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LRTAP
Long-range Transboundary Air Pollution

Climate change and reactive nitrogen as *modifiers* of vegetation responses to ozone pollution

Key messages

- Climatic conditions, rising carbon dioxide and other pollutants modify the responses of vegetation to ozone.
- As well as directly impacting on plant growth, these modifiers influence the amount of ozone flux into the leaf by causing changes in the opening or closing of leaf pores.
- In so doing, the Phytotoxic Ozone Dose (POD) is altered leading to changes in the magnitude of effects on growth, crop yield and ecosystem services.
- Responses to gradual long-term changes in background ozone, reactive nitrogen and climate will differ from responses to extreme pollution and climate events, likely to become more frequent in the coming decades.

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Working Group on Effects
of the
Convention on Long-range Transboundary Air Pollution

Ozone and nitrogen pollution

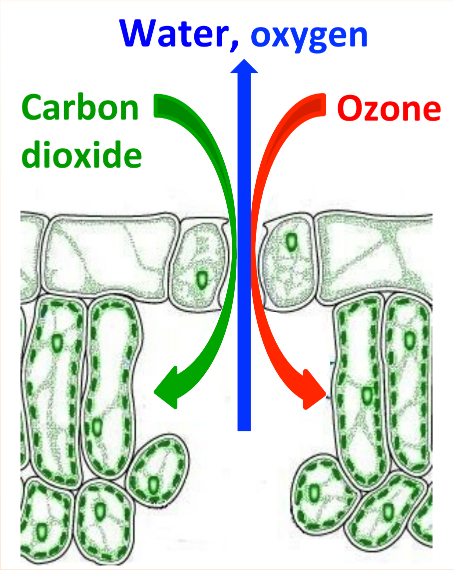
In the 20th century, ground-level ozone concentrations have more than doubled. At the same time, synthetic fertilizer production together with industrialisation, population growth and associated demand for food has resulted in a five-fold increase in emission of reactive nitrogen compounds. Both ozone and nitrogen affect vegetation, often in contrasting ways. For example, ozone tends to reduce plant growth, whereas nitrogen tends to stimulate plant growth up to a certain level, above which detrimental effects occur. However, enhanced nitrogen deposition is known to reduce plant diversity in areas and habitats were plants are adapted to low atmospheric nitrogen input. Few studies have determined their combined impacts on vegetation.




The climate is changing

The global climate is warming due to a considerable rise in greenhouse gases such as carbon dioxide, methane and ozone, especially in the last 50 years. Future increases in greenhouse gases and global temperature will depend on energy use and emission abatement scenarios (*IPCC, 2013. Climate Change 2013: The Physical Science Basis*). A warmer climate will have fewer frost days and increased summer dryness with greater risk of drought in mid-continental areas. In addition, the frequency and duration of extreme temperatures, rainfall and drought is likely to increase. As the 'uptake' of ozone by vegetation is dependant on temperature, air humidity and soil water content, changes in the climate will affect the impact of ozone on vegetation. Hence, it is important to study the interactive impacts of ozone, nitrogen and changing climate on vegetation to predict future trends in effects.

Ozone impacts in rising carbon dioxide



A schematic showing a cross section through a leaf. Arrows show the uptake of carbon dioxide and ozone, and the release of water and oxygen through leaf pores.

Ozone fluxes into leaves

Carbon dioxide is taken up through small pores in leaves and converted into sugars for plant growth in daylight in a process called photosynthesis. Through the same pores, water is evaporated from leaves, oxygen released to the atmosphere and ozone taken up (see picture). The amount of ozone taken up depends on the size of the leaf pores, which varies with leaf age and environmental conditions such as temperature, humidity, light intensity and soil water content. Ozone itself will also affect opening of the pores, however, the effects vary with concentration and plant species. The damage to plants is determined by the accumulated 'uptake' of ozone, known as the Phytotoxic Ozone Dose (POD).

Carbon dioxide as a modifier of ozone flux

In many plant species, a rise in atmospheric carbon dioxide concentrations will stimulate photosynthesis and plant growth. Ozone, however, has the opposite effect. Evidence confirms the positive impacts of elevated carbon dioxide and negative impacts of ozone on crop yield (*IPCC, 2014. Climate Change 2014: Impacts, Adaptation, and Vulnerability*). Elevated carbon dioxide might also reduce the opening of leaf pores, which will provide some protection to plants from ozone. However, some studies in forests suggest that this might not be the case at the canopy level (see table). The response of vegetation to a combination of elevated carbon dioxide and ozone is finely balanced depending on their relative concentrations in the atmosphere.

Percentage accumulated leaf and canopy ozone fluxes in a mixed aspen-birch stand, relative to ambient air (= 100%), under free-air carbon dioxide and ozone enrichment near Rhinelander, Wisconsin, USA. Values are the mean for 2004 and 2005; no flux threshold was assumed (Modified from Uddling et al., 2010. Environmental Pollution 158: 2023 – 2031).

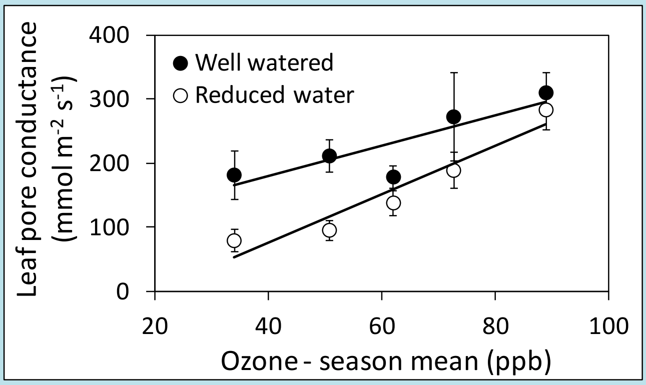
Ozone fluxes (%)	Ambient air	Elevated carbon dioxide (CO_2)	Elevated ozone (O_3)	Elevated CO_2 & O_3
Sunlit leaf	100	114	192	156
Canopy	100	123	152	160

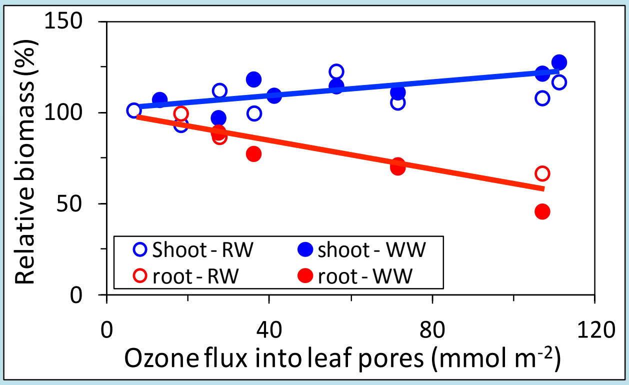
Ozone, warming and drought impacts

Whilst elevated ozone and carbon dioxide might partially compensate for each other's effects, crop yield losses might be greater when elevated ozone combines with high temperature, particularly during grain filling stages in cereals when elevated ozone causes premature leaf die-back. Studies have documented a large negative sensitivity of crop yields to extreme daytime temperatures around 30°C, depending on crop and region (*IPCC, 2014. Climate Change 2014: Impacts, Adaptation, and Vulnerability*). However, little is known about the combined effect of ozone and a few degrees rise in temperature on vegetation. Although the latter might stimulate plant growth and crop yield in areas where temperature is currently limiting growth and yield, a rise in temperature is also likely to result in higher ground-level ozone concentrations. Risk to food security are generally greater in low latitude areas where elevated temperature might coincide with increased occurrences of drought.

It has been reported that drought-induced closure of leaf pores will limit ozone uptake and impact. However, various recent studies have shown that the expected protective effect of drought on the deleterious plant responses to ozone does not occur. Ozone itself might affect the sensitivity of opening of the leaf pores (see graph on the left), which might lead to underestimation of ozone uptake if this effect is not taken into account. Exposure to increasing background ozone concentrations, as currently occurs in Europe, might make plants more susceptible to drought in the future, especially as ozone tends to reduce root biomass more than above-ground biomass (see graph on the right).

Dactylis glomerata
(cock's-foot or orchard grass)





Left – Elevated ozone concentrations enhance opening of leaf pores in the grass species Dactylis glomerata, more so in 'drought' (reduced water) than well watered plants.
Right – Compared to well watered (WW), reduced water (RW) did not protect against ozone effects on biomass in Dactylis glomerata, with root biomass being negatively affected by ozone (Modified from Hayes et al., 2012. Global Change Biology 18: 948-959).

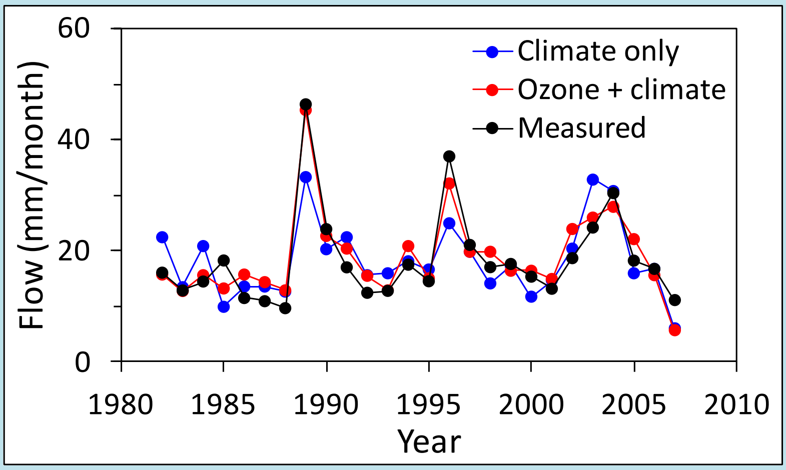
Ozone impacts on the global carbon and water cycle: feedbacks to the climate

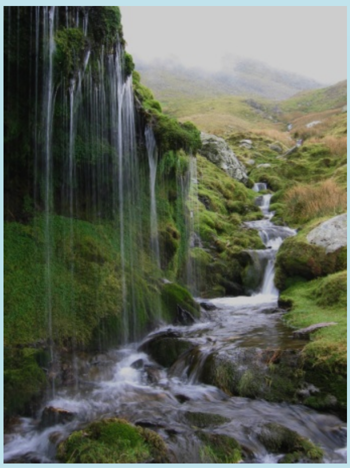
Carbon dioxide is the greenhouse gas contributing most to global warming and ozone is the third most important greenhouse gas. As an air pollutant, ozone reduces growth of sensitive species and therefore uptake of carbon dioxide and potential storage of carbon in trees and soil. It has been estimated that ozone reduces annual carbon sequestration in the living biomass of trees by ca. 10% (*Karlsson et al., 2012. In: Harmens and Mills. Ozone pollution: Impacts on carbon sequestration in Europe*). As a consequence, less ozone and carbon dioxide will be taken up by vegetation, resulting in further enhanced global warming. Ozone might contribute as much to global warming via its effect on vegetation, as via its effect as a greenhouse gas (*Sitch et al., 2007. Nature 448: 791-794*).

2000 - 2040	Change total carbon (%)	Change water runoff (%)
Ozone reducing leaf pore size	-4.4	4.5
No effect ozone on leaf pore size	-4.8	0.6

Modelling suggests that ozone reduces carbon sequestration in vegetation and soil in the future. Effect on water runoff depends on the response of leaf pores to ozone (Sitch et al., 2012. In: Harmens and Mills. Ozone pollution: Impacts on carbon sequestration in Europe).

The effect of ozone on the water cycle is very much dependant on the response of leaf pores to elevated ozone concentrations. As contrasting responses have been observed in experiments, contrasting results have been modelled for run off and stream flow (see table and figure). For a southern Appalachian forest in the USA, it was reported that, based on the analysis of 18 – 26 year data records, ambient ozone reduced stream flow in rivers due to an enhanced water loss via the leaf pores in tree leaves (*Sun et al., 2012. Global Change Biology 18: 3395–3409*).

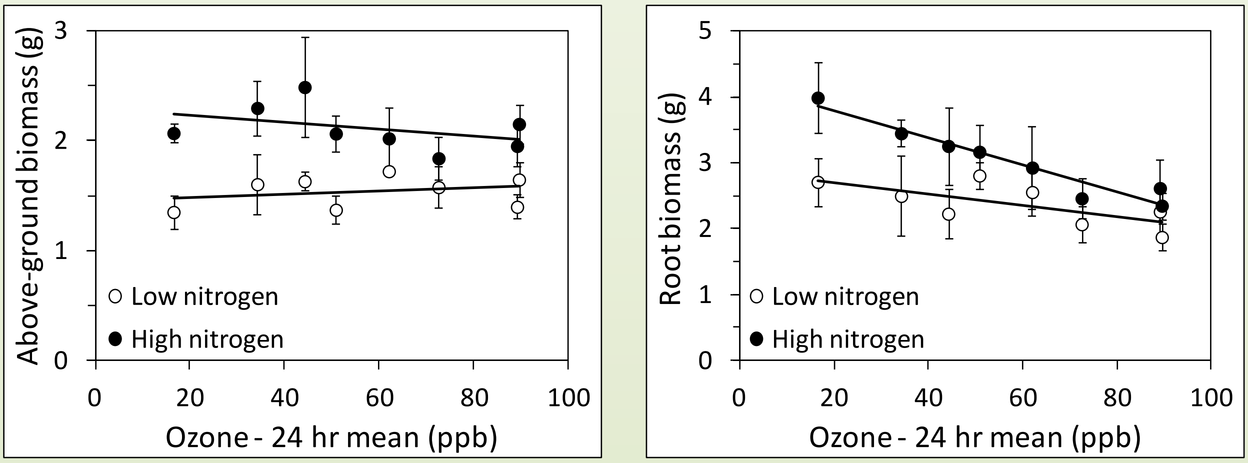




Empirical models of annual variations in late season stream flow were significantly improved for the 94 ha Walker Branch catchment, Tennessee, USA when climate and ozone were included as environmental variables (R^2 = 0.78) compared to including climate only (R^2 = 0.51). Modified from Sun et al., 2012. Global Change Biology 18: 3395–3409.

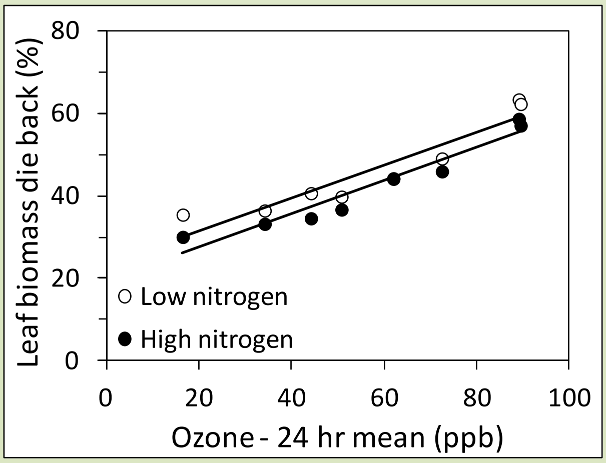
Ozone and nitrogen impacts on vegetation

Surprisingly few studies have looked at the combined impact of ozone and nitrogen on vegetation. Nitrogen tends to increase plant growth and crop yield, whereas ozone has the opposite effect with high concentrations tending to reduce root growth and seed production more than shoot growth. Reduced root growth will result in less nitrogen uptake from the soil and a lower nitrogen use efficiency of the plant, both in crops and (semi-)natural vegetation. Effects on plants tend to be mainly additive, but are generally less than additive at high nitrogen and ozone exposure, when high nitrogen reduces ozone impacts and high ozone reduces the growth enhancing effect of high nitrogen (see figure below). In wheat ozone reduces protein and starch yield (*Broberg et al., 2015. Environmental Pollution 197: 203-213*). Little is known about the interactive impacts of ozone and nitrogen on plant diversity.



Modifying effect of nitrogen on the response to ozone of above-ground (left) and root biomass (right) of Dactylis glomerata. At high ozone, the stimulating effect of nitrogen on biomass is reduced (above-ground) or has even disappeared (roots). Modified from Wyness et al., 2011. Environmental Pollution 159: 2493-2499.

Ozone induces early leaf die-back in sensitive plant species, resulting in early leaf fall. In the grass species *Dactylis glomerata*, nitrogen does not modify the early leaf die-back caused by ozone (see figure to the right). The nitrogen content in leaves exposed to elevated ozone is often higher due to a reduction in nitrogen re-sorption in leaves prior to leaf fall (*Uddling et al., 2006. Tree Physiology 26: 113-120; Lindroth et al., 2001. Environmental Pollution 115: 395-404; Hayes et al., unpublished*). This will affect nitrogen cycling in the soil where leaf litter is decomposed.



Nitrogen does not modify early leaf die-back caused by ozone in the grass species Dactylis glomerata. Modified from Wyness et al., 2011. Environmental Pollution 159: 2493-2499.

Conclusions

- Interactions between air pollution and climate change are complex and responses of vegetation to a combination of changing environmental drivers cannot simply be extrapolated from responses to single drivers.

- Experimental and modelling evidence indicates that interactions between elevated carbon dioxide and ozone, mean temperature and extremes, water, and nitrogen are nonlinear, variable, and difficult to predict.

- Combined impacts of ozone and nitrogen on vegetation appear to be additive to a certain level of ozone exposure, but are less than additive at high ozone exposure.

- Two types of interactions need to be considered differently: i) responses to gradual long-term changes in background ozone, reactive nitrogen and climate; ii) responses to extreme pollution and climate events, likely to become more frequent in the coming decades. Although heat, drought and ozone stress frequently occur together, surprisingly few studies have considered their combined impacts nor the effect of additional nitrogen under these conditions.



Recommendations and future challenges

- New sources of data are needed to support the development, parameterisation and validation of multi-factor models capable of predicting multi-stress impacts at a range of spatial and time-scales. Hence, more field-based studies are needed to assess the impacts of combined air pollution (e.g. ozone and nitrogen) and climate change (e.g. warming, drought, flooding, elevated carbon dioxide) components on vegetation.

- There is a need and challenge to upscale leaf-level responses to multiple stresses to whole plant and ecosystem responses, including impacts on below-ground processes.

Ozone impacts on vegetation in a nitrogen enriched and changing climate

In this brochure we have summarised how ozone impacts on vegetation are modified in a nitrogen enriched world and a changing climate (elevated carbon dioxide, global warming, increased drought). Interactions are non-linear, not simply additive, and therefore need complex modelling to predict impacts. More field-based data is needed on the response of crops and (semi-)natural vegetation and ecosystems to multiple stresses to support the development, parameterisation and validation of multi-factor models capable of predicting multi-stress impacts at a range of spatial and time-scales. Progress is being made with such modelling within the EU Framework Programme 7 project ECLAIRE (*Effects of Climate Change on Air Pollution and Response Strategies for European Ecosystems*), and new developments will be reported in the near future.

This brochure was produced by the ICP Vegetation, an International Cooperative Programme reporting on effects of air pollution on vegetation to the Working Group on Effects of the UNECE Convention on Long-range Transboundary Air Pollution.

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