a large part of the global total and its increase. When China and India develop, subsidies will probably decrease or be stopped, so the efficiency will have to increase. This will not be only in the environmentally oriented scenarios.

The strong increase of fertilizer use in the A1 scenario has several reasons. Most importantly, the strong increase in income leads to higher total consumption, and also to an increasing consumption of livestock products. The latter requires the production of feedstock. Along with strong economic growth goes the rapid modernization of the livestock sector with higher fraction of Nr rich concentrate feed and conversion byproducts. This leads to a very high total production.
The increasing soil Nr uptake efficiency, which is also part of the storyline, is slowing down the increase in fertilizer consumption. As shown in table 1, our scenario assumptions include a strong increase in Nr uptake efficiency in all scenarios. In the B scenarios it reaches levels that can be seen as very optimistic, as no current region comes close to this value presently.
We also assume a catch-up concerning the efficiency, such that all regions reach the same NUE in 2045. E.g. China wil therefore have much higher growth rates in efficiency than the Europen Union.
To make the development of nitrogen efficiency more clear, we will also include thes values both globally and regionally into the new tables in the supplementary material.

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Additional to the new table in the supplementary material, the new chapter 4.2 (see end of this manuscript for a full version of the new chapter 4.2) explains the implications of our scenario assumptions and discusses the future development of Soil Nr uptake efficiency (SNUE).

16. Page 2771, last paragraph: global simulated fertilizer use for 2005 agrees with the statistics, but the regional results do not. This is rather frightening, if after 10 years the model already deviates from the data, because the effect of wrong scenario assumptions will be dramatic after 100 years. The regions where fertilizer use is underestimated are those where nitrogen use is most important globally (see also 15 above), and this means a considerable overestimation in other regions. It is also interesting to discuss the large difference between IFA and FAO regional data, which seems to be especially large in the period 2005-2010.

We agree, that our regional estimates are of a lower quality than the global estimates. These variations can be largely explained by trade dynamics. These dynamics are extremely difficult to predict (and our model certainly has a simplified representation compared to more economically oriented CGE models), but have a strong impact on regional results. However, the global estimates are not necessarily influenced by this. If grains are exported from Europe to North America, more fertilizer will be used in Europe, but less in North America. These two trends cancel out more or less on a global level, but have a strong effect on the regional budgets.

In the new section 4.2 (see end of this manuscript for a full version of the new chapter 4.2), we enter the following text:
“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.“

Trade is not the only origin of uncertainty. Also our underlying GDP and population scenarios are itself scenarios with high uncertainty. SRES GDP estimates in China diverge by factor 0.4 to 1.1 from actual GDP measured in 2010, in MEA by factor 1.2 to 1.8. As our scenarios are just representative pathways, I think that they are not outside the uncertainty range.

Moreover, after the diverse changes to the model undertaken for the review, our results are now differnt.

Inorganic fertilizer consumption in Europe stagnates or only slightly increases in all scenarios, which is absolutely in line with the development since the 90s. Also China shows a continuous increase in consumption, even though at slower pace than in the last decades.
In India, fertilizer consumption rose sharply in the last decades, while our projections

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suggest a stagnating or only little increasing fertilizer consumption. Pacific OECD (Japan, New Zealand and Australia) in contrast, arise as new exporter of crop products and have a strongly increasing fertilizer demand.

We will rewrite the section (page 2771 last paragraph) as follows, also taking up your comment on the differences between IFADATA and FAOSTAT (which was new to us): "Data on historic fertilizer consumption is provided by IFADATA (2011) and FAOSTAT (2012). 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. However, 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."

Some minor comments are: - Page 2759, last para: the existing model must be extended, or has been ?

We changed it to "has been".

Atmospheric deposition: is it the same for all scenarios? That is strange, because the scenarios are so different, probably also causing differences in emissions and thus deposition.

We agree that atmospheric deposition should be consistent with Nr emissions in each scenario.

Therefore we decided to connect the growth rate of atmospheric deposition to the growth rate of the amount of Nr that volatilizes in the form of NOx and NHy during cropland fertilization.
In reality, NOx and NHy emissions from industry and traffic, also determine the deposition rates. However, as a major part of volatilized Nr will be deposited close to the emission source, the largest part of cropland atmospheric deposition should also stem from agricultural Nox and Nhx emissions.

P2763 line 5
"The regional amount of atmospheric deposition on croplands for 1995 is taken from Dentener (2006). For future scenarios, we assume that the atmospheric deposition per cropland area grows with the same growth rate as the average regional agricultural NOx and NHy emissions (see chapter 2.3.4)."

P. 2785 line 4 ff
"A major part of the Nr lost from field in the form of NOx and NHy as well as other Nr 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 atmospheric deposition rates per area for each region (r_i^{dep}). For the future we assume, that these deposition rates grow with the same growth rate as the agricultural NOx and NHy emissions $N(x_t)^{volat}_{(t,i)}$ (see A35 in section A.3.5). This implies the assumption that cropland deposition of NOx and NHy from non-agricultural sources grow with the same growth rate as agricultural NOx and NHy emissions. As a large part of volatilized Nr will be deposited close to the emission source, the largest part of cropland atmospheric deposition probably stems from agricultural NOx and NHx.

$N(x_t)^{dep}_{(t,i)} = N(x_t)^{volat}_{(t,i)})/(N(x_t)^{volat}_{(t-1,i)} \cdot \sum_{(j,v,w)} X(x_t)^{area}_{(t-1,j,v,w)} \cdot r_i^{dep}$ "

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finally on page 2788, we add the following lines after line 15:

"The NOx and NHy volatilisation on cropland area $N(x_t)^{volat}_{t,i}$, which is required for the calculation of atmospheric deposition in formula A23, section A.3, is calculated as follows

$$N(x_t)^{volat}_{(t,i)} = N(x_t)^{fert}_{(t,i)} \cdot r_i^{(gas\_fert)} + (N(x_t)_(t,i)^m + N(x_t)^{ex}_{(t,i,l,grazp)} + N(x_t)^{ex}_{(t,i,l,grazc)}) \cdot r_i^{gas\_m} + (N(x_t)^{ex}_{(t,i,l,house)} \cdot r_i^{gas\_awms}$$ "

We come to very similar results than Dentener (2006), with a global total of 26-31 Tg Nr in 2045 (old implementation 27-30 Tg Nr). Also on a regional level, atmospheric deposition rates match very well, only in AFR deposition is higher and in SAS it is lower compared to the old implementation.
Our estimates for atmospheric deposition can be found in the new additional output table in the supplementary material.

- Page 2769, last para: N accumulation is not considered in this paper.

We agree that N accumulation is not considered. We should make more clear that our calculations of soil organic matter loss only estimate soil Nr depletion, not accumulation.

We therefore change the sentence as follows
"Accumulation or depletion of Nr in soils has so far been neglected in future scenarios (Bouwman et al., 2009, 2011), assuming that soil organic matter reached a stable equilibrium and all excessive Nr will volatilize or leach. 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 the depletion of soil organic matter after transformation of natural vegetation or pasture to cropland has released 25 Tg Nr in 1995. ..."

- Page 2771, first para: using constant excretion rates implies that the feed conversion ratio decreases and excretion per unit of product decreases, which re-

flects an improving efficiency. Simply assuming an increasing efficiency sounds counterintuitive.

We do not agree that an increasing feeding efficiency is counterintuitive. In an interregional comparison one can well see that developed countries have higher feeding efficiencies.

However we should make more clear, on which assumptions both methods are based, and what are eventual shortcomings.

We think that the implementation by Bouwman et al. (2011) underestimates manure excretion. While the modernization of the livestock sector should indeed decrease the amount of manure per livestock unit, this does not mean that productivity improvements are not connected to changing excretion rates at all. IPCC (1996) for example estimates excretion rates of dairy cattle to be 60 kg Nr per animal in Africa, while in North America, excretion rates are 100 kg Nr per animal. At the same time, the excretion per livestock product is 1.75 kg Nr / t DM in Africa and 0.4 kg Nr/ tDM in North America. Productivity improvements are therefore connected both to an decrease in excretion per animal products and an increase in excretion per animal.

In contrast to Bouwman et al (2011), our methodology has the disadvantage that while all regions converge towards European productivity, no productivity improvements beyond the European level are possible. This in turn translates into an overestimation of manure excretion. We make this point more clear in the new chapter 4.2

"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.“

and on p. 2771 line 4:

"Secondly, Bouwman et al. (2011) assume rising Nr excretion rates per animal for the past, but constant rates for the future, such that weight gains of animals are not connected to higher excretion rates. As the current excretion rates in developing regions are still lower than in developed regions (IPCC 1996), this assumption might underestimate the growth of excretion rates in developing regions. Our implementation calculates excretion rates based on the feed baskets and the Nr in livestock products. Under the assumption that developing countries increasingly adopt the feeding practices of Europe, this top-down approach results in increasing excretion rates per animal in developing regions. However, as we assume no productivity improvements in developed countries, we tend to overestimate future manure excretion in developed countries."

- Page 2779: the IMAGE model also accounts for nutrient withdrawal by fodder crops.

I assume that in the context of page 2779, you mean that the IMAGE model also accounts for conversion byproducts. We were not aware of this, and therefore we delete the sentence
"So far, they have not been accounted for in most global material flow analysis, an exception being Wirsenius (2000) and Weindl et al. (2010)."

As we also write on page 2757 line 16 that
"Above all, most studies do not consider fodder crops and belowground residues as major Nr withdrawals from cropland soils."

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we will also change this sentence. Even though in earlier estimates like Sheldrick (1996) or Liu (2010) fodder crops were not included, large models like the IMAGE model probably account for fodder crops. We therefore reformulate the paragraph more conservative:

"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 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."

- Page 2791, line 19-23: a comparison with 2012 food demand statistics is needed here.

The comparison of actual food demand and simulated food demand is done in figures A2 and A3. The past observations overlap with our simulated results in the year 1990-2009. In addition, we now add the following sentence:
"The food demand projections are based on population and income growth of the SRES scenarios. As can be seen in figure A2 and A3, the historical data is met more or less precisely depending on the scenario. Global food calory demand diverges in 2005 by 98 PJ (+0.4%) (B1) to 452 PJ (1.7%) (B1), while meat demand diverges by -244 PJ (-5.2%) (A2) to +60 PJ (1.2%) (B2). The largest differences can be observed in the estimates for CPA, where the A2 scenario diverges by -422 PJ (-31.5%) while the B2 scenario almost matches the observed data with 15 PJ (+1.1%). Large parts of these variations in estimates are determined by the uncertainty of the original SRES projections for population and GDP."

The newest available year for FAOSTAT food supply statistics is 2007. As the SRES data is only available in 5 year timesteps, we compared the data to 2005.

- Table 1: fertilizer use in some world regions is insignificant. When fertilizer use increases in such places, efficiency will go down.

We do not agree, that efficiency should necessarily go down when fertilizer use increases.

Certainly, the Nr efficiency of a farming system would go down if additional fertilizer was applied with all other parameters staying equal.
But in our model, the increased fertilizer application is a consequence of increased production, which requires larger amounts of fertilizers. Thereby, the amount of fertilizer has no influence on the crop yields, but the given crop yield and the given soil nutrient uptake efficience determine the amount of Nr, that is required for fertilization.

We will make this point more clear in the last paragraph of section 2.3.3 on page 2763 In future scenarios, the soil withdrawals and the fixed SNUE determine the requirements for soil Nr inputs. If the amount of organic fertilizers is not sufficient, the model can apply as much nitrogen fertilizer as it requires to balance out the budget. In our model, the Nr inputs to crops have no influence on the yield. We assume in reverse that a given crop yield can only be reached with sufficient Nr inputs. An eventual Nr limitation is already reflected in the height of the crop-yield.“

I do not know how the soil organic matter loss would add to the inputs and determine the efficiency, but this needs explanation on a regional level, for example with a few examples.

Soil Nr uptake efficiency (SNUE) is deteminded in 1995 as described in the Appendix A3.4. As this paragraph was not written very well, we rewrote it (see answer to comment 3). In table 3, which includes all soil inputs and withdrawals on a global scale, we replace the name of the line "IN/OUT" and "IN*/OUT*" by "NUE" and "NUE*". Additionally, we add two rows with "SNUE" and "SNUE*".

Finally, in the new supplementary material, all Nr inputs and withdrawals which are used for the calculation of NUE and SNUE in 1995 are listed, both globally and regionally. This table allows to see, how large the contribution of organic matter loss, fertilizer or residues is to the regional budgets.

As we referred several times only to fragments of the new chapter 4.2, we will in the following show the full chapter 4.2 in one piece. It shall be located on page 2770, between the chapters “The current state of the agricultural Nr cycle” and “The future expansion of the Nr cycle”.

"**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 external shocks or abrupt changes of dynamics. They merely diverge in the interpretation of past dynamics or the magnitude of change assigned to certain trends. Population grows at least until the mid of the 21st century, and declines first in developed 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.

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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. "

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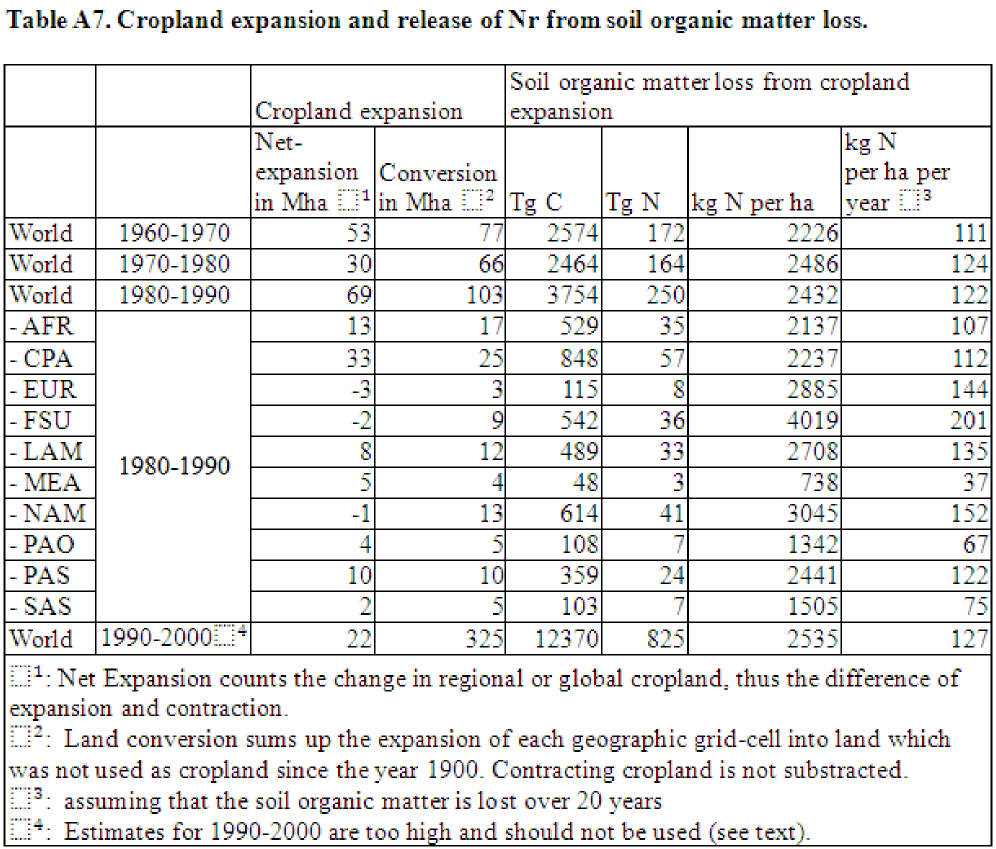

Table A7. Cropland expansion and release of Nr from soil organic matter loss.

		Cropland expansion		Soil organic matter loss from cropland expansion			
		Net-expansion in Mha [1]	Conversion in Mha [2]	Tg C	Tg N	kg N per ha	kg N per ha per year [3]
World	1960-1970	53	77	2574	172	2226	111
World	1970-1980	30	66	2464	164	2486	124
World	1980-1990	69	103	3754	250	2432	122
- AFR	1980-1990	13	17	529	35	2137	107
- CPA		33	25	848	57	2237	112
- EUR		-3	3	115	8	2885	144
- FSU		-2	9	542	36	4019	201
- LAM		8	12	489	33	2708	135
- MEA		5	4	48	3	738	37
- NAM		-1	13	614	41	3045	152
- PAO		4	5	108	7	1342	67
- PAS		10	10	359	24	2441	122
- SAS		2	5	103	7	1505	75
World	1990-2000 [4]	22	325	12370	825	2535	127

[1]: Net Expansion counts the change in regional or global cropland, thus the difference of expansion and contraction.

[2]: Land conversion sums up the expansion of each geographic grid-cell into land which was not used as cropland since the year 1900. Contracting cropland is not substracted.

[3]: assuming that the soil organic matter is lost over 20 years

[4]: Estimates for 1990-2000 are too high and should not be used (see text).

Fig. 1. Table A7: Cropland expansion and release of Nr from soil organic matter loss.

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