NITROGEN MANAGEMENT INTERACTIONS WITH CLIMATE CHANGE: A POLICY BRIEF TO INFORM THE GOTHENBURG PROTOCOL REVISION

Informal document to the Executive Body for the Convention
(28th Session, 13th-17th December, 2010) from the Task Force on Reactive Nitrogen

In response to a request of the 27th session of the Executive Body (ECE/EB.AIR/99, Para. 86 (c)), the Task Force on Reactive Nitrogen agreed to deliver a report on "Nitrogen and Climate" to inform the Gothenburg Protocol revision process.

This report is primarily directed at Executive Body delegates of CLRTAP Signatory countries and other air pollution policy makers. The document is an executive summary of a more elaborated report prepared by the TFRN on "nitrogen management and the mitigation of air pollution and climate change", to be released by the end of 2011. This report is also intended to inform the UNFCCC for its preparation of the 5th Assessment Report.

0. Main messages

- Nitrogen emissions to air and waters greatly contribute to both air pollution and climate change.

- Nitrogen management measures may affect air pollution, climate change, food production and biodiversity simultaneously.

- There are various management measures with synergistic effects on air pollution mitigation and climate change mitigation.

- The relationships between nitrogen management and climate change mitigation are complex. There is still a limited understanding of the interactions between nitrogen management, air pollution mitigation and climate change mitigation at regional and global scales. It is recommended that the Convention (through TFRN) should collaborate with IPCC to further explore the intricacies of relation between nitrogen and climate policy.

- Not only direct effects of NH_3 and NO_x emissions to air should be considered in a cost-benefit analysis, but in addition a chain of consecutive additional effects, including those on climate change.

1. Role of this document

1. The efforts of the CLRTAP in relation to nitrogen started out with a single pollutant strategy focused on NO_x. Subsequently, gradual integration between SO_2, NO_x, VOC and NH_3 led in 1999 to the multi-pollutant multi-effect Gothenburg Protocol. Since then, it has become even more clearly recognized how different forms of nitrogen pollution are interlinked. The establishment of the Task Force on Reactive Nitrogen (TFRN) has provided the basis to start developing a more-integrated approach towards all forms of reactive nitrogen (N_r) linking to the whole N-cycle and to climate. The TFRN thus aims to link a primary focus on air pollution threats of N_r, with their interactions with other nitrogen forms, including water pollution and perturbation of climate.

2. Both air pollution and climate change have their origin in human perturbation of element cycles (carbon, nitrogen and others) at regional and global scales. This common basis has been known for some time, but policies on the mitigation of air pollution and climate change have been developed and implemented rather separately.

3. The report is one of the first attempts to identify possible synergetic and antagonistic effects between nitrogen management and the mitigation of air pollution and climate change. This executive summary has the character of a quick scan, as time for its preparation has been limited and information on interactions between nitrogen management and the mitigation of air pollution and climate change is still scarce.

4. Nitrogen plays a key role in air pollution (via NOx and NH_3 emissions, and indirectly on O_3) and directly (through N_2O emissions and aerosols) and indirectly (through its effect on CO_2, CH_4 and O_3 emissions) also in climate change. Nitrogen also plays key roles in food production and biodiversity loss.

5. This document primarily focuses on the UNECE region. It should be kept in mind that there are regions with ‘too little nitrogen’ (for food production, notably in Africa) and there are regions with ‘too much nitrogen’ (causing air pollution, acidification and eutrophication of surface waters and climate change through N_2O emissions, notably in affluent countries and countries with intensive agriculture and little mitigation), This distinction between regions is important. Further, some of the emissions have regional effects, others have global effects, which further complicates the picture.

6. The following questions are addressed in this document:
    a. Are there significant synergies between N_r and climate that would affect current air pollution policies?
    b. Are effects of NO_x and NH_3 emissions on climate change an additional motivation/justification for abatement of air pollution emissions, besides effects on human health, ecosystems etc.?
    c. Do these effects alter the priorities to reduce air emissions (intensity, spatial pattern etc.) in addition to the reductions needed for abatement of other nitrogen effects?
    d. Are present NO_x and NH_3 emissions and emission scenarios going to have different effects under a future climate than at present?

2. Why Nitrogen and climate?

7. The nitrogen cycle and the carbon cycle are closely linked. Both are changing rapidly. In the last six decades, human production of reactive nitrogen has been larger than production from all natural terrestrial systems. At the same time, rapid increases in atmospheric concentrations of greenhouse gases have most likely led to climate change.

8. Nitrogen-cycle changes and greenhouse gas emissions have the same drivers: population growth, diet, demand for energy, food, livestock feed and fiber, and land-use change.

9. The approximate doubling of the level of reactive nitrogen in circulation is largely as a result of fertilizer manufacture, application, fossil-fuel burning and widespread cultivation of legumes, rice and other crops. This massive alteration of the nitrogen cycle affects each of climate, food security, energy security, human health and ecosystem services.

10. The long-term consequences of huge changes to the nitrogen cycle are yet to be fully realized, but have been largely ignored in global environmental assessments and climate policy. The first full, continental-scale assessment of reactive nitrogen in the environment is, however, now underway. The European Nitrogen Assessment (ENA) is being prepared with the support of the European Science Foundation, the European Commission and other contributions, as a contribution to the work of the Task Force. It sets the problem in context by providing a multidisciplinary introduction to the key processes in the nitrogen cycle, its consequences, the management options, future scenarios and cost-benefit analysis.

11. The anthropogenic drivers for both N and climate include a growing population, food production, feed production for livestock, livestock, fiber production, energy (fossil fuel) use, land-use changes and social equity. Directly or indirectly, these lead to planetary-scale changes to biogeochemical cycles, which result in changes in our biological and ecological systems. There are many feedbacks that can affect human interventions. Climate change is especially challenging because it has a direct relationship with our primary drivers, food production and energy use. But drivers that affect climate often also affect the nitrogen cycle, the phosphorus cycle, water quality and quantity, and other biogeochemical cycles.

12. A key characteristic of climate change is the long residence time of non-reactive greenhouse gases in the atmosphere, such as N_2O and CO_2. The effects of the greenhouse gases are expressed in the global warming potential. CO_2, is the reference chemical, so it has a value of one. N_2O is a more potent greenhouse gas, with a value of 300. Current policies will only take effect in the long term because measures, because these will be not sufficient to reduce atmospheric concentrations of greenhouse gases. At best, concentrations will stabilize over the coming decades.

13. Other parts of the biogeochemical cycles are more reactive leading to shorter atmospheric residence times and a significantly reduced impact on Earth's radiative

balance in the long term. A good example is the formation of aerosols, having a complex effect on climate: Aerosols affect Earth's radiative balance directly (they reflect incoming solar radiation) and indirectly (they affect cloud formation), but the lifetime of these aerosols in the atmosphere is in the order of hours to weeks. It is important to note that nitrogen compounds represent a significant fraction of these aerosols, including ammonium sulphates and ammonium nitrate.

14. The effects of increased Nr in the environment has led to policies limiting emissions to air and losses to soil and waters. The effects of increasing concentrations of greenhouse gases has led to policies reducing the emissions of greenhouse gases. There are relationships between the drivers of nitrogen and climate and between the policies and there is merit in finding the synergies between these.

3. Pathways of N_r to the environment and their relation with climate

15. Once an N_r molecule has been created, it may remain in the environment for a considerable time. It has been estimated that only about half the N_r produced in agriculture will end up in the human food chain, in other products or be denitrified back to N_2; the other half is lost as N_r pollution to the environment.

16. Part of the N_r locked in fossil fuels (coal, oil), together with additional N_r created during the combustion process from atmospheric N_2 at high temperatures, will become available to the environment as NO_x or N_2O, unless technology prevents it from reaching the atmosphere. Selective reduction processes (both catalytic or non-catalytic) are able to remove 80-90 % of the N_r in flue gases.

17. Other sources of N_r that enter the environment include those arising from agriculture. These include NH_3, NO_x and N_2O to the air, and nitrate (NO_3) to groundwater and surface waters, which lead to many problems. These include groundwater pollution, freshwater eutrophication, estuary eutrophication and hypoxia; air pollution (NO_x, O_3, PM) and human health impacts; ecosystem and crop yield impacts; deposition to ecosystems, affecting biodiversity and ecosystem services, climate; and, stratospheric O_3.

18. Reactive nitrogen is highly mobile. Over time, one atom of N_r can contribute to several of these environmental effects as it cascades through the environment (Fig. 1, from PBL). During the 'nitrogen cascade', N_r contributes to different effects in space and time. Strictly, the endpoint of the cascade is when N_r is permanently locked up (e.g. in geological deposits) or denitrified back to N_2. However, in practice, a near endpoint is the build up of the atmospheric N_2O pool; Because of its long lifetime and chemistry and contributes to both climate change and stratospheric ozone destruction.

19. Recent overviews show the environmental impacts of N_r and the importance of nitrogen management to reduce these impacts. From the perspective of air pollution abatement policy, this means that not only direct effects of NH_3, NO_x emissions should be considered in a cost-benefit analysis, but in addition a chain of consecutive additional effects, including those on climate change.

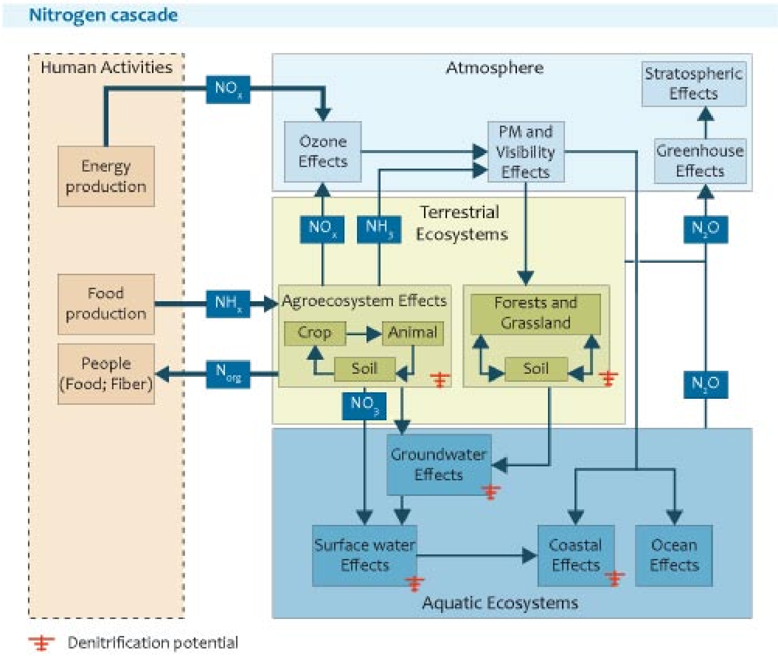

Figure 1. Illustration of the nitrogen cascade (www.pbl.nl).

4. Direct and indirect links between nitrogen and climate

20. At different points of the cascade (Fig. 1), one nitrogen molecule can have a direct or indirect effect on greenhouse gas sources and sinks and on climate.

21. Here we list the most important of these links and provide a first quantification. More background on these links is provided in the scientific report that is currently drafted.

22. The most important **direct links** between N and climate include:
    a. N_2O formation during fertilizer production, after fertilizer and manure application and N deposition to different media. N_2O is a strong greenhouse gas;
    b. O_3 formation from NO_x. O_3 is the third most important greenhouse gas;
    c. Aerosol formation affecting radiative forcing, where N-containing aerosols have a direct cooling effect (which is in addition to an indirect effect through cloud formation).

23. The most important **indirect links** between N and climate include:
    a. Alteration of the biospheric CO_2 sink due to increased supply of N_r. About half of the carbon that is emitted to the atmosphere is taken up by the biosphere; N_r affects net CO_2 uptake from the atmosphere in terrestrial systems, rivers, estuaries and the open ocean in positively (by increasing productivity or reducing the rate of organic matter breakdown) and negatively (in situations where it accelerates organic matter breakdown).
    b. Excess N deposition either increasing or reducing ecosystem productivity and so C-sequestration. Therefore, the level of N production and deposition is important.

c. Changes in ecosystem CH_4 production and consumption; N_r deposition to wetlands may fuel plant production and reduce methane consumption by bacteria, leading to an overall increase CH_4 emissions from wetlands.
d. Changes in ruminants CH_4 production and emission: Increased N_r supply can be associated with more digestable diets, potentially reducing CH_4 emission from ruminants.
e. O_3 formed from NO_x and VOC emissions reduces plant productivity, and therefore reduces CO_2 uptake from the atmosphere.

24. There are many more (in)direct interlinkages which are unquantified, small or negligible, including NH_3 as a greenhouse gas; industrial formation and release of nitrogen trifluoride (NF_3), which is a very strong greenhouse gas; the role of organic N in the N-cycle and its relation to the carbon cycle; reduction in soil microbes, vegetation uptake and water uptake of CO_2 in areas where excess N deposition leads to nutrient imbalances in these ecosystems; manure processing producing biogas and CH_4 leakages resulting from these facilities; the NH_3-based chemical industry affecting climate during the processes and from the wastes; etc. These interactions are not included here.

25. It is essential to take account of the level of N_r in the environment when quantifying the relationships between biospheric N and C. For each system, we can expect a different absolute effect on the fluxes, but the general concept remains the same. When N_r input from natural or manmade sources is small there is a net increase in CO_2 uptake up to a maximum. When this maximum is exceeded, the net gain in CO_2 uptake may remain stable. At some point, as N_r input rises even higher, CO_2 uptake can be reduced, as existing plant/soil systems are destabilized. Furthermore, when N_r input reaches levels in excess of plant needs, more N_2O is produced, which can negates the benefits of higher biospheric CO_2 uptake.

26. We can define three stages in the relationship between N_r supply and response of climate relevant effects:
a. an initial increase in N_r input leads to a net-CO_2 gain. This can only be tolerated in an area where biodiversity protection is not the top priority (such as cultivated lands for agriculture) because biodiversity is reduced already at low N_r levels;
b. a net-increase in CO_2 uptake where there remains a net benefit, which is not fully negated by increased N_2O emissions. Here careful management of N_r and soil condition is essential;
c. Higher levels of N_r supply, where increased Nr inputs always provide a net warming effect (e.g. N_2O increases outweigh any CO_2 gains), at the same time causing other adverse effects. Where reduction in N_r input will always yield a net beneficial (cooling) effect on the greenhouse gas balance and other effects are diminished at the same time.

27. It should be noted that that mitigation from stage (c) down to stage (b) represents a 'no-regret' action, as it has both a net cooling effect at the same time reducing other environmental threats. Further management of N_r from stage (b) down to stage (a) may be of net societal benefit, depending on the economic trade-off of costs and benefits. Thus it is important to consider the full cascade of N_r, and including the other

impacts on water quality and air quality, including on human health, biodiversity and other ecosystem services.

(a) Quantification of the direct and indirect links between nitrogen and climate

28. Currently, there is only a qualitative description of the major links between nitrogen and climate. Quantification of links is only available in some aspects. Table 1 provides a summary of the main links from the chapter prepared for the European Nitrogen Assessment (ENA).

29. The most important contributions to greenhouse-gas emissions are N_2O, O_3 (which is linked to NO_x emissions by chemical reactions in the lower atmosphere) and the effect of atmospheric N_r deposition on biospheric C-sequestration. For the overall effect on radiative forcing, next in importance after the overall effect on alteration of greenhouse-gas balance is the effect of aerosols, which is highly variable in space and time.

30. Based on all the contributions considered here Table 1 indicates that the net cooling effects (-43 mW m^{-2}, mainly of aerosols and additional CO_2 uptake due to N_r) are larger than the warming effect (25 mW m^{-2}) by a factor of ~2 (see Table 1). The overall net cooling effect of -18 mW m^{-2} is not significantly different from zero given the uncertainties.

Table 1. Summary of best estimates of N_r global radiative forcing attributed to European anthropogenic emissions, and their uncertainty ranges (in mW m^{-2}). After ENA draft version August 2010.

	Best estimate	Min	Max
C cycle interactions			
Increase in terrestrial C sequestration due to atmospheric N_r deposition to forests	-17	-23	-11
N_2O			
Increase in atmospheric N_2O concentration	+17	14.8	19.1
Gas phase chemistry	**-1.7**	**-6.4**	**+3.1**
Reduction in CH_4 lifetime due to O_3 formation	-4.6	-6.7	-2.4
Increase in tropospheric O_3 production	+2.9	+0.3	+5.5
Aerosol direct effects	**-16.5**		
Increase in H_2SO_4 production from SO_2	-10.1	N/A	N/A
Neutralisation of H_2SO_4	+4.7	N/A	N/A
Coarse nitrate production	negligible		
NH_4NO_3 direct effect	-11.1		
Aerosol indirect effects	**No estimate**		

31. Table 1 indicates that, within the uncertainties, the cooling effects of N_r at least balance the warming effects on climate. Given the many other adverse effects of Nr on air, water and soil water quality, it is evident that this indicates that smart approaches to manage Nr use and effects are needed in order to minimize the negative

consequences. This requires that the non-linear effects of N_r (paragraph 33) are considered and that the economic costs and benefits of the different N_r threats are evaluated. (See informal document to WGSR-47 on nitrogen costs and benefits.)

(b) The influence of climate on nitrogen

32. In addition to the effect of N on climate change, climate change is expected to influence the N cycle. Climate change leads to temperature and precipitation changes causing shifts in growing seasons, different wind patterns, sea level changes, etc. For example, both VOC and NH_3 emissions are strongly temperature-dependent and a warmer climate may therefore significantly increase their emission, atmospheric transport and deposition. Both N fixation and denitrification are affected by temperature, N availability and soil moisture. In addition, parameters affect concentrations of O_3, CO_2 and oxidized and reduced nitrogen, N_2O and N-containing aerosol, which may have feedbacks on the net greenhouse gas balance. Furthermore, climate change alters nutrient stoichiometry in estuaries, leading to hypoxic areas, for example.

33. The biogeochemical cycle of N_r is therefore linked to climate in profound but nonlinear ways that are, at present, difficult to predict. Nevertheless, the potential for significant amplification of N_r-related impacts is substantial, and should be examined in greater detail. There is currently not enough quantitative information about the influence of climate change and increase in CO_2 concentrations on the N-cycle. Therefore, it is not possible to determine what happens if we do not take these relationships into account and what we under or over estimate.

(c) The UNECE region and the rest of the world

34. Through globalisation and climate change, the regions of the world have become increasingly interconnected. Substantial Nr transfers occur through shipping and import, while the markets controlling agricultural production are global in scale. In the same way the effects of N_r on climate connect the different regions.

35. The availability of Nr is not spread equitably across the planet. Developed countries (such as in the UNECE region) typically have excess N_r. Other regions, including much of Africa and South America, have a deficiency of N_r, which limits food production, affecting the carbon and water cycles, so that a different net effect of N_r on climate can be expected in such regions.

36. The global economy artificially transports much N_r around the world, concentrating N_r in regions where it already in excess of thresholds for environmental effects. Between 1995 and 2005, global trade of N_r containing commodities increased two-fold faster than the rate of N_r fixation. Regions that consume N-containing products, such as meat and milk, are often far removed from regions that produce the commodity and thus do not have to bear the environmental cost of the production. For example, intensive livestock rearing requires intensive soy production for feedstock. Globalization means that exporting soy to a region good for intensive livestock breeding leads to depleted nutrients in one region, and a build up of nutrients in another.

37. Since the UNECE is a net importer of food from developing regions, the nitrogen balance on the global scale and in relation to climate also needs to be considered. For example, even if European N_r emissions have a net cooling effect, the overall N_r consumption patterns of Europe may still result in European N_r interactions having a wider net warming effect. These wider interactions remain to be quantified.

5. Implications of the climate links for nitrogen management

38. At present the options to reduce N emissions under the revision of the Gothenburg protocol have focused on a pollutant perspective for NO_x and NH_3. It is also relevant however, to consider the options for better nitrogen management considering the overall nitrogen cycle.

39. Several options exist to improve nitrogen management. These options will remain valid despite scientific uncertainties in key areas, for example a lack of quantitative relationship between the N and C cycles, and large regional variations.

40. Management options include:
    a. Improve efficiency of N fertilizer use, and manage its use for optimal C sequestration and low N_2O emissions. This may also include increasing fertilizer use for food production in some regions while improving agricultural practices simultaneously.
    b. Use best available technologies for fossil-fuel combustion to reduce NO_x emissions
    c. Improve livestock feeding strategies and manure management
    d. Promote dietary changes and waste less food (consumer behavior)
    e. Improve human waste treatment [This is also essential in the context of phosphorus, a critical non-renewable resource and a key component of fertilizers]

41. Some of these measures are inexpensive, but might require changes in human behavior. Measures 1.-3. are promoted as part of the Gothenburg Protocol revision, e.g. of Annexes II (National Emission Ceilings), V (NO_x measures) and IX (NH_3 and other agricultural measures).

42. If the quantitative relationships from Table 1 hold, the N-management options described above may lead to a net warming in the absence of other concurrent strategies to reduce greenhouse-gas emissions. However, it is equally clear that there is potential for more targeted or ‘smart nitrogen management’, within this package that can give significant climate benefits. For example, improving the efficiency of N_r use in agriculture has the potential to simultaneously reduce N_2O emissions and the fossil fuel requirements for fertilizer production.

43. At the same time, reducing Nr losses through better management will lead to substantial benefits on ecosystem services and human health. As indicated by the European Nitrogen Assessment (Informal document on costs and benefits to WGSR-47), the economic costs associated with these effects are likely to be much larger than the

climate related costs. We therefore recommend a long-term strategy to manage N that prioritizes the positive effects on climate and the other benefits.

6. Scenarios for future reactive nitrogen, climate, environment and human impacts

44. Future projections of major drivers that influence the nitrogen and carbon cycle are available from IPCC, International Assessment of Agricultural Knowledge, Science and Technology for Development (IAASTD) and others. Translating these into scenarios for N_r, climate, environment and human impacts including options for N_r management is essential to provide directions for optimal Nr use. Basic work has been done within the ENA.

45. In addition, a simple conceptual model of the future global use of nitrogen is based on the expected developments of drivers alone (Fig. 2). In this system, five driving parameters (population growth, biofuels use, food equity, increased N-use efficiency and diet optimization) are used to project future fertilizer N_r demands. As this century unfolds, the parameters are expected to change from just a slight increase to roughly doubling with respect to the current situation.

46. Figure 2 shows the result of the translation of four Special Report on Emission Scenarios (SRES) scenarios into scenarios for fertilizer use. These projections are well within the low estimates provided by the FAO. There are also within some higher estimates in scientific literature presenting a two-to-three-fold increase in nitrogen fertilizer use by the second half of the 21st century, assuming continuation of past practices.

47. In all four scenarios, anticipated improvement in efficiency will compensate for much of the increased fertilizer demand. Furthermore, global protein supply is not expected to improve towards ‘food equity’ in the scenarios predicting high population growth (A2 and B2 projections). Drivers of high nitrogen will thus not occur simultaneously, leading to smaller differences in annual nitrogen demand (100 – 150 Tg N) than would be expected from the population projection alone.

48. When bioenergy calls for a large increase in crop production nitrogen demand for fertilizers is expected to double to nearly 200 Tg N per year.

49. Despite the uncertainties and the non-inclusion of many important drivers, all scenarios point towards an increase in future production of reactive nitrogen. This will increase the pressures on the environment, and uneven distribution will only exacerbate the problem regionally.

50. Scenarios for the future release of or fate of N in the environment are still in their infancy. Moreover, such scenarios should not be misunderstood as predictions; they have always served to provide guidance for action. The scenarios for nitrogen management will result in an effect on climate and on other co-benefits.

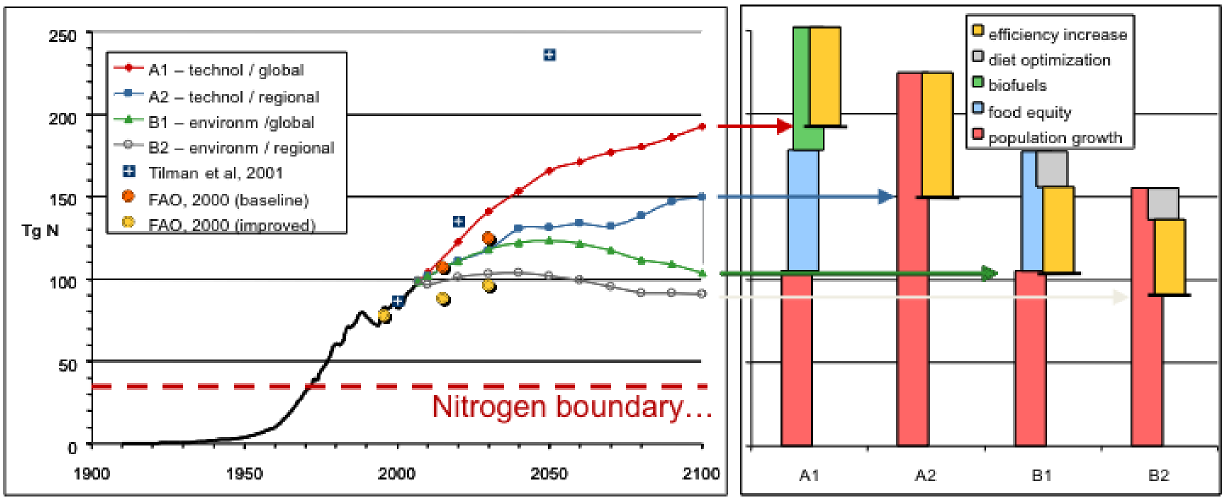

Figure 2. Global nitrogen fertilizer consumption scenarios (left) and the impact of individual drivers on 2100 consumption (right). This resulting consumption is always the sum (denoted at the end points of the respective arrows) of elements increasing as well as decreasing nitrogen consumption. Other relevant estimates are presented for comparison. The A1, B1, A2 and B2 scenarios draw from the assumptions of the IPCC emission scenarios. The 'nitrogen boundary' is based on the estimate of a global limit on sustainable N_r production.

7. Summary

51. The nitrogen cycle, the carbon cycle and climate are closely linked at regional and global levels. All three are changing rapidly. Human activity has doubled the level of reactive nitrogen (N_r) in circulation.

52. Nitrogen cycle changes and greenhouse gas emissions have the same drivers, especially population growth, food production and consumption, energy use and land use changes.

53. Human activity is strongly affecting the C and N cycles. The changes have largely the same drivers, especially population growth, food production and consumption, energy use and land use changes.

54. Not only direct effects of NH_3 and NO_x emissions to air should be considered in a cost-benefit analysis of air pollution abatement, but in addition a chain of consecutive additional effects, including those on climate change.

55. There are major links between nitrogen and climate, both directly (N_2O emissions, O_3 and aerosols affecting the radiative balance) as well as indirectly (affecting the biosphere uptake of carbon, changing CH_4 chemistry and emissions, O_3 damage to crops and trees affecting carbon uptake being the most important).

56. Currently, there is only limited understanding of the quantitative effects of N management on climate change. A preliminary assessment suggests that the human perturbations of the N cycle has a net cooling effect, mostly due to the effect of N on

C sequestration in ecosystems and the effect of direct aerosol formation. However, these estimates are uncertain. We conclude that present knowledge does not allow quantifying the full interactions between changes in N emissions and climate change.

57. As seen from air pollution abatement policy, present knowledge is insufficient to fully quantify additional benefits (in terms of avoided costs and effects) of NO_x and ammonia emissions when taking into account the relationships with climate change.

58. However, there are many no-regret N abatement measures with positive effects on climate change mitigation. These measures require careful scrutiny and judicious implementation. Air pollution abatement policy should assess all effects of nitrogen emissions (including substantial benefits on ecosystem services and human health).

59. In designing strategies to mitigate Nr, smart approaches should nevertheless be sought that seek multiple benefits for air pollution, climate and other effects. In particular, measures that promote an overall improvement in N use efficiency in agriculture should be prioritized, as these have the potential to reduce each of regional air pollution (such as NH_3 and NO_x), water pollution (such as nitrate) and greenhouse gas emissions (N_2O), while reducing the energy requirement for new fertilizer production.

60. Possible next steps are to closely work together with IPCC associates to further explore the interlinkages between N management and air pollution and climate change mitigation. We suggest establishing a research program for assessing these linkages, for example via GAINS, also in collaboration with EU, IGBP, IPCC.