Informal document no. 17

Nitrogen management interactions with climate change: a policy brief to inform the Gothenburg Protocol revision

Informal document to the WGSR-47 (30 August – 3 September 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 (TFRN) agreed to deliver a report on "Nitrogen and Climate" to inform the Gothenburg Protocol revision process.

The informal document presented here is the executive summary of the draft report on "Nitrogen and Climate". This document is primarily directed at Executive Body delegates of CLRTAP Signatory countries and other air pollution policy makers. The full report will be released by the end of 2011. The full report is also meant to inform the UNFCCC / IPCC for the preparation of the 5th Assessment Report.

In providing this informal document to WGSR-47, the Task Force would welcome feedback so that the full report can be made most useful for the Executive Body.

I. Main messages

- Nitrogen emissions to air greatly contribute to both air pollution and climate change, with significant interactions with water pollution.

- Nitrogen management measures (including pollution mitigation) often affect air pollution, climate change, food production and biodiversity simultaneously.

- There are several nitrogen management measures with synergistic effects on air pollution mitigation and climate change mitigation. Nitrogen management can therefore provide a contribution to meeting climate targets.

- 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.

- Effective climate change mitigation must be based on a full understanding of the relationships and interactions between de the carbon and nitrogen cycles.

- Cost-benefit analyses of NH_3 and NO_x emissions abatement policies should also consider effects on climate change.

- It is recommended that the Convention should collaborate with IPCC to further explore the relation between nitrogen and climate policy.

II. 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) linked to air pollution and other societal issues, including climate change.

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 current 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.

4. Nitrogen plays a key role in air pollution (via NO_x and NH_3 emissions, and indirectly on O_3) and also in climate change (directly through N_2O emissions and aerosols, and indirectly through its effect on CO_2, CH_4 and O_3 emissions). 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. In addition, some of the N_r emissions have regional effects, while others have global effects.

6. The term ‘nitrogen management’ is used here. This refers to the active management of N_r and its exchange with N_2 to meet multiple societal objectives, including benefits in agriculture, mitigation options to reduce adverse environmental effects, and adaptation options to reduce the adverse consequences of climate change on these effects.

7. The following questions are addressed in the detailed report under preparation. The present summary report provides a start in addressing these questions:
    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 N_r 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?

III. Why Nitrogen and Climate?

8. Human perturbations of the nitrogen and carbon cycles have led to rapid increases in atmospheric greenhouse gases, notably carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), and these greenhouse gases (GHG) contribute to global warming and climate change. Commonly, climate change is associated with emissions of CO_2 and CH_4 through fossil fuel combustion and land use changes, but the carbon cycle is intimate related to the nitrogen cycle. Perturbations of the nitrogen cycle may contribute to climate change as well, directly through N_2O emissions and indirectly through the effects of nitrogen on CO_2 and CH_4 emissions. Effective climate change mitigation must be based therefore on a full understanding of the relationships and interactions between de the carbon and nitrogen cycles.

9. The global level of reactive nitrogen in circulation has effectively doubled due to anthropogenic activity. This is mainly the result of nitrogen fertilizer use, fossil-fuel burning and widespread cultivation of legumes.

10. Nitrogen management and climate change mitigation are especially challenging because they have a direct relationship with the key drivers, food production and energy use. Drivers that affect climate change also affect the nitrogen cycle, and often also other biogeochemical cycles like the water and phosphorus cycles, and thereby also water quality and quantity. There is a delicate balance between climate benefits of nitrogen management and the co-benefits for human health, ecosystem services and food production to feed the world.

11. The long-term consequences of the 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 funds, 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.

12. The residence time of greenhouse gases in the atmosphere differs between gases, with the effects of the greenhouse gases in terms of climate change 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, in part because of its longer residence time. Climate change mitigation policies will only take effect in the long term because measures on the table to tackle climate change will not reduce atmospheric concentrations of greenhouse gases in the short term. At best, concentrations will stabilize over the coming decades.

13. Emissions of NO_X and NH_3 to air affect 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). The lifetime of these aerosols in the atmosphere is in the order of hours to weeks. Decreasing NO_X and NH_3 -induced aerosol formation therefore has a short-term effect on climate. However, if they continue to be emitted in the atmosphere, they will also affect long-term climate change.

14. Nitrogen has a relatively long residence time in the biosphere before it is denitrified to di-nitrogen gas (N_2) and N_2O. As a consequence, once 'fixed' as reactive nitrogen (N_r), it has a long potential effect on climate.

15. Finally, N_r induced effects on ecosystems have long-term consequences on their interactions with a changing climate. This includes the knock-on consequences of N_r induced biodiversity change on climate.

16. These are important reasons why nitrogen should be taken into account in discussions on climate change as well as on air pollution.

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

17. The main source of N_r is food production (agriculture), emitting NH_3, NO_x and N_2O to the air, and nitrate (NO_3) to groundwater and surface waters. The second most important source is fossil fuel combustion emitting NO_x and N_2O to air.

18. 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 used in agriculture will end up in food, feed and fiber; the other half is lost as N_r pollution.

19. Reactive nitrogen is highly mobile. Over time, one atom of N_r can contribute to several environmental effects as it cascades through the environment (Fig. 1). During this '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.

20. 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 and 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.

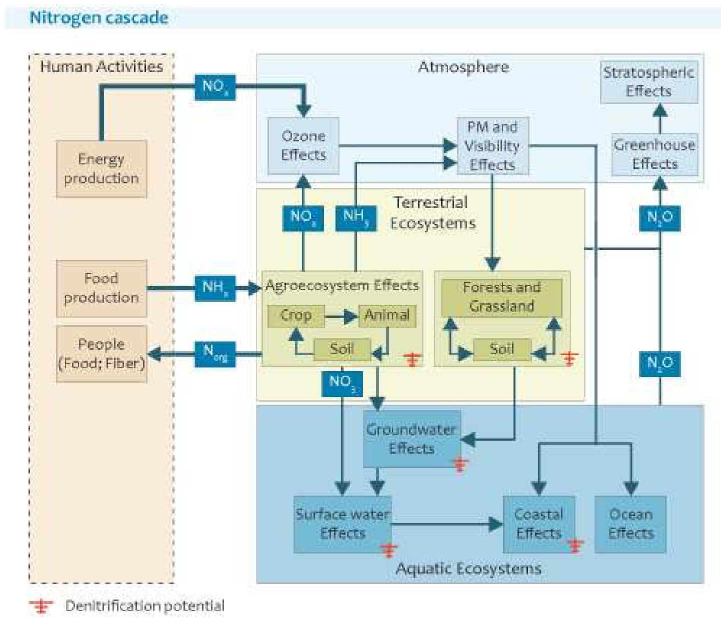

Figure 1. Illustration of the nitrogen cascade (www.pbl.nl).

V. Direct and indirect links between nitrogen and climate

21. 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. Here we list the most important of these links and provide a first quantitative estimate.

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 from fossil fuel combustion to the atmosphere annually is taken up by the biosphere annually. N_r affects net CO_2 uptake from the atmosphere in terrestrial systems, rivers, estuaries and the open ocean positively (by increasing productivity) and negatively (in situations where it accelerates organic matter breakdown).
    b. Atmospheric N deposition may increase or reduce the productivity of natural ecosystems and so C-sequestration, depending on the state of the natural ecosystem and the level of N deposition.
    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 net increase of 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 interlinkages which are unquantified, small or negligible. They are not taken into account in this report.

25. It is essential to take account of the level of N_r input when quantifying the relationships between N_r input and C sequestration in ecosystems. For each system, we can expect a different absolute effect on the fluxes, but the general concept remains the same. When N_r input is small there is a net increase in CO_2 uptake by ecosystems, 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. This negates the benefits of a higher biospheric CO_2 uptake through N_r deposition.

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. Since biodiversity is reduced already at low N_r levels, this can only be tolerated in ecosystems where biodiversity protection is not the top priority;
    b. a positive net climate effect where the increase in CO_2 uptake is not fully negated by increased emissions of N_2O, CH_4 etc. Here careful N_r and soil management is essential, considering all N_r effects;
    c. high levels of N_r supply where a reduction of N_r will always yield a net beneficial effect on the greenhouse gas balance and other effects are diminished at the same time.

27. It should be noted that mitigation from stage (c) to stage (b) represents a 'no-regret' action, as it has both a net cooling effect and at the same time reducing other N_r losses. Further decreases of N_r input from stage (b) 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 climate and other impacts on water and air quality, human health, and biodiversity.

(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 by aerosols and additional CO_2 uptake due to N_r) are larger than the warming effect (25 mW m^{-2}) by a factor of almost 2 (see Table 1). However, given the uncertainties, the overall net cooling effect of -18 mW m^{-2} is not significantly different from zero.

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}). From the European Nitrogen Assessment, chapter 16, 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. The data presented in Table 1 also emphasize that smart approaches to manage N_r use and effects are needed in order to minimize the negative consequences. This requires that the non-linear effects of N_r (paragraph 26) are considered and that the economic costs and benefits of the different threats caused by N_r emissions are evaluated. (See Informal Document No. 7 to WGSR-47 on nitrogen costs and benefits.)

(b) The influence of climate on nitrogen

32. Climate change is expected to influence also 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. Furthermore, climate change alters nutrient stoichiometry in estuaries, which may lead to hypoxic areas.

33. The biogeochemical cycle of N_r is therefore linked to climate in profound but nonlinear ways that are, at present, difficult to predict in full. 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 N_r transfers occur through shipping and import, while the markets for most agricultural products (commodities) are global in scale. In the same way the effects of N_r on climate connect the different regions.

35. The availability of N_r 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 transports much N_r around the world, concentrating N_r in regions where it is 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 soybean production for feedstock. Transporting soybean to a region good for intensive livestock breeding leads to depleted nutrients in one region where the feed is produced), and a build up of nutrients in another (where the feed is consumed by animals, but most of the N_r contained in the feed is excreted again in manure).

37. Since the UNECE is a net importer of food from developing regions, the nitrogen balance on the global scale 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 net warming effect. These wider interactions remain to be quantified.

VI. Implications of the climate links for nitrogen management

38. At present the options to reduce N_r 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. Key nitrogen management actions 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 practices, reducing the major losses of NH_3 and nitrates.
    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 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 summary effect of all 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 NH_3 and N_2O emissions and the fossil fuel requirements for fertilizer production.

43. At the same time, reducing N_r losses through better management will lead to substantial benefits on ecosystem services and human health. As indicated by the European Nitrogen Assessment (see Informal Document No. 7 on costs and benefits to WGSR-47), the economic costs associated with these non-climate effects are likely to be much larger than costs to be allocated to N_2O emissions. Nitrogen management and also air pollution abatement policy should assess all effects of nitrogen emissions (including substantial benefits on ecosystem services and human health).

VII. 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 N_r use. Basic work has been done within the European Nitrogen Assessment (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 scenarios from the Special Report on Emission Scenarios (SRES) into scenarios for fertilizer use. These projections are well within the low estimates provided by the FAO. There are also 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. 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.

48. 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.

49. Scenarios for the future release of or fate of N_r 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.

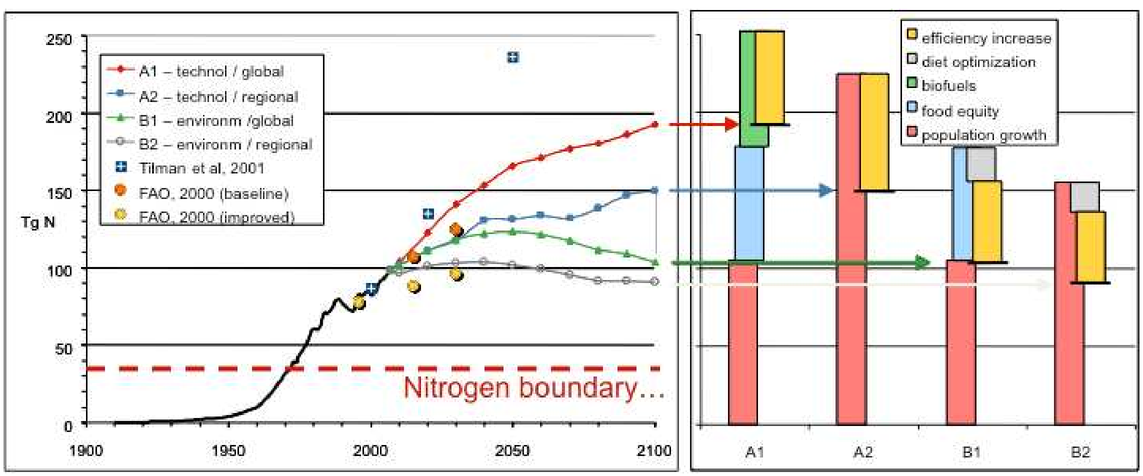

Figure 2. Global nitrogen fertilizer consumption scenarios (left) and the impact of individual drivers on 2100 consumption (right). This resulting consumption is always the sum (denoted at the end points of the respective arrows) of elements increasing as well as decreasing nitrogen consumption. Other 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. (From Erisman et al. 2008, Nature Geoscience, 1, 636-639).

VIII. Summary

50. The nitrogen and carbon cycles are closely linked at regional and global levels. Both cycles affect air pollutions and climate change, but in complex ways.

51. Human activity is strongly affecting the C and N cycles. Human activity has doubled the level of reactive nitrogen (N_r) in circulation.

52. Changes of the N and C cycles have largely the same drivers, especially population growth, food production and consumption, energy use and land use changes.

53. 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.

54. 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).

55. 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 very uncertain. We conclude that present knowledge does not allow quantifying the full interactions between changes in N emissions and climate change.

56. 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.

57. However, there are many no-regret N_r abatement measures with benefits for 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).

58. In designing strategies to mitigate N_r, smart approaches should be sought that seek multiple benefits for air pollution, climate change 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.

59. Possible next steps are to closely work together with IPCC 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 in collaboration between the CLRTAP, IPCC, IGBP and EU.