Atmospheric Environment 77 (2013) 318–324

Contents lists available at SciVerse ScienceDirect

Atmospheric Environment

journal homepage: www.elsevier.com/locate/atmosenv

European characterization factors for damage to natural vegetation by ozone in life cycle impact assessment

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HIGHLIGHTS

- Characterization Factors expressing damage to natural vegetation by ozone were derived.
- Emissions and deposition of NO_x and NMVOC in 65 European regions were included.
- Characterization factors were largest for NO_x emissions in Southern European regions.
- NO_x contributes for 81% to ozone damage in natural vegetation in Europe.
- NO_x contributes more to ozone than to acidification effects on natural vegetation.

ARTICLE INFO

Article history:
Received 8 February 2013
Received in revised form
1 May 2013
Accepted 3 May 2013

Keywords:
Atmospheric fate factor
NO_x and NMVOC
AOT40
Trees and grassland
Effect factor
Species sensitivity distribution

ABSTRACT

Spatially explicit characterization factors (CFs) for tropospheric ozone damage on natural vegetation caused by anthropogenic NO_x and NMVOC emissions are presented for 65 European regions. The CFs were defined as the area-integrated increase in the potentially affected fraction (PAF) of trees and grassland species due to a change in emission of NO_x and NMVOCs. The CF consists of a Fate Factor, quantifying the relationship between the emission of precursor substances and ozone exposure, and an area-integrated Effect Factor, quantifying the relationship between ozone exposure and the damage to natural vegetation. The relationships describing the ecological effects of a pollutant were based on a lognormal relationship between the PAF and ground level ozone concentration. We found higher CFs for NO_x compared to NMVOC, and these were largest in south European regions. Furthermore, we found that both the fate factor and effect factor contribute to the spatial differences found in the CFs. Our study shows that effects caused by ozone exposure from NO_x emissions are larger than those of acidification caused by NO_x, indicating the importance of including ozone effects to natural vegetation in life cycle assessment studies.

1. Introduction

Long term surveys show that tropospheric ozone background concentrations have significantly increased over recent decades, and concentrations are predicted to further increase with 0.5–2% per year over the next 50 years in the Northern Hemisphere (Vingarzan, 2004; Derwent et al., 2007). Tropospheric ozone in a given area can have several sources, such as downward transport of stratospheric ozone to the troposphere or by photochemical reactions of nitrogen oxides (NO_x) and non-methane volatile organic compounds (NMVOCs). NO_x and NMVOC are primary precursor substances originating from anthropogenic and non-anthropogenic emissions. These pollutants can come from local sources or long-range transport (Ainsworth et al., 2012). Ozone is recognized as an important air pollutant, affecting human health and vegetation, including trees and grassland species (Ashmore, 2005). Adverse effects in plants include reduction of growth and seed production, premature senescence, reduced ability to withstand stressors, and increased leaf injuries (Emberson et al., 2003).

In life cycle impact assessment (LCIA), characterization factors (CFs) estimate the environmental impact of a pollutant per unit of emission (Udo de Haes et al., 2002). Although CFs are available for

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http://dx.doi.org/10.1016/j.atmosenv.2013.05.009

human health damage caused by ozone (e.g. Van Zelm et al., 2008), studies assessing the impact to natural ecosystems have yet only included regionalized fate and exposure modelling, excluding effects on natural vegetation (Bare, 2011; Hauschild et al., 2006; Frechette-Marleau et al., 2008). Recently, Van Goethem et al. (2013) developed quantitative exposure–effect relationships for ozone on natural vegetation (forests and natural grasslands, respectively). These relationships can be used to include ozone effects on natural ecosystems in LCIA.

The aim of this study was to determine region-specific characterization factors for damage on natural vegetation of tropospheric ozone caused by anthropogenic NO_x and NMVOC emissions. The CFs were characterized for 65 European regions and subsequently compared to assess the differences in impact between the regions. Furthermore, normalization factors for ozone exposure on natural vegetation were presented. The normalization factor equals the potentially affected fraction of natural plant species in Europe due to emissions of NO_x and NMVOC in 2010 per capita.

2. Methods

2.1. Characterization factors

The characterisation factors were defined as the area-integrated change in Potentially Affected Fraction (PAF) of forest and natural grassland species due to a change in emission of ozone precursor substances, i.e. NO_x or NMVOC (in $m^2\ yr\ kg^{-1}$). The CF consists of a Fate Factor (FF), quantifying the relationship between the emission of precursor substances and ozone exposure, and an Effect Factor (EF), quantifying the relationship between ozone exposure and the damage to natural vegetation. Ozone exposure is expressed as the sum of the differences between the hourly mean ozone concentration and 40 ppb during daylight hours over the relevant growing season (AOT40 in ppm h). The CFs for ozone were calculated for 65 European regions separately as;

$$\mathrm{CF}_{x,i,e} = \sum_j \sum_e \left(\mathrm{FF}_{x,i\to j} \cdot \mathrm{EF}_{j,e}\right) \tag{1}$$

where $\mathrm{FF}_{x,i\to j}$ (ppm h yr kg^{-1}) is the partial fate factor representing the change in AOT40 in receiving grid j (spatial resolution of 0.5 × 0.5°) following a change in the emission of substance x (i.e. NO_x and NMVOCs) in region i and the effect factor $\mathrm{EF}_{j,e}$ ($m^2\ ppm^{-1}$ h) is the change in the PAF of species of vegetation e (i.e. trees and grasslands) in grid j due to a change in ozone exposure.

2.2. Fate factor

The partial fate factor ($\mathrm{FF}_{i\to j}$, unit: ppm h yr kg^{-1}) represents the change in AOT40 in a receiving compartment cell j ($\Delta\mathrm{AOT40}_{i,j}$, unit: ppb h) due to a change of emission of precursor x in region i (ΔM_i, [kg yr^{-1}]):

$$\mathrm{FF}_{x,i\to j} = \frac{\Delta\mathrm{AOT40}_j}{\Delta M_i} \tag{2}$$

The exposure is taken over time and for daytime only (Tuovinen, 2000). The AOT40 exposure index is a measure of chronic ozone exposure widely used in the risk assessment of ozone (LRTAP, 2004).

Partial fate factors for the European continent were determined with the EMEP atmospheric chemical transport model, which simulates emissions, atmospheric transport, chemical transformation, and removal from air of NO_x and NMVOCs and estimates ground level ozone concentrations (Tarrasón, 2009a). To calculate FFs for the grassland vegetation, the change in AOT40 on 1 m ground level height was used. For the trees vegetation the upper canopy height (3 m) was used. The model divides Europe into 65 emission source regions (EMEP, 2008), and receptor grid cells of 0.5° × 0.5°. To derive the partial fate factors, emissions of NO_x and NMVOCs are decreased by 15% compared to the baseline emission inventory for each region. The 15% represents a realistic “quasi-marginal” change of emissions but still allows to assume sufficient linearity and to downscale the change of impacts to a unit of emission change (Tarrasón, 2009b). FFs were determined for each region, precursor pollutant, and 2010 background emissions. The emission dataset for 2010 corresponds to the baseline Current Legislation (CLE) scenario, developed by IIASA for the development of the Thematic Strategy on Air (Amann et al., 2008; Tarrasón, 2009b). Because of inter-annual variability in the meteorology, average results based on meteorological years 1996, 1997, 1998, and 2000 were derived as these years represent typical conditions (Tarrasón, 2009a).

2.3. Effect factor

EFs were derived via the following steps. First, species-specific AOT40 exposure–biomass response functions, as reported by Van Goethem et al. (2013), were used to derive EC50 values for trees and grassland species. The species-specific EC50 equals the AOT40 at which there is a 50% reduction in biomass compared to a situation with no ozone over-exposure, i.e. AOT40 = 0. We selected the EC50, as it follows the same approach employed for toxicity in LCA (see e.g. Rosenbaum et al., 2008). Note that some species showed to be insensitive to ozone exposure, i.e. no EC50 value was derived for these species. In a second step, we used the EC50-values to derive a Species Sensitivity Distribution (SSD) for respectively forest and natural grassland species, taking into account the fraction of species with no biomass decrease. An SSDs represents a cumulative stressor-response distribution based on single-species sensitivity data. Assuming a lognormal species sensitivity distribution for ozone exposure, the PAF can be derived as:

$$\mathrm{PAF}_{j,e} = \frac{1 - f_{\mathrm{nbd}}}{\sigma_e \cdot \sqrt{2\cdot\pi} \cdot \mathrm{AOT40}_{j,e} \cdot \ln 10} \cdot \int_0^{\mathrm{AOT40}} \exp \times \left(-\frac{1}{2} \cdot \left(\frac{\log\left(\mathrm{AOT40}_{j,e}\right) - \mu_e}{\sigma_e} \right)^2 \right) \mathrm{dAOT40} \tag{3}$$

where $\mathrm{AOT40}_{j,e}$ represents the ambient ozone concentration in grid j of vegetation type e (either forest or natural grassland), μ_e is the average of the ^{10}logEC50 values for ozone in AOT40-units (ppm h), as observed for different species in vegetation type e, f_{nbd} is the fraction of species with no biomass decrease and σ_e is the standard deviation of the ^{10}logEC50-data within vegetation type e.

In a third step, we calculated the marginal change in PAF due to the marginal change in ground level ozone exposure (in ppm h), equal to the derivative of Equation (3), via:

$$\frac{\partial \mathrm{PAF}_{j,e}}{\partial \mathrm{AOT40}_j} = \frac{1 - f_{\mathrm{nbd}}}{\sigma_e \cdot \sqrt{2\cdot\pi} \cdot \mathrm{AOT40}_{j,e} \cdot \ln 10} \cdot \exp \times \left(-\frac{1}{2} \cdot \left(\frac{\log\left(\mathrm{AOT40}_{j,e}\right) - \mu_e}{\sigma_e} \right)^2 \right) \tag{4}$$

In a final step, the grid-specific marginal effect factor (MEF) per vegetation type was defined as:

$$\mathrm{MEF}_{j,e} = \frac{\partial \mathrm{PAF}_{j,e}}{\partial \mathrm{AOT40}_j} \cdot A_{j,e} \tag{5}$$