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# Effects of Climate Change on Air Pollution Impacts and Response Strategies for European Ecosystems

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# D22.3 – ÉCLAIRE Key Messages for Policy Makers

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# Contents

**Executive Summary**

1. This report provides a summary of the main scientific messages that are emerging from ÉCLAIRE in relation to the Key Questions that were set out at the start of the project. It provides an update on the messages reported last year. A further update is provided in the final report.

2. The main scientific messages described are set out particularly as these are relevant to policy makers. ÉCLAIRE has a strong focus in delivering scientific support for air pollution policy development, including substantial engagement with the UNECE Convention on Long-range Transboundary Air Pollution (LRTAP) and with the European Commission, DG Environment, especially providing science input to support revision of the EU Air Quality Package, including its proposed revision of the National Emissions Ceilings Directive (NECD).

3. The central goal of ÉCLAIRE is to assess how future climate change may alter the extent to which air pollutants have adverse effects on terrestrial ecosystems. **The emerging message is that climate change will worsen the threat of air pollutants on Europe's ecosystems:**

- Climate warming is estimated to increase the emissions of many trace gases, such as ammonia ($NH_3$), soil emissions of nitrogen oxides ($NO_x$) and important biogenic volatile organic compounds (BVOCs). Although there are many trade-offs, overall these effects would tend to increase ground-level concentrations of $NH_3$, $NO_x$ and ozone ($O_3$), particles ($PM_{2.5}$), as well as atmospheric nitrogen deposition.
- Climate warming may increase the vulnerability of ecosystems towards air pollutant exposure or atmospheric deposition. Such effects may occur as a consequence of combined perturbation, as well as through specific interactions, such as between drought, $O_3$, N and aerosol exposure.

4. Based on ÉCLAIRE results to date, the first of these interactions (climate-emission-concentration-deposition) is likely to be very significant. Unless decisive mitigation actions are taken, it is anticipated that ongoing climate warming will increase agricultural $NH_3$ and $NO_x$ emissions. This is likely to be exacerbated by increases in other biogenic emissions (e.g. BVOCs from forests). Together, these changes pose a challenge for national emissions ceilings and air quality objectives related to nitrogen, ozone and particulate pollution, especially if combined with foreseen increases in economic activities.

5. ÉCLAIRE has also identified additional interactions which complicate these responses. For example, future warming anticipated to be accompanied by increases in $CO_2$ concentrations, so that some BVOC emissions (like isoprene) may not increase in practice. Conversely, for other BVOCs (like monoterpenes), the extent of $CO_2$ trade-off is much less certain, and cannot be counted on to moderate the effect of temperature in increasing BVOC emissions.

6. Modelling studies in ÉCLAIRE capture the probability distributions of different plant species according environmental variables. These studies illustrate how a combination of

nitrogen deposition (leading to acidification and eutrophication) can combine with climate warming to lead to a larger change than would have occurred with only one of these factors changing on its own. This points to a substantial worsening of the overall air pollution threat under future climate scenarios.

6. The findings of ÉCLAIRE highlight the priority for further concrete actions to mitigate air pollution emissions if a further worsening of the air pollution threat to Europe's ecosystems is to be avoided, including on the Natura 2000 network.

7. Substantial input has been provided by the ÉCLAIRE team to support preparation and discussion of the EU Air Quality Package of, especially the proposal for revision of the National Emissions Ceilings Directive. Support has continued also for LRTAP, including both policy development through the Working Group on Strategies and Review (WGSR) and technical work through the Working Group on Effects (WGE) and EMEP Steering Body.

8. Specifically the ÉCLAIRE team has led inputs to the LTRAP Task Force on Reactive Nitrogen (providing the foundation for the new Annex III on ammonia of the proposed NECD), the Task Force on Integrated Assessment Modelling (providing analysis of mitigation options and cost-benefit analysis) and the International Cooperative Programmes on Vegetation and Mapping & Modelling, providing the basis for revision and mapping of critical loads and levels across Europe.

9. The ÉCLAIRE team have reported to the WGSR estimates of the valuation of ecosystem damage associated with N pollution, as well as developed a proposed revision of the Framework Code of Good Agricultural Practice for preventing Ammonia emissions (in support of the revised Gothenburg Protocol and NECD review). In order to support this process, DG Environment provided additional resources for to allow the ÉCLAIRE team to host a stakeholder workshop to develop international consensus on the latter, to allow approval by the LRTAP Executive Body in December 2014, allowing the document to be used as part of the NECD revision.

10. Wider policy engagement by the ÉCLAIRE team has increasingly highlighted the need to develop integrated solutions. Through the "Our Nutrient World" report for the United Nations Environment Programme (UNEP), ÉCLAIRE has highlighted the multiple win-wins that would result from improving 'economy wide nitrogen use efficiency'. This would offer simultaneous benefits for the economy, food security, air pollution, climate, water quality and biodiversity.

11. A special report, "Nitrogen on the Table", on the effects of dietary choice on nitrogen pollution will be launched at the European Parliament (January 2016). It shows that a 'demitarian' scenario halving meat and dairy intake would reduce N pollution by 40%.

12. The period 2014-2017 will be critical for the EU to address what will be the European contribution to the 'International Nitrogen Management System' (INMS). This is now being prepared in partnership with UNEP, GEF, OECD, FAO, other countries and key industry and NGO stakeholders, with the opportunity Europe to strengthen its global leadership.

# 1. Progress in answering the Key Questions

Measurement campaigns and associated modelling and cost-benefit analysis work have continued to address the component parts of key questions set within the project. Emerging results and conclusions in relation to the key question are as follows:

**Q1: What are the expected impacts on ecosystems due to changing ozone and N-deposition under a range of climate change scenarios, taking into consideration the associated changes in atmospheric $CO_2$, aerosol and acidification?**

13. ***Climate change is expected to increase the threat to ecosystems through multiple pathways.***
14. ÉCLAIRE findings show that temperature increase will cause higher emissions of $NH_3$, soil $NO_x$ and BVOCs, especially from agricultural and other biogenic sources. This will increase nitrogen deposition, which will exacerbate the threat to biodiversity from climate change, as well as increase $O_3$ and PM levels. Increased N deposition will also increase the rate of $N_2O$ emissions from soils, tending to accelerate climate change in a pollution-climate feedback.
15. The results show that the interaction between climate warming and tropospheric $O_3$ is complicated by interactions that occur when atmospheric $CO_2$ concentrations increase at the same time. This is because, while warming tends to increase BVOC emissions, parallel increases $CO_2$ concentrations can in some instances offset this effect. The evidence for this interaction is strongest in the case of the BVOC isoprene. By contrast, in the case of monoterpenes, there remains substantial debate whether any such trade-off exists. In this context, there is insufficient evidence to assume that the $CO_2$ interaction will be sufficient to mitigate the expected effect of BVOC emissions in increasing tropospheric $O_3$ concentrations.
16. Although higher nitrogen deposition will enhance the rate of carbon uptake and storage, this potential benefit must be weighed against the adverse effects on increasing $N_2O$ emissions and adverse effects on biodiversity. In addition, the anticipated worsening of ozone damage to plants linked to climate change will reduce the rate of carbon uptake and storage, and thereby accelerate climate change.
17. The fertilization effect of atmospheric N deposition can partially offset the negative effects of $O_3$ on above ground C uptake by foliage and storage in stems, but not on below-ground storage in roots, with implications for associated soil processes involved in GHG emissions.
18. ÉCLAIRE results indicate that in Europe future stomatal uptake of ozone by plants will be influenced by methane-induced increases in hemispheric background $O_3$ concentrations, and by additional controls of $NO_x$ and VOC emissions from European sources, which are reducing peak $O_3$ concentrations. This highlights the

co-benefits of methane mitigation for climate change and the protection of agricultural crops and natural vegetation.

19. $NH_3$ emission is primarily associated with increasing C sequestration, while $NO_x$ emission (since they also form $O_3$) may provide little net benefit for C storage. The net effects also depend on the role of N emission/deposition in increasing $N_2O$ emissions (warming) and atmospheric aerosol loading (cooling).
20. Expected enhancements in vegetation growth due to both nitrogen inputs in agriculture and climate change appear to be significantly reduced by $O_3$ reducing **Nitrogen Use Efficiency** (also linked to reduced root: shoot ratio, see above). This means that $O_3$ pollution has an adverse effect on the wider nitrogen cycle, increasing $NO_3$ leaching and $N_2O$ emissions from soils, resulting in further environmental problems.
21. Climate-induced increases in primary emissions, will also affect atmospheric lifetimes of pollutants and resulting N deposition patterns. However, modelled future patterns of European pollution deposition are found to be much less dependent on anticipated changes in precipitation.
22. ÉCLAIRE has identified a new relationship between plant stress responses and soil NO emissions, which would constitute a further feedback loop between climate change and air pollution. However, further work will be required to incorporate this mechanism into vegetation exchange models and to assess its overall relevance.
23. Climate change induced increases in other threats (such as insect attacks), will increase biotic stress, which has been found to alter BVOC emission profiles. This will increase the formation of secondary organic aerosols, which are an important component of $PM_{2.5}$ that affects human health. At the same time, there are potential feedbacks on photosynthesis through global dimming through increased aerosol loading.

**Q2 Which of these effects off-set and which aggravate each other, and how do the mitigation and adaptation measures recommended under climate change relate to those currently being recommended to meet air pollution effects targets?**

24. Temperature increase from climate change is likely to increase $NO_x$ and $NH_3$ emissions from agriculture and soils, and thereby counter-act currently discussed efforts to reduce emissions of these substances. This reinforces the need for stringent $NO_x$ and $NH_3$ emission reductions if the suggested air quality improvements are to be met and maintained in the future. Without such mitigation measures, the adverse effects of nitrogen deposition on European ecosystems, especially in relation to protecting the Natura 2000 network, are anticipated to worsen, which would compromise the ability to meet wider commitments under the Habitats Directive.
25. A significant off-set can be expected between anticipated future decreases in $NO_x$ emissions and anticipated future increases in $NH_3$ emissions, especially when considering current emission reduction plans and the effects of climate change on

emissions. While further reductions in $NO_x$ emissions can be expected over the 21st century (e.g. Gothenburg Protocol and NECD revision), current plans include little commitment to reduce ammonia emissions. Potentially, European ammonia emissions could increase by as much as 40% by 2100 due to climate change, while potential increases in livestock numbers to meet global food/feed aspirations may further increase this. This result highlights the importance of incorporating climate factors into official national $NH_3$ emissions inventories to properly account for this interaction.

26. The interactions between N, $O_3$, C, climate and biodiversity indicate several potential trade-offs in regard of mitigation and adaptation measures. In principle, N deposition benefits for C storage (esp from $NH_3$ rather than $NO_x$) could argue for increasing N emissions, while the detrimental effects on biodiversity and air quality (PM effects on health) would point to the need to reduce emissions. These issues can be addressed increasingly focusing efforts on improving economy-wide *nitrogen use efficiency* which would provide win-wins for environment and the Green Economy. This implies a synergy between improving both production and consumption, while incorporating the best in mitigation technologies that keep N where it is needed for production. Significant effort has been placed by the ÉCLAIRE coordination team over the last year in applying these ideas with CLRTAP, OECD and UNEP (see Sections 4-6).
27. Recent ÉCLAIRE work allows us to hypothesise that in managed forests, at the European level, the impacts of tree species selections will likely make a significant contribution to the pattern and magnitude of BVOC emissions, in addition to changes in emissions due to temperature and/or $CO_2$ changes alone. In Europe, climate adaptation in silvocultural practice will be more important in driving changes in tree species composition than natural adaptation.
28. Recent ÉCLAIRE results suggest that, during heat waves, ecosystems that are not normally associated with high BVOC emissions (demonstrated for moorland) become important sources of isoprene.
29. A model simulation suggests that, at the annual European average, evaporation of volatile $NH_4NO_3$ near and with plant canopies may increase nitrogen dry deposition from this aerosol component by a factor of four and lower surface concentrations by 30%.
30. ÉCLAIRE has identified that leaf litter plays a significant role in exchange processes, which is not represented in the models: not only can it dominate the moisture response of NO emissions from the ground, senescent leaves have also been found to be an efficient sink for ozone.
31. The collaboration in ÉCLAIRE also identified the need for a new land-atmosphere trace gas and aerosol modelling system which was not envisaged at the outset of the project. This has led to the development of the ESX model (ÉCLAIRE Ecosystem Surface eXchange). Developments have been made to the ESX system, preparing it to become a key tool to interpret and assimilate the flux measurements. It is a community effort, and will be shared with other project collaborations such as PEGASOS. The modular nature of the modelling allows the different processes being modelled to be treated at varying levels of complexity, incorporating state-of-the-art process

descriptions, as well as simplifications that are sufficiently efficient computationally for implementation into Chemistry Transport Models.

32. Model developments have been made to account mechanistically for the co-deposition of pollutants on leaf surfaces (DEWS model) and the DO3SE model now has a photosynthesis based stomatal conductance parameterisation (allowing $CO_2$ and nitrogen availability to be taken into account).
33. Assessment of the phytotoxic effects of ozone has progressed by improving the uptake routines in dynamic global vegetation models.
34. These technical developments will provide the foundation for further analysis of trade-offs and synergies as part of the longer term legacy of ÉCLAIRE, especially within the framework of the UNECE Convention on Long-range Transboundary Air Pollution (LRTAP).

**Q3: What are the relative effects of long-range global and continental atmospheric transport vs. regional and local transport on ecosystems in a changing climate?**

35. ECLAIRE results highlight two potentially important pathways for how the impacts of climate change on atmospheric chemistry and transport of pollutants could affect ecosystems: (i) as indicated above, $NO_x$ and $NH_3$ emissions from soils and leaf litter increase with temperature, and (ii) higher $CH_4$ emissions will enhance the formation of background $O_3$ to concentrations with adverse effects on plants. While the first effect will put additional stress to ecosystems at the local scale (close to the sources of $NH_3$ emissions), the second mechanism is of hemispheric nature and will cause damage to agricultural production and natural vegetation at the regional/global scale. It is a remaining uncertainty how the interaction between increasing temperature and $CO_2$ and BVOCs may alter the spatial distribution of elevated tropospheric $O_3$.
36. To address these interactions ÉCLAIRE modelling work has focused on developing high resolution spatially resolved emissions data as a basis for modelling analysis of $NH_3$, $O_3$ and $NO_2$ on a 5 km x 5 km resolution and nested down to 1 km x 1 km resolution in Scotland and the Netherlands, to examine the interplay of regional and local variations.
37. Application of the emerging findings has been used to inform policy development in regard of the links between air pollution and the Natura 2000 network, highlighting how local mitigation measures for nitrogen can be more cost effective in reducing adverse effects in agricultural landscapes than national measures, pointing to a need for both national emissions ceilings and local air quality policy.
38. Based on discussions with the ÉCLAIRE team, an opportunity to introduce an Air Quality limit value for ammonia over Natura 2000 areas was discussed with DG Environment, although it was at this point in time not possible to take this forward within the current Air Quality Package.

**Q4: What are the appropriate metrics to assess ozone and nitrogen impacts on plants and soils, when considering state-of-the-art understanding of interactions with $CO_2$ and climate, and the different effects of wet vs. dry deposition on physiological responses?**

39. ÉCLAIRE has shown that air concentration-based metrics (ozone critical levels, ammonia critical levels) and flux based approaches (critical loads for nitrogen deposition, flux based thresholds for ozone effects, such as the Phytotoxic Ozone Dose, POD) continue to be relevant. While flux based approaches are more sophisticated, they cannot currently address all situations (e.g. flux based approach for $O_3$ is limited to selected species, while critical loads for nitrogen currently do not distinguish differential effects of N form).
40. Further evidence has emerged within ÉCLAIRE of different effects between wet deposited N in oxidized or reduced form and dry deposited $NH_3$ for bog ecosystems. This highlights a higher sensitivity to $NH_3$ than wet N deposition, which can in part be accounted for by a lower critical level for moss and lichen species. Further evidence of these differentials now needs to be obtained for other ecosystem types to allow generalization to incorporate these differences into the next generation of critical load approaches to take account of differences between wet/dry deposition and oxidized/reduced nitrogen.
41. The developing interface with cost-benefit analysis indicates a need to focus increasingly on ecosystem dose-response relationships, and this has been addressed within ÉCLAIRE in order to inform the developing dose-response-valuation chain.
42. ÉCLAIRE has also investigated novel pollution interactions. Studies of leaf processes have indicated that drought impacts are increased by particle deposition to leaf surfaces, with a first dose-response relationship established for ambient conditions, which is necessary as a foundation for incorporation into dynamic global vegetation models. The implication of this interaction is that PM air pollution (hygroscopic aerosol, the inorganic fraction of $PM_{2.5}$) can exacerbate the effects of drought.
43. Source-receptor matrices have been tested to include indicators not applied previously. Specifically, this includes POD, with threshold deposition rates of 1 or 3 nmol $m^{-2}$ $s^{-1}$ (POD1 and POD3, respectively). Any linear combination of such indicators, including N deposition, can now be simulated in the effects module of the GAINS model.

**Q5: What is the relative contribution of climate dependence in biogenic emissions and deposition vs. climate dependence of ecosystem thresholds and responses in determining the overall effect of climate change on air pollution impacts?**

44. At present, the indication is that climate change will primarily alter air pollution impacts on ecosystems through the dependence on emissions (and hence deposition), while alteration of ecosystem sensitivity to given air pollution levels will be a smaller (or harder to generalize) effect.
45. While the effects of temperature on biogenic and agricultural emissions are well established ($NH_3$, some BVOCs, soil NO), the main effects of climate on ecosystem vulnerability will operate via alterations in drought stress, soil turn over processes and net photosynthesis. Drought stress may exacerbate some pollution effects such as

limiting plant N uptake leading to larger N pollution losses in the environment and may be worsened under increasing background $O_3$ exposure due to $O_3$-induced loss in stomatal control or due to aerosol deposition on leaf surfaces.

46. Biodiversity, carbon sequestration, resource use efficiency (water, nitrogen, $CO_2$) and feedbacks to air quality have been agreed as the most important policy relevant factors to link with the cost-benefit analysis in ÉCLAIRE. Therefore modelling activity has been harmonised to reflect this.

**Q6: Which mitigation and/or adaptation measures are required to reduce the damage to "acceptable" levels to protect carbon stocks and ecosystem functioning? How do the costs associated with the emission abatement compare with the economic benefits of reduced damage?**

47. Recent experiments and analytical work in ÉCLAIRE has further established evidence of the benefits of reducing nitrogen emissions. Lower $NO_x$ emissions will reduce vegetation exposure to ground-level $O_3$, and thereby deliver positive benefits to forest growth and agricultural crops. Less excess nitrogen deposition will also contribute to the achievement of biodiversity policy targets.
48. Precursor emission reductions (of especially methane) that affect background $O_3$ on the hemispheric scale are also needed to prevent future increases in exposure of vegetation to ground level $O_3$
49. Balancing the ozone damage and biodiversity loss against possible increases in carbon stocks and productivity of higher nitrogen availability remains a complex task, especially with respect to economic considerations. ÉCLAIRE has highlighted the wider issues which will likely need to be taken into consideration (or considered as context along with an ecosystem based analysis), to reflect on the problem comprehensively, this includes:
    - Long-term potential impacts, such as soil chemistry saturation and associated ecosystem thresholds,
    - The health-related costs of air pollution,
    - Wider effects from nitrogen pollution, such as eutrophication.
50. Support provided by the ÉCLAIRE team to the Gothenburg Protocol and NECD revision processes has highlighted that mitigation measures for $NO_x$ are becoming increasingly expensive, while many low-cost mitigation options for $NH_3$ are still available (because they have not yet been adopted in many countries). This is illustrated in Figure 1, which shows the benefit:cost ratio for further air pollution mitigation beyond existing commitments for 2020, including estimates of health and ecosystem costs vs the cost of mitigation actions. The current position as illustrated by this graphic suggests that a further 1100 kt $NH_3$-N mitigation is cost-optimal, whilst only a further 300 kt $NO_x$-N mitigation is cost-optimal.

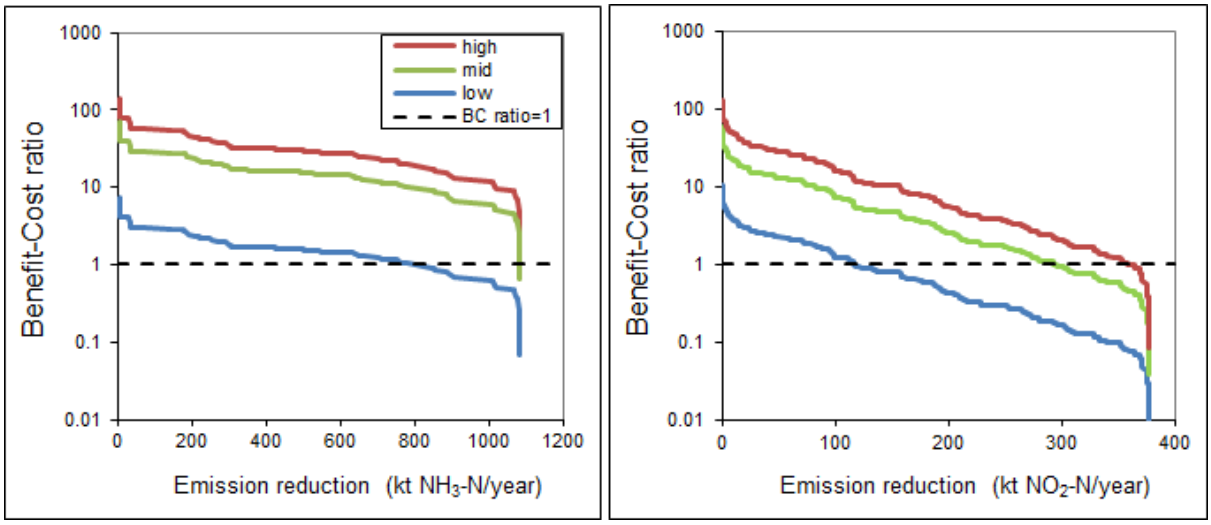


**Figure 1**: Comparison of the estimated health, ecosystem and climate benefits to the costs of ammonia and nitrogen oxides mitigation (van Grinsven et al., ES&T, 2013, see select publications list).

## Q7: How can effective and cost-efficient policies on emission abatement be devised in the future?

51. As a foundation for improved assessment, ÉCLAIRE has developed an improved basis for incorporating ecosystem costs into the overall valuation chain. In due course this will allow the assessment of Figure 1 to be further refined, and has highlighted the challenge of valuing ecosystem effects of air pollution.
52. For the regulatory (GHG related) and provisioning (crops, timber) services, available results from other components of ÉCLAIRE indicate some potential for a degree of balance between the harmful effects of ozone and the beneficial effects of nitrogen deposition depending on relative concentrations/deposition rates. Further to this, there are outstanding questions about the sustainability of beneficial impacts of nitrogen deposition, perhaps concerning the availability of non-N nutrients in the longer term, interactions with pests and pathogens and ozone negating the beneficial effects of N on root growth. This is problematic for the subsequent analysis, as it raises questions about even the direction of overall impacts.
53. For ecosystems and biodiversity, however, the same does not apply, with N deposition and $O_3$ exposure both demonstrated to have negative impacts. Progress was made in the development of a novel indicator, the "habitat suitability index" (HSI). The HSI can be used in scenario analysis of ecosystem impacts of emission mitigation strategies simulated in the GAINS system. Developing and testing of this indicator requires that the modelling of soil chemical processes (VSD+ model) is linked to a methodology that assesses the probability of occurrence of plant species (PROPS model) on a European scale. Typical species in habitats classified under the European Nature Information System (EUNIS) are identified and tested in the context of new indicator

development. Habitat-specific conditions are defined as a combination of current acidification critical loads with the nutrient critical loads and take into account climate related indicators.

54. Given these issues, ÉCLAIRE has particularly focused on the challenging question of valuing changes in biodiversity. The monetary evaluation of ecosystems is subject to significant uncertainties. While the ecosystem services approach works adequately for $O_3$ (where the focus is on showing significant impacts for wood production and carbon sequestration), it is problematic for nitrogen as this tends to stimulate forest growth (at least in the short term), while leading to a loss in biodiversity.
55. In order to develop an understanding of how to integrate these services in a more general and comparable scheme, an accounting framework was created by ÉCLAIRE. The total accounting framework consists of:
    - Marketed ecosystem services,
    - Willingness-to-pay for non-marketed services,
    - Restoration costs,
    - Elimination costs,
    - Legal requirement approach on conservation,
    - Nitrogen Use Efficiency approach.
56. Work in ÉCLAIRE has improved the quantification of impacts of climate change in dose-response relationships for air pollution effects on ecosystems. By factoring these issues into the integrated assessment modelling, and cost-benefit analysis, the toolbox will be developed for emission control policies that are cost-effective also under a changed climate.
57. Pending completion of the work, the emerging message is that climate change is likely to worsen the effects of air pollution ecosystems, especially by tending to increase agricultural and biogenic emissions, but also potentially by alteration of ecosystem sensitivity. The latter is expected to be especially sensitive to the pollution indicator and local ecosystem in question. Two key messages emerge:
    - Under current revision of the NECD, *measures for ammonia offer a particularly high benefit:cost ratio*, which is mainly because available 'low hanging fruit' for mitigation have yet to be implemented. Such ammonia-focused mitigation actions become particularly important in the context of future climate change which would otherwise tend to increase emissions.
    - In the long term, current approaches to national emissions inventories used for Europe wide inventories need to be extended with a more process-based approach allowing improved assessment of more dynamic future situations. In this way, the *effects of future climate conditions should be incorporated into official projections*. This will need to be matched by further efforts to include the effects of *technological development* and *altered management practices* under future climate conditions.

# 2. Specific objectives of ÉCLAIRE

**S1:** To develop improved process-based emissions parameterization of $NH_3$, NO and VOCs from natural and agricultural ecosystems in response to climate and pollutant deposition for incorporation into atmospheric Chemistry-Transport Models (CTMs), based on existing and new flux measurements in the field and laboratory, applying these to develop spatially resolved emission scenarios in response to climate, $CO_2$ and air pollutant change

**S2:** To determine the chief processes in atmospheric chemistry that respond to climate and air pollution change and the consequences for ozone and aerosol production and atmospheric lifetimes, in the context of the global $O_3$ background.

**S3:** To develop improved multi-layer dry deposition / bi-directional exchange parameterisations for $O_3$, $NO_x$, $NH_3$, VOCs and aerosols, taking into account near-surface chemical interactions and the role of local/regional spatial interactions, based on existing and new flux measurements and high resolution models and to estimate European patterns of air concentrations and deposition under climate change.

**S4:** To integrate the results of meta-analyses of existing datasets with the results of targeted experiments for contrasting European climates and ecosystems, thereby assessing the climate-dependence of thresholds for land ecosystem responses to air pollution, including the roles of ozone, N-deposition and interactions with VOCs, nitrogen form (wet/dry deposition) and aerosol.

**S5:** To develop improved process-based parameterizations in dynamic global vegetation models (DGVMs) and soil vegetation models (DSVMs) to assess the combined interacting impacts of air quality, climate change and nutrient availability on plant productivity, carbon sequestration and plant species diversity and their uncertainties.

**S6:** To develop novel thresholds and dose-response relationships for air pollutants (especially for $O_3$ and N) under climate change, integrated into process-based models verified by experimental studies at site scales and mapped at the European scale, quantifying the effect of climate change scenarios.

**S7:** To assess the extent to which climate change alters the transport distance and spatial structure of air pollution impacts on land ecosystems considering local, regional, continental and global interactions, focusing on nitrogen and ozone effects.

**S8:** To apply the novel metrics to quantify multi-stress response of vegetation and soils, including effects on carbon storage and biodiversity to improve the overall risk assessments of pollution-climate effects on ecosystems at the European scale as the basis for development of mitigation options.

**S9:** To quantify the overall economic impacts of air pollution effects on land ecosystems and soils, including the valuation of ecosystem and other services, and the extent to which climate change contributes by altering emissions versus ecosystem vulnerability.

# 3. Deviations and reasons

The present update of the document 'ÉCLAIRE Key Messages for Policy Makers' is delivered later than originally planned due to the need to provide intense direct reporting and input to the EU Air Quality process including revision of the National Emissions Ceilings Directive. This has allowed the ÉCLAIRE coordination team to give substantial policy support, which has further enhanced the wider impact of the project, as listed in the following Meetings, Press and Publications sections.

# 4. Key Meetings

The following provides a summary of key meetings where the ÉCLAIRE coordinator and team are delivering ÉCLAIRE outcomes for support of European and global policy development (The list represents only a section illustrating mainly outputs that involved the coordinator. It typifies the strong policy engagement of the ÉCLAIRE team).

11/15 Invited presentation: Nitroen strategies at the science-policy interface. Workshop to review and develop a proposed German Nitrogen Strategy. German Ministry of Environment and Umweltbundesampt, Berlin.

11/15 Invited Presentation to European Commission: Sustainable Food. Horizon scanning at the Junction of Health Environment and Bioeconomy (JHEB), 11 November 2015, Brussels.

10/15 Canada Deputy Environment Minister Guest Lecturer, plus briefing to Environment Canada and Agricluture Canada: 'Managing the Human Impacts of Nitrogen Pollution', Ottawa, Canada.

09/15 Invited lecture: "Opportunities to reduce ammonia and methane emissions in the context of revising the National Emissions Ceilings Directive". European Parliament, ALDE Grouping, hosted by Catherine Bearder MEP.

09/15 Final Conference of the EU ECLAIRE project, Edinburgh. Conference chair and presentations.

09/15 Invited keynote lecture: 'Challenges for Long Term Ecosystem Research in the context of the global nitrogen cycle". ILTER Symposium, Rome.

09/15 Invited speaker: Expert Workshop on Sustainable Intensification of Agriculture and Nutrient Recovery and Reuse. Milan EXPO, European Commission and RISE.

09/15 Invited presentation "Challenges for developing an international science support system for nitrogen policy". BBSRC Symposium on 'Tackling the global nitrogen crisis: what are the solutions?" Oxford.

09/15 Invited Lecture: 'Landscape variability and impacts of ammonia in relation to the Habitats Directive', ALTERNET Summer School (Peyresq, France).

07/15 Invited presentation and panelist: "Controlling environmental nitrogen. How can it be done? How will it reduce impacts?" Milan EXPO event: "Sustainable food production and air pollution: reducing emissions generates many benefits".

06/15 Presentation as co-chair of TFRN, "Nitrogen, the Circular Economy and the potential for $NO_x$ recapture and utilization". UNECE Task Force on Technical and Economic Issues, Brussels.

05/15 Invited Presentation: "Nitrogen leakage in the EU and the challenge to retrieve it", European Parliament hearing on 'Nutrient Cycling in a Circular Economy', Brussels, organized by the Baltic Sea Action Group and chaired by Sirpa Pietikaïnen, MEP, Rapporteur for the EU Circular Economy package.

04/15 Co-chair and introductory presentation: 10th meeting of the UNECE Task Force on Reactive Nitrogen (TFRN-10), Lisbon.

02/15 Invited contributor and speaker: "Opportunities to reduce ammonia emissions". European Parliament Breakfast meeting and the European Environment Bureau, Brussels.

02/15 Rapporteur: Research needs on nitrogen in agriculture. DG Agriculture Workshop in developing research priorities on Carbon and Nitrogen cycles, Brussels.

02/15 Invited presentation: "Managing human impact on the nitrogen cycle" Environmental Policy Committee (EPOC), Organization for Economic Cooperation and Development (OECD), Paris.

01/15 Invited presentation: "Our Nutrient World: Nitrogen indicators and Future Aspirations". Sustainable Development Solutions Network (SDSN) and International Fertilizer Manufacturers Association (IFA) workshop on nutrient sustainable development goals. Paris.

12/14 Invited presentation: "Task Force on Reactive Nitrogen: From Ammonia Codes to the Nitrogen Green Economy" Executive Body (EB-33) of the UNECE Convention on Long Range Transboundary Air Pollution (Palais des Nations, Geneva). http://www.unece.org/index.php?id=33291#/

12/14 Invited Presentation: "How does climate change alter the air pollution threat to terrestrial ecosystems. ACCENT+ Conference, Brussels.

11/14 EU 'Foresight' Expert Panel on *Junction of Health, Environment and Bioeconomy* (JHEB), Brussels, and contribution to Workshop on EU Foresight on Bioeconomy.

11/14 Conference chair and presentation: "TFRN Special Workshop: The Revised UNECE Framework Code on Ammonia Emissions" organized jointly with the European

Commission and Pracis, Edinburgh. (see http://www.ceh.ac.uk/news/press/ammonia-framework-code-edinburgh-workshop-press-release.asp )

10/14 Conference chair and overview: "ÉCLAIRE Open Science Conference: Integrating Impacts of Air Pollution and Climate Change on Ecosystems.", Budapest, Hungary.

10/14 Invited presentation: "Targeted research on the global N cycle: towards an International Nitrogen Management System (INMS)", kick-off meeting of the INMS preparation phase, with United Nations Environment Programme and Global Environment Facility, Washington DC.

09/14 Invited presentation: "Overview of international nitrogen related activities", First meeting of the EU Nitrogen Expert Panel, Windsor, UK.

09/14 Invited Lecture: 'Landscape variability and impacts of ammonia in relation to the Habitats Directive', ALTERNET Summer School (Peyresq, France).

09/14 Invited presentation as member of EU 'Foresight' Expert Panel on *Junction of Health, Environment and Bioeconomy* (JHEB), Brussels.

07/14 Invited presentations: Mark Sutton: 'Task Force on Reactive Nitrogen: Implementation and new Opportunities' and Rob Maas: presentation on nitrogen ecosystem damage costs. Working Group on Strategies and Review (WGSR-52) of the UNECE, CLRTAP (Palais des Nations, Geneva).

06/14 First United Nations Environment Assembly (UNEA), Nairobi: Mark Sutton Presentation on nitrogen management options to UNEP Chief Scientist, and contribution to Green Room civil society events on nitrogen.

06/14 Invited Talk: "True cost accounting and the nitrogen cycle". Mark Sutton. Nourish Scotland and the Sustainable Food Trust, workshop on 'True Cost Accounting: How can we pay for sustainable food?", Edinburgh Centre for Carbon Innovation. http://www.nourishscotland.org/events/true-cost-accounting-can-pay-sustainable-food/

05/14 Invited Lecture: "From ammonia to the global nitrogen cycle: Why should we care?", Mark Sutton. Department of Environment and Primary Industries (DEPI), Ellinbank Dairy Research Centre, Victoria.

05/14 Invited Industry Round-Table: "Reactive Nitrogen: Key Scientific Findings & Update on Major Initiatives" Mark Sutton. 82nd Annual Conference of the International Fertilizer Manufacturers Association, Sydney, Australia (http://issuu.com/ifa-fertilizer/docs/2014_ifa_fert_agric_may )

04/14 ECLAIRE special session (Rob Maas, J.-P. Hettelingh, W. Winiwarter) at the 24th CCE Workshop and 30th Task Force Meeting of the ICP Modelling and Mapping, 7-10th April 2014, Rome, Italy.

04/14 Press Briefing: Food choice, agriculture and future European nitrogen policies. Mark Sutton, Henk Westhoek and Alessandra DiMarco. Science Media Centre, London.

04/14 Invited Presentations: "Nitrogen Science and Policy Support" to the "OECD Expert Workshop on Economy-wide Nitrogen Balances and Indicators", Mark Sutton, Albert Bleeker, Wilfried Winiwarter, Adrian Leip. OECD Working Party on Environmental Information, Paris.

03/14 Co-chair and introductory presentation: 9th meeting Task Force on Reactive Nitrogen (TFRN-9), Madrid. Mark Sutton, Clare Howard, and many of the ECLAIRE team.

03/14 Invited Guest Lecture to the Indian Agricultural Research Centre, Dehli: "Nitrogen Global Challenges". Mark Sutton.

03/14 Invited Presentation on "Developing the International Nitrogen Management System (INMS)". Mark Sutton and Albert Bleeker, Steering Group Workshop of the UNEP Global Partnership on Nutrient Management, Bhubaneshwar, India.

12/13 Invited talk: "An integrated approach to tackling nitrogen deposition". Workshop on Nitrogen deposition and the Nature Directives (Atlantic Region under Natura 2000 implementation), hosted by JNCC and Defra, Peterborough, UK. Mark Sutton and Rob Maas.

11/13 Conference chair, 6th International Nitrogen Conference, "Just Enough Nitrogen, perspectives on how to get there for too much and too little regions". Including keynote lecture: "Global Nitrogen Assessment: from Our Nutrient World to the International Nitrogen Management System (INMS)." Kampala, Uganda. Mark Sutton and many of the ÉCLAIRE team.

10/13 Meeting of the Task Force on Integrated Assessment Modelling under the Convention on Long-range Transboundary Air Pollution (Zagreb)

10/13 2nd Annual meeting of the EU ÉCLAIRE project, Zagreb. (100 participants).

10/13 Invited keynote Lecture and Chair of Panel discussion: Global Conference on Land-Ocean Connections GLOC-2, Jamaica (in partnership with UNEP for intersessional review of the GPA, showing how air pollution and global nutrient pollution may be linked, Mark Sutton).

9/13 Presentation to UNEP Lead Authors meeting (Geneva): Nitrous oxide the forgotten pollutant (Mark Sutton).

6/13 European Green Week, Brussels, Session: "Science and Evidence for EU air quality policy" hosted by DG Research. Invited presentation: "The Nitrogen Challenge", and panel discussion with experts (Mark Sutton, David Fowler, Markus Ammann, Clare Howard).

6/13 European Green Week, Brussels, Session: "Air Quality and Agriculture" hosted by DG Environment. Invited Keynote lecture: "Why worry about ammonia and what can we do about it?" and panel discussion with industry and NGO representatives (in support of the EU Air Quality policy review, Mark Sutton).

5/13 European Parliament, "Forum on fertilizers and nutrients for growth". Invited Keynote speaker: "Our Nutrient World: The challenge to produce more food and energy with less pollution" and panel discussion with MEPs. (Mark Sutton) (www.fertilizersforum.com)

5/13 Global Partnership on Nutrient Management, hosted by US Dept Agriculture and UNEP, Washington DC. Invited lecture: "Nitrogen management for food, energy & environmental security. Research outcomes, policy support & next steps".

5/13 Invited presentation: 'Task Force on Reactive Nitrogen: Opportunities, costs/benefits & actions for nitrogen mitigation.' Report to the Working Group on Strategies and Review (WGSR-51) of the UNECE Convention on Long Range Transboundary Air Pollution, see UNECE documents. (Palais des Nations, Geneva).

04/13 Co-chair and introductory presentation: 8th meeting Task Force on Reactive Nitrogen (TFRN-6), Copenhagen. Mark Sutton, Clare Howard and several of the ÉCLAIRE team.

04/13 European Air Science Policy Forum, organized at Farmleigh, Dublin under the Irish Presidency of the EU. Invited presentation: 'Challenges and opportunities for nitrogen emission reduction strategies'. Mark Sutton, Mike Holland, Markus Amman.

04/13 Meeting with Industry: BASF First Fireside Chat on Nitrogen, Germany. Invited lecture: 'Strategies for mitigating ammonia in agricultural landscapes.' Mark Sutton, Klaus Butterbach Bahl.

04/13 Presentation at 23nd CCE Workshop and 29th Task Force Meeting of the ICP Modelling and Mapping, Copenhagen, Denmark (W. Winiwarter)

03/13 Swedish Air Pollution Progamme (SCARP) Final Conference, Stockholm. Invited lecture: 'Nitrogen and the Environment: From Europe to a Global Perspective'. Peringe Grennfelt (host) , Mark Sutton and others.

02/13 United Nations Environment Programme (UNEP), Governing Council and Global Ministerial Environmental Forum, Nairobi. Launch of "Our Nutrient World" report, presentation and press conference, plus preceding press conference at London, Science Media Centre (Mark Sutton).

# 5. Selected Press

Air pollution and climate change – a vicious circle. Cordis, RTD Success Stories. [Highlight outcomes of the ECLAIRE project]. December 2015

Sutton M., Brownlie W., Howard C. and Navé B. (2015) Fluch und Segen zugleich. *dlz agrarmagazin* (November 2015) pp 116-119. ["Blessing and a curse together"].

*Lancet Respiratory Medicine*, Editorial: Short-lived climate pollutants: a focus for hot air. (31 October 2015) **386**, 1707. [Following up our article Brunekreef et al. http://dx.doi.org/10.1016/ on National Emissions Ceilings, agriculture and human health].

Oliver Morton, 'Wizard ideas for cleaning up nitrogen pollution', *The Economist* (Nov/Dec 2015), p 34.

*Planet Earth*, Tackle farm emissions to fight air pollution, say UN experts. Autumn 2015, p 3. http://www.ceh.ac.uk/press/target-farm-emissions-combat-air-pollution-and-crop-loss-say-un-experts

BBC Radio 4 *Farming Today* programme (0645, 1 October 2015). Interview on ammonia emission reduction ahead of the vote by MEPs on the proposed National Emissions Ceilings. Interview Mark Sutton together with Pekka Pesonen, Secretary General, COPA-COGECA (Interviewer: Charlotte Smith). http://www.bbc.co.uk/programmes/b06d935c

United Nations Economic Commission for Europe, "UNECE joins international effort to reduce nitrogen pollution". http://www.unece.org/info/media/unece-weekly/news-detail.html?extern=1&inter_lang=en&news=652&profil=default

European Commission, Agricultural ammonia emissions could be reduced without affecting crop yield. *Science for Environmental Policy. News Alert.* Issue 414. 21 May 2015. http://ec.europa.eu/environment/integration/research/newsalert/newsalert.htm

European Commission, Joint Research Centre. Nitrogen – too much of a good thing. 4 May 2015

Kajsa Lindqvist. Editorial: Ammonia emissions are cheap to reduce. *Acid News* 2014, no. 4. http://www.airclim.org/acidnews/editorial-ammonia-emissions-are-cheap-reduce

Uzbekistan Report, Information Agency. A new "Ammonia Framework Code" adopted in Geneva. (16 December 2014) http://news.uzreport.uz/news_1_e_127355.html

UNEP (2014) Excess nitrogen in the environment. Chapter 1 in: UNEP Yearbook 2014 emerging issues. pp 6-11. United Nations Environment Programme (http://www.unep.org/yearbook/2014/PDF/chapt1.pdf)

CEH News Release, "Experts meet in Edinburgh to agree international action on reducing agriculture's contribution to air pollution" (13 November 2014) http://www.ceh.ac.uk/news/press/ammonia-framework-code-edinburgh-workshop-press-release.asp

Dick Veerman, "Mestbeleid: de werkelijke daders gaan al jaren vrijuit" (Manure policy: the real perpetrators go unpunished for years) *Foodlog*. 13 October 2014. http://www.foodlog.nl/artikel/rammelend-mestbeleid-kan-tot-schadeclaims-leiden/allcomments/

*Observer Radio*, Antiga and Barbuda (21 September 2014, live). Half-hour interview on how agriculture and the food system of the Caribbean can respond to the challenges of climate change.

Geesje Rotgers, "Emissies ammoniak veel te hoog ingeschat". *V-focus* August 2014. http://www.v-focus.nl/wp-content/uploads/2015/01/Emissies_ammoniak_veel_te_hoog_ingeschat.pdf (Ammonia emissions are overestimated)

Ilona Amos, *The Scotsman* (3 August 2014) Book shows how sustainable food could boost health. http://www.scotsman.com/news/environment/book-shows-how-sustainable-food-could-boost-health-1-3497489

BBC York (31 July 2014, pre-recording). Interview with Paul Hudson for the Paul Hudson Weather Show. http://www.bbc.co.uk/programmes/p01994lw/broadcasts/upcoming

BBC World News TV (1640 on 22 July 2014, live) Interview jointly with Fuchsia Dunlop (writer / journalist on Chinese cuisine) on beef, food choice, air pollution and the environment (Interviewer: Ros Atkins).

BBC Radio Scotland *Newsdrive* programme (1620 on 22 July 2014, live). Interview on beef, food choice,air pollution and the environment (Interviewer: Bill Whiteford). http://www.bbc.co.uk/programmes/b049fgdc

Damian Carrington, *The Guardian* (21 July 2014). Giving up beef will reduce carbon footprint more than cars, says expert. http://www.theguardian.com/environment/2014/jul/21/giving-up-beef-reduce-carbon-footprint-more-than-cars

Matt McGrath, *BBC News.* (21 July 2014) Beef environment cost 10 times that of other livestock. www.bbc.com/news/science-environment-28409704

Katie Valentine, *Climate Progress.* (27 June 2014) Not eating meat can cut your food-related carbon emissions almost in half, study finds. http://thinkprogress.org/climate/2014/06/27/3454129/eating-meat-carbon-emissions/

Kajsa Lindqvist, *Acid News*. (2014, no. 2) Diet shifts could reduce nitrogen pollution. http://www.airclim.org/acidnews/diet-shifts-could-reduce-nitrogen-pollution

Andrew Marshall, *Farmonline*. (Australia) Up in smoke: ag's billion-dollar vanishing act. 2 June 2014. http://www.farmonline.com.au/news/agriculture/cropping/general-news/up-in-smoke-ags-billiondollar-vanishing-act/2699945.aspx?storypage=0

European Commission, *Horizon 2020 News.* Researchers study the effects of air pollution on European ecosystems. (May 2014). https://ec.europa.eu/programmes/horizon2020/en/news/researchers-study-effects-air-pollution-european-ecosystems

*Agriculture and Rural Convention*, Part 1: how to cut EU agri-food Greenhouse Gas Emissions by 40%. 5 May 2014. http://www.arc2020.eu/front/2014/05/heres-how-to-cut-the-eus-agri-food-greenhouse-gas-emissions-by-40/

Alex Kirby, *Climate News Network*, Be a demitarian and cool the climate. 27 April 2014. http://www.climatenewsnetwork.net/2014/04/be-a-demitarian-and-cool-the-climate/

*Food Climate Research Network*, The influence of food choices on nitrogen emissions and the European environment - ENA special report, 25 April 2014. http://www.fcrn.org.uk/research-library/climate-change/greenhouse-gases/influence-food-choices-nitrogen-emissions-and-europ

BBC Radio Scotland. *News Drive.* Live interview with Mhairi Stuart (anchor), Mark Sutton and Nigel Miller (President of National Farmers Union for Scotland) 1715, 25 April 2014.

Tamara Jones, *Planet Earth Online*, Halving your meat intake would be good for the environment. 25 April 2014. http://planetearth.nerc.ac.uk/news/story.aspx?id=1661

Press Association, *MSN News*, Calls to halve meat consumption. 25 April 2014. http://news.uk.msn.com/uk/calls-to-halve-meat-consumption

BBC Radio 4: *Farming Today* programme, 25 April 2014. Nitrogen Pollution, Meat Consumption, Hedgehogs. http://www.bbc.co.uk/programmes/b0418wy3 (Interviewer Charlotte Smith).

Ben Webster, *The Times*, Raise taxes on meat to turn us into demitarians, says UN, 25 April 2014, p 17. (also web edition: "Put tax on meat to cut pollution and improve diet, says UN report": http://www.thetimes.co.uk/tto/environment/article4072005.ece

Nina Chertsey, *Reuters*, EU should halve meat, dairy consumption to cut nitrogen - report. 25 April 2014. http://www.reuters.com/article/2014/04/25/food-environment-idUSL6N0NH1X120140425 and syndicated to around 400 other news sites

Centre for Ecology and Hydrology, Nitrogen on the Table, Pollution, Climate and Land use, 25 April 2014. http://www.ceh.ac.uk/news/news_archive/nitrogen-pollution-why-what-we-eat-matters_2014_20.html and press release at: http://www.ceh.ac.uk/news/press/whywhatweeatmatters.asp

Olivia Midgley, *Farmers Guardian*, Eating less meat will slash nitrogen pollution, scientists claim. 25 April 2014 http://www.farmersguardian.com/home/livestock/eating-less-meat-will-slash-nitrogen-pollution-scientists-claim/63943.article

Adam Vaugham, *The Guardian*, Halving meat and dairy consumption could slash farming emissions. Adopting a 'demitarian' diet would lead to a 25-40% reduction in nitrogen emissions from agriculture in Europe, report shows. 25 April 2014. http://www.theguardian.com/environment/2014/apr/25/halve-meat-dairy-consumption-slash-emissions-farming

Emily Beament, Halve meat consumption to 'slash nitrogen pollution'. 25 April 2014. http://www.irishexaminer.com/archives/2014/0425/world/halve-meat-consumption-to-aposslash-nitrogen-pollutionapos-266476.html

Science Media Centre, Nitrogen pollution, climate and land use: why what we eat matters. http://www.sciencemediacentre.org/nitrogen-pollution-climate-and-land-use-why-what-we-eat-matters/ 25 April 2014.

BBC Radio 4: *Farming Today* programme, 11 April 2014. Interview on effects of nitrogen on nature and the options for ammonia mitigation in European policy development. (Interviewer, Kaz Graham).

European Commission (2014) The value of acknowledging societal costs of $N_2O$ emissions. *Science for Environmental Policy* (23 January 2014, Issue 358). http://ec.europa.eu/environment/integration/research/newsalert/pdf/358na1.pdf

BBC Radio 4: *Frontiers* programme: 'Nitrogen Fixing'. 4 Dec 2013, 21:00. Half-hour documentary. 100 years since the first synthetic fertilizers, http://downloads.bbc.co.uk/podcasts/radio4/frontiers/frontiers_20131204-2145a.mp3

European Commission, Science for Environmental Policy In-depth Report. Nitrogen pollution and the European Environment (Sept 2013) http://ec.europa.eu/environment/integration/research/newsalert/pdf/IR6.pdf

HortiBiz. Nitrogen can improve production Africa. Interview with Mark Sutton and Ugandan Commissioner for Crop Protection, Komayombi Bulegeya. http://www.hortibiz.com/hortibiz/nieuws/nitrogen-can-improve-crop-production-africa/

BBC World. (2013) Live TV interview hosted by Jon Sopel with Mark Sutton and Robin McKie (Science Editor, the Guardian). Haber Nitrogen – from war to environmental challenges. 15:40 on 11/11/2013.

McGrath, Matt (2013) UN highlights role of farming in closing emissions gap. BBC News on-line http://www.bbc.co.uk/news/science-environment-24817837 5/11/2013.

McKie, Robin (2013) From fertiliser to Zyklon B: 100 years of the scientific discovery that brought life and death. *The Observer*, 3 November 2013. p 15. http://www.theguardian.com/science/2013/nov/03/fritz-haber-fertiliser-ammonia-centenary

European Commission: (2013) Science for Environmental Policy. *Nitrogen Pollution and the European Environment: Implications for Air Quality Policy.* September 2013. 28 pp. http://ec.europa.eu/environment/integration/research/newsalert/pdf/IR6.pdf

Braakman J. (2013) Nederland verliest onderzoekskwaliteit *Boerderij* (The Farmer) 7 June 2013, p 14. ('Netherlands loses research quality')

IIASA (2013) The nitrogen quandary. (17 June 2013). http://www.iiasa.ac.at/web/home/resources/mediacenter/FeatureArticles/The-Nitrogen-Quandary.en.html

CEH news (2013) Leaking ammonia leading to biodiversity loss and health risks, new themed volume of papers reveals (28 May 2013). http://www.ceh.ac.uk/news/news_archive/leaking-ammonia-fertilisers-biodiversity-loss-health_2013_36.html

Sutton, M. (2013) The other global crunch: nitrogen, environment and the economic opportunities. *G8 Magazine*. The UK Summit: Loch Erne. p 164

Lindqvist, K. (2013) Call for international nitrogen framework. *Acid News*, June 2013, pp 6-7. http://airclim.org/acidnews/call-international-nitrogen-framework

European Environmental Bureau (2013) Ammonia control options for better air quality. Recommendations to the EU for its 2013 'Year of Air'. http://www.eeb.org/?LinkServID=E1B5ACC1-5056-B741-DB92489757EB9AC0&showMeta=0&aa

Sutton, M. (2013) Should we all stop eating meat? United Nations Economic Commission for Europe: Expert Opinion. http://www.unece.org/index.php?id=32617

Qui, J. (2013) Nitrogen pollution soars in China. *Nature News.* http://www.nature.com/news/nitrogen-pollution-soars-in-china-1.12470

Noualhat, L. (2013) La viande doit redevenir un aliment special. Interview Mark Sutton, auteur d'un rapport pour le Programme des Nations unies pour l'environnement, prône une diminution drastique de notre consommation. *Liberation* (22 February 2013) + 218 comments. http://www.liberation.fr/terre/2013/02/22/la-viande-doit-revenir-un-aliment-special_883874

Smith, B.P., Burns, P. & Reading, S. (2013) Communicating 'Our Nutrient World' – a report for UNEP (Published 18 February 2013). March 2013. Centre for Ecology & Hydrology 12 pp. **http://www.ceh.ac.uk/news/news_archive/CommunicatingOurNutrientWorld.html** (this summary document lists about **300 news items** on the story, including live interviews on Radio 4 (Today Programme and Farming Today), LBC Radio, BBC Wales, New South Wales Radio (ABC), and newspapers including, Independent, Guardian, Times of India etc.

Schuetz C.F. (2013) Would you halve your meat consumption to save the planet. *International Herald Tribune.* http://rendezvous.blogs.nytimes.com/2013/02/22/would-you-halve-your-meat-consumption-to-save-the-environment/

Harvey F. (2013) Halve meat consumption, scientists urge rich world. *The Guardian* (18 February 2013) + 240 comments + 14300 facebook shares.

Danny Fortson (2013) Putting a price on the world. *Sunday Times, Colour Supplement*. 13 January 2013.

# 6. Selected publications

The following publications are listed as particularly of relevance for a policy audience.

**Books**

Westhoek H., Lesschen J.P.,Rood T., Leip A., Wagner S., De Marco A., Murphy-Bokern D., Pallière C., Howard C.M., Oenema O. & Sutton M.A. (2015) *Nitrogen on the Table: The influence of food choices on nitrogen emissions and the European environment.* (European Nitrogen Assessment Special Report on Nitrogen and Food.) Centre for Ecology and Hydrology, UK. 67 pp. [ISBN: 978-1-906698-51-5]

UNECE (2015) *United Nations Economic Commission for Europe Framework Code for Good Agricultural Practice for Reducing Ammonia Emissions* (authors: S. Bittman, M. Dedina, B. Amon, H. Menzi, J. Webb, K.Groenestein,T. Misselbrook, N. Hutchings, H. Dohler, K. van der Hoek, S. Gyldenkærne, L. Valli, C. Pallière, C. Howard, O. Oenema and M.A. Sutton) United Nations Economic Commission for Europe, Geneva.

Reis S, Sutton MA, Howard CM (eds) (2014) *Costs of ammonia abatement and the climate co-benefits*. Springer.

Sutton M.A., Mason K.E., Sheppard L.J., Sverdrup H., Haeuber R. and Hicks W.K. (2014). (eds.) *Nitrogen Deposition, Critical Loads and Biodiversity.* (Proceedings of the International Nitrogen Initiative Workshop, linking experts of the Convention on Long-range Transboundary Air Pollution and the Convention on Biological Diversity). Springer: Dordrecht. 534 pp.

Bittman, S., Dedina, M., Howard C.M., Oenema, O. and Sutton, M.A. (2014) (eds.) *Options for ammonia mitigation: Guidance from the UNECE Task Force on Reactive Nitrogen.* TFRN-CLRTAP, Centre for Ecology and Hydrology, UK. [ ISBN: 978-1-906698-46-1]

UNEP (2013) *Drawing Down $N_2O$ to Protect Climate and the Ozone Layer.* A UNEP Synthesis Report. (Eds.: J. Alcamo, S.A. Leonard, A.R. Ravishankara and M.A. Sutton). ISBN: 978-92-807-3358-7. (14 + 57 pp), United Nations Environment Programme, Nairobi.

Fowler D., Brunekreef B., Fuzzi S., Monks P.S., Sutton M.A., Braseur G.P., Friedrich R., Passante L.G., Jiménez Mingo J.M. (2013) Research Findings in support of the EU Air Quality Review. (eds. Maione M. and Fuzzi S.). European Commission, Directorate-General for Research and Innovation, Brussels. 57 pp.

Fowler D., Pyle J.A., Raven J.A. and Sutton M.A. (2013) The global nitrogen cycle of the twenty-first century. (Special Issue) *Philosophical Transactions of the Royal Society, Series B.* **368** (1621).

Sutton M.A., Bleeker A., Howard C.M., Bekunda M., Grizzetti B., de Vries W., van Grinsven H.J.M., Abrol Y.P., Adhya T.K., Billen G.,. Davidson E.A, Datta A., Diaz R., Erisman J.W., Liu X.J., Oenema O., Palm C., Raghuram N., Reis S., Scholz R.W., Sims T., Westhoek H. & Zhang F.S., with contributions from Ayyappan S., Bouwman A.F., Bustamante M., Fowler D., Galloway J.N., Gavito M.E., Garnier J., Greenwood S., Hellums D.T., Holland M., Hoysall C., Jaramillo V.J., Klimont Z., Ometto J.P., Pathak H., Plocq Fichelet V., Powlson D., Ramakrishna K., Roy A., Sanders K., Sharma C., Singh B., Singh U., Yan X.Y. & Zhang Y. (2013) *Our Nutrient World: The challenge to produce more food and energy with less pollution.* Global Overview of Nutrient Management. Centre for Ecology and Hydrology, Edinburgh on behalf of the Global Partnership on Nutrient Management and the International Nitrogen Initiative. 114 pp. http://initrogen.org/index.php/publications/our-nutrient-world/

**Journal Papers**

Mills G., Harmens H., Wagg S., Sharps K., Hayes F., Fowler M., Sutton M., Davies B. (2015) Ozone impacts on vegetation in a nitrogen enriched and changing climate. *Environmental Pollution* (in press).

Bealey W.J., Dore A.J., Dragosits U., Reis S., Reay D.S. and Sutton M.A. (2016) The potential for tree planting strategies to reduce local and regional ecosystem impacts of agricultural ammonia emissions *Journal of Environmental Management* **165**, 106-116.

Theobald M.R., Sanz-Cobena A., Vallejo A. and Sutton M.A. (2015) Suitability and uncertainty of two models for the simulation of ammonia dispersion from a pig farm located in an area with frequent calm conditions. *Atmospheric Environment* **102**, 167-175.

Fowler D., C.E. Steadman, D. Stevenson, M. Coyle, R.M. Rees, U.M. Skiba, M.A. Sutton, J.N. Cape, A.J. Dore, M. Vieno, D. Simpson, S. Zaehle, B.D. Stocker, M. Rinaldi, M.C. Facchini, C.R. Flechard, E. Nemitz, M. Twigg, J.W. Erisman, J.N. Galloway (2015) Effects of global change during the 21st century on the nitrogen cycle. *Atmospheric Chemistry and Physics. Discussions*. **15**, 1747-1868.

Brunekreef B., Harrison R.M., Künzli N., Querol X., Sutton M.A., Heederik D.J.J. and Sigsgaard T. (2015) Reducing the health effect of particles from agriculture. *Lancet Respiratory Medicine* (8 October 2015), http://dx.doi.org/10.1016/ S2213-2600(15)00413-0.

Leip A., Billen G., Garnier J., Grizzetti B., Lassaletta L., Reis S., Simpson D., Sutton M.A., de Vries W., Weiss F. and Westhoek H. (2015) Impacts of European livestock production: nitrogen, sulphur, phosphorus and greenhouse gas emissions, land-use, water eutrophication and biodiversity. *Environ. Res. Lett.* **10**, 115004.

R.M. McKenzie, M.Z. Özel., J.N. Cape, J. Drewer, K.J. Dinsmore, E. Nemitz, J.M. Hamilton, M.A. Sutton, M.W. Gallagher, U. Skiba. (2015) *Biogeosciences Discuss*. 12, 515-554, doi: 10.5194/bgd-12-515-2015.

Schneidemesser, E. Von., Monks P.S., Allan J.D., Bruwiler L., Forster P., Fowler D., Lauer D., Morgan W.T., Paasonen P., Righi M., Sindelarova K. and Sutton M.A. (2015) Chemistry and the linkages between air quality and climate. *Chemical Reviews*, **115**, 3856-3897. DOI: 10.1021/acs.chemrev.5b00089

Helfter C., Campbell C., Dinsmore K. J., Drewer J., Coyle M., Anderson M., Skiba U., Nemitz E., Billett M. F., and Sutton M. A. (2015) Drivers of long-term variability in $CO_2$ net ecosystem exchange in a temperate peatland. *Biogeosciences* **12**, 1799-1811. doi:10.5194/bg-12-1799-2015.

Vogt E., Braban C.F., Dragosits U., Durand P., Sutton M.A., Theobald M.R., Rees R.M, McDonald C., Murray S. and Billett M.F. (2015) Catchment land use effects on fluxes and concentrations of organic and inorganic nitrogen in streams. *Agriculture, Ecosystems & Environment*, **199**, 320-332. doi:10.1016/j.agee.2014.10.010

Van Damme M., Clarisse L., Dammers E., Liu X., Nowak J.B., Clerbaux C., Flechard C.R., Galy-Lacaux C., Xu W., Neuman J.A., Tang Y.S., Sutton M.A., Erisman, J.W. and Coheur P.F. (2015) Towards validation of ammonia ($NH_3$) measurements from the IASI satellite. *Atmos. Meas. Tech.* **8**, 1575-1591, doi:10.5194/amt-8-1575-2015.

Oenema O., Ju X.T., de Klein C., Alfaro M., del Prado A., Lesschen J.P., Zheng X.H, Velthof G., Ma L., Gao B., Kroeze C., and Sutton M. (2014) Reducing nitrous oxide emissions from the global food system. *Current Opinion in Environmental Sustainability*, **9**, 55-64.

Sheppard L.J., Leith I.D., Mizunuma T., Leeson S., Kivimaki S., Cape J.N., Dijk N., Leaver D., Sutton M.A., Fowler D., Berg L.J.L, Crossley A., Field C., Smart S. (2014) Inertia in an ombrotrophic bog ecosystem in response to 9 years' realistic perturbation by wet deposition of nitrogen, separated by form. *Global change biology* **20** (2), 566-580.

Sanz-Cobena A., Lassaletta L. Estellés F., Del Prado A., Guardia G., Abalos D., Aguilera E., Pardo G., Vallejo A., Sutton M.A., Garnier J. and Billen G. (2014) Yield-scaled mitigation of ammonia emission from N fertilization: the Spanish case. *Environ. Res. Letters* 9, 125005. doi:10.1088/1748-9326/9/12/125005

Theobald M.R., Sanz-Cobena A., Vallejo A. and Sutton M.A. (2014) Suitability and uncertainty of two models for the simulation of ammonia dispersion from a pig farm located in an area with frequent calm conditions. *Atmospheric Environment* **102**, 167-175.

Vieno M., Heal M.R., Hallsworth S., Famulari D., Doherty R.M., Dore A.J., Tang Y.S., Braban C.F., Leaver D., Sutton M.A., and Reis S. (2014) The role of long-range transport and domestic emissions in determining atmospheric secondary inorganic particle concentrations across the UK. *Atmospheric Chemistry and Physics* **14**, 8435-8447. doi: 10.5194/acp-14-8435-2014

Gu, Baojing, Sutton M.A., Chang S.X., Ge Y., Chang J. (2014) Agricultural ammonia emissions contribute to China's urban air pollution. *Frontiers in Ecology and Environment* 265-266 doi:10.1890/14.WB.007 http://www.esajournals.org/doi/abs/10.1890/14.WB.007

Westhoek H., Lesschen J.P., Rood T., Wagner S., De Marco A., Murphy-Bockern D., Leip A., van Grinsven H., Sutton M.A. and Oenema O. (2014) Food choices, health and environment: Effects of cutting Europe's meat and dairy intake. *Global Environmental Change* http://dx.doi.org/10.1016/j.gloenvcha.2014.02.004

Sutton M.A., Skiba U.M., van Grinsven H., Oenema O., Watson C., Williams J., Hellums D., Maas R., Gyldenkaerne S., Pathak H. and Winiwarter W. (2014) Green Economy thinking and the control of nitrous oxide emissions. *Environmental Development* **9** (Jan 2014), http://dx.doi.org/10.1016/j.envdev.2013.10.002.

Simpson, D.; Arneth, A.; Mills, G.; Solberg, S. & Uddling, J. (2014) Ozone - the persistent menace; interactions with the N cycle and climate change *Current Op. Environ. Sust.*, 9-10, 9-19

Jones L., Provins A., Holland M., Mills G., Hayes F., Emmett B., Hall J., Sheppard L., Smith R., Sutton M., Hicks K., Ashmore M., Haines-Young R., Harper-Simmonds L. (2013) A review and application of the evidence for nitrogen impacts on ecosystem services. *Ecosystem Services.*

Winiwarter W., Erisman J.W., Galloway J.N., Klimont Z. and Sutton M.A. (2013) Estimating environmentally relevant fixed nitrogen demand in the 21st century. *Climatic Change* **120**, 889–90. http://dx.doi.org/10.1007/s10584-013-0834-0

Fowler D., Coyle M., Skiba U., Sutton M.A., Cape J.N., Reis S., Sheppard L.J., Jenkins A., Grizzetti B., Galloway J.N., Vitousek P., Leach A., Bouwman A.F., Butterbach-Bahl K., Dentener F., Stevenson D., Amann M. and Voss M. (2013) The global nitrogen cycle of the twenty-first century. *Philosophical Transactions of the Royal Society, B.* 368: 2130164. http://dx.doi.org/10.1098/rstb.2013.0164

Sutton M.A., Howard C.M., Bleeker A. and Datta A. (2013) The global nutrient challenge: From science to public engagement. *Environmental Development* **6**, 80-85.

Sutton M.A., Reis R., Riddick S.N., Dragosits U., Nemitz E., Theobald M.R., Tang Y.S., Braban C.F., Vieno M., Dore A.J., Mitchell R.F., Wanless S., Daunt F., Fowler D., Blackall T.D., Milford. C., Flechard C.F., Loubet B., Massad R., Cellier P., Coheur P.F., Clarisse L., van Damme M., Ngadi, Y., Clerbaux C., Skjøth C.A., Geels C., Hertel O., Wichink Kruit R.J., Pinder, R.W., Bash J.O., Walker J.D., Simpson D., Horvath, L., Misselbrook, T.H., Bleeker A., Dentener F. &Wim de Vries V. (2013) Toward a climate-dependent paradigm of ammonia emission & deposition. *Phil. Trans. Roy. Soc. (Ser. B).* 368: 20130166. http://dx.doi.org/10.1098/rstb.2013.0166

Van Grinsven H.J.M., Holland M., Jacobsen B.H., Klimont Z., Sutton M.A. and Willems W.J. (2013) Costs and benefits of nitrogen for Europe and implications for mitigation. *Environmental Science & Technology* **47**, 3571-3579. dx.doi.org/10.1021/es303804g

Sutton M.A. and Bleeker A. (2013) The shape of nitrogen to come. *Nature* **494**, 435-437. doi:10.1038/nature11954

**Additional documents related to specific policy processes**

ECLAIRE (2014) Effects of Climate Change on Air Pollution Impacts and Response Strategies for European Ecosystems (ECLAIRE) project report containing key messages for policy makers (Informal document n° 4). Executive Body of the CLRTAP (EB-33), Geneva (8-12 Dec 2014). http://www.unece.org/fileadmin/DAM/env/documents/2014/AIR/EB/Informal_Document_4_ECLAIRE_Policymakers_report.pdf

UNECE (2014) Draft revised United Nations Economic Commission for Europe Framework Code for Good Agricultural Practice for Reducing Ammonia Emissions Prepared by the co-Chairs of the TFRN. http://www.unece.org/fileadmin/DAM/env/documents/2014/AIR/EB/ECE_EB_AIR_2014_8_E.pdf ECE/EB.AIR/2014/8.

UNECE (2014) Guidance document on preventing and abating ammonia emissions from agricultural sources. Executive Body for the Convention on Long-range Transboundary Air Pollution. (ECE.EB/AIR/120). http://www.unece.org/fileadmin/DAM/env/documents/2012/EB/ECE_EB.AIR_120_ENG.pdf

Westhoek H., Lesschen J.P., Rood T., Wagner S., Leip A., De Marco Alessandra, Murphy-Bockern D., Sutton M.A. and Oenema O. (2014). European Nitrogen Assessment Special Report on Nitrogen and Food. *Nitrogen on the Table. The influence of food choices on nitrogen emissions and the European environment.* Executive Summary. Task Force on Reactive Nitrogen http://www.clrtap-tfrn.org/ and http://www.clrtap-tfrn.org/webfm_send/555

Bleeker A., Sutton M., Winiwarter W. and Leip A. (2013) Economy-wide nitrogen balances and indicators: Concept and methodology. Organistion for Economic Cooperation and Development (OECD) (Working Party on Environmental Information), ENV/EPOC/WPEI(2012)4/REV1. Paris.

European Commission (2013) Annex III to the: Proposal for a DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on the reduction of national emissions of certain atmospheric pollutants and amending Directive 2003/35/EC. (COM/2013/0920 final - 2013/0443 (COD) ) (December 2013). [Draws on material prepared by TFRN as options for Annex IX revision of the Gothenburg Protocol]

UNECE (2013) Executive Body for the Convention on Long-Range Transboundary Air Pollution. Working Group on Strategies and Review. 51st Session. (30April – 1 May 2013). Report of the Task Force on Reactive Nitrogen. ECE/EB.AIR/WG.5/2013/3 (in English, French and Russian) 9 pp (prepared by the co-chairs) http://www.unece.org/index.php?id=31868