Ozone (O₃) pollution, unlike fluoride or sulphur dioxide pollution, leaves no elemental residue that can be detected by analytical techniques. Therefore, ozone-induced visible injury on needles and leaves is the only easily detectable evidence in the field. This comes about as a result of oxidative stress, leading to a cascade of adverse physiological and morphological effects. In combination with the measurement of ozone concentrations and the modelling of O₃ metrics such as exposures and ozone uptake, the assessment of ozone visible injury can be valuable to estimate the potential risk for European ecosystems that are exposed to elevated ambient ozone concentrations.

Widespread visible foliage damage in European forest. Visible injury to foliage is considered one of the most responsive indicators to assess ozone risk for vegetation and to identify potential hotspots for adverse ozone effects on forest ecosystems. Injury data from ICP Forests Level II plots were evaluated over the period of 2002 to 2014 (Figure 3-1). Overall, 285 woody species from 169 plots in 19 countries were recorded, of which 26% were reported as symptomatic. Common beech showed the highest frequency of symptomatic observations (40.5%). When considering plots with at least eight years of records, there was an overall decreasing trend for the frequency of symptomatic species, which parallels the significant decrease of ozone concentrations. Apart from the European-wide survey conducted within ICP Forests, other studies provided evidence of visible injury on forest species: two examples are reported below.

(i) Wayfarer: an effective in situ bioindicator. As far as visible foliage damage is concerned, a single-species approach can be helpful in reducing the inherent variability typical of a multi-species approach. Observations were carried out over the period 2010-2015 on 10-30 randomly selected sites over a 6,000 km² area in Trentino, Italy. They showed a consistent spatial and temporal pattern, linking visible foliage damage on wayfarer with ozone concentration modelled and measured by conventional monitors (Figure 3-2). In 2015, in conjunction with a particularly dry summer, injury to foliage was less frequent on dry sites.
Dots (symptoms)
- 1 year of data
- 2 to 5 years
- >5 years

Background (concentrations)
- >60 ppb
- 50 to 60 ppb
- 40 to 50 ppb
- 30 to 40 ppb
- 20 to 30 ppb
- < 20 ppb
- NA

symptom occurrence 0%
>0 to 50%
>50%

Figure 3.1: Spatial pattern of plots showing available survey years (size of dots) and the frequency of years when species on the plot were found symptomatic (colour of dots) during 2002-2014 across large parts of Europe against the seasonal mean ozone concentrations (coloured forested areas).

Figure 3.2: Ozone-induced symptoms on wayfarer (Viburnum lantana) leaves: stippling (left) and bronzing (right).

Long-term observation on Aleppo pine. In south-eastern France, data on forest response indicators (i.e. crown defoliation, crown discolouration, and visible foliage ozone damage) were collected in stands of Aleppo pine and of stone pine over 20 years. Ozone concentrations and meteorological data were also measured. At forest sites, a decline in ozone injury was found, in parallel with declining modelled ozone concentrations. However, defoliation was increasing, likely due to drier and warmer weather. Climatically-caused soil drought may have lowered ozone uptake by tree needles.
Different ozone metrics to evaluate ozone risk. The assessment of the risk posed by ozone to vegetation can be assessed according to different metrics: concentration, accumulated exposure along the vegetative season (as discussed above), and uptake by the foliage. The latter is the ozone flux-based approach, which accounts for a series of environmental factors and provides the accumulated Phytotoxic Ozone Dose (POD) (measured in mmol [O$_3$] per m$^2$ of Projected Leaf Area (PLA)).

POD can be calculated with threshold (i.e., POD$_1$) or without (POD$_0$). Several studies have been carried out over the past years. Two recent examples are reported:

(i) Norway spruce in the Tatra Mountains. POD for Norway spruce was modelled for 2015 in the High Tatra Mountains in Slovakia for three different altitudes between 800 and 1,800 metres. Model outputs were considerably affected by different length of growing seasons, with POD values between 15 and 20 mmol per m$^2$ PLA (Figure 3-3). A potential high risk for vegetation was estimated.

(ii) AOT40 and POD in France and Italy. Modelled exposure-related AOT40 (Accumulated Ozone above the Threshold of 40 parts per billion) and flux-based POD with and without an hourly threshold were correlated with tree response parameters (i.e., defoliation, discoloration, and visible foliage ozone damage) in 2012 and 2013 in south-eastern France and north-western Italy. While AOT40 was more strongly correlated with non-specific indicators of ozone (i.e., crown defoliation and discoloration), the flux-based metrics, especially POD0 were better correlated to visible ozone injury.

The above-indicated ICP Forests long-term and related ICP Vegetation case studies, with both ICPS co-operating under the auspices of the Working Group on Effects (WGE) of the United Nation Economic Commission for Europe (UNECE), were presented at the 5th ICP Forests Scientific Conference in Luxembourg in 2016. They demonstrate the potential of the Central ICP Forests database on the one hand, but also the urgent need for integrated studies across Europe to enable meaningful statements on the state of European forests.

Further Reading:


Soil and freshwater acidification was a main concern when international clean air initiatives under the umbrella of the UNECE started in the 1970s and 1980s. While human-activity-generated deposition has declined over the past decades, we still need to consider legacy effects of acidifying substances that have accumulated in forest soils. Monitoring and evaluating soil acidification - in Europe and in individual countries - is therefore still highly relevant for current and future forest management decisions.

Although an essential nutrient for all living organisms, nitrogen can be harmful in many ecosystem types if available in excess. Forest soils in parts of central Europe, an area once highly loaded by inorganic nitrogen deposition, show now the first signs of recovery. However, large parts of Europe still suffer from inorganic nitrogen inputs above critical levels. Its control is therefore absolutely necessary. Only efficient monitoring systems can provide sufficient accurate information in order to maintain forest ecosystems in an appropriate condition.

Current ozone (O₃) levels are high enough to negatively affect vegetation and may become worse in the future. To provide a scientifically-sound basis for decision-makers, a comprehensive knowledge of spatial and temporal patterns of ozone concentration and its effects on vegetation is crucial. Therefore, long-term measurements of environmental drivers such as ozone concentrations that may affect forest conditions across Europe are essential to derive cause-effect relationships for a proper risk assessment under climate change.