Institution: University of York
Unit of Assessment: 7, Earth Systems and Environmental Science
Title of case study: Development of risk assessment methods for the impacts of ground level ozone (O_3) on ecosystems to inform European atmospheric emission reduction strategies.

1. Summary of the impact (indicative maximum 100 words)

Research by Lisa Emberson has led to tighter controls on air pollutant precursor emissions of ozone (O_3) across Europe benefiting crop and forest productivity, and grassland species composition. Emberson's research led to new risk assessment methods, based on knowledge of atmospheric exchange processes and plant eco-physiology, which assess O_3 uptake and related damage using novel flux-based 'Critical Levels'. These new methods are being used to optimise emission reduction policy by 26 parties (member states) who have signed and ratified the United Nations Economic Commission for Europe (UNECE) Gothenburg Protocol established under the Convention on Long Range Transboundary Air Pollution (LRTAP).

2. Underpinning research (indicative maximum 500 words)

By the early 1990s a large body of experimental data existed describing the adverse impact of O_3 on crops, forests and grassland ecosystems. In Europe, efforts were made to compile data from standardised experiments to develop concentration based exposure-response relationships. These were used to establish 'Critical Levels' (CLs) providing a policy tool for use in the 'effects based' approach adopted by the UNECE LRTAP to optimise emission control across the region. However, these concentration-based risk assessments were compromised in their policy use since they were not suitable for quantification of ecosystem damage and therefore could not be used to estimate the benefits of emission reduction methods. This was due to their only being able to provide an assessment of potential impacts since they did not incorporate modifying factors (dependent upon species traits and prevailing environmental conditions) considered to affect plants sensitivity to O_3.

Emberson's research centred on the development and application of a novel flux-based risk assessment method. This method applied knowledge of plant ecophysiological processes to estimate relative potential O_3 uptake or stomatal O_3 flux (O_3 uptake via the leaf pores) and showed that the geographical distribution of relative risk differed substantially when using flux *vs*. concentration based methods (Emberson et al., 2000). This flux-based method was parameterised for important European vegetation types forming the core of what was later to become known as the DO_3SE (Deposition of Ozone and Stomatal Exchange) model (Emberson et al., 2007). This York developed model is the single model upon which the flux modelling methods now used by the LRTAP Convention are based.

To enhance the practical application of this flux-based method Emberson worked with colleagues from the European Monitoring and Evaluation Programme (EMEP) in Norway who assess European air quality for the LRTAP Convention. These colleagues use a chemical transport model (CTM) to provide estimates of atmospheric O_3 concentration. Incorporation of equations based on standard micrometeorological theory into the DO_3SE model allowed estimates of the O_3 transfer from the CTM output height to the vegetated surface. The original leaf level stomatal O_3 flux model was also developed for an entire canopy adding non-stomatal O_3 deposition processes (Emberson et al., 2001). This allowed DO_3SE to provide the estimate of total O_3 deposition in the EMEP CTM integrating the assessment of O_3 loss to the vegetated surface layer as well as O_3 ecosystem damage. Evaluation against European observational data showed the model performed well for a range of vegetation types and climatic conditions (Tuovinen et al., 2004).

The DO_3SE stomatal flux model was used in collaboration with experimentalists from across Europe; to derive novel flux-response relationships for a number of crop (Pleijel et al. 2007); forest

(Karlsson et al., 2004; Karlsson et al., 2007) and semi-natural grassland (Emberson et al., in prep) species. These flux-response relationships have been used to establish new flux-based CLs (Mills et al., 2011a); as such they provide tools to ensure ecosystem protection and allow cost-benefit analysis of emission reductions to improve food security, carbon sequestration and biodiversity.

The validity of the flux-based approach was tested through collaboration with colleagues who host one of the LRTAP Task Forces which assesses air quality damage to vegetation (Integrated Co-operative Programme on Vegetation). These colleagues collate observational and standardised experimental data describing O_3 effects on vegetation across Europe; comparisons of the concentration and flux-based methods clearly showed that flux provided a far more realistic indication of the geographical distribution of O_3 damage across Europe (Mills et al. 2011b).

This research has been conducted since 1999 at the Stockholm Environment Institute (SEI), part of the Environment Dept. of the University of York where Emberson was first employed as a research associate and is now the Centre Director of the SEI York centre; as well as a senior lecturer in the Environment Dept.

3. References to the research (indicative maximum of six references)

Emberson, L.D., **Ashmore, M.R., Cambridge, H.M.**, Simpson, D., Tuovinen, J.-P. (2000) Modelling stomatal ozone flux across Europe. Environmental Pollution 109: 403-413 DOI: 10.1016/S0269-7491(00)00043-9 This paper has been cited 237 times in Scopus as of 13/11/2013

Emberson, L.D. Simpson, D., Tuovinen, J.-P., Ashmore, M.R., **and Cambridge, H.M.** (2001) Modelling and Mapping ozone deposition in Europe. Water, Air and Soil Pollution 130, 577-582 DOI: 10.1023/A:1013851116524 This paper has been cited 46 times in Scopus as of 13/11/2013

Emberson, L.D., Buker, P., Ashmore, M.R. (2007) Assessing the risk caused by ground level ozone to European forest trees: A case study in pine, beech and oak across different climate regions. Environmental Pollution 147 (3): 454-466 DOI: 10.1016/j.envpol.2006.10.026
This paper has been cited 37 times in Scopus as of 13/11/2013

Pleijel H, Danielsson H, **Emberson L,** Mills, G. and **Ashmore, M.R.** (2007) Ozone risk assessment for agricultural crops in Europe: Further development of stomatal flux and flux-response relationships for European wheat and potato Atmospheric Environment 41 (14): 3022-3040 DOI: 10.1016/j.atmosenv.2006.12.002 This paper has been cited 67 times in Scopus as of 13/11/2013

Karlsson, P.E., Braun, S., Broadmeadow, M., Elvira, S., **Emberson, L.,** Gimeno, B.S., Le Thiec, D., Novak, K. , Oksanen, E. , Schaub, M., Uddling, J., Wilkinson, M. (2007) Risk assessments for forest trees: The performance of the ozone flux versus the AOT concepts. Environmental Pollution 146 (3): 608-616 DOI: 10.1016/j.envpol.2006.06.012 This paper has been cited 47 times in Scopus as of 13/11/2013

Mills, G., Hayes, F., Simpson, D., **Emberson, L.,** Norris, D., **Bueker, P.** (2011b) Evidence of widespread effects of ozone on crops and (semi-)natural vegetation in Europe (1990–2006) in relation to AOT40- and flux-based risk maps Global Change Biology 17 (1): 592-613 DOI: 10.1111/j.1365-2486.2010.02217.x This paper is published in a high impact factor journal (6.91) and has been cited 38 times in Scopus as of 13/11/2013

4. Details of the impact (indicative maximum 750 words)

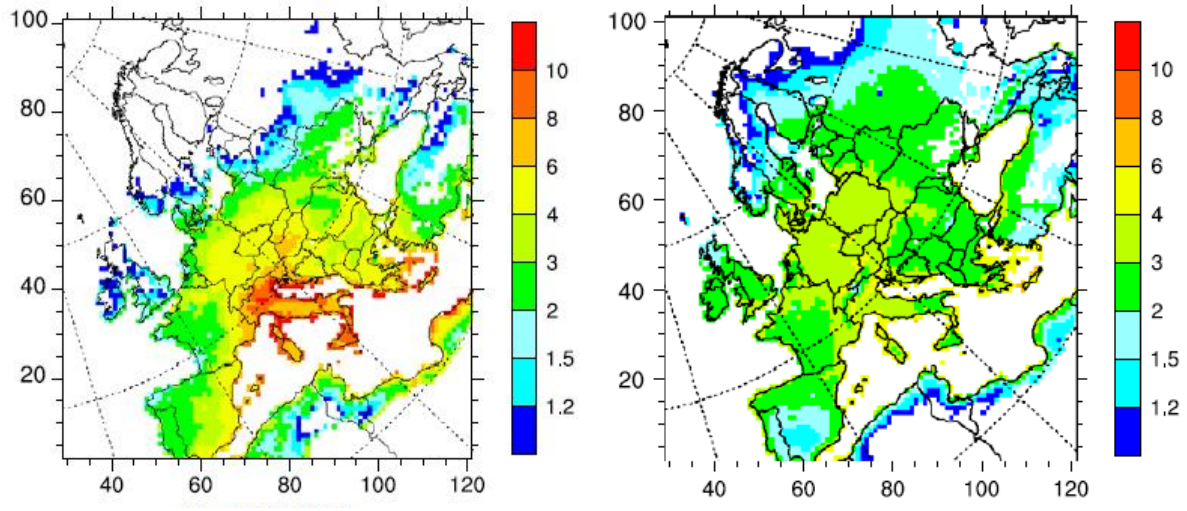
The UNECE LRTAP Convention oversees the assessment of scientific evidence that form the basis of their effects based approach to identifying air pollution emission control options across Europe; detailed in their 'multi-pollutant, multi-effect Gothenburg Protocol on Acidification, Eutrophication and Ground Level O_3'. This Protocol has been the driving force for the establishment of European legislation (EU Directives) on air quality policy as well as global, European and national air quality targets. Emberson's research was instrumental in revising CLs

for O_3 which have been used by the Gothenburg Protocol (Mills et al., 2011a). The revision of the Protocol was conducted in May 2012. The following outlines the different aspects of Emberson's research that led to the revision of these O_3 air quality guidelines hence changing European emission control policy.

Development of the UNECEs LRTAP Chemical Transfer Model (CTM).
Development of the new DO_3SE O_3 deposition model for use in the EMEP CTM (Emberson et al., 2000b) allowed the flux-based methods to be applied across Europe for risk assessment and policy formulation. Peer review of the DO_3SE deposition methodology at a UNECE *ad hoc* workshop hosted by Emberson and Ashmore (also a York staff member) in Harrogate, 2002 allowed DO_3SE to become part of the 'Unified EMEP model', the official model of the LRTAP Convention for use in European modelling of emission control scenarios for O_3 (Simpson et al., 2003). This model provides input to the LRTAP Conventions Integrated Assessment Modelling effort that applies cost-benefit methods to identify emission reduction options to guide European air quality policy.

Development of UNECEs LRTAP critical levels (CLs) for air quality risk assessment
The series of LRTAP Convention endorsed scientific workshops concluded that flux-based risk assessments performed using DO_3SE offered an improved geographical representation of risk to the existing concentration based methods and should be recommended for adoption by the LRTAP Convention. This led to revisions of the LRTAP Conventions Mapping Manual which documents the procedures and parameters to be used by member states of the LRTAP Convention in calculating and mapping CLs of air pollutants. The revised chapter described the DO_3SE stomatal flux algorithm, procedures for applying this across Europe, and the associated CLs and flux-response relationships from which they are derived; Fig 1 provides a comparison of the exceedance of CLs estimated using both concentration- and flux-based methods. The use of the flux-based method increases the geographical extent-, but alters the magnitude-of risk of the forest area across Europe (with increases in risk in more Northerly locations and reductions in risk in Mediterranean regions).

Fig 1. Comparison of concentration and flux based exceedance of critical levels (CLs) (levels below which ecosystem protection is ensured according to current knowledge) for European forests (Simpson et al., 2007) where values ≤ 1 represent no risk of damage and those > 1 represent risk of damage.



Concentration Flux

Development of air quality policy: *Revision of UNECE LRTAP Gothenburg Protocol*
Emberson and colleagues research to develop new methodologies to assess vegetation damage from ground level O_3 resulted in formal adoption by the LRTAP Convention of new CLs to protect ecosystems into the revised Gothenburg Protocol in May 2012. The current 2012 revised protocol

has been signed and ratified by 31 and 26 countries or regions respectively across Europe (as well as the United States of America) and acts to control emissions of pollutants that will result in dangerous atmospheric levels of a number of different air pollutants (including nitrogen oxides and volatile organic compounds that are the primary local and regional pre-cursors of ground level O_3). The protocol is legally binding and once implemented should ensure the exposure of vegetation to excessive O_3 levels will be 44% down on 1990 levels.

Emberson's research has also raised awareness of the damaging effects of O_3 to ecosystems globally. This led to O_3 impacts on agricultural productivity being considered in an assessment of cost-benefits in controlling short-lived climate pollutants by a recent WMO/UNEP Black Carbon and Ozone report; since publication of this work various national action plans have been developed to combat short-lived climate pollutants in countries across the world. This initiative is led by the Climate and Clean Air Coalition established by Hilary Clinton of the US Department of State. Research showing the significance of O_3 effects on staple crops in South Asia (e.g. Emberson et al., 2009) also led the Malé Declaration to include O_3 effects on crop productivity as a challenge to overcome through international negotiation to control and prevent air pollution in the seven south Asian Malé Declaration countries. Emberson's research has also helped identify the threat to ecosystems from the hemispheric transport of O_3 and its precursor pollutants highlighting the need for globally coordinated action to control precursor emissions as regions are increasingly unable to manage air quality through domestic emission reduction policies (Emberson & West, 2010).

5. Sources to corroborate the impact (indicative maximum of 10 references)

UNECE Gothenburg Protocol
http://www.unece.org/env/lrtap/multi_h1.html [see 'Consolidated text of the amended protocol' document; Part III Critical Levels of Ozone ; A. For the Parties with geographical scope of EMEP; Part 6. pp 20]
Mills, G., Pleijel, H., Braun, S., **Büker, P**., Bermejo, V., Danielsson, H., **Emberson, L.**, Grünhage, L., González Fernández, I., Harmens, H., Hayes, F., Karlsson, P.E., Simpson, D., (2011a) New stomatal flux-based critical levels for ozone effects on vegetation Short communication
UNECE CLRTAP Mapping Manual
http://icpvegetation.ceh.ac.uk/manuals/mapping_manual.html
Chapter 3: Mapping Critical Levels for Vegetation
EMEP Unified model description
Unified EMEP model code version 'rv3', released as open source under the GPL license v3 in February 2008 http://www.gnu.org/copyleft/gpl.html .
Simpson, D., Benedictow, Berge, H., Bergstrom, R., **Emberson, L.D.**, Fagerli, H., Flechard, C.R., Hayman, G.D., Gauss, M., Jonson, J.E., Jenkin, M.E., Nyıri, A., Richter, C., Semeena, V.S., Tsyro, S., Tuovinen, J.-P., Valdebenito, A., and Wind, P. (2012) The EMEP MSC-W chemical transport model – technical description. Atmospheric, Chemistry and Physics, 12: 7825-7865.
UNEP/WMO Integrated Assessment of Black Carbon and Tropospheric Ozone
http://www.unep.org/dewa/Portals/67/pdf/Black_Carbon.pdf
Malé Declaration on Control and Prevention of Air Pollution and its likely transboundary effects for South Asia.
http://www.rrcap.ait.asia/male/
Climate Change And Clean Air Coalition
http://www.unep.org/ccac/
UNECE LRTAP Hemispheric Transport of Air Pollution (HTAP) 2010 Assessment
http://www.htap.org/
West, J.J. and Emberson, L. (2010) Chapter 5: Impacts on Health, Ecosystems and Climate. In: Hemispheric Transport of Air Pollution 2010. Part A. Ozone and Aerosols. Eds Dentener, F., Keating, T., Akimoto, H. Air Pollution Studies No. 17. United Nations, 2010.