Centre for
Ecology & Hydrology
NATURAL ENVIRONMENT RESEARCH COUNCIL

Air Pollution and Vegetation

ICP Vegetation[1] Annual Report 2009/2010

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[1] International Cooperative Programme on Effects of Air Pollution on Natural Vegetation and Crops.

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Photos, map and graph of the covers were the courtesy of:
Front cover – Laurence Jones
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Executive Summary

Background

The International Cooperative Programme on Effects of Air Pollution on Natural Vegetation and Crops (ICP Vegetation) was established in the late 1980s, initially with the aim of assessing the impacts of air pollutants on crops, but in the most recent decade impacts on (semi-)natural vegetation have also been considered. The ICP Vegetation is led by the UK and has its Programme Coordination Centre at the Centre for Ecology and Hydrology (CEH) in Bangor. It is one of seven ICPs and Task Forces that report to the Working Group on Effects (WGE) of the Convention on Long-range Transboundary Air Pollution (LRTAP Convention) on the effects of atmospheric pollutants on different components of the environment (e.g. forests, fresh waters, materials) and health in Europe and North-America. Today, the ICP Vegetation comprises an enthusiastic group of over 200 scientists from 35 countries in the UNECE region with outreach activities to other regions such as Asia, Central America and South Africa. An overview of contributions to the WGE work-plan and other research activities in the year 2009/10 is provided in this report.

Annual Task Force Meeting

The Programme Coordination Centre organised the 23rd ICP Vegetation Task Force Meeting, 1 - 3 February 2010 in Tervuren, Belgium, in collaboration with the local hosts at the Veterinary and Agrochemical Research Centre (CODA-CERVA). The meeting was attended by 53 experts from 18 Parties to the Convention. Also present were a representative from EMEP/MSC-East and four experts from Cuba and Japan. The Task Force discussed the progress with the work-plan items for 2010 and the medium-term work-plan for 2011-2013 for the air pollutants ozone, heavy metals, nutrient nitrogen and persistent organic pollutants (POPs). Follow-on discussions from the workshop on 'Flux-based assessment of ozone effects for air pollution policy' were a major component of the ozone discussions.

Reporting to the Convention and other publications

In addition to this report, the ICP Vegetation Programme Coordination Centre has provided technical reports on 'Effects of air pollution on natural vegetation and crops' and 'Flux-based assessment of ozone effects for air pollution policy' to the WGE. It has also contributed to the joint report of the WGE and to a two-page WGE colour leaflet on 'Atmospheric nitrogen deposition: a threat to the environment and human health'. In addition, it contributed to a chapter on 'New flux-based critical levels for ozone-effects on vegetation' in the EMEP[1] Status Report 1/2010. Further analyses on the relationship between heavy metal concentrations in mosses and modelled atmospheric depositions were reported in the EMEP Status Report 2/2010. Five scientific papers are currently in press. The ICP Vegetation web site was updated regularly with new information.

Contributions to the WGE common work-plan

Targets for 2020 and 2050 and application in ex-post integrated assessment

The targets for impacts of ozone on vegetation were set to avoid most (by 2020) and all (by 2050) detectable ozone damage to receptors and a reduction in ecosystem services, such as carbon sequestration. Indicators to achieve these targets are a reduction in (2020) or no exceedance (2050) of ozone critical levels for vegetation. The ICP Vegetation Task Force recommended to apply the principal of gap closure to reduce exceedances in 2020. The aim is to secure food production and quality, protect against loss of carbon storage and loss of ecosystem services (e.g. flood prevention, protection from soil erosion and avalanches) provided by trees and protect against loss of fodder quality and vitality of (semi-)natural

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[1] Co-operative programme for monitoring and evaluation of the long-range transmission of air pollutants in Europe.

vegetation. Application of flux-based critical levels for vegetation in an ex-post integrated assessment will be conducted once baseline, harmonized data on concentrations and depositions become available for the revision of the Gothenburg Protocol. The ex-post analysis will provide additional, effects-based indicators, currently not included in the GAINS (Greenhouse Gas and Air Pollution Interactions and Synergies) model optimisation process, for the negotiations concerning the revision of the Gothenburg Protocol.

Robustness of air pollution effects in integrated assessment modelling

The main uncertainties associated with the flux-based critical levels of ozone for vegetation arise from the effects of soil moisture on the stomatal ozone flux and the extrapolation from different ozone exposure systems to field conditions or to different climatic regions. For trees, an additional source of uncertainty lies in the application of critical levels derived from young trees growing in exposure facilities to mature trees growing within a forest stand. Ozone critical levels for (semi-)natural vegetation are the most uncertain. However, robustness in the understanding of ozone damage on crops and (semi-) natural vegetation in Europe has been substantiated by the compilation of observed effects in ambient air. Several meta-analyses of results in peer-reviewed papers confirm that current ambient ozone concentrations have an adverse effect on plant photosynthesis and reduce crop productivity and tree growth. Furthermore, an epidemiological study in Switzerland has shown that the flux-based critical level for beech would have protected mature beech trees from adverse effects of ozone.

Links between air pollution effects and biological diversity

Although different sensitivities to ozone have been identified for plant species and communities, there is hardly any field-based evidence of the impacts of ozone on plant diversity as little field-based research has been done yet. Legumes (i.e. nitrogen fixing forbs) have been identified as a particularly ozone-sensitive plant group.

Trends in selected monitored and modelled parameters

Exceedance of flux-based critical levels for vegetation is highest in parts of central and southern Europe; no clear temporal trends regarding ozone critical level exceedances have been observed due to year to year fluctuations in ozone concentrations and climatic conditions. For most heavy metals, there has been a Europe-wide decline in their concentrations in mosses since 1990 (but not for chromium and mercury), with the highest concentrations being observed in Belgium and eastern Europe in 2005/6.

Progress with ICP Vegetation research activities in 2009/10

Ozone biomonitoring experiment with bean in 2009

Since 2008, participants of the ICP Vegetation have been conducting biomonitoring campaigns using ozone-sensitive (S156) and ozone-resistant (R123) genotypes of *Phaseolus vulgaris* (Bush bean, French Dwarf bean). In 2009, the extent of leaf injury on the sensitive variety was not directly related to the AOT40[2] at the site, similarly the ratio of S/R seed weight was not directly related to AOT40. However, plants with a lot of injury had fewer seeds than those with less injury, so that overall there was a decrease in the ratio of S/R seed weight with increasing leaf injury score of the sensitive variety. Stomatal conductance data were also collated at selected sites and this dataset will be extended further in 2010 and 2011 to enable development of a robust stomatal conductance model, which may better explain the variation in S/R seed yield and pod weight across Europe.

Ozone impacts in Mediterranean areas

Current ambient ozone concentrations in Mediterranean areas have been shown to induce negative impacts on the production, quality and/or appearance of over 20 agricultural and

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[2] The sum of the differences between the hourly mean ozone concentration (in ppb) and 40 ppb for each hour when the concentration exceeds 40 ppb, accumulated during daylight hours.

horticultural crop species of economical importance. Reductions in yield and/or leaf appearance have been observed in for example wheat, potato, tomato, beans, watermelon and lettuce. Ambient ozone concentrations have also caused visible leaf damage and effects on growth and physiology in ozone sensitive deciduous tree species such as beech and some evergreen forest species common in the Mediterranean area. Little information is available on the ozone sensitivity of Mediterranean herbaceous plant communities. There is a clear need for new effects-based data on the impacts of ozone on vegetation and develop robust stomatal flux-effect relationships for Mediterranean climatic conditions and representative plant species.

Ozone flux modelling methods and their application to different climatic regions

In recent years, climate-specific ozone flux modelling methods were developed for crops and forest tree species, resulting in the development of statistically robust flux-response relationships from which it has been possible to derive critical levels of ozone for vegetation at the European scale. As yet, no climatic region-specific parameterisations are available for (semi-)natural vegetation. For national scale integrated risk assessment, the application of climate specific stomatal flux data and parameterisations of the stomatal flux model might be more appropriate than the use of parameterisations agreed for European scale integrated risk assessment.

New/revised flux-based critical levels of ozone for vegetation: assessment of ozone effects for air pollution policy

Ten new/revised flux-based critical levels of ozone for vegetation were agreed following discussions at the LRTAP Convention workshop on ‘Flux-based assessment of ozone effects for air pollution policy’, November 2009, Ispra, Italy, and follow-on discussions at the 23rd Task Force meeting of the ICP Vegetation in 2010. In addition, these flux-based critical levels were also approved at the Task Force meetings of ICP Forests and ICP Modelling and Mapping in 2010. The stomatal flux parameter previously described as $AF_{st}Y$[3] was renamed as the Phytotoxic Ozone Dose above a threshold of Y (POD_Y). For **crops**, flux-based critical levels were derived from robust flux-effect relationships for wheat (grain yield, protein content, 1000 grain weight), potato (tuber yield) and tomato (fruit yield). For **forest trees**, flux-based critical levels were derived from robust flux-effect relationships for Norway spruce and combined beech and birch (annual whole tree growth). For **(semi-) natural vegetation**, indicator species were choosen to derive flux-based critical levels for this diverse and complex vegetation group. *Trifolium* species are amongst the most sensitive to ozone, with reductions in biomass, forage quality and reproductive ability noted at ambient and near-ambient concentrations in many parts of Europe. Since *Trifolium* species also have an important role as nitrogen fixers within grassland ecosystems, these species have been selected to be indicator species for productive grasslands and grasslands of high conservation value. In addition, a provisional critical level for grasslands of high conservation value was established using *Viola* species as indicator species.

The following **policy-relevant indicators** for ozone effects on vegetation were derived:

i) Agricultural crops: a POD_6 of 2 mmol m^{-2} to protect security of food supplies by protecting against loss of protein yield, an important crop quality parameter (note: a POD_6 of 1 mmol m^{-2} was also defined to protect against loss of yield quantity);

ii) Forest trees: a POD_1 of 4 mmol m^{-2} to protect against loss of carbon storage in living trees and loss of ecosystem services such as soil erosion, avalanche protection and flood prevention;

iii) Grasslands and pastures: a POD_1 of 2 mmol m^{-2} to protect against loss of vitality and fodder quality in productive grasslands;

iv) Grassland areas of high conservation value: a POD_1 of 2 mmol m^{-2} to protect against loss of vitality of natural species.

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[3] Accumulated stomatal flux above a threshold of Y nmol m^{-2} s^{-1} over a stated time period during daylight hours.

Progress with European heavy metals and nitrogen in mosses survey 2010/11

The next European heavy metals and nitrogen in mosses survey will be conducted in 2010/11. So far, sixteen out of a potential thirty countries have confirmed participation for heavy metals, whilst eight out of a potential eighteen countries have confirmed participation for nitrogen. In 2010, the ICP Vegetation Task Force recommended to include a pilot study of mosses as biomonitors of persistent organic pollutants (POPs). In contrast to heavy metals, the use of mosses for monitoring atmospheric deposition of organic compounds such as polycyclic aromatic hydrocarbons (PAHs) and polychlorinated biphenyls (PCBs) has so far received little attention. This is surprising as mosses have been shown, for example, to retain atmospherically deposited PAHs as efficiently as trace metals. Selected countries have confirmed participation in this pilot study.

Relationship between heavy metal concentration in mosses and EMEP modelled deposition

Further detailed statistical analysis of data for 1990, 1995 and 2000 confirmed results reported for 2005, i.e. at the European scale cadmium and lead concentrations in mosses are primarily determined by the rate of atmospheric deposition of these metals as modelled by EMEP. For mercury, the variation of its concentraton in mosses appears to be due to other factors than the rate of atmospheric deposition. The lack of correlation between EMEP modelled deposition values for mercury and observed concentrations in moss may relate to the specific chemistry of mercury (a global pollutant) and corresponding interactions with the moss. Data from Norway suggest that the deposition pattern depicted by the moss survey might be a better measure of the net mercury supply to the terrestrial ecosystem than that indicated by EMEP modelled calculations. For cadmium and lead, the correlations between their concentrations in mosses and EMEP modelled atmospheric depostion were country-specific, with correlation coefficients (r) ranging from highly positive (r = 0.88) to slightly negative (r = -0.28). Correlations often improved when they were based on EMEP grid-cells containing at least three moss sampling sites, resulting from averaging of site-specific conditions. In general, the correlations were higher for total deposition than wet or dry deposition. The European moss survey has an important role in identifying spatial patterns and temporal trends in atmospheric heavy metal pollution across Europe.

New activities of the ICP Vegetation

Following the success of the ozone ‘Evidence Report’, the ICP Vegetation Task Force has agreed to conduct the following reviews, to be published as a glossy report:

- Impacts of ozone on food security;
- Impacts of ozone on carbon sequestration and ozone absorption by vegetation and the implications for climate change.

In both reports the current state of knowledge will be reviewed with a focus on Europe and implications for policy will be discussed. In the food security report, the implications of increasing atmospheric ozone concentrations will also be assessed for south-east Asia and the impacts of ozone in a changing climate, with a focus on ozone and drought interactions, will be considered. In the carbon sequestration report, the impacts of ozone on carbon storage in forests and grasslands in Europe will be estimated.

In addition to the above glossy reports, the ICP Vegetation will also conduct a review on the use of mosses as biomonitors of atmospheric persistent organic pollutants (POPs) to establish whether mosses can be used as biomonitors of (groups of) POPs.

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EXECUTIVE SUMMARY

1. Introduction

1.1 Background

The International Cooperative Programme on Effects of Air Pollution on Natural Vegetation and Crops (ICP Vegetation) was established in the late 1980s, initially with the aim to assess the impacts of air pollutants on crops, but in later years also on (semi-)natural vegetation. The ICP Vegetation is led by the UK and has its Programme Coordination Centre at the Centre for Ecology and Hydrology (CEH) in Bangor. The ICP Vegetation is one of seven ICPs and Task Forces that report to the Working Group on Effects (WGE) of the Convention on Long-range Transboundary Air Pollution (LRTAP Convention) on the effects of atmospheric pollutants on different components of the environment (e.g. forests, fresh waters, materials) and health in Europe and North-America. The Convention provides the essential framework for controlling and reducing damage to human health and the environment caused by transboundary air pollution. So far, eight international Protocols have been drafted by the Convention to deal with major long-range air pollution problems. ICP Vegetation focuses on the following air pollution problems: quantifying the risks to vegetation posed by ozone pollution and the atmospheric deposition of heavy metals and nitrogen to vegetation. Currently, the work of the ICP Vegetation contributes to the revision of the Gothenburg Protocol, aiming to abate acidification, eutrophication and ground-level ozone.

Today, the ICP Vegetation comprises an enthusiastic group of over 200 scientists from 35 countries in the UNECE region; in addition, scientists from Cuba, India, Japan and South Africa participate (Table 1.1). The ICP Vegetation stimulates outreach activities to other regions in the world and invites scientists in those regions to collaborate with and participate in the programme of the ICP Vegetation. The contact details for lead scientists for each group are included in Annex 1. In many countries, several other scientists (too numerous to mention individually) also contribute to the biomonitoring programmes, analysis and modelling procedures that comprise the work of the ICP Vegetation.

Table 1.1. Countries participating in the ICP Vegetation; in italics: not a Party to the LRTAP Convention.

Austria
Belarus
Belgium
Bulgaria
China
Croatia
Cuba
Czech Republic
Denmark
Estonia
Finland
France
FYR of Macedonia
Germany
Greece
Hungary
Iceland
India
Italy
Japan
Latvia
Lithuania
Netherlands
Norway
Poland
Portugal
Romania
Russian Federation
Serbia
Slovakia
Slovenia
South Africa
Spain
Sweden
Switzerland
Turkey
Ukraine
United Kingdom
USA
Uzbekistan

1.2 Air pollution problems addressed by the ICP Vegetation

1.2.1 Ozone

Ozone is a naturally occurring chemical present in both the stratosphere (in the ‘ozone layer’, 10 – 40 km above the earth) and the troposphere (0 – 10 km above the earth).

Additional photochemical reactions involving NO_x, carbon monoxide and non-methane volatile organic compounds (NMVOCs) released due to anthropogenic emissions (especially from vehicle sources) increase the concentration of ozone in the troposphere. These emissions have caused a steady rise in the background ozone concentrations in Europe and the USA since the 1950s (The Royal Society, 2008). Superimposed on the background tropospheric ozone are ozone episodes where elevated ozone concentrations in excess of 50-60 ppb can last for several days. Ozone episodes can cause short-term responses in plants such as the development of visible leaf injury (fine bronze or pale yellow specks on the upper surface of leaves) or reductions in photosynthesis. If episodes are frequent, longer-term responses such as reductions in growth and yield and early die-back can occur.

The negotiations concerning ozone for the Gothenburg Protocol (1999) were based on exceedance of a concentration-based long-term critical level of ozone for crops and (semi-) natural vegetation. This value, an AOT40 of 3 ppm h accumulated over three months was set at the Kuopio Workshop in 1996 (Kärenlampi and Skärby, 1996) and is still considered to be the lowest AOT40 at which significant yield loss due to ozone can be detected for agricultural crops and (semi-)natural vegetation dominated by annuals, according to current knowledge (LRTAP Convention, 2004). However, several important limitations and uncertainties have been recognised for using the concentration-based approach. The real impacts of ozone depend on the amount of ozone reaching the sites of damage within the leaf, whereas AOTX-based critical levels only consider the ozone concentration at the top of the canopy. The Gerzensee Workshop in 1999 (Fuhrer and Achermann, 1999) recognised the importance of developing an alternative critical level approach based on the flux of ozone from the exterior of the leaf through the stomatal pores to the sites of damage (stomatal flux). This flux-based method provides an indication of the degree of risk for adverse effects of ozone on vegetation with a stronger biological basis than the concentration-based method. The flux-based approach required the development of mathematical models to estimate stomatal flux, primarily from knowledge of stomatal responses to environmental factors (Emberson *et al*., 2000; Pleijel *et al*., 2007). During 2009/10, flux-based critical levels of ozone for vegetation were reviewed at an LRTAP Convention workshop in Ispra, November 2009 and ten new/revised flux-based critical levels were agreed at follow-on discussions at the 23rd ICP Vegetation Task Force meeting, February 2010 (see Chapter 4).

The Executive Body of the LRTAP Convention decided at its 25th meeting in December 2007 (ECE/EB.AIR/91) to start the revision of the Gothenburg Protocol by mandating the Working Group on Strategies and Review to commence, in 2008, negotiations on further obligations to reduce emissions of air pollutants contributing to acidification, eutrophication and ground-level ozone. The outcome of the revision is currently scheduled to be presented to the Executive Body in December 2011. The ozone sub-group of the ICP Vegetation contributes models, state of knowledge reports and information to the LRTAP Convention on the impacts of ambient ozone on vegetation; dose-response relationships for species and vegetation types; ozone fluxes, vegetation characteristics and stomatal conductance; flux modelling methods and the derivation of critical levels and risk assessment for policy application.

1.2.2 Heavy metals

Concern over the accumulation of heavy metals in ecosystems, and their impacts on the environment and human health, increased during the 1980s and 1990s. Currently some of the most significant sources include:

- Metals industry (Al, As, Cr, Cu, Fe, Zn);
- Other manufacturing industries and construction (As, Cd, Cr, Hg, Ni, Pb);
- Electricity and heat production (Cd, Hg, Ni);

- Road transportation (Cu and Sb from brake wear, Pb and V from petrol, Zn from tires);
- Petroleum refining (Ni, V);
- Phosphate fertilisers in agricultural areas (Cd).

The heavy metals cadmium, lead and mercury were targeted in the 1998 Aarhus Protocol as the environment and human health were expected to be most at risk from adverse effects of these metals. Atmospheric deposition of metals has a direct effect on the contamination of crops used for animal and human consumption (Harmens *et al*., 2005).

The ICP Vegetation is addressing a short-fall of data on heavy metal deposition to vegetation by coordinating a well-established programme that monitors the deposition of heavy metals to mosses. The programme, originally established in 1980 as a Swedish initiative, involves the collection of naturally-occurring mosses and determination of their heavy metal concentration at five-year intervals. Surveys have taken place every five years since 1980, with the four most recent surveys being pan-European in scale. Ca. 6,000 moss samples have been collected in 28 countries in the most recent 2005/6 European survey. Spatial and temporal trends (1990 – 2005) in the concentrations of heavy metals in mosses across Europe have been described by Harmens *et al.* (2008a; in press). The next European moss survey is scheduled for 2010/11 and will include the determination of nitrogen and a pilot study of mosses as biomonitors of persistent organic pollutants (POPs; see Section 3.2.5).

1.2.3 Nitrogen

In recent decades, concern over the impact of nitrogen on low nutrient ecosystems such as heathlands, moorlands, blanket bogs and (semi-)natural grassland has increased (Bobbink *et al*., 2003). The empirical critical loads for nitrogen were reviewed and revised at a recent LRTAP Convention workshop in the Netherlands, June 2010 (ECE/EB.AIR/WG.1/2010/14). In 2009, the WGE gathered evidence on the impacts of airborne nitrogen on the environment and human health with the aim of drawing attention to the current threat of atmospheric nitrogen deposition to the environment and human health (ECE/EB.AIR/WG.1/2009/15). Details on the contribution of the ICP Vegetation can be found in Harmens *et al.* (2009). Previously, plant communities most likely to be at risk from both enhanced nitrogen and ozone pollution across Europe were identified (Harmens *et al*., 2006). In 2005/6, the total nitrogen concentration in mosses was determined for the first time at almost 3,000 sites to assess the application of mosses as biomonitors of nitrogen deposition at the European scale (Harmens *et al*., 2008b; Schröder *et al*., in press a). The European nitrogen in moss survey will be repeated in 2010/11. There are many groups within Europe studying atmospheric nitrogen fluxes and their impact on vegetation (e.g. Nitrogen in Europe (NinE), NitroEurope, COST 729). The ICP Vegetation maintains close links with these groups to provide up-to-date information on the impacts of nitrogen on vegetation to the WGE of the LRTAP Convention. Currently, the draft report of the European Nitrogen Assessment (ENA) is available for consultation and the final report will be launched in April 2011 (http://www.nine-esf.org).

1.3 Work-plan items for the ICP Vegetation in 2010

The following activities were agreed at the 28th session of the WGE (ECE/EB.AIR/WG.1/2009/4) and the 27th session of the Executive Body of the LRTAP Convention (ECE/EB.AIR/2009/1) to be priority areas of work for the ICP Vegetation in 2010:

- Report on ozone biomonitoring experiment with bean in 2009;
- Report on ozone impacts in Mediterranean areas;

- Review of ozone flux modelling methods and their application to different climatic regions;
- Report of workshop on ‘Flux-based assessment of ozone effects for air pollution policy’;
- Progress report on European heavy metals and nitrogen in mosses survey 2010/11;
- Report on the relationship between heavy metal concentration in mosses and EMEP modelled deposition.

In addition, the ICP Vegetation was requested to report on the following common work-plan items of the WGE:

- The development of targets for 2020 and 2050 and application in ex-post integrated assessment using harmonized data on concentrations and depositions, in collaboration with the Task Force on Integrated Assessment Modelling;
- The updating of robustness of air pollution effects in integrated assessment modelling;
- The links between air pollution effects and biological diversity;
- Quantified trends in selected key monitored and modelled parameters, based on the guidelines on reporting of monitoring and modelling of air pollution effects.

Progress with each of these work-plan activities is described in Chapter 3, with details of the new/revised critical levels of ozone for vegetation being described in Chapter 4. New activities of the ICP Vegetation are described in Chapter 5 and Chapter 6 summarises the key achievements in 2009/10 together with the medium-term work-plan for 2011 – 2013 (updated at the 23rd ICP Vegetation Task Force Meeting, 1 – 3 February 2010, Tervuren, Belgium).

2. Coordination activities

2.1 Annual Task Force Meeting

The Programme Coordination Centre organised the 23rd ICP Vegetation Task Force meeting, 1 - 3 February 2010 in Tervuren, Belgium, in collaboration with the local hosts at the Veterinary and Agrochemical Research Centre (CODA-CERVA). The meeting was attended by 53 experts from 18 Parties to the Convention. Also present were a representative from EMEP/MSC-East and four experts from Cuba and Japan. The Task Force discussed the progress with the work-plan items for 2010 (see Section 1.3) and the medium-term work-plan for 2011 - 2013 (see Section 6.2) for the air pollutants ozone, heavy metals, nutrient nitrogen and persistant organic pollutants (POPs). Follow-on discussions from the workshop on 'Flux-based assessment of ozone effects for air pollution policy' were an important component of the ozone discussions at the Task Force meeting. A book of abstracts, details of presentations and the minutes of the 23rd Task Force meeting are available from the ICP Vegetation web site (http://icpvegetation.ceh.ac.uk).

The main decisions made at the Task Force meeting were:

Ozone – i) the adoption of ten new/revised flux-based critical levels of ozone for vegetation and their application in integrated assessment modelling for air pollution policy (see Chapter 4); ii) to produce glossy state of knowledge reports on the impacts of ozone on food security (see Section 5.1), and on the impacts of ozone on carbon sequestration and ozone absorption by vegetation and the implications for climate change (see Section 5.2); iii) to continue the ozone biomonitoring experiments with bean (see Section 3.2.1) and to include a survey on the impacts of ambient ozone on leafy salad crops in 2010 (see Section 5.1).

Heavy metals, nitrogen and POPs – i) to continue the preparations for and conduct the next European heavy metals and nitrogen in mosses survey in 2010/11 (see Section 3.2.5), ii) to conduct a pilot study on mosses as biomonitors of POPs in the 2010/11 European moss survey (see Section 3.2.5); iii) to review the use of mosses as biomonitors of atmospheric deposition of POPs (see Section 5.3).

The Task Force acknowledged and encouraged further fruitful collaborations with the bodies and centres under the Steering Body to EMEP, in particular EMEP/MSC-West, EMEP/MSC-East, the Task Force on Integrated Assessment Modelling and the Task Force on the Hemispheric Transport of Air Pollution, and bodies under the Working Group of Strategies and Review, in particular the Task Force on Reactive Nitrogen. In addition, the Task Force encouraged further development of outreach activities to other regions in the world.

The 24th Task Force meeting will be held at the Forschungsstelle für Umweltbeobachtung (FUB) – Research Group for Environmental Monitoring, Rapperswil, Switzerland, from 31 January – 2 February 2011.

2.2 Reports to the LRTAP Convention

The ICP Vegetation Programme Coordination Centre has reported progress with the 2010 work-plan items in the following documents for the 29th session of the WGE (http://www.unece.org/env/lrtap/WorkingGroups/wge/29meeting.htm):

- ECE/EB.AIR/WG.1/2010/3: Joint report of the ICPs and Task Force on Health;
- ECE/EB.AIR/WG.1/2010/8: Effects of air pollution on natural vegetation and crops (technical report from the ICP Vegetation);

- ECE/EB.AIR/WG.1/2010/13: Flux-based assessment of ozone effects for air pollution policy (prepared by the ICP Vegetation).

For the draft workplan for 2011, see ECE/EB.AIR/WG.5/2010/16 or ECE/EB.AIR/2010/5.

The Programme Coordination Centre for the ICP Vegetation has produced the current annual glossy report and contributed to a two-page WGE colour leaflet on 'Atmospheric nitrogen deposition: a threat to the environment and human health'. The Programme Coordination Centre also participated in the LRTAP Convention workshop on 'The review and revision of empirical critical loads and dose-response relationships', 23 – 25 June 2010, Noordwijkerhout, the Netherlands. The outcome of this nitrogen workshop has been reported in ECE/EB.AIR/WG.1/2010/14. In addition, the Programme Coordination Centre contributed to a chapter on 'New flux-based critical levels for ozone-effects on vegetation' in the EMEP Status Report 1/2010. Further analyses on the relationship between heavy metal concentrations in mosses and modelled atmospheric depositions were reported in the EMEP Status Report 2/2010. The Programme Coordination Centre and participants of the ICP Vegetation also contributed to the 2010 Assessment Report of the Task Force on Hemispheric Transport of Air Pollution, in particular to Chapter A5: 'Impacts on Health, Ecosystems, and Climate'.

2.3 Scientific papers

The following papers describing results from the ICP Vegetation have been submitted and accepted for publication this year:

Harmens, H., Norris, D.A., Steinnes, E., Kubin, E., Piispanen, J., Alber, R., Aleksiayenak, Y., Blum, O., Coşkun, M., Dam, M., De Temmerman, L., Fernández, J.A., Frolova, M., Frontasyeva, M., González-Miqueo, L., Grodzińska, K., Jeran, Z., Korzekwa, S., Krmar, M., Kvietkus, K., Leblond, S., Liiv, S., Magnússon, S.H., Maňkovská, B., Pesch, R., Rühling, Å., Santamaria, J.M., Schröder, W., Spiric, Z., Suchara, I., Thöni, L., Urumov, V., Yurukova, L., Zechmeister, H.G. (In press). Mosses as biomonitors of atmospheric heavy metal deposition: spatial and temporal trends in Europe. Environmental Pollution.

Holy, M., Pesch, R., Schröder, W., Harmens, H., Ilyin, I., Alber, R., Aleksiayenak, Y., Blum, O., Coşkun, M., Dam, M., De Temmerman, L., Fedorets, N., Figueira, R., Frolova, M., Frontasyeva, M., Goltsova, N., González Miqueo, L., Grodzińska, K., Jeran, Z., Korzekwa, S., Krmar, M., Kubin, E., Kvietkus, K., Larsen, M., Leblond, S., Liiv, S., Magnússon,S., Maňkovská, B., Mocanu, R., Piispanen, J., Rühling, Å., Santamaria, J., Steinnes, E., Suchara, I., Thöni, L., Turcsányi, G., Urumov, V., Wolterbeek, H.T., Yurukova, L., Zechmeister, H.G. (In press). First thorough identification of factors associated with Cd, Hg and Pb concentrations in mosses sampled in the European surveys 1990, 1995, 2000 and 2005. Journal of Atmospheric Chemistry.

Mills, G., Hayes, F., Simpson, D., Emberson, L., Norris, D., Harmens, H., Büker, P. (In press). 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.

Schröder, W., Holy, M., Pesch, R., Harmens, H., Fagerli, H., Alber, R., Coşkun, M., De Temmerman, L., Frolova, M., González-Miqueo, L., Jeran, Z., Kubin, E., Leblond, S., Liiv, S., Maňkovská, B., Piispanen, J., Santamaría, J.M., Simonèiè, P., Suchara, I., Yurukova, L., Thöni. L., Zechmeister, H.G. (In press). First Europe-wide correlation analysis identifying factors best explaining the total nitrogen concentration in mosses. Atmospheric Environment.

Schröder, W., Holy, M., Pesch, R., Harmens, H., Ilyin, I., Steinnes, E., Alber, R., Aleksiayenak, Y., Blum, O., Coşkun, M., Dam, M., De Temmerman, L., Frolova, M., Frontasyeva, M., González-Miqueo, L., Grodzińska, K., Jeran, Z., Korzekwa, S., Krmar, M., Kubin, E., Kvietkus, K., Leblond, S., Liiv, S., Magnússon,S., Maňkovská, B., Piispanen, J., Rühling, Å., Santamaria, J., Spiric, Z., Suchara, I., Thöni, L., Urumov, V., Yurukova, L., Zechmeister, H.G. (In press). Are cadmium, lead and mercury concentrations in mosses across Europe primarily determined by atmospheric deposition of these metals? Journal of Soil and Sediments.

3. Ongoing research activities in 2009/10

In this chapter, progress made with the WGE common work-plan items and the ICP Vegetation work-plan for 2010 is summarised.

3.1 Contributions to WGE common work-plan items

3.1.1 Targets for 2020 and 2050 and application in ex-post integrated assessment

The targets for impacts of ozone on vegetation were set to avoid most (by 2020) and all (by 2050) detectable ozone damage to receptors and a reduction in ecosystem services, such as carbon sequestration (Harmens *et al.*, 2009). Indicators to achieve these targets are a reduction in (2020) or no exceedance (2050) of ozone critical levels for vegetation (see Chapter 4). We recommend the application of the gap closure principal to reduce exceedances in 2020. The aim is to secure food production and quality, protect against loss of carbon storage and loss of ecosystem services (e.g. flood prevention, protection from soil erosion and avalanches) provided by trees and protect against loss of fodder quality and vitality of (semi-)natural vegetation.

Although AOT40 was used in the development of the Gothenburg Protocol, nowadays the accumulated ozone flux via the stomatal pores on the leaf surface is considered to provide a more biologically sound method for describing observed ozone effects on vegetation (see Chapter 4). Based on evidence provided by the ICP Vegetation (Hayes *et al.*, 2007b; Mills *et al.*, 2008), the Executive Body of the Convention noted in 2008 that the implementation of existing legislation would not attain the ambition levels set out in article 2 of the Gothenburg Protocol, in particular, it would not provide a significant reduction in effects of ozone on health and vegetation, and the policies aiming only at health effects would not protect vegetation in large areas of Europe (ECE/EB.AIR/96). The Executive body decided that ozone effects on vegetation should be incorporatedd in integrated assessment modelling, especially in work for the revision of the Gothenburg Protocol, and recommended that flux-based methods be used. However, currently the GAINS (Greenhouse Gas and Air Pollution Interactions and Synergies; http://gains.iiasa.ac.at/index.php/home-page/241-on-line-access-to-gains) model, used to optimise cost-benefits for the revision of the Gothenburg Protocol, can only include concentration-based critical levels of ozone for vegetation (i.e. AOT40), in addition to the health metric for ozone. Application of flux-based critical levels of ozone for vegetation in an ex-post integrated assessment outside the GAINS model optimisation procedure will be conducted once base-line, harmonized data on concentrations and depositions become available for the revision of the Gothenburg Protocol. The ex-post integrated assessment will provide additional effects-based indicators, in addition to those used in the GAINS model, for the revision of the Gothenburg Protocol. At a later stage, it is anticipated that the ex-post analysis will also be conducted with selected future scenarios that have been applied within the GAINS model.

3.1.2 Robustness of air pollution effects in integrated assessment modelling

Here we summarise the robustness of ozone impacts on vegetation; further details on uncertainties associated with the flux-based approach to establish ozone critical levels for vegetation are described in Chapter 4. The main uncertainties arise from the effects of soil moisture on ozone flux together with the extrapolation from different exposure systems to field conditions that are different from those inside experimental systems. Soil moisture, which has the potential to strongly limit ozone uptake by vegetation, varies on a local scale which is hard to model. In experiments used to derive flux-based ozone critical levels for vegetation, soil moisture was typically kept at a level that did not induce any water stress. Although the flux approach represents a way to quantify several of the important factors that modify ozone uptake that may differ between exposure systems and the field, the application of flux-effect relationships still depends on extrapolation from one set of conditions to another. For some Mediterranean areas the flux-based methodology may under-estimate effects and for crops in these areas, a modified vapour pressure deficit function may be required.

For **crops**, the robustness in the understanding of ozone damage in Europe has been substantiated by the compilation of observed effects in ambient air (Hayes *et al*., 2007b; Mills *et al*., in press). This showed ozone injury occurrence on 27 species of agricultural and horticultural crops in 12 countries, and beneficial effects on yield of growing crops in filtered air from which ozone was excluded. There is also a coherent pattern of response in crops when combining experiments from different countries with different climatic conditions and for a range of varieties (Pleijel *et al*., 2007). A recent meta-analysis of results in peer-reviewed studies of ozone effects on wheat indicated that ozone concentrations between 31 and 59 parts per billion (ppb) (average 43 ppb) were associated with a significant decrease in the grain yield (18%) and biomass (16%) relative to charcoal-filtered air treatments (Feng *et al*., 2008).

For **forest trees**, an additional source of uncertainty lies in the application of critical levels derived from effects on trees of up to 10 years of age growing in an exposure facility, to mature trees growing within a forest stand. It is encouraging, however, that an epidemiological study has shown that the flux-based critical level for birch and beech would have protected mature beech trees in Switzerland (Braun *et al*., 2010). In addition, a recent meta-analysis of published data on tree responses indicated that an ambient ozone concentration of ca. 40 ppb was sufficient to reduce the total tree biomass by 7% compared with pre-industrial levels (Wittig *et al*., 2009). Consistency of results across countries provides further strength to the derived flux-based critical levels for forest trees (e.g. Karlsson *et al*., 2007).

The ozone critical levels for **(semi-)natural vegetation** can be considered the most uncertain. This is mainly due to the complexity of these ecosystems, with uncertainty increasing from productive grasslands, to low input grasslands and being highest for natural ecosystems. Uncertainties at present associated with the flux-based approach for (semi-) natural vegetation, include variability of the maximum stomatal conductance, genotypic variability within a species, diversity of communities, soil moisture modelling, competition and management effects. Recently, it was shown that ambient ozone concentrations were sufficient to induce injury on 95 species of forbs and grasses in Europe over the period 1990 – 2006, indicating that this vegetation type is already responding to ozone (Hayes *et al*., 2007b). In addition, experimental exposure studies have shown changes in plant communities (reviewed by Ashmore, 2005; Bassin *et al*., 2007). However, a long-term ozone exposure of a complex intact long-standing alpine meadow community showed no response to enhanced ozone, suggesting that under such conditions there may be either a build up of genetic resistance within the population to the already high ambient ozone or that there is a natural buffering of response to environmental stress in this high altitude environment (Bassin *et al*., 2009).

3.1.3 Links between air pollution effects and biological diversity

Although different sensitivities to ozone have been identified for plant species (Hayes *et al*., 2007a) and communities (Mills *et al*., 2007b), there is hardly any field-based evidence of the impacts of ozone on plant diversity as little field-based research has been done yet. In the field, impacts of ambient ozone on vegetation will be difficult to disentangle from other drivers of change such as nitrogen pollution, climate change and changes in land use and management. As mentioned in Section 3.1.2, a long-term ozone exposure of a complex intact long-standing alpine meadow community showed no response to enhanced ozone

(Bassin *et al.*, 2009). Legumes (i.e. nitrogen fixing forbs) have been identified as a particularly sensitive plant group (Harmens *et al.*, 2009; Hayes *et al.*, 2007b; 2009; 2010), hence it is expected that their abundance will decline in an atmosphere with rising ozone background concentrations.

3.1.4 Trends in selected monitored and modelled parameters

Evidence of widespread ozone damage to vegetation in Europe was recently reviewed (Hayes *et al.*, 2007b). At the local scale, there was evidence of higher ozone damage in years with higher ozone concentrations (e.g. in 2003 and 2006) in regions of Europe where climatic conditions were conducive to high ozone fluxes. However, the timescale and density of data points were insufficient to allow any long-term trends related, for example, to the changing ozone profile (lower peaks, increasing background), to be identified. In general, there was more ozone damage to vegetation in areas with the highest ozone fluxes and flux-based critical level exceedances (parts of central and southern Europe), but damage was also observed in areas of northern Europe where flux-based critical levels were exceeded but concentration-based critical levels were not exceeded.

The European moss survey showed that the highest nitrogen concentration in mosses in 2005/6 were found in central and eastern Europe and the lowest concentrations in north-western Europe (Harmens *et al.*, 2008b; Mills *et al.*, 2008). No temporal trends for nitrogen concentrations in mosses are available yet. In general, the highest heavy metal concentrations in mosses in 2005/6 were found in parts of eastern Europe and Belgium (Harmens *et al.*, 2008a; in press). Europe-wide the concentrations of arsenic, cadmium, iron, lead and vanadium declined the most since 1990 (by 45-72%), the decline in the concentration of copper, nickel and zinc was intermediate (20-30%), with no significant reduction being found for chromium (2 per cent) and mercury (12% since 1995).

3.2 Progress with ICP Vegetation work-plan items

3.2.1 Ozone biomonitoring experiment with bean in 2009

Since 2008, participants of the ICP Vegetation have been conducting biomonitoring campaigns using ozone-sensitive (S156) and ozone-resistant (R123) genotypes of *Phaseolus vulgaris* (Bush bean, French Dwarf bean) that had been selected at the USDA-ARS Plant Science Unit field site near Raleigh, North Carolina, USA. From genetic crosses the S156 and R123 lines were selected and then tested in a bioindicator experiment reported by Burkey *et al.* (2005). A trial of bean biomonitoring system was conducted in selected European countries during the summer of 2008 (Harmens *et al.*, 2009) and the ICP Vegetation Task Force recommended to extend this further in 2009.

For the ICP Vegetation biomonitoring study in 2009, bean seeds of the strains S156 and R123 were kindly provided by Kent Burkey (USA). The experimental protocol was modified slightly from that used in 2008 to standardise growing conditions based on the knowledge gained from the pilot study in 2008, and to recommend two key stages at which to assess the plants for ozone injury – at flowering and two weeks after the onset of flowering (ICP Vegetation, 2009). Beans were supplied to 21 sites from 12 countries and participants received their bean seeds in April 2009. Exposure to ambient air began in May-June at the majority of sites, with participants continuing the experiment until 50% of pods were brown (typically at the end of August). Plant, climate and pollutant data were received by the Programme Coordination Centre from fifteen sites in ten countries in 2009 (Table 3.1).

Table 3.1. Countries and sites that submitted data for the ozone biomonitoring experiment with bean in 2009. Beans were exposed to ambient air and at some sites also to elevated ozone in exposure chambers; selected sites submitted stomatal conductance (g_s) data.

Country	Site	Ambient air	Chambers	Data on g_s
Austria	Seibersdorf	x		
Belgium	Tervuren	x	x	x
France	Champenoux	x		
Germany[1]	Braunschweig	x		
	Hohenheim	x		x
Greece	Heraklion	x		x
Hungary	Gödöllõ	x		
Italy	Bari	x		x
	Pisa	x		
	Rome	x		x
Slovenia	Ljubljana	x		
	Zavodnje	x		x
Spain	Valencia	x		x
UK	Ascot	x	x	x
	Bangor	x	x	

[1] Processed (but no raw) ambient air and chamber data were also received from the site in Linden.

Participants indicated that injury symptoms were easy to identify and ozone injury symptoms were observed at the majority of sites. The number of leaves in each of the injury classes 0, 1-5%, 5-25% and >25% was recorded at each site and more extensive and more severe injury was observed on the sensitive variety. From the raw data provided by participants, an injury score was calculated for each variety, which gave an increased weighting to leaves which were most severely injured. Progression of injury development through the exposure season at selected example sites is shown in Figure 3.1.

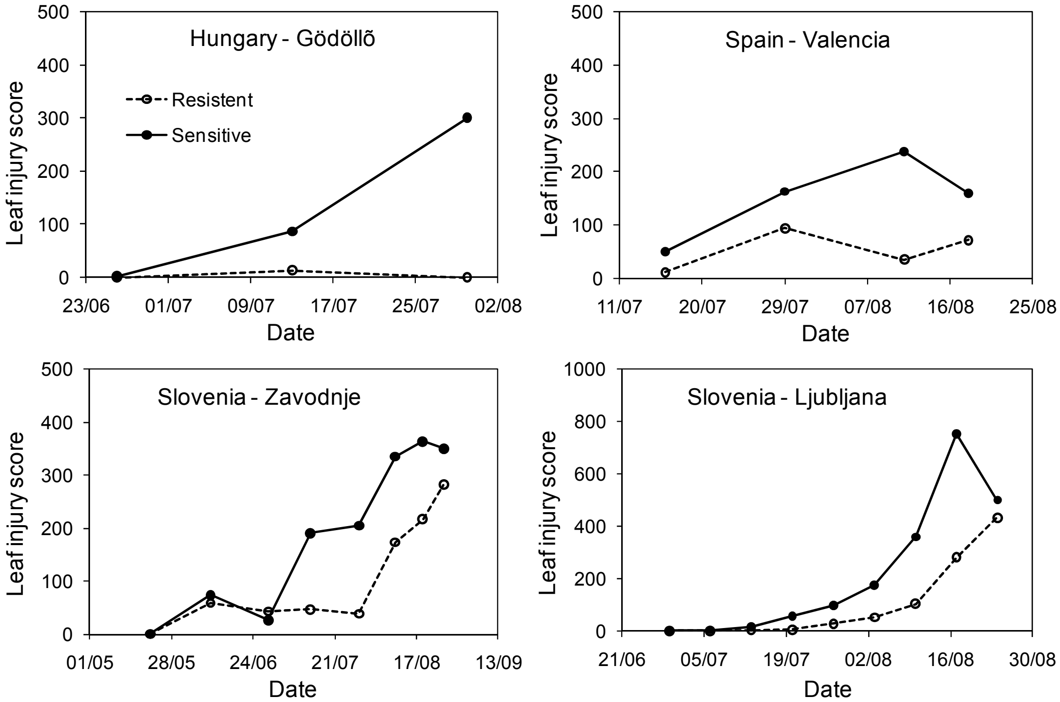

Figure 3.1. Development of ozone injury on the sensitive and resistant varieties of bean (*Phaseolus vulgaris*) at selected sites across Europe in 2009 (note the different scale of the Y-axis for Slovenia-Ljubljana).

The extent of injury on the sensitive variety was not directly related to the AOT40 at the site, similarly the ratio of S/R seed weight was not directly related to AOT40, however, plants with a lot of injury had fewer seeds than those with less injury, so that overall there was a decrease in the ratio of S/R seed weight with increasing injury score of the sensitive variety. Analysis of the data on pod weight and ozone concentration (12-hour mean) showed that for some sites the 2008 and 2009 data fitted well with the relationships established by Burkey *et al.* (2005) using chamber studies (Figure 3.2a), however, there was a lot of scatter in the relationship when data was used from the wide climatic range across Europe. Four sites (Belgium-Tervuren, Germany-Linden, UK-Ascot and UK-Bangor) also performed ozone exposure studies with the beans in chambers (Table 3.1). Exposure results at an individual site were linear, with data from ambient air studies performed at the same site fitting well with the relationship (e.g. from Germany-Linden, Figure 3.2b). This suggests that climate variations between sites affect the dose-response relationship and that a stomatal flux-effect relationship might better explain the observed effects.

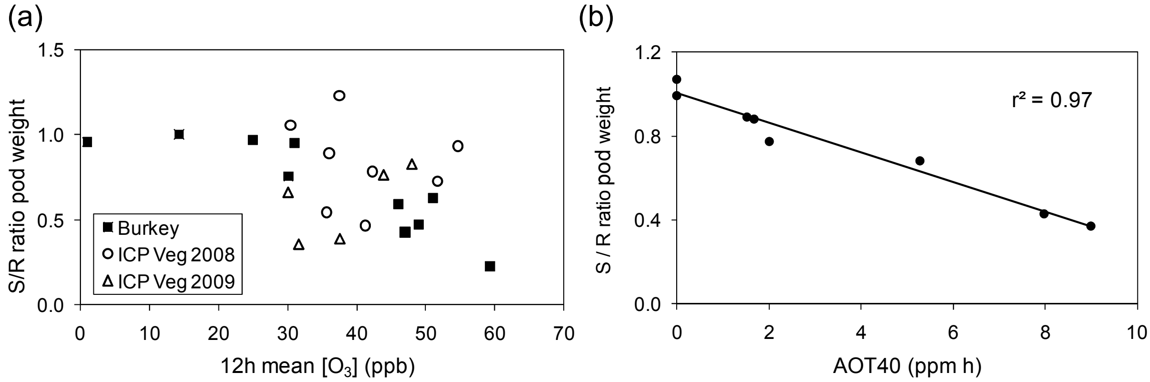

Figure 3.2. (a) Relationship between S/R ratio for pod weight of bean and ozone (12-hour mean) for data from ICP Vegetation sites in 2008 and 2009 compared with that from Burkey *et al*. (2005) in chamber studies and (b) ratio of pod weight in relation to AOT40 in open-top chambers and in ambient air at Linden-Germany in 2009.

Stomatal conductance measurements were made at selected sites in 2009 (Table 3.1) to initiate a stomatal conductance dataset in ambient air conditions. This dataset will be extended further in 2010 and 2011 to enable the development of a robust stomatal conductance model, which may better explain the variation in sensitive/resistant seed yield and pod weight across Europe. A similar number of countries and sites have confirmed participation in 2010, with participation from the Ukraine, China, Cuba, Japan and South Africa providing import permits can be gained for the seeds in time for the growing season.

3.2.2 Ozone impacts in Mediterranean areas

Some of the highest ozone concentrations in Europe are found in the crop growing areas of the Mediterranean region. In these areas, current ambient ozone concentrations have been shown to induce negative impacts on the production and quality of over 20 agricultural and horticultural crop species of economical importance (Fumagalli *et al*., 2001). Reductions in yield have been observed in for example potato, tomato, bean, watermelon, artichoke and lettuce (Calvo *et al*., 2007, 2009; Gerosa *et al*., 2009a; Gimeno *et al*., 1999; Goumenaki *et al*., 2007; Sanz *et al*., 2002). Moreover, effects on food quality like reduced sugar concentration (Figure 3.3a), delayed fruit ripeness or alterations in nutritional value have been observed in bean, tomato and watermelon (Bermejo, 2002; Gimeno *et al*., 1999; Iriti *et al*., 2009), resulting in a decrease in their marketable value. In tomato, virus infection rates were increased at elevated ozone exposure (Porcuna, 1997). In some cases, high ozone episodes caused high economic losses in commercial fields over large areas due to the appearance of visible injury on leafy crops such as lettuce, spinach and chichory (Fumagalli *et al.*, 2001). Ozone can also induce physiological effects on orchard species of great economical importance in the Mediterranean areas like citrus or olive tree (Iglesias et *al.*, 2006; Minnocci *et al.*, 1999).

Ambient ozone concentrations also cause visible leaf damage and effects on growth and plant physiology in some evergreen species representative of Mediterranean forests, such as Holm oak, Kermes oak, Carob tree and Aleppo pine (Alonso *et al.*, 2002; Elvira *et al.*, 1998, 2004; Ferretti *et al.*, 2007a; Inclán *et al.*, 1999; Kivimaenpaa *et al.*, 2010; Manes *et al.*, 2001; Ribas *et al.*, 2005; Sanz *et al.*, 2000 Velissariou *et al.*, 1992). Other evergreen trees and shrubs frequently found in Mediterranean forests like Phillyrea tree, strawberry tree, mastic plant or laurel have also been shown to be sensitive to ozone (Nali *et al.*, 2004; Reig-Arminana *et al.*, 2004).

Deciduous tree species such as oak, beech, poplar, ash or maple more usually found in the humid areas of the Mediterranean region such as mountains, river plains and northern areas respond to ambient ozone by developing foliar symptoms and other physiological effects such as reduced photosynthesis (Bussotti *et al.*, 2007; Calatayud and Cerveró 2007; Ferretti *et al.*, 2007a,b; Gerosa *et al.*, 2009b; Guidi *et al.*, 1998; Paoletti *et al.*, 2007a, 2009). In some cases, effects in the field are less severe than predicted from experimental studies despite the high ozone levels frequently registered in this area. This is most likely due to interactions between ozone and other environmental stresses such as drought that reduce ozone flux (Alonso *et al.*, 2001; Manes *et al.*, 2001; Ribas *et al.*, 2005; Vitale *et al.*, 2008). On the other hand, some experimental results indicate that increased levels of ozone can deteriorate forest response to other common environmental stresses such as drought, high radiation levels and pests, contributing to reduce forest health (Alonso *et al.*, 2001, 2002; Paoletti *et al.*, 2007b).

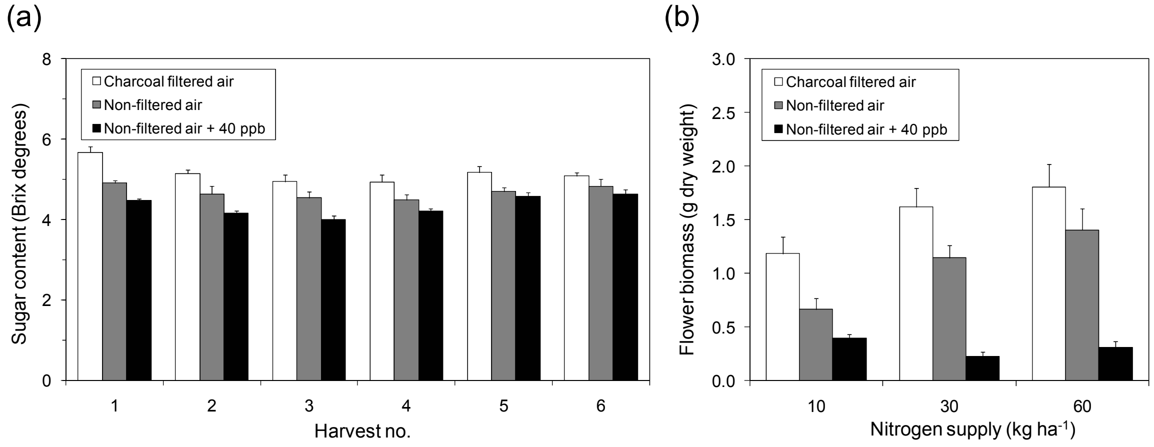

Figure 3.3. Ozone effects on (a) the sugar content of tomato (adapted from Bermejo, 2002) and (b) the flower production of knotted clover (*Trifolium striatum*) at different nitrogen supply (adapted from Sanz *et al.*, 2007).

There is scarcity of information on the ozone sensitivity of the Mediterranean herbaceous plant communities. Ozone pollution reduced growth, flower and seed production (Figure 3.3b) and forage quality in sensitive annual legume species growing in the Dehesas grassland (Gimeno *et al.*, 2004a,b; Sanz *et al.*, 2005, 2007), a characteristic traditional managed ecosystem covering extensive areas of the Mediterranean landscape. Interspecific variability of plant response to ozone can directly affect the structure and species composition of this high biodiverse ecosystem. Other environmental factors such as increased nitrogen deposition or drought may mitigate negative ozone effects on semi-natural species under moderate ozone concentrations (Sanz *et al*., 2005, 2007).

Despite the high ozone concentrations frequently experienced in Mediterranean areas, observed ozone impacts were often less severe than expected due to interactions with climatic conditions and other environmental stresses such as drought. This supports the further development of the flux-based approach, with specific parameterisations of the flux model being required for Mediterranean areas to account for differences in climate, species ecophysiology and ozone sensitivity compared with central and northern European climatic conditions and species. Stomatal flux-based critical levels for Mediterranean vegetation are still subject to considerable uncertainties in terms of dry deposition modelling and dose-response relationship derivation (see Chapter 4). Hence, it is recommended to also maintain concentration-based critical levels of ozone for vegetation for risk assessment in Mediterranean areas until further scientific information becomes available to strengthen the flux-based approach in this region. There is a clear need to enhance the availability of effects-based data on the impacts of ozone on vegetation in Mediterranean climatic conditions, develop robust stomatal flux-effect relationships and hence establish robust ozone critical levels to protect Mediterranean vegetation. Further studies are required to quantify those impacts in the light of climate change with the aim to protect food production and quality, carbon storage capacity of Mediterranean forests and annual pasture biodiversity conservation in Mediterranean areas.

3.2.3 Ozone flux modelling methods and their application to different climatic regions

In recent years, climate-specific ozone flux modelling methods were developed for crops and forest tree species, resulting in the development of statistically robust flux-response relationships from which it has been possible to derive critical levels of ozone for vegetation at the European scale (see Chapter 4). In this method climate specific stomatal flux data were pooled and it was assumed that only the variation in stomatal flux by climatic conditions determines species response to ozone, i.e. climatic and species-specific effects on for example the detoxification of ozone were not taken into account (Ferretti *et al*., 2007b). Care should be taken when applying the parameterisations for European scale integrated risk assessment to the national scale, for which the application of non-pooled climate specific stomatal flux data and parameterisations of the stomatal flux model might be more appropriate. As yet, no climate region-specific parameterisations are available for (semi-) natural vegetation. Further discussion on application of the ozone flux modelling methods to different climatic regions is included in Chapter 4.

3.2.4 Workshop on 'Flux-based assessment of ozone effects for air pollution policy'

Details of the workshop on 'Flux-based assessment of ozone effects for air pollution policy', including setting new/revised flux-based critical levels are provided in Chapter 4.

3.2.5 Progress with European heavy metals and nitrogen in mosses survey 2010/11

The European moss biomonitoring network was originally established in 1990 to estimate atmospheric heavy metal deposition at the European scale (Rühling, 1994). The moss technique is based on the fact that carpet-forming, ectohydric mosses obtain most trace elements and nutrients directly from precipitation and dry deposition with little uptake from the substrate. The technique provides an alternative, time-integrated measure of heavy metal and potentially nitrogen deposition from the atmosphere to terrestrial ecosystems (Harmens *et al*., 2008a,b; in press). It is easier and cheaper than conventional precipitation analysis as it avoids the need for deploying large numbers of precipitation collectors with an associated long-term programme of routine sample collection and analysis. Therefore, a much higher sampling density can be achieved than with conventional precipitation analysis.

In 2008, the ICP Vegetation Task Force agreed to conduct the next European survey on heavy metal and nitrogen concentrations in naturally occurring mosses in 2010/11. So far, sixteen out of thirty and eight out of eighteen countries have confirmed participation for heavy metals and nitrogen respectively. In 2010, the Task Force recommended to include a pilot study on mosses as biomonitors of persistent organic pollutants (POPs). In contrast to heavy metals, the use of mosses for monitoring atmospheric deposition of organic compounds such as polycyclic aromatic hydrocarbons (PAHs) and polychlorinated biphenyls (PCBs) has so far received little attention (Holoubek *et al.*, 2000; Zechmeister *et al.*, 2003). This is surprising as mosses have been shown for example to retain atmospherically deposited PAHs as efficiently as trace metals (Milukaite, 1998).

3.2.6 Relationship between heavy metal concentration in mosses and EMEP modelled deposition

As a contribution in kind, Prof. Winfried Schröder and colleagues at the University of Vechta, Germany, conducted detailed statistical analysis of factors influencing the spatial variation of heavy metal concentrations in mosses. Previous analysis of the 2005 European data showed that cadmium and lead concentrations in mosses were primarily determined by the rate of atmospheric deposition of these metals as modelled by the EMEP atmospheric transport model MSCE-HM; this was not the case for mercury (Harmens *et al.*, 2009; Schröder *et al.*, in press b). Further analysis of data for 1990, 1995 and 2000 were in agreement with the results for 2005 (Table 3.2; Holy *et al.*, in press). For mercury, the variation of its concentraton in mosses appears to be due to factors other than the emission or atmospheric deposition of mercury; these factors include the analytical method, moss species sampled, distance to pollution sources and the proportion of forested area.

Table 3.2. Spearman rank correlation coefficients between the cadmium, lead and mercury concentrations in mosses and EMEP modelled total atmospheric deposition in the year of sampling; n.a. = not available, n.s. = not significant at P = 0.05 (Holy *et al.*, in press).

Metal	1990	1995	2000	2005
Cadmium	0.62	0.64	0.69	0.65
Lead	0.68	0.68	0.68	0.73
Mercury	n.a.	n.s.	0.22	0.17

For cadmium and lead, further analyses of the correlations between the concentrations in mosses and the EMEP modelled atmospheric deposition were conducted as a contribution in kind by Dr Ilia Ilyin of EMEP/MSC-East. Despite the good correlations at the European scale, country-specific correlations were found with correlation coefficients (r) ranging from highly positive (r = 0.88) to slightly negative (r = -0.28; Figure 3.4). Factors most likely contributing to the observed range in correlation coefficients include: (i) the comparison of site-specific heavy metal concentrations in mosses with modelled deposition averaged in the 50 x 50 km^2 EMEP grid; (ii) moss data including input from local pollution source, whereas the EMEP model aims to model long-range transboundary air pollution; (iii) uncertainties in the moss and modelled EMEP deposition data; (iv) some limitations and confounding factors identified in the application of mosses as biomonitors of atmospheric heavy metal deposition (e.g. Berg and Steinnes, 1997; Harmens *et al.*, 2008c; Zechmeister *et al.*, 2003). Indeed, correlations often improved when they were based on EMEP grid-cells containing at least three moss sampling sites, resulting from averaging of site-specific conditions. Previous analysis of the 2000 data for lead had already shown that correlations improved significantly when calculated for Scandinavia only, i.e. in a comparison of data from locations primarily affected by long-range transboundary air pollution (Harmens *et al.*, 2006). The country-specific correlations were hardly affected by relating the metal concentrations in mosses (representing the accumulation during the most recent three years of growth at time of sampling) with the accumulated deposition in the last year or the last three years before moss sampling (Holy *et al.*, in press). In some countries the correlations improved when relating the concentration in mosses to wet instead of total deposition of the metal, however, generally the correlations were highest for total deposition. Correlations with dry deposition were often lower than those with total deposition.

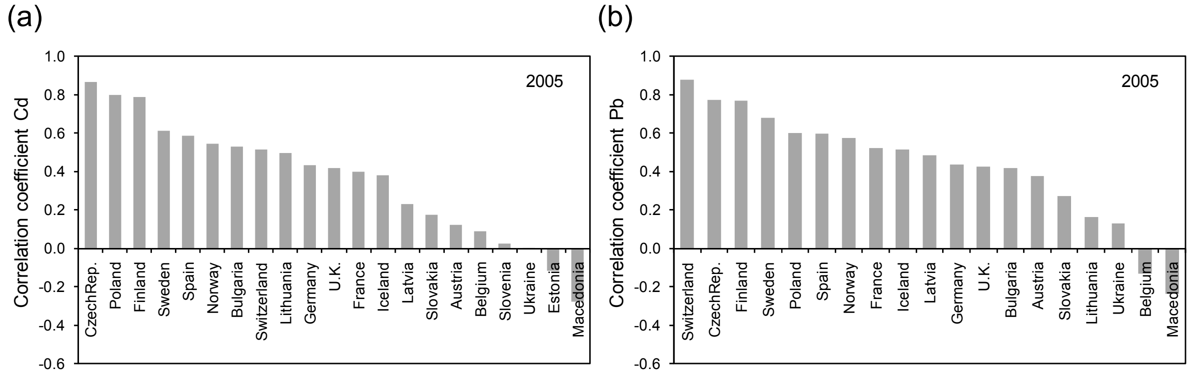

Figure 3.4. Country-specific correlations between metal concentrations in mosses and EMEP modelled atmospheric total deposition for 2005 for (a) cadmium and (b) lead. Source of deposition data: EMEP/MSC-East.

As mercury in ambient air is predominantly found in the vapour phase and has a residence time of the order of one year it has to be considered as a global pollutant (Schroeder and Munthe, 1998) without distinct spatial deposition patterns. The lack of correlation between EMEP modelled deposition values for mercury and observed concentrations in moss may relate to the specific chemistry of mercury and corresponding interactions with the moss. In Scandinavia the mercury deposition as measured by precipitation analysis showed a steep increase from north to south (Iverfeldt, 1991), similar to that of other metals predominantly supplied by long-range atmospheric transport. In moss collected in Norway during the same period, however, the mercury level was fairly uniform with no distinct north-south gradient (Steinnes and Anderson, 1991). This geographical distribution of mercury has been confirmed in more recent moss surveys (Steinnes *et al.*, 2003), and indicates that wet deposition of Hg^{2+} alone cannot be responsible for the geographical distribution observed. The moss must also be able to retain dry deposited gaseous mercury to a significant extent. Indeed, several studies have shown the importance of dry deposited gaseous mercury to mercury concentrations in vegetation (De Temmerman *et al.*, 2007, 2009; Lodenius *et al.*, 2003). In addition, Arctic Mercury Depletion Events (Schroeder *et al.*, 1998) might be contributing to the mercury deposition in the north of Europe and possibly explain part of the elevated mercury concentrations observed in moss in northern Norway (Berg *et al.*, 2008). Hence, it might well be that in some areas the deposition pattern depicted by the moss survey is a better measure of the net mercury supply to the terrestrial ecosystem than that indicated by EMEP modelled calculations. Despite the discrepancies between the spatial variation of the mercury concentrations in mosses and EMEP modelled atmospheric deposition, temporal trends of both parameters showed a similar tendency of decline between 1995 and 2005; similar temporal trends for both parameters were also observed for cadmium and lead (Harmens *et al.*, 2009; in press). In conclusion, the European moss survey has an important role in identifying spatial and temporal trends in atmospheric heavy metal pollution across Europe and in monitoring the success of air pollution control policies implemented in Europe for heavy metals.

4. New/revised flux-based critical levels of ozone

4.1 Background

The detrimental effects of ground-level ozone on vegetation have been addressed in developing international air pollution policies. Examples of these include the Convention's Gothenburg Protocol and legislation in North America and the European Union. The indicators used in the Gothenburg Protocol to protect vegetation were based on AOT40. Scientific research has developed further and currently the accumulated ozone flux via plant stomata (Phytotoxic Ozone Dose above a threshold of Y nmol m^{-2} s^{-1}, POD_Y, previously described as $AF_{st}Y$) is considered to provide a biologically more sound method for describing observed effects (LRTAP Convention, 2004). It is calculated from the effects of climate (temperature, humidity, light), ozone, soil (moisture availability) and plant development (growth stage) on the extent of opening of the stomatal pores on leaf surfaces through which ozone enters the plant (Emberson *et al.*, 2000). Led by the ICP Vegetation, several workshops held under the WGE have developed ozone flux modelling methods and indicators for use in integrated assessment modelling. Tentative mapping of ozone flux in Europe indicated risks in areas which would not be protected by the indicator for health effects of ozone (Mills *et al.*, 2008). Hence, the Executive Body of the Convention has agreed to explore the use of the flux-based methods for vegetation in the work on the revision of the Gothenburg Protocol (see Section 3.1.1).

Here we describe the results of the workshop on 'Flux-based assessment of ozone effects for air pollution policy', held from 9 - 12 November, 2009, Ispra, Italy, and the follow-on discussions at the 23rd Task Force meeting of the ICP Vegetation, held from 1 - 3 February 2010, Tervuren, Belgium (see Section 2.1). The workshop was organised by the Programme Coordination Centre of the ICP Vegetation and hosted by the Joint Research Centre (JRC) of the European Commission. It was attended by 42 experts from 12 Parties to the Convention. Also present were representatives of the ICP on Assessment and Monitoring of Air Pollution Effects on Forests (ICP Forests), Task Force on Integrated Assessment Modelling (TFIAM), the Centre for Integrated Assessment Modelling (CIAM) and the Meteorological Synthesizing Centre - West (MSC-W) of the EMEP Steering Body, JRC and a member of the LRTAP Convention secretariat. Given the importance of defining robust methodologies, the workshop concluded that it would be beneficial to conduct further modelling before finalizing critical levels, dose-response functions and recommendations for their application. Hence, a common methodology was agreed, with results of the new analyses presented at the 23rd ICP Vegetation Task Force meeting. Further details can be found in the Modelling and Mapping Manual of the LRTAP Convention (LRTAP Convention, 2004).

Aim and objectives

The **aim** was to provide quantified regional indicators for the impacts of ozone on vegetation, for use in the revision of the Gothenburg Protocol. The **objectives** were to:

a) Review the needs of the LRTAP Convention in using flux-based methodology;
b) Review recent progress with developing flux-effect relationships for crops, forest trees and (semi-)natural vegetation, and to agree on those relationships and new critical levels;
c) Recommend ways to apply these relationships in policymaking;
d) Recommend changes to the Modelling and Mapping Manual of the LRTAP Convention.

4.2 Methodology

All fluxes were calculated at the leaf level using the DO_3SE (Deposition of Ozone for Stomatal Exchange) model (http://sei-international.org/do3se). For each dose-response function, the method of Fuhrer *et al*. (1997) was used to determine relative yield/biomass, whereby the effects in each experiment were calculated relative to the absolute yield/biomass at 0 flux in that experiment, calculated by linear regression. The data from all experiments were then combined and subjected to linear regression analysis. The critical levels were calculated from agreed reductions of effects (see Table 4.1), taking into account the statistical robustness of the flux-effect relationship. The workshop agreed that, presently, it is not needed to include a function for the CO_2 response of stomatal conductance, since the time horizon considered in e.g. the revision of the Gothenburg Protocol is too short to lead to changes in CO_2 concentrations that would be high enough to substantially influence stomatal conductance. However, a function describing the CO_2 effect on stomatal conductance has been derived and could to be developed for long-term assessments.

4.3 New/revised critical levels and their application

The Task Force approved the critical levels shown in Table 4.1. The response functions used to set these critical levels are described below for crops, forest trees, and (semi-) natural vegetation. For each receptor, agreed modifications to the Modelling and Mapping Manual are described together with recommendations for integrated assessment modelling and comments on robustness and sources of uncertainty.

Table 4.1. New/revised flux-based critical levels for effects of ozone on vegetation.
Please note that there are different flux model parameterisations for each species.

Receptor	Effect (% reduction)	Parameter*	Critical level (mmol m^{-2})
Wheat	Grain yield (5%)	POD_6	1
Wheat	1000 grain weight (5%)	POD_6	2
Wheat	Protein yield (5%)	POD_6	2
Potato	Tuber yield (5%)	POD_6	5
Tomato	Fruit yield (5%)	POD_6	2
Norway spruce	Biomass (2%)	POD_1	8
Birch and beech	Biomass (4%)	POD_1	4
Productive grasslands (clover)	Biomass (10%)	POD_1	2
Conservation grasslands (clover)	Biomass (10%)	POD_1	2
Conservation grasslands (*Viola* spp), provisional	Biomass (15%)	POD_1	6

* POD_Y = Phytotoxic Ozone Dose above a threshold Y

4.3.1 Crops

Revision of critical levels
A pan-European assessment showed that ambient ozone causes visible leaf injury on several crop species including wheat, potato, bean and tomato (Hayes *et al*., 2007b, Mills *et al*., in press). Such injury is associated with economic losses when the value of the crop depends on the visual appearance of the leaves such as for the ozone-sensitive horticultural

crops of spinach, lettuce and chicory. Visible leaf injury is a response to short-term ozone episodes and a critical level is described in the Modelling and Mapping Manual (LRTAP Convention, 2004) to protect against this type of damage. No new data were presented to suggest that this critical level should be modified. Ozone exposure studies at concentrations within the range experienced in Europe have shown that reductions in the quantity and quality of yield (e.g. protein yield) also occur in response to prolonged exposure to ozone for ozone-sensitive crops. It was agreed at the Task Force meeting that new/revised flux-based functions and critical levels should be included in the Modelling and Mapping Manual (LRTAP Convention, 2004) together wih the existing AOT40-based critical levels for agricultural and horticultural crops.

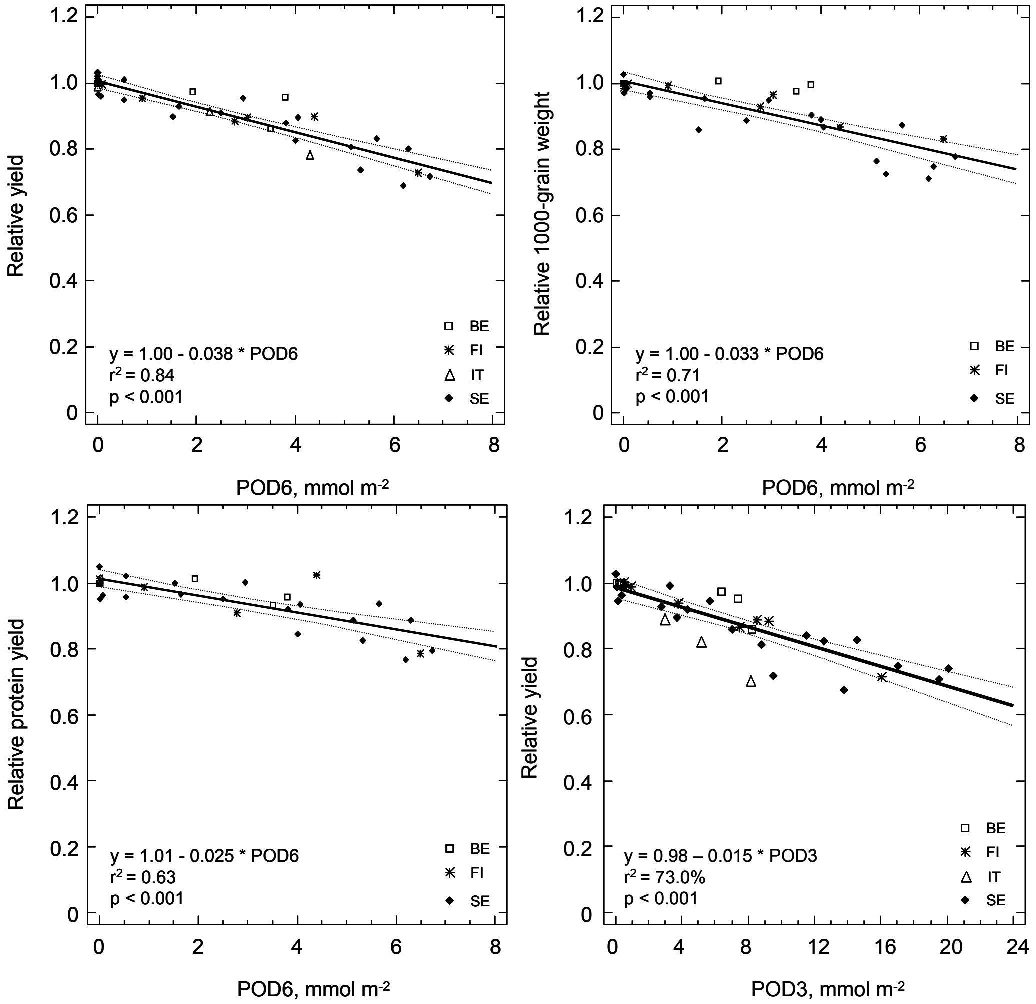

Figure 4.1. The relationship between the relative yield of wheat and stomatal ozone flux for the wheat flag leaf based on five wheat cultivars from three or four European Countries (BE: Belgium, FI: Finland, IT: Italy, SE: Sweden) using effective temperature sum to describe phenology: a) grain yield, b) 1000-grain weight, c) protein yield and d) grain yield for a generic crops based on wheat parameterisation. The dashed lines indicate the 95%-confidence intervals.

Flux-based response functions for effects of ozone on wheat (grain yield, protein content, 1000-grain weight), potato (tuber yield), tomato (fruit yield), oilseed rape (oil content, seed yield), broccoli (floret yield) and bean (seed yield) were reviewed. The Task Force approved the use of functions for wheat, potato and tomato for derivation of critical levels, based on the range of cultivars and countries represented for each and the statistical strength of the regression function (Figure 4.1 and 4.2). Critical levels were derived for a 5% reduction in the yield quantity/quality parameter (Table 4.1). Further modifications to the methodology within the Modelling and Mapping Manual (LRTAP Convention, 2004) were agreed: a small change in molecular diffusivity ratio, a change in the phenology function for wheat based on additional information from Germany, Sweden and France, a small change in the description of the height for ozone concentration relevant to risk assessment, a revised vapour pressure deficit (VPD) function for wheat to be applied in Mediterranean areas, and the use of plant available water content (PAW) instead of soil water potential.

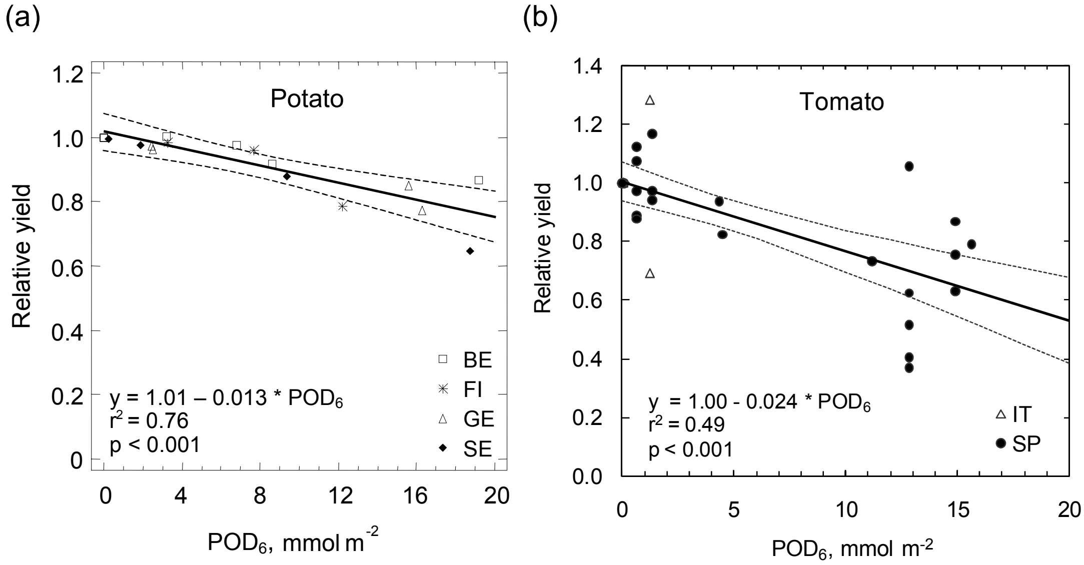

Figure 4.2. The relationship between the relative a) tuber yield of potato and POD_6 for sunlit leaves based on data from four European Countries (BE: Belgium, FI: Finland, GE: Germany, SE: Sweden) and b) tomato fruit yield and POD_6 for sunlit leaves based on data from Italy (IT) and Spain (SP). The dashed lines indicate the 95% confidence intervals.

Indicators for integrated assessment modelling

Two procedures were suggested for integrated assessment modelling: (i) use of specific critical levels with exceedance calculated using the full flux model and (ii) assessment of the scale of damage using a generic crop function. The Task Force recommended that the **critical levels most suited to integrated assessment modelling** were those for protein yield in wheat and for fruit yield in tomato (Table 4.1). Exceedance of these critical levels can be used to assess the **impact of ozone on food security**. The generic crop model, based on POD_3 (formerly $AF_{st}3$) is included in the Modelling and Mapping Manual for flux-based risk assessment within large-scale integrated assessment modelling. This method uses a lower threshold than the full flux models used to derive critical levels (Y = 3 compared to 6 nmol m^{-2} s^{-1}), and is simplified by only including inputs for light, temperature and humidity (as vapour pressure deficit) and by assuming that soil water availability is not limiting to crop growth (i.e. crops are irrigated during dry periods). In a new development, a generic crop flux-effect relationship has been derived for use in **assessing the scale of risk of damage to crops** (Figure 4.1d). It was agreed that the latter should be used with colours to indicate the potential severity of damage to a generic crop in European-scale maps. For some Mediterranean areas the flux-based methodology may under-estimate effects and a modified VPD function should be applied if Mediterranean-specific integrated assessment modelling is conducted.

Robustness, confirming results and sources of uncertainty

The robustness, confirming results and main sources of uncertainty are summarised in Section 3.1.2. The Task Force agreed that the new critical levels for crops were derived from sufficiently robust relationships that were all significant at the $P < 0.001$ level. Of the three horticultural crops for which response-functions were derived (bean, lettuce and tomato), the Task Force agreed that only the function for tomato was appropriate for the derivation of critical levels (Figure 4.2b). It should be noted, however, that tomato is the least sensitive of the three crops and the use of this critical level or function to quantify impacts may lead to an underestimation of the damage to all horticultural crops.

4.3.2 Forest trees

Revision of critical levels

Ozone causes negative effects on forest trees such as reduced photosynthesis, premature leaf shedding and growth reductions. Some forest tree species are present in large areas of Europe: birch, Scots pine and Norway spruce are particularly important in central and northern Europe; beech and deciduous oaks are frequent across several European regions, in particular in central and southern areas; Holm oak and Aleppo pine are frequent in Mediterranean Europe. Sensitivity to ozone has been detected in all of these species, with effects such as biomass reduction commonly reported (e.g. Karlsson *et al.*, 2007). Negative effects of ambient ozone on forest trees are already occurring all over Europe. For example, visible injury has been detected in ICP Forests surveys (Ferretti *et al.*, 2007a), reduced stem growth has been reported in Switzerland (Braun *et al.*, 2007) and leaf loss occurs in Greece.

It was agreed at the Task Force Meeting that the AOT40-based critical levels should be retained in the Modelling and Mapping Manual (LRTAP Convention, 2004). Following the workshop in Ispra, datasets were compiled from nine sources and hourly ozone fluxes were calculated for each species and year using the DO$_3$SE (Deposition of Ozone for Stomatal Exchange) model, available online at http://sei-international.org/index.php/tools, and using the "real tree" parameterisations provided in the Modelling and Mapping Manual. Where effects were reported over more than one year, the mean biomass effect and mean flux were determined by dividing the total by the number of years of ozone exposure. Across Europe, the effects of ozone on trees are best correlated with modelled ozone uptake by the leaves, i.e. the stomatal ozone flux. For trees, dose-response relationships are strongest when there is either no threshold or a small threshold above which flux is accumulated (i.e. POD$_0$ or POD$_1$). As there is a strong biological support for the use of a threshold to represent the detoxification capacity of the trees, expert judgement has been used to set Y to 1 for forest trees, i.e. POD$_1$ is to be used.

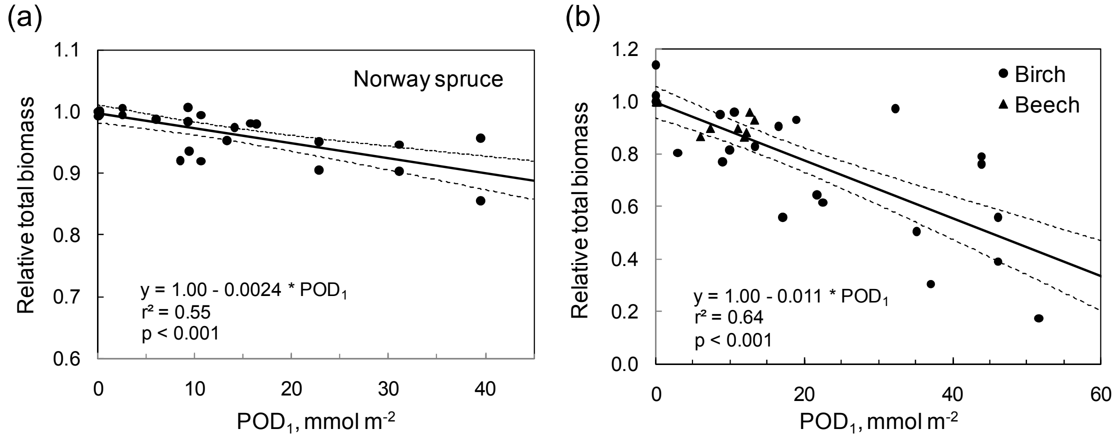

Figure 4.3. The relationship between the relative total biomass and POD$_1$ for sunlit leaves of a) Norway spruce (*Picea abies*) based on data from France, Sweden and Switzerland, and b) birch (*Betula pendula*) and beech (*Fagus sylvatica*) based on data from Finland, Sweden and Switzerland. The dashed lines indicate the 95%-confidence intervals; note the different starting point of the Y-axis for Norway spruce.

Using data from ozone exposure experiments, new ozone flux-effect relationships have been developed for the following key forest tree species: Norway spruce, beech and birch, oak species excluding Holm oak, Holm oak and Aleppo pine. Of these, the functions for Norway spruce and combined beech and birch were selected as being sufficiently robust for the derivation of critical levels due to their statistical strength and good representation of the data sets for Europe (Figure 4.3, Table 4.1). It should be noted, however, that there is insufficient data available yet to derive a critical level specific to trees in the Mediterranean area, and that the suggested critical levels may not be fully applicable in this area as they were not derived from experiments conducted in a Mediterranean climate. Critical levels have been derived for the cumulative ozone flux responsible for either a 2% (Norway spruce) or a 4% (beech/birch) reduction in annual growth (whole tree biomass) of young trees of up to 10 years of age, dependant on species. The age criterion is set to reflect the age of the trees used in the ozone exposure experiments contributing data to the response function. Although the above critical levels are derived from data on biomass reduction, it is expected that there will be additional benefit for protection against reductions in carbon storage, soil erosion, avalanches, flood amelioration and loss in tree biodiversity.

Indicators for integrated assessment modelling

As with crops, two procedures are suggested for integrated assessment modelling: (i) use of specific critical levels with exceedance calculated using the full flux model and (ii) assessment of the scale of damage using generic forest tree flux models. To provide the greatest protection against **loss of carbon storage capacity** in the living biomass of trees and **other beneficial ecosystem services** provided by trees such **as reducing soil erosion, avalanches and flooding**, we recommend the use of the flux-based critical level for beech and birch (POD_1 of 4 mmol m^{-2}) or that for Norway spruce (POD_1 of 8 mmol m^{-2}). Flux models for a generic deciduous tree and a generic Mediterranean evergreen tree, based on $POD_{1.6}$ (formerly $AF_{st}1.6$) are included in the Modelling and Mapping Manual for flux-based risk assessment within large-scale integrated assessment modelling. This method is simplified by only including inputs for light, temperature and humidity (as vapour pressure deficit) and by assuming that soil water availability is not limiting to tree growth. This method is useful for a **"worse-case" risk assessment for Europe**. For some Mediterranean areas the current flux-based methodology may under-estimate effects.

Robustness, confirming results and sources of uncertainty

The robustness, confirming results and main sources of uncertainty are summarised in Section 3.1.2. The ICP Vegetation Task Force agreed that the new critical levels were derived from sufficiently robust relationships that were all significant at the $P < 0.001$ level. For each species, data was from at least three independent sources and from experiments conducted in three countries. Data presented at the workshop showed that ozone fluxes calculated from sap flow measurements of mature trees growing in forest stands were in broad agreement with those from the DO_3SE model (Braun *et al*., in press). Overall, regression analysis of the dataset used to derive new flux-based critical levels showed that effects relationships were stronger for POD_1 than for AOT40.

4.3.3 (Semi-)natural vegetation

Revision of critical levels

Ozone negatively impacts on (semi-)vegetation by causing early die-back, reduced seed production, reduced growth and reduced ability to withstand other stresses such as drought and over-wintering in sensitive species. This vegetation type is the most florally diverse of the receptors types considered - there are 4000+ species of (semi-)natural vegetation in Europe – making the generalisations needed for setting critical levels difficult. Discussions at the workshop and Task Force meeting were focussed on establishing critical levels for indicator species of three permanent grassland types: (a) Productive grasslands that are intensively managed and grazed; (b) Grasslands of high conservation value with low management and little/low fertilizer input; and (c) Natural unmanaged ecosystems (excluding forests). Arable non-permanent grassland is considered a crop rather than a (semi-)natural community. Hayes *et al*. (2007b) found that effects of ozone were most widespread across Europe for species of the genus *Trifolium* (clover species). Ozone exposure experiments have confirmed that these species are amongst the most sensitive to ozone, with reductions in biomass, forage quality and reproductive ability noted at ambient and near-ambient concentrations in many parts of Europe. Since *Trifolium* species have an important role as nitrogen fixers within grassland ecosystems, these species are ideal indicators of potential damage to (semi-)natural vegetation. Many other species, such as *Campanula* spp. (e.g. harebell) and *Viola* spp. (violet and pansy species) are ozone sensitive and could also be used as indicator species of relevance to areas of high conservation value.

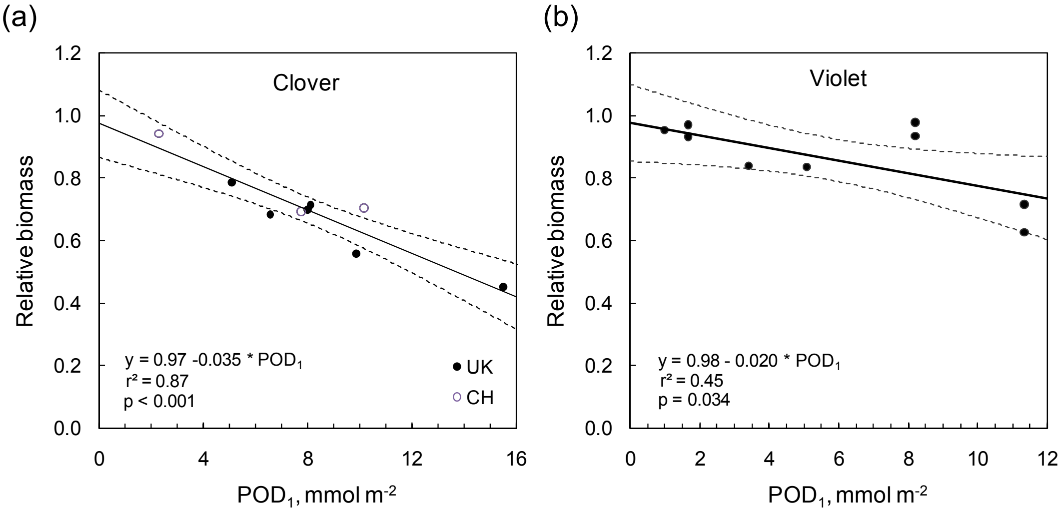

Figure 4.4. The relationship between the relative above-ground biomass and POD_1 for sunlit leaves for a) clover (*Trifolium* spp) and b) violet (*Viola* spp), based on data from the UK and Switzerland and the UK, respectively. The dashed lines indicate the 95%-confidence intervals.

Concentration-based response functions have been derived for over 80 species of (semi-) natural vegetation, with one third of tested species being classified as sensitive to ozone (Hayes *et al*., 2007a). Based on the known sensitivity of the component species, the following types of (semi-)natural vegetation have been identified as being potentially sensitive to ozone: dry grasslands, seasonally-wet and wet grasslands, woodland fringes, alpine and sub-alpine grasslands and temperate shrub heathlands (Mills *et al*., 2007b). On the basis of this and other analysis, two AOT40-based critical levels currently exist in the Modelling and Mapping Manual (LRTAP Convention, 2004) for effects on the growth and seed production of plant communities dominated by (i) annuals and (ii) perennials. The Task Force agreed that these should be retained.

As for crops and forest trees, there is a strong biological basis for the use of flux-based methodology for (semi-)natural vegetation, however, the complexity of these communities in the natural world adds an extra layer of complexity to flux modelling. Although a multi-layer flux model for the component species within grasslands has been developed, the workshop agreed that it was not currently possible to apply this across Europe due to the wide variation in species composition, growth rates and management practice. Thus, as an initial step towards defining flux-based critical levels for this vegetation type, flux models and effects data for widespread representative species were used. The resulting response functions are from experiments in which the selected species was growing in competition with other grassland species, as would be occurring in the natural environment. For (semi-) natural vegetation, flux-based response relationships are strongest when there is either no threshold or a small threshold above which flux is accumulated (i.e. POD_0 or POD_1). As there is strong support for the use of a threshold to represent the detoxification capacity of the species, expert judgement has been used to set Y to 1 nmol m^{-2} s^{-1} for (semi-)natural vegetation.

Several potential representative species were suggested at the workshop. Compilation of data in preparation for the Task Force meeting revealed that for only one species, *Trifolium repens*, was there flux-effect data available from more than one country. Since this species is widespread in Europe and has an important role in ecosystems (see above), this response function was accepted by the Task Force as suitable for use as indicative of effects on perennial grassland. Data for *Viola* species, although only from experiments from the UK, were from two seasons of experiments and for two species, and thus were considered suitable for a **provisional** critical level for early-season exposure of grasslands of high conservation value.

The flux-based critical levels for (semi-)natural vegetation (Figure 4.4, Table 4.1) are for the following types of grassland:

> *Productive grasslands.* These were considered important for calculating ozone deposition to perennial grasslands across Europe and provide an indication of effects on productivity and biogeochemical cycling.The representative species for productive grasslands are the *Trifolium* spp (clover species); the new flux-based critical level protects against a 10% reduction in biomass.
>
> *Grasslands of high conservation value.* Currently very few flux-effect relationships exist for this type of vegetation. The Task Force agreed that the critical level for clover is also applicable to this vegetation type. For central and northern Europe, a provisional flux-based critical level was proposed for *Viola* spp. (violets) as a representative family that is widespread and sensitive to early-season ozone exposure. This provisional critical level will protect against a biomass reduction of 15% for this species. For Mediterranean climates, it was not yet possible to derive a specific critical level, but a flux model for a typical *Trifolium* species from the Dehesa grassland will be included in the Modelling and Mapping Manual. This could be used in a similar way to the generic crop and forest tree critical levels to identify areas where this species is predicted to be at risk of damage in Mediterranean areas, with the extent of risk increasing with increasing flux.
>
> *Natural ecosystems.* No flux-based critical level could be derived yet for these, but it is assumed that the critical level for clover would provide adequate protection.

Indicators for integrated assessment modelling

No progress has been made towards deriving a flux model for a generic grassland due to the complexity of partitioning modelled fluxes to the component species and the inability to appropriately represent the diversity of grasslands across Europe. Instead, the Task Force agreed that the full flux model should be used for the indicator species, and applied as follows:

> (i) For protection of the vitality of fodder quality and pasture, use the critical level for productive grasslands of a POD_1 of 2 mmol m^{-2}.
>
> (ii) For protection of the vitality of natural species, use the critical level for grasslands of high conservation value of a POD_1 of 2 mmol m^{-2} or the provisional critical level for *Viola* species of 6 mmol m^{-2}. These critical levels may also protect against loss of biodiversity but this has not yet been confirmed experimentally.

As these critical levels could not be set using data from the Mediterranean areas, additional uncertainty may be associated with these areas in Europe-wide integrated assessment modelling.

Robustness, confirming results and sources of uncertainty

The robustness, confirming results and main sources of uncertainty are summarised in Section 3.1.2. Biomonitoring experiments performed by the ICP Vegetation using an ozone sensitive variety of *Trifolium repens* have indicated effects in 10 countries, with biomass reductions being correlated with EMEP modelled flux at the 50 x 50 km^2 grid (Hayes *et al.*, 2007b; Mills *et al.*, in press), providing strong support for the use of *Trifolium* species as indicators for the flux-based critical levels for grasslands.

4.4 Conclusions and recommendations

The workshop and Task Force concluded that current scientific knowledge supports the application of flux-based methods in the development of air pollution policies to protect vegetation from harmful effects of ozone. It was noted that in some Mediterranean areas the flux-based methodology may under-estimate effects. The Task Force meeting proposed the following policy-relevant indicators for receptors:

(a) **Agricultural crops**: a POD_6 of 2 mmol m^{-2} to protect security of food supplies by protecting against loss of protein yield, an important crop quality parameter (note: a POD_6 of 1 mmol m^{-2} was also defined to protect against loss of yield quantity);

(b) **Forest trees**: a POD_1 of 4 mmol m^{-2} to protect against loss of carbon storage in living trees and loss of ecosystem services such as soil erosion, avalanche protection and flood prevention;

(c) **Grasslands and pastures**: a POD_1 of 2 mmol m^{-2} to protect against loss of vitality and fodder quality in productive grasslands;

(d) **Grassland areas of high conservation value**: a POD_1 of 2 mmol m^{-2} to protect against loss of vitality of natural species.

It was recommended that the flux-based indicators should be included in the EMEP and GAINS model. Further collaboration with the EMEP centres is encouraged to explore the possibility of including the indicators in the GAINS model optimisation and to carry out ex-post analysis for the revision of the Gothenburg Protocol (see Section 3.1.1). The workshop and Task Force meeting drew attention to the significant co-benefits of reducing ozone critical level exceedances for vegetation for food security, carbon sequestration and global warming. It was emphasized that the selected indicators did not contain the carry-over effects for trees and natural vegetation. The negative consequences of ozone exposure having an effect the following year, such as reduced vitality or seed production, could be significant.

Future work is required on:

- Further long-term, field-based exposure experiments to increase the range of vegetation included, in particular in areas where current data are scarce, e.g. in Mediterannean areas and eastern Europe;
- Further modelling of fluxes and effects in complex ecosystems;
- Comparison of effects shown in Europe with effects reported from other continents (e.g. Asia, Central America);
- Analysis of the interactive effects of multiple pollutants (ozone, nitrogen, particulate matter) and climate change.

5. New activities of the ICP Vegetation

5.1 Review of ozone impacts on food security

In 2010, the ICP Vegetation will conduct a review of the current state of knowledge of the potential impacts of ozone on food security. Wherever possible, assessments will be flux-based to reflect the conclusion of the 'Evidence Report' (Hayes *et al*., 2007b) that flux-based risk assessments are more strongly correlated with damage in the field than AOT40-based assessments.

The **aims** of this review are to:

- Further develop an existing ozone sensitivity index for crops, including flux-based considerations;
- Assess the implications of increasing atmospheric ozone concentrations for food security in Europe and globally, using south-east Asia as a case-study;
- Consider the impacts of ozone in a changing climate with special focus on ozone and drought interactions;
- Use the above to write a glossy report on the current state of knowledge of ozone impacts on food security at the local, regional (Europe and south-east Asia) and global scale, including policy implications.

The crops sensitivity index based on AOT40-based assessments (Mills *et al*., 2007a) will be updated with new information that has become available from 2005 onwards. A new crop sensitivity index will be developed based on the flux-based response functions currently available for crops (see Chapter 4). Using selected countries as examples, participants in the ICP Vegetation will contribute text describing the food security concerns in their countries in relation to rising ozone pollution. Ultimately, this work will provide European maps on the EMEP 50 x 50 km^2 grid estimating ozone effects on crop production for several crops across the EU 27 member states, including for wheat, potato and tomato. In order to estimate the impacts of ozone on the marketability of leafy crops, participants of the ICP Vegetation in selected countries will survey the visible leaf injury caused by ozone after an ozone episode in commercial fields and glasshouses in 2010. As an example of outreach activities, we will include within the report a section on ozone impacts on crop production in Asia. In addition, current knowledge of ozone impacts on crops in a warmer, drier climate with higher CO_2 concentrations and the impacts on crops at a global scale will be reviewed. The regional (Europe, Asia) and global considerations will be discussed in relation to appropriate policy responses and research recommendations at the regional and hemispheric level.

5.2 Review of the impacts of ozone on carbon sequestration and ozone absorption by vegetation and the implications for climate change

In 2011, the ICP Vegetation will produce a glossy state of knowledge report on the impacts of ozone on carbon sequestration and ozone absorption by vegetation and the implications for climate change. Although ozone is now considered to be the third most important anthropogenic greenhouse gas (IPCC, 2007), the adverse impacts of ground-level ozone on biomass production and the consequences for the global carbon and water cycle have only recently been included in a global climate modelling as a first attempt. This initial modelling has predicted that rising ground-level ozone pollution during the 21st century will suppress the global land carbon sink by reducing photosynthesis (and hence net primary productivity) and stomatal conductance. The reduced uptake of carbon dioxide and ozone by vegetation will lead to further increased atmospheric carbon dioxide and ozone concentrations and enhanced radiative forcing (Sitch *et al*., 2007). It was suggested that this indirect radiative forcing by the damaging effects of ozone on plants might be as important for global warming as the direct radiative forcing due to increases in ground-level ozone concentrations.

The **aims** of this study are to:

- Review current knowledge on the impacts of ozone on carbon sequestration and ozone absorption by vegetation and implications for climate change;
- Estimate the impacts of ozone on carbon storage in forests and grasslands in Europe using flux-based methods and an offline global land surface model;
- Use the above to write a glossy report on the current state of knowledge.

The review of current knowledge will include: i) Effects of ozone on CO_2 absorption and carbon sequestration; ii) Effects of ozone on ozone absorption by and deposition to vegetation, consequences for ground-level ozone concentrations and the associated risk of impacts on vegetation and human health; iii) Identification of vegetation types most likely to be contributing to predicted effects; iv) Interactions with elevated CO_2, reduced nitrogen deposition and predicted frequency of drought; v) Implications for climate change, including radiative forcing and the global water cycle. Two modelling approaches will be applied to estimate the impacts of ozone on carbon storage in forests and grasslands in Europe: i) the DO_3SE model (Deposition of ozone for stomatal exchange, http://sei-international.org/index.php/tools) applying European flux-effect relationships (see Chapter 4) and ii) the JULES model (Joint UK Land Environment Simulator; http://www.jchmr.org/jules), incorporating direct ozone effects on the land carbon cycle. The JULES model will also be applied at the global scale to assess impacts on carbon sequestration globally, applying the most up-to-date ozone and CO_2 concentration scenarios and taking into account the damaging effects of ozone on stomatal control. This will allow comparison of both methods at the European scale and place the European results in a global context. The global modelling will provide an update of the initial modelling conducted by Sitch *et al*. (2007).

5.3 Review of the application of mosses as biomonitors of persistent organic pollutants (POPs)

In 2011, the ICP Vegetation will review the current knowledge of the use of mosses as biomonitors of persistent organic pollutants (POPs). In contrast to heavy metals, the use of mosses for monitoring atmospheric deposition of organic compounds such as polycyclic aromatic hydrocarbons (PAHs) and polychlorinated biphenyls (PCBs) has so far received little attention. The 1998 Protocol on POPs was adopted and signed as a result of the concern that POPs are resistant to degradation in the environment and have a potential for both long-range transport and bioaccumulation in living organisms. They are toxic and have been associated with a wide range of adverse affects on the environment and human health (WHO, 2003). Where mosses have been used as bioindicators of (groups of) POPs, such studies have been conducted primarily in the vicinity of local emissions sources. For example, in the Czech Republic, spatial patterns and temporal trends in the concentrations of POPs in mosses resembled those of concentrations in ambient air (Holoubek *et al*., 2007).

The **aims** of this review are to:

- Review the current knowledge of mosses as biomonitors of POPs;
- Investigate whether mosses can be used as biomonitors of atmospheric deposition of POPs at the European scale and if so, which POPs in particular.

The medium-term work-plan of the ICP Vegetation and further priorities for the future regarding ozone, nitrogen, heavy metals and POPs are described in Chapter 6.

6. Conclusions and future work-plan

6.1 Summary of major achievements in 2009/10

- Coordinated from CEH Bangor in the UK, the ICP Vegetation continues to comprise over 200 scientists from 35 countries in the UNECE region with outreach activities to other regions such as Asia, Central America and South Africa.

- Fifty eight delegates from 18 Parties to the Convention, Cuba and Japan, including a representative from EMEP/MSC-East, attended the 23rd ICP Vegetation Task Force Meeting, 1 - 3 February 2010 in Tervuren, Belgium.

- The ICP Vegetation Programme Coordination Centre has produced two technical reports for the WGE of the LRTAP Convention and contributed to the joint report of the WGE. It also contributed to a chapter on 'New flux-based critical levels for ozone-effects on vegetation' in the EMEP Status Report 1/2010 and a two-page WGE colour leaflet on 'Atmospheric nitrogen deposition: a threat to the environment and human health'. Further analyses on the relationship between heavy metal concentrations in mosses and modelled atmospheric depositions were reported in the EMEP Status Report 2/2010. The Programme Coordination Centre either led or contributed to five papers in scientific journals.

- The ICP Vegetation contributed to all the common work-plan items of the WGE:
  i) Targets for impacts of ozone on vegetation were set to avoid most (by 2020) and all (by 2050) detectable ozone damage to receptors and a reduction in ecosystem services. Indicators to achieve these targets are a reduction in (2020) or no exceedance (2050) of ozone critical levels for vegetation;
  ii) Main uncertainties associated with the flux-based critical levels of ozone for vegetation arise from the effects of soil moisture on the stomatal ozone flux and the extrapolation from different exposure systems to field conditions outside of the experimental systems or to different climatic regions. For trees, an additional source of uncertainty lies in the application of critical levels derived from young trees growing in exposure facilities to mature trees growing within a forest stand. Ozone critical levels for (semi-)natural vegetation are the most uncertain;
  iii) Little field-based evidence exists of the impacts of ozone on plant diversity;
  iv) Exceedance of flux-based critical levels for vegetation is highest in parts of central and southern Europe; no clear temporal trends regarding ozone critical level exceedances have been observed. For most heavy metals, there has been a Europe-wide decline in their concentrations in mosses since 1990, with highest concentrations currently being observed in Belgium and eastern Europe.

- ICP Vegetation participants conducted ozone biomonitoring studies with *Phaseolus vulgaris* (bean) across Europe using an ozone-sensitive (S) and -resistent (R) variety. The extent of leaf injury on the sensitive variety was not directly related to the AOT40 at the site, similarly the ratio of S/R seed weight was not directly related to AOT40. However, plants with a lot of injury had fewer seeds than those with less injury, so overall there was a decrease in the ratio of S/R seed weight with increasing leaf injury score of the sensitive variety. The ICP Vegetation is committed to establish a flux-effect relationship for bean in the next few years.

- Current ambient ozone concentrations in the Mediterranean area induced negative impacts on the production, quality and appearance of over 20 agricultural and horticultural crop species of economical importance. Ambient ozone concentrations also caused visible leaf damage and effects on growth and plant physiology in ozone sensitive deciduous tree species such as beech and some evergreen forest species common in the Mediterranean area, such as Holm oak, carob tree and Aleppo pine. There is scarcity of information on the ozone sensitivity of the Mediterranean herbaceous plant communities. There is a clear need for new effects-based data on the impacts of ozone on vegetation and to develop robust stomatal flux-effect relationships for Mediterranean climatic conditions.

- In recent years, climate-specific ozone flux modelling methods were developed for crops and forest tree species, resulting in the development of statistically robust flux-response relationships from which it has been possible to derive critical levels of ozone for vegetation at the European scale. As yet, no climate region-specific parameterisations are available for (semi-)natural vegetation. For national scale integrated risk assessment, the application of climate specific stomatal flux data and parameterisations of the stomatal flux model might be more appropriate than the use of parameterisations agreed for European scale integrated risk assessment.

- In the last year, ten new/revised flux-based critical levels of ozone for species of crops, forest trees and (semi-)natural vegetation were approved. A new stomatal flux parameter was defined as the Phytotoxic Ozone Dose above a threshold of Y (POD_Y), previously described as $AF_{st}Y$. The following **policy-relevant indicators** for ozone effects on vegetation were derived:
  i) Agricultural crops: a POD_6 of 2 mmol m^{-2} to protect security of food supplies by protecting against loss of protein yield, an important crop quality parameter;
  ii) Forest trees: a POD_1 of 4 mmol m^{-2} to protect against loss of carbon storage in living trees and loss of ecosystem services such as soil erosion, avalanche protection and flood prevention;
  iii) Grasslands and pastures: a POD_1 of 2 mmol m^{-2} to protect against loss of vitality and fodder quality in productive grasslands;
  iv) Grassland areas of high conservation value: a POD_1 of 2 mmol m^{-2} to protect against loss of vitality of natural species.

- So far, sixteen out of thirty, and eight out of eighteen countries have confirmed participation in the European moss survey 2010/11 for heavy metals and nitrogen respectively. In 2010, the ICP Vegetation Task Force recommended to include a pilot study of mosses as biomonitors of persistent organic pollutants (POPs) in the moss survey; some countries have confirmed participation in this pilot study.

- Detailed statistical analysis of factors influencing the spatial variation of heavy metal concentrations in mosses since 1990 have confirmed that the variation of cadmium and lead concentration in mosses is primarily due to variation is atmospheric depostion of these metals as modelled by EMEP. This is not the case for the more global pollutant mercury, which might be due to the specific chemistry of mercury and the corresponding interactions with the moss. However, it might well be that in some areas the deposition pattern depicted by the moss survey is a better measure of the net mercury supply to terrestrial ecosystems than that indicated by the EMEP model. For cadmium and lead, country-specific correlations between the concentrations in mosses and the EMEP modelled atmospheric deposition were observed.

6.2 Future work-plan (2011-2013) for the ICP Vegetation

***Ozone* -** There is a clear need to incorporate the ozone flux-based method for vegetation into integrated assessment modelling for the revision of the Gothenburg Protocol. The ICP Vegetation will support this process in close collaboration with subsidiary bodies of EMEP. Additional priorities for the future include reviews on the impacts of ozone on i) food security and ii) carbon sequestration and linkages between ozone and climate change, together with further collation of evidence on the damaging effects of ozone in the field, including biomonitoring studies.

***Nitrogen* -** There is a need to further develop policy relevant indicators of the impacts of nitrogen on vegetation and to enhance our knowledge on the impacts of nitrogen on Mediterranean habitats. The relationship between nitrogen concentration in mosses and atmospheric nitrogen deposition requires further investigation at various geographical scales, including new data for 2010/11. A challenge for the future will be to relate the nitrogen concentration in mosses with impacts of nitrogen on vegetation and to investigate whether critical levels for nitrogen concentration in mosses can be defined.

Heavy metals – The focus in the coming years will be on the next European mosses survey 2010/11. A challenge for the future will be to relate the heavy metal concentration in mosses with impacts of heavy metals on vegetation. To enhance the application of the heavy metals in mosses data, further integration with other European datasets needs to be explored.

Persistent organic pollutants (POPs) – A pilot study on mosses as biomonitors of POPs will be conducted in selected European countries in the 2010/11 moss survey. In addition, the ICP Vegetation will review the use of mosses as biomonitors of POPs.

The following medium-term work-plan was agreed at the 23rd Task Force Meeting of the ICP Vegetation (Tervuren, Belgium, 1 – 3 February 2010):

2011:

- Report on the 2010 biomonitoring exercise for ozone;
- Report on ozone impacts on food security;
- Progress report on European heavy metals and nitrogen in mosses survey 2010/11;
- Report on mosses as biomonitors of POPs.

2012:

- Report on the 2011 biomonitoring exercise for ozone;
- Report on ozone, carbon sequestration, and linkages between ozone and climate change;
- Progress report on European heavy metals and nitrogen in mosses survey 2010/11;
- Report on the relationship between i) heavy metal and ii) nitrogen concentrations in mosses and impacts on ecosystems.

2013:

- Report on the 2012 biomonitoring exercise for ozone;
- Development of flux-effect relationships for leaf injury and yield reduction in bean;
- Report on ozone impacts on biodiversity (tentatively);
- Report on the European heavy metals and nitrogen in mosses survey 2010/11.

Common workplan items of the WGE will be decided annually at the previous year's session of the WGE in September.

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Annex 1. Participation in the ICP Vegetation

In many countries, several other scientists (too numerous to include here) also contribute to the work programme of the ICP Vegetation.

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