Project No. 282910

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

Seventh Framework Programme

Theme: Environment

D22.2 – ÉCLAIRE Key Messages for Policy Makers

Due date of deliverable: **01/10/2013** Actual submission date: **30/7/2014**

Start Date of Project: **01/10/2011** Duration: **48 months**

Organisation name of lead contractor for this deliverable :
NERC

Project co-funded by the European Commission within the 7th Framework Programme		
Dissemination Level		
PU	Public	☒
PP	Restricted to other programme participants (including the Commission	☐
RE	Restricted to a group specified by the consortium (including the	☐
CO	Confidential, only for members of the consortium (including the Commission Services)	☐

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, and will be further updated before the end of the project.

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 (CLRTAP) and with the European Commission, DG Environment, especially providing science input to support revision of the EU Air Quality Package, including 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 biogenic volatile organic compounds (BVOCs). These effects are expected to increase ground-level concentrations of NH_3, NO_x and ozone (O_3), 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 and other biogenic emissions, posing a challenge for national emissions ceilings and air quality objectives related to nitrogen and ozone pollution.

5. Further evidence from the measurement and modelling activities of ÉCLAIRE is still needed before definitive statements can be agreed by the project in regard of the second of these interactions (climate-pollution-ecosystem vulnerability). Potentially, the two effects may combine, leading to a substantial worsening of the overall air pollution threat of air pollution under future climate scenarios.

6. The ongoing efforts of ÉCLAIRE focus on working to quantify these relationships more precisely for the different components. The findings highlights 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. During the last year substantial input has been provided by the ÉCLAIRE team to support the preparation of the EU Air Quality Package, especially the proposal for revision of the National Emissions Ceilings Directive, and this support has continued in CLRTAP, 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 CLTRAP 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 for use in the NECD revision.

9. Most recently, the ÉCLAIRE team have reported to the WGSR first estimates of the valuation of ecosystem damage associated with N pollution, as well as reported 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). DG Environment has indicated its interest to provide additional resources to speed and develop international consensus on the latter, to allow approval by the CLRTAP Executive Body in December 2014, allowing the document to be delivered to support the NECD revision.

10. As the ÉCLAIRE outcomes begin to be finalized towards 2015, these will provide a basis to complement existing health benefit assessment with the assessment for ecosystems, as well as incorporate the implications of future climate change for emissions, effects and mitigation options, as a basis to inform future air pollution, climate and nature policy development.

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?

- Enhanced N deposition and O_3 are found to have both beneficial and adverse effects. While N deposition, per se, generally increases rates of C uptake, O_3 reduces C uptake and storage. These effects suggest that, while NH_3 emission is primarily associated with increasing C sequestration, 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).
- Climate change is expected to alter both the magnitude of primary emissions, especially from biogenic/agricultural sources (NH_3, soil NO_x, BVOCs), as well as pollutant the atmospheric lifetimes and resulting N deposition patterns. The emerging results indicate that future climates are likely to increase NH_3 emissions strongly, along with increase in soil NO_x and VOC emissions, which will propagate to increases in N deposition and tropospheric O_3. By contrast modelled future N deposition patterns are found to be much less dependent on anticipated changes in precipitation.
- Experiments combining enhanced (wet) N deposition with O_3 exposure indicate the potential for significant interaction, where O_3 has larger effects at high N input rates. Subject to further analysis, this can also be expressed as saying that O_3 reduces plant Nitrogen Use Efficiency (also linked to reduced root: shoot ratio), implying that O_3 may have knock on effects by worsening nitrogen pollution, including NO_3 leaching and N_2O.
- Decreased gross primary productivity (i.e. photosynthesis) has been identified in association with peak episodes in stomatal ozone deposition. This occurred at sites receiving high flux doses of ozone, and suggested that as much as 19% of the photosynthesis reduction was due to ozone.
- BVOC emission profiles have been found to be impacted by biotic stress (e.g. insect attack, drought stress), leading to profiles which result in more secondary organic aerosol formation. This means that plant biotic stress has impacts for human health, global dimming and further potential feedbacks on photosynthesis through increased aerosol loading. Climate change impacts on biotic stress and its resulting feedbacks will therefore need to be addressed in future studies to ensure it is accounted for in mitigation policies.
- A new relationship between plant stress responses and soil NO emissions has been identified, which will require further work to incorporate into vegetation exchange models, as this implies a further feedback between climate change and air pollution.

- The growing importance of understanding the controls on BVOC emissions has been confirmed by recent work in ÉCLAIRE, including how BVOCs respond to changes in temperature and CO_2.
- Data mining has yielded key information on response relationships for effects of O_3 on biomass and several physiological parameters that contribute to growth. This type of information is now being incorporated into the models in the ÉCLAIRE project which will in due course allowing them to link O_3, N and other interactions.
- Further data analysis of experimental work continues to tease out the interactions between nitrogen and ozone deposition which have been observed in ÉCLAIRE experiments.

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?

- A significant off-set can be anticipated between changes in NO_x and NH_3 emissions considering committed emissions and anticipated climate change. While further reductions in NO_x emissions can be expected over the 21st century (e.g. Gothenburg Protocol and NECD revision), climate induced increases in NH_3 emissions (potentially by ~40%), combined with low take-up of available mitigation actions, would tend offset the benefits of reduced NO_x emissions for N deposition and aerosol formation. This result highlights the dual importance of a) applying available technical measures to reduce NH_3 emissions if adverse effects are to be avoided and b) ultimately incorporating climate sensitivity into official national NH_3 emissions inventories to properly account for this interaction.
- 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 effects on biodiversity and air quality (PM effects on health) would point to the need to reduce emissions. These issues can be resolved by a focus not only on reducing emissions, but on simultaneous improvement of economy-wide *nitrogen use efficiency*, offering win-wins for environment and the Green Economy. 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).
- Recent ÉCLAIRE work allows us to hypothesise that in managed forests, at the European level, the impacts of tree species selections will likely have a higher impact on the pattern and magnitude of BVOC emissions, than natural adaptation of tree species to climate change.
- The work in ÉCLAIRE has led to the initiation and development of a new land-atmosphere trace gas and aerosol modelling system: ESX (ÉCLAIRE Surface eXchange). Developments have been made to the ESX system, allowing it to become the primary tool to interpret and assimilate the flux measurements that are being made across the ÉCLAIRE network. It is a community effort, and will be shared with other projects, such as PEGASOS. The modular nature of the modelling is allowing 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.

- Model developments (which will be incorporated into the ESX system), 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).
- Assessment of the toxic effects of ozone has progressed by improving the uptake routines in dynamic global vegetation models.
- These technical developments provide the foundation for further analysis of trade-offs and synergies across ÉCLAIRE.

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?

- As noted above, the analysis shows that the largest effects of a changing climate are likely to be on increasing biogenic/agricultural emissions rather than on changing atmospheric lifetimes and the spatial patterns of O_3 levels and N deposition. Nevertheless, the spatial patterns remain extremely important given the combination of scales involved, from hemispheric scale (O_3 background), though regional scale (O_3 and N deposition) to local scale (N deposition).
- To address these interactions ongoing 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.
- 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.
- 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 the DG Environment, although it was not possible to take this forward within the current Air Quality Package. (This is because it was decided not to renegotiate the Air Quality Directive, which was in part linked to challenges in meeting NO_x limit values).

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?

- Work in 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).
- Further evidence has emerged within ÉCLAIRE of different effects between wet deposited N in oxidized or reduced form and dry deposited NH3 for bog ecosystems. This highlights a higher sensitivity to NH3 than wet N deposition, which can in part be accounted for by a lower critical level for moss and lichen species. Future evidence of such differences from more ecosystem types would be needed before these differences can be generalized to inform wet/dry, oxidized/reduced critical loads.
- 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.
- ÉCLAIRE has also invested novel pollution interactions. Studies of leaf processes have indicated that drought impacts are increased by particle deposition to leaf surfaces. This early finding opens up new challenges for generalization which will require more comprehensive data experimental assessment. In addition, it has been found that drought can reduce ozone formation by decreasing emissions of BVOCs.
- 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 (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?

- 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. However, it should be emphasized that further ongoing work will be necessary in ÉCLAIRE before a definitive answer can be given.
- While the effects of temperature on biogenic and agricultural emissions are well established (NH_3, VOCs, soil NO), the main effects of climate on ecosystem sensitivity will operate via alterations in drought stress, soil turn over processes and net photosynthesis. While drought stress may exacerbate some pollution effects (e.g. limiting plant N uptake and leading to larger pollution losses), it may mitigate against other effects (e.g. closing stomata and limiting O_3 uptake). Conversely, some interations, such as the newly identified effect of leaf surface aerosol on plant water relations may act to increase plant water stress.

- 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.
- Results of a meta-analysis, looking at single and combined effects of changes in climate, nitrogen availability, carbon dioxide and ozone exposure in forests and forest soils have been added to the empirical model 'GrowUp'.

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?

- Recent experiments and analytical work in the project 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.
- Precursor emissions that affect background O_3 on the hemispheric scale are also proving to be important in determining exposure of vegetation to ground level O_3 (especially methane).
- Balancing the ozone damage and biodiversity loss against possible increases in carbon stocks and productivity, remains a complex task, especially with respect to economic considerations. The project 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:
    - Longterm 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
- Support provided by the ÉCLAIRE team to the Gothenburg Protocol and NECD revision process has highlighted that mitigation measures for NO_x are becoming increasingly expensive, while many low-cost mitigation options for NH_3 are still available (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, but only a further 300 kt NO_x-N mitigation.

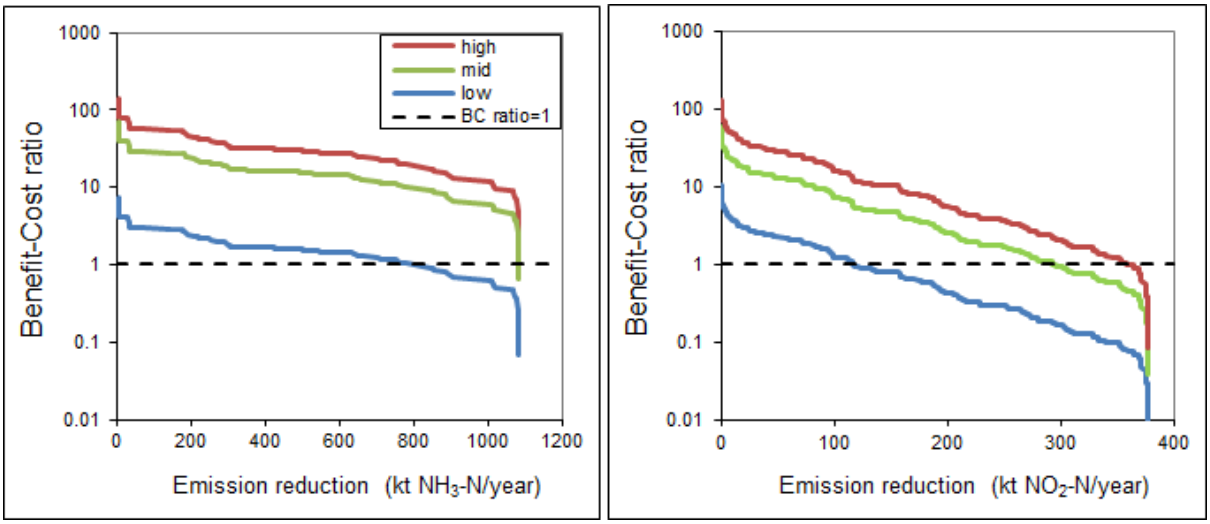

Figure 1: Comparison of the estimated health, ecosystem and climate benefits to the costs of ammonia and nitrogen oxides mitigation (van Grinsven et al., ES&T, 2013, see select publications list).

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

- As a foundation for improved assessment ÉCLAIRE is developing an improved basis for incorporating ecosystem costs into the overall valuation chain. This is expected to update the initial assessment shown in Figure 1, and has highlighted the challenge of valuing ecosystem effects of air pollution.
- For the regulatory (GHG related) and provisioning (crops, timber) services, available results from other components of ECLAIRE indicate some degree of balance between the harmful effects of ozone and the beneficial effects of nitrogen deposition. 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 and interactions with pests and pathogens. This is problematic for the subsequent analysis, as it raises questions about even the direction of overall impacts.
- For ecosystems and biodiversity, however, the same does not apply, with N deposition and O_3 exposure both demonstrated to have negative impacts. For this reason, together with the fact that quantification of effects on ecosystems is more challenging that for (e.g.) crops and forests, the main focus of this activity is on valuation of changes in biodiversity.
- The ecosystem valuation process is subject to significant uncertainty, seemingly more so than for impacts to human health. A variety of methods have been developed for valuation of ecosystems, for example in terms of restoration costs, 'regulatory revealed preference' and individual willingness to pay, and these are currently being reconsidered under ÉCLAIRE. One possibility is to use a number of methods and then to explore consistency in final outcomes.

- Work in ÉCLAIRE is also leading to the development of an improved knowledge chain that quantifies the impacts of climate change into the 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.
- 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 has 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 replaced with a more process based approach allowing the links between meteorology and emissions to be addressed. In this way, future climate scenarios could be directly incorporated in to official international projections. This would also take on board the reality that national emissions will vary with time according to prevailing meteorology and long-term climate change.

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

This document 'ÉCLAIRE Key Messages for Policy Makers' is delivered several months later than originally planned due to the need to provide intense direct reporting to a wide range of policy processes during 2013 and the early part of 2014. 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).

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 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 1st Annual meeting of the EU ÉCLAIRE project, Edinbugh. (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.

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

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

Reis S, Sutton MA, Howard CM (eds) (2014) *Costs of ammonia abatement and the climate co-benefits*. Springer Publishers (in progress, publication planned for autumn 2014)

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

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.

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

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

.