Project No. 282910

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

Seventh Framework Programme

Theme: Environment

D22.4 – ÉCLAIRE Key Messages for Policy Makers

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		
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PP	Restricted to other programme participants (including the Commission	☐
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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.

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, the overall effect these effects would tend to increase ground-level concentrations of NH_3, NO_x and atmospheric N deposition, while posing a substantial risk of increasing O_3 and particulate matter ($PM_{2.5}$) concentrations.
- Climate warming appears to 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, O_3 and PM 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 (especially 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 substantial worsening of the air pollution threat under future climate scenarios. ÉCLAIRE has also found that O_3 reduces crop nitrogen use efficiency (NUE), posing knock-on risks for nitrate pollution and nitrous oxide emissions.

6. The ÉCLAIRE findings 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, especially the proposed 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 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, allowing the document to be used as part of the NECD revision.

10. Wider policy engagement by the ÉCLAIRE team has highlighted the need to develop integrated solutions. Through the "Our Nutrient World" report for the United Nations Environment Programme (UNEP), ÉCLAIRE has pointed to the 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?

Climate change is expected to increase the threat to ecosystems through multiple pathways.

13. The main driver for future changes in N and O_3 deposition will be changes in anthropogenic emissions, including those associated with adaptation to climate change, through changes in agricultural practice (management practice, crops selection), forestry (tree species selection), land-use and policy responses to climate change. However, the emissions are further modified through direct climate effects on the emission processes.
14. Climate change is expected to alter both the magnitude of primary emissions, especially from biogenic/agricultural sources (NH_3, soil NO_x, some BVOCs), as well as pollutant atmospheric lifetimes and resulting N deposition patterns. Results indicate that future climates are likely to increase NH_3 emissions strongly, along with increase in soil NO_x in drying areas, which will propagate to increases in N deposition, especially close to source, and organic $PM_{2.5}$.
15. A warmer climate is expected to increase BVOC emissions, while higher CO_2 concentrations have a more complex effect. CO_2 stimulates plant growth (enhancing BVOC emissions), but also dampens leaf-level emissions of some BVOC. In the case of isoprene the CO_2 effect is expected to offset the temperature effect. There is insufficient evidence to conclude that CO_2 trade-off will cancel a warming effect on monoterpene emissions. In addition, natural species adaptation and future human choices in agricultural and forest species in response to climate change may alter BVOC emissions significantly. The result is that net of climate change (directly and indirectly through land-use change) on tropospheric O_3 remains less clear.
16. While precursor emissions will increase, the likely effect on inorganic $PM_{2.5}$ concentrations is likely to be more complex. By contrast, climate change is expected to increase future N deposition through the warming effect, while anticipated changes in precipitation have a much smaller effect (only changing the location, but not the amount of deposition).

Effects via climate stress and extreme events

17. Effects of climate-related stress (drought, insect attack) and extreme events (fires, windfall, heavy rain) on emissions are likely to be significant but remain uncertain. For example, 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 need to be quantified better in future studies to judge whether it needs to be accounted for in mitigation policies.

Interactions between air pollution and climate policies for nitrogen and methane

18. A significant off-set can be anticipated between changes in NO_x and NH_3 emission changes considering 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, combined with low take-up of available mitigation actions, will reduce the benefits of NO_x controls for N deposition and $PM_{2.5}$ control. 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.
19. Methane emission control is increasingly recognised as a win-win strategy whose control reduces climate change at the same time as reducing the production of O_3.

Interactions on ecosystem responses to ozone and nitrogen

20. Plant productivity is generally increased by N and CO_2, and decreased by O_3 and each of these effects may be altered under climate change.
21. Ozone pollution is likely to decrease Nitrogen Use Efficiency and increase N losses. Under elevated O_3, less N is used for growth, while plants are also less good at N resorption before litter-fall, so that more N is deposited to soils in leaf litter. The result is that O_3 is likely to have knock-on effects by worsening nitrogen pollution, including and biodiversity changes, nitrate leaching and increased N_2O emission.
22. Certain legumes are very ozone sensitive. This may lead to reduced N fixation in some ecosystems. Experimental evidence indicates that the differential sensitivity of species to ozone can lead to changes in community structure in developing grassland communities.

Effects through nitrogen processes in forests

23. In N-limited forests, especially in boreal forests, N deposition enhances growth and carbon sequestration. Accumulated N deposition over time, however, tends to decrease C:N ratios in biomass, soil organic layer and to a lesser extent the soil mineral layer, and with a continuous elevated N input, the ecosystem may approach "N saturation".

24. In this stage, the N leaching will increase above background levels, associated with soil acidification in terms of elevated leaching of base cations or aluminium, causing relative nutrient deficiencies, which may be aggravated by a loss of mycorrhiza or root damage.
25. ECLAIRE has shown that positive impacts of N on growth occur below 15 kg N ha^{-1} yr^{-1}, but reverse between 15-25 kg N $ha^{-1}yr^{-1}$. One may consider 15 kg N ha^{-1} yr^{-1} a critical load for forest growth. At an N deposition below this load, there may still be adverse impacts on other forest ecosystem compartments, such as changes in ground vegetation and in mycorrhiza.

Other ecosystem effects linking air pollution and climate

26. Increased temperatures are likely to increase species-richness, but also cause loss of cold-tolerant species that may be important for conservation of biodiversity.
27. Increased temperatures will increase N turnover, worsening effects of N on biodiversity and air- and water-quality in the short term, but potentially reducing accumulated N and so enhancing forest growth in N limited (especially boreal) forests.
28. Dryer soil and dryer air under climate change as well as elevated CO_2 may reduce stomatal O_3 uptake by vegetation and thus counteract adverse O_3 effects. These changes also have other important effects on ecosystems which need to be considered, i.e. they are not generally positive. Chronic exposure to ozone can cause plants to be less tolerant of drought.
29. Longer growing seasons, higher temperatures (in cooler climates) and to some extent the climate change promotion of O_3 formation will aggravate effects of O_3. In Northern Europe, an earlier start of the growing season may lead to an increasing overlap with the high O_3 concentrations of the so-called O_3 spring peak, possibly increasing environmental risks.

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?

Interactions between pollution components

30. While N deposition generally increases rates of carbon uptake by vegetation, ozone reduces C uptake and storage in vegetation. The form of N deposition also affects the response. Overall, NH_3 emission is associated with reduced N that contributes to C sequestration, but also has more adverse impacts on biodiversity than NO_y deposition. Conversely, NO_x emissions contribute to C sequestration, but also promote ozone formation that decreases C storage. Both components contribute to the cooling effect of aerosol, e.g. as ammonium nitrate, while deposition of both forms contribute to warming by increasing nitrous oxide (N_2O) emissions. It should be noted that increases in C storage induced by N deposition are likely to be a transient benefit and will decrease in the future.

31. Although certain effects of pairs of environmental drivers, such as N, O_3, CO_2 and temperature, may be opposing, this cannot be extrapolated to say that effects by such pairs are cancelling each other out in general, since mechanisms of action are specific for the different environmental drivers. ECLAIRE has particularly shown that this is the case with the N and O_3 interaction, where exposure to O_3 can almost completely cancel the productivity benefit of N inputs in some ecosystems experiments.

Interactions for forests

32. The enhanced forest growth and C sequestration since approximately 1950 up to 2005 is most likely mainly due to elevate N deposition. The implication of the ECLAIRE findings is that this would have been even larger in the absence of elevated ambient ozone concentrations. It seems that CO_2 fertilization and temperature increase have so far played a comparatively minor role.
33. For the future, the expected forest growth is highly uncertain. When neglecting possible limitation by non-nitrogen nutrients (as is currently the case in nearly all earth system models), it seems likely that the expected large increase in CO_2 and temperature will further enhance forest growth and C sequestration, especially in Central Europe. In southern Europe, more limited water availability (drought stress) will most likely offset the growth enhancing effects of CO_2 and temperature rise. For other parts of Europe, especially in N. Europe, these effects will most likely be compensated by limited N availability in view of expected decreased N deposition (N limiting the CO_2 fertilization effect).
34. When accounting for the possible limitation by non-nitrogen nutrients, such as phosphate, calcium, magnesium and potassium, it is likely that no further increase in forest growth is to be expected because these nutrients will limiting growth, especially phosphorus.

Other interactions to be considered

35. Several other changes can alter circulation of nitrogen in the environment and extent of ozone impacts. These include large scale land-use change, such as increased short-rotation forestry for biofuel production, which can change N deposition patterns as well as lead to increases or decreases in BVOC emission depending on species selection.
36. In addition, land-use changes that alter albedo of land can affect N and O_3 effects. These include policies to avoid low albedo of farmland by reducing periods of bare soil and promoting high albedo in cities.

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?

37. Impacts of air pollution on European ecosystems occur over a range of spatial scales from the global scale (O_3 background), though regional scale (O_3 and N deposition) to

local scale (N deposition and $PM_{2.5}$, NH_3 exposure). In a changing climate, the spatial patterns of impacts are likely to change as a result of changing emissions, land use and atmospheric processes.

Atmospheric transport changes for nitrogen compounds

38. Around 90-95% of impacts due to N deposition to European ecosystems are the result of European emissions. However, at a national level N deposition has contributions from both national emissions as well as emissions from neighbouring countries.
39. A warmer climate will most likely increase the relative contribution of NH_3 to N deposition and thus increase near-source impacts relative to those at longer ranges. A warmer climate may also increase the evaporation of ammonium aerosol, leading to an increase in NH_3 concentrations and may also affect the atmospheric lifetime of ammonia due to changes in compensation points.
40. Changes in precipitation patterns are likely to affect the spatial patterns of impacts as well. For example, reduced rainfall in southern Europe may increase the atmospheric lifetime of ammonium as a result of reduced wet deposition, leading to larger transport distances.

Atmospheric transport changes for photochemical oxidants

41. Impacts of O_3 in Europe are the result of pre-cursor emissions both from within Europe and worldwide. Summertime ozone concentrations in Europe are strongly influenced by European pre-cursor emissions whereas non-European pre-cursor emissions, of which methane is key, dominate the rest of the year.
42. A warmer climate could lead to increased water vapour, which would most likely decrease the O_3 background, especially in summer, partially offsetting the effect of increasing non-European pre-cursor emissions. However, increasing temperatures could also decrease atmospheric sinks, such as the reaction with PAN, tending to increase O_3 concentrations.
43. Reduced rainfall in southern Europe will increase the drought stress of vegetation, which would reduce O_3 deposition in the region, thus mitigating ecosystem impacts to some extent but exacerbating the impacts to human health due to increased O_3 concentrations.
44. As well as increasing temperatures and changing precipitation patterns, climate change is likely to alter global circulation patterns. Climate models predict an increase in atmospheric stagnation over Europe, which would exacerbate the impacts of O_3, especially those due to European precursor emissions.

Interactions between air pollution and Natura 2000

45. 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.

46. 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?

47. ECLAIRE has shown that, in contrast to concentration-based metrics, flux-based metrics that incorporate the modifying effects of climate, soil and plant factors on ozone uptake provide opportunities to incorporate the combined effects of pollutant interactions and climate change on plant response.

Metrics related to nitrogen and its interaction with sulphur

48. Nitrogen deposition occurs in a number of different forms (i.e. wet and dry deposition, NH_x and NO_y). The ECLAIRE experiments have demonstrated that direct effects, from atmospheric concentrations, are stronger when N is in the reduced form as ammonia. This points to the need for further development of effects metrics that distinguish the effects of NH_x and NO_y, dry/wet deposition on biodiversity. In contrast, there insufficient evidence to show that N effects mediated by soil processes depend on N form.
49. For N deposition effects on plant diversity, metrics should consider not only reduction in species diversity but also probabilities of the presence/absence of important species. This is important in the context of climate change, as plant species diversity may increase under a warming climate, while a simultaneous loss of key conservation species occurs.
50. For nitrogen (and S) a new biodiversity based indicator has been developed and mapped over Europe (Habitat Suitability Index). From this, preliminary thresholds for N (and S) deposition have been derived, and explored in integrated assessment (GAINS model). This indicator also depends on climate variables, and first tests of its climate sensitivity have been carried out. There is a need to further investigate the interpretation of these thresholds ("protection levels/loads"), especially for a non-expert audience given that the approach may appear to imply a different overall level of threat compared with previous approaches.

Metrics to assess N and O_3 combinations

51. ECLAIRE has produced O_3 dose-response relationships for tree and crop species with novel response variables (e.g. net annual increment for forests; nitrogen use efficiency, protein and starch yield, and grain mass yield for crops (wheat). Methods to incorporate the modifying effect of N on the sensitivity of these dose-response relationships have also been developed. These relationships can be used to: i) define

scientifically determined ‘no-effect’ thresholds; ii) set policy relevant ‘target’ thresholds and iii) to quantify damage due to exceedance of the ‘no-effect’ threshold.

52. The interactions observed between N and O_3 exposure in ECLAIRE are particularly significant. For example, the potential has been shown in field experiments for high O_3 to negate the productivity benefits of N inputs. Such interactions point to the need to develop new metrics of N and O_3 impacts that can take account of these interactions. For this purpose the development of process based models, such as DO_3SE at the plant scale and CLM and OCN on a global scale are providing a basis to start to assess the interactions.
53. There are clear interactive effects on plant species composition resulting from interactions between N deposition and O_3 that occur over the short-term (1-2 years). However, there is no clear indication of whether these combined N and O_3 effects will be positive or negative over the longer-term. Long-term monitoring of changes in plant species diversity with prevailing pollution concentrations and climate is essential to understand these dynamics better.

Metrics to assess aerosol impacts on plant drought stress

54. ECLAIRE studies have indicated that reducing aerosol deposition to leaves may increase drought tolerance due to the removal of the wicking effect that can enhance water loss *via* stomata even when stomatal conductance is low. Experimental studies combined with monitoring of aerosol concentrations in a polluted part of central Europe have provided the basis to establish a first dose-response relationship between total hygroscopic aerosol concentrations and the minimum value of stomatal conductance under drought conditions. This approach provides the basis for model tests in DGVMs and also needs to be extended to consider the dose-response relationship for the overall stomatal response to drought.

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?

55. The findings of ECLAIRE indicate that climate change will occur through several mechanisms:

- Climate induced increases in emissions, especially of NH_3 from agriculture and NOx from agricultural and forest soils, but also some BVOCs, leading to increases in N deposition and a risk of higher O_3 concentrations.
- Climate induced changes in partitioning between aerosol and gas phases in the atmosphere leading to a relative increase in gas phase concentrations, such as NH_3 and nitric acid (HNO_3), which may to some degree moderate expected increases in particulate matter concentrations under a future climate.

- Interactions with other atmospheric components, especially with parallel increases in CO_2 concentrations which are expected to moderate the increase in O_3 concentrations driven by the temperature effect on BVOC emissions.
- Changes in ecosystem vulnerability to a set concentration or flux of N or O_3 air pollution.
- Parallel changes in habitat suitability due to changing climate which combine with air pollution effects to further threaten sensitive plant communities.

56. With each of these interactions identified in ECLAIRE as being of significant importance it is hard to immediately generalise which of the factors is most important.
57. While the effects of temperature on biogenic and agricultural emissions are well established (NH_3, some BVOCs, soil NO), effects of climate on ecosystem vulnerability will operate via alterations in drought stress, soil turn over processes and net photosynthesis. Drought 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.
58. An ECLAIRE scenario was developed and analysed using the GAINS model. This compared the climate driven increase in NH_3 emissions with the effect of climate change as an additional stressor on Habitat Suitability. While acknowledging uncertainties, for this analysis up to 2050, the effect of climate as an additional stressor to habitats was found to be even larger than the effect of climate on increasing NH_3 emissions.
59. The key message, however, is that both of these type of factors are important. With some exceptions (like the CO_2 effect) the changes mostly operate in the same direction: future climate change worsens the effects of air pollution on European ecosystems.

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?

60. 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. While atmospheric deposition still fosters forest growth in N-limited regions of Europe, adverse conditions have been observed, especially in the long run, on biomass accumulation in regions more exposed to air pollution.
61. Balancing the O_3 damage and biodiversity loss from N against its contribution to possible increases in C stocks and productivity remains a complex task, especially with respect to economic considerations. ECLAIRE has highlighted the wider issues which

will likely need to be considered as context along with an ecosystem services based analysis, to reflect on the problem comprehensively.

62. Precursor emissions that affect background O_3 on the hemispheric scale are proving to be important in determining exposure of vegetation to ground level O_3 (especially methane). Further reductions of ozone fluxes in Europe require tackling precursor emissions at the hemispheric scale (especially of methane).
63. Ammonia and NO_x reduction is also beneficial to reduce PM exposure and human health effects Cost-effective health driven air pollution policy will also reduce excess nitrogen on nature. For ammonia low cost measures are widely available, especially for large farms.

Costs compared with the benefits of emission abatement

64. Benefits of a scenario implementing maximum technical reductions in the EU for crops, timber production and carbon sequestration are €1.8 billion. Less excess nitrogen deposition will also contribute to the achievement of existing biodiversity commitments.
65. Support provided by ECLAIRE 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 have not yet been adopted in many countries. This is illustrated in **Figure 30**, 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.

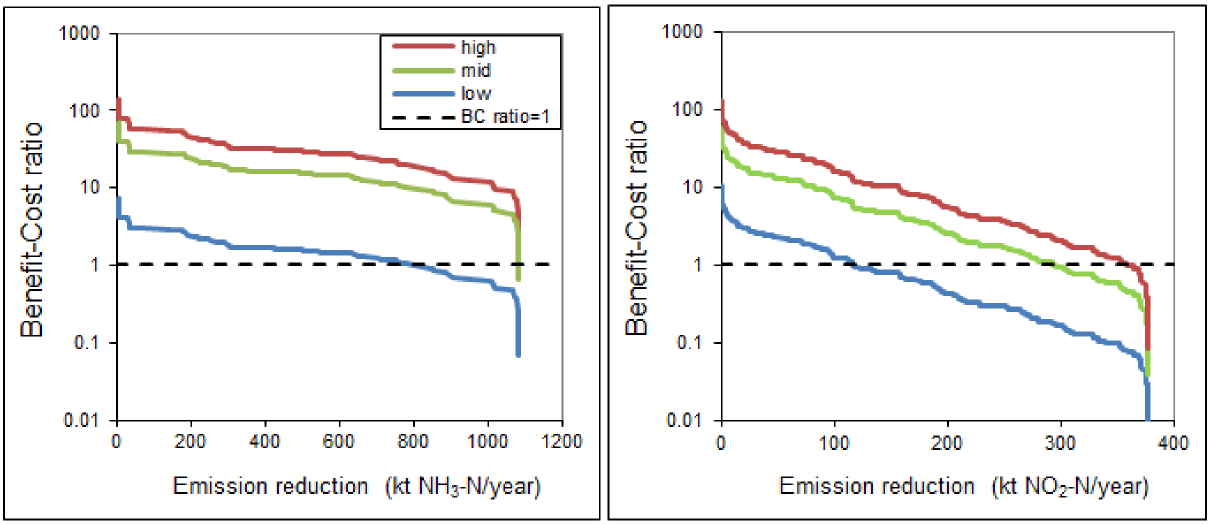

Figure 1: Comparison of the estimated health, ecosystem and climate benefits to the costs of ammonia and nitrogen oxides mitigation (van Grinsven et al., ES&T, 2013, see select publications list).

66. Health driven air pollution policy will also reduce excess nitrogen on nature by ~44%. An illustrative ECLAIRE scenario that reduces excess deposition with 2% more will

cost €23 mln. The benefits of such an additional reduction will be 50-1000% higher, depending on the methodology for biodiversity valuation.

Wider approaches to air pollution mitigation strategies

67. Additional nitrogen reduction is needed to keep the risks for biodiversity constant in a changing climate. New technologies and structural changes in production and consumption will be needed to increase the scope for further reductions in excess nitrogen deposition and ozone fluxes. Increased nitrogen use efficiency will lead to cost savings in food production and consumption on a longer time scale (Sutton et al., 2013, Sutton and Bleeker, 2013).
68. The issue of food consumption is closely linked to the nitrogen cycle given the major role of nitrogen in food and feed production and in livestock rearing. A special report facilitated through ECLAIRE in partnership with the UNECE Task Force on Reactive Nitrogen, "Nitrogen on the Table" found that halving consumption of meat and dairy products across Europe would lead to around a 40% reduction in Nitrogen pollution, while liberating large areas of agricultural land for other uses (e.g. bioenergy production). Overall the nitrogen use efficiency of the European food system was doubled under this scenario (Westhoek et al., 2015).

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

Technical developments from ECLAIRE

69. 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.
70. 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.
71. 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.

72. 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.
73. 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 (i.e. Regulatory revealed preference),
    - Legal requirement approach on conservation,
    - Nitrogen Use Efficiency approach.
74. Comparison of these approaches leads to the conclusion that the ecosystem benefits amount to around 2.5 (1.5 - 11) billion Euro per year (under a Maximum Technically Feasible Reduction scenario for 2030), which add a further 5% to the quantified benefits for improving human health. Willingness to pay approaches give mid-range or low estimates, while the highest value is associated with the regulatory revealed preference.

Towards future approaches

75. The results from the ECLAIRE project continue to demonstrate that an integrated approach to addressing the scientific questions is necessary to develop an integrated policy perspective. This integration then allows the selection of win-win scenarios or informs prioritisation needs, which leads to more effective policies. It turns out that the most effective way forward is to reduce emissions of NH_3 in Europe to halt the loss of biodiversity, and of CH_4 at the hemispheric scale to reduce ozone damage. Specific actions are as follows:
    - Reducing nitrogen deposition has benefits for both ecosystems biodiversity and human health. This allows for cost sharing during implementation of measures, which increases their overall cost-effectiveness. The first cost-benefit analyses for ecosystems from ECLAIRE can therefore support the development of integrated cost-effective policy.
    - While N deposition enhances net primary production of ecosystems in the short term in N limited areas, excess N may have negative effects on biomass growth in the long run. This points to further benefits in reducing nitrogen emissions in Europe
    - Decreasing NH_3 has both health and ecosystem benefits with low cost measures available.

- Action on methane will have benefits for both air pollution and climate but will require hemispheric integration of the relevant policies to maximise effectiveness.
- Monitoring is an essential part of the process, from establishing current trends through to gauging the impact of policy measures.
- Adopting a win-win approach may require broader top-down policymaking strategies, which make the consideration of more than one pollutant or sector more achievable. At the least a more integrated consideration of the range of issues is needed.
- Policy is most effective when it has the support of the general public, therefore increasing efforts to communicate clear messages on effects and solutions is essential.
- The multiple effects of nitrogen pollution across the nitrogen cycle link air and water pollution, climate change and biodiversity. A joined-up nitrogen strategy would therefore have benefits in overcoming barriers-to-change, highlighting win-win for businesses and the environment. The ECLAIRE community is stimulating this activity through its leadership of the International Nitrogen Management System (INMS) in cooperation with the UN Environment Programme (UNEP) and the International Nitrogen Initiative (INI).
- Behavioural changes offer a very important part of the suite of available solutions, to reduce air pollution impacts on ecosystems. Highlighting effects on cherished species, the co-benefits of improved diet for health and engaging the public in data gathering through citizen science activities may aid in the process.

76. In addition to the underpinning science, ECLAIRE has been extremely active in providing support for European policy development. Key outcomes include support to the EU policy review (e.g. Fowler et al., 2013; Brunekreef et al., 2015), guidance on pollution mitigation and costs (Bittman et al., 2014; Reis et al., 2015; UNECE, 2015) and examination of the pollution and land use relationships for future food choice scenarios (Westhoek et al., 2015).
77. Two final 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

None

4. Key Meetings 2013-2015

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 during 2013-2015. The list represents only a section illustrating mainly outputs that involved the coordinator. It typifies the strong policy engagement of ÉCLAIRE.

11/15 Invited presentation: Nitrogen 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 Agriculture 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 for 2013-2015

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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

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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).

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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

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6. Selected publications

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

Selected Books

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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.

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