STOMATAL OZONE FLUXES TO FOREST VEGETATION UNDER DIFFERENT SOIL WATER CONDITIONS

SVETLANA BIČÁROVÁ[1], HANA PAVLENDOVÁ[2]
[1]*Geophysical Institute, Slovak Academy of Sciences, workplace S. Lesná, 059 60 T. Lomnica, Slovakia*
[2]*National Forest Centre – Forest Research Institute, T. G. Masaryka 22, 960 92 Zvolen, Slovakia*

Modelling of total and stomatal ozone (O_3) fluxes is new method for estimation of phytotoxicity of O_3 pollution to forest vegetation. Stomatal flux-based critical levels for effects of O_3 on growth take into account the varying influences of meteorological parameters, soil characteristics, O_3 concentration and phenology. This work focuses on the sensitivity of Norway spruce to O_3 air pollution to different weather and soil water conditions at research plot Stará Lesná in the High Tatras during growing season 2014. Data of stomatal O_3 fluxes and soil water potential (SWP) calculated by model DO_3SE (Deposition of Ozone for Stomatal Exchange) are used for evaluation both dry (June) and wet (July) events in 2014. Model estimations are compared to field measurements of SWP. Comparison of modelled and measured values of soil water characteristics may contribute to improving of parametrization of DO_3SE model inputs. In addition, model estimation of Phytotoxic Ozone Dose ($POD_{1.6}$) under drought and water stress conditions for selected field sites are also presented.

Keywords: ozone phytotoxicity, spruce forest, deposition velocity, stomatal conductance, soil water potential

INTRODUCTION

Tropospheric ozone (O_3) acts as a phytotoxin which produces an oxidative stress in plants. Among common air pollutants, O_3 and Nitrogen (N), potentially the most damaging to forest vegetation, reach high concentrations over large regions of the world (De Marco et al., 2015). Current state of knowledge of climate change, air pollution and atmospheric deposition interactions and their synergetic effects on forest ecosystems were presented at international congress IUFRO 2015 (International Union of Forest Research Organisation).

Challenges of future research towards consolidating forest health, sustainability and ecosystem services worldwide is to understand linkages between genetic responses and resulting physiological activities. In adult forest trees under free-air fumigation, O_3 caused "noise" in gene expression. In younger trees, gene responses sharpened as coordinated regulation of all shikimate pathway genes became apparent, with overlaps even between transcriptome and proteome levels of two enzymes (Matyssek et al., 2015). Bioinformatics analysis of the proteomics data showed that elevated O_3 changed the protein expression in leaves, which led to biochemical and functional change in plant (Chen et al., 2015). Negative effect of O_3 was observed in biochemical photosynthetic activities such as maximum rate of carboxylation (*V*cmax) and maximum rate of electron transport (*J*max), while stomatal limitation of photosynthesis was reduced (Watanabe, 2015). In general, the environmental stresses may reduce the genetic diversity. Pine stands with low inbreeding level were found to be more tolerant to the impact of the unfavorable environmental factors than the stands with high level of inbreeding (Augustaitis et al., 2015).

Climate change is projected to reduce the benefits of O_3 precursor emissions controls leading to a higher O_3 uptake. However, the drier and warmer climate should induce a soil drought leading to a lower O_3 uptake. These two effects, acting together in an opposite way, could mitigate the harmful impacts of O_3 on forests (Dalstein-Richier et al., 2015). Exposure of O_3 together with climate factors (temperature and water availability), nutrient (nitrogen, base cations, phosphorous) availability, and carbon dioxide (CO_2) exposure are considered as drivers of carbon sequestration of forest ecosystems. The combined effects of these drivers in forests and forest soils can either be synergistic (amplifying), antagonistic (dampening) or neutral (no interaction), (De Vries et al., 2015).

Ground level ozone still poses a serious threat to forest ecosystems across Europe and represents a priority for the UNECE Convention on Long-range Transboundary Air Pollution (Schaub et al., 2015). N deposition, O_3 and their interactions with biotic/abiotic drivers have received recent attention for their impact on forest health and growth. Data cover drivers (e.g. climate, deposition, tropospheric ozone) and responses (e.g. health, growth, phenology, diversity, nutrients). Results reveal the importance of monitoring data for detecting trends (e.g. foliar nutrition, its effect on forest health), identifying threshold/exceedance (e.g. critical limits/loads) and their development (e.g. dynamic modeling), identifying relationships (e.g. nitrogen deposition-carbon sequestration; climate and forest health; soil solution, climate, soil and forest characteristics), and for calibrating models for scenario analysis (e.g. economic value of European forests under climate change), (Ferretti et al., 2015). A free-air-O_3-fumigation experiment with willow in the Sapporo Experimental Forest, Japan showed that elevated O_3 reduced dry masses of the cuttings, branches, leaves, and roots, separately, and the total biomass, per plant. There was a high variability in the EDU treatments (Agathokleous et al., 2015). The antiozonant ethylenediurea (N-[-2-(2-oxo-1-imidazolidinyl) ethyl]-N'-phenylurea]), abbreviated EDU, has been widely used as a protectant of plants against O_3. Preliminary results show that EDU accelerated bud development and delayed early leaf senescence induced by O_3. EDU treatment increased coarse roots density, fine root length and stem diameter but did not increase the ratio of mychorrhizal infection in roots compared to the plants treated with water (Carriero et al., 2015).

Ozone effect depends on the amount of gas entering through stomata rather than on the concentration of O_3 in the air. Stomatal O_3 ozone flux and Phytotoxic Ozone Dose (POD1) can be calculated by DO_3SE model (Deposition of O_3 for Stomatal Exchange). Model estimations of POD1 for Norway spruce (*Picea abies* (L.) Karst) indicate phytotoxicity of O_3 at six research plots with altitudes from 810 to 2634 m a.s.l. along vertical and spatial profile in High Tatra Mts. during vegetation season 2014. Critical level 8 $mmol.m^{-2}$ PLA recommended for spruce protection was exceeded at all research plots even in year with low ozone concentrations. Besides O_3 concentrations, in lower altitudes, the main limiting factor for O_3 flux is soil water availability (Pavlendová et al., 2015). On the other hand, deposition velocity (*vd*) and O_3 fluxes to Norway spruce forest calculated by model DO_3SE suggest phytotoxic effect of O_3 for both extreme dry (2003) and wet rainfall (2010) seasons.

Expected results linked to lower values of stomatal O_3 flux and PODy in dry than wet year due to water control loss through stomata closure were not confirmed. It is assumed that despite extreme low precipitation in 2003, mountainous environment accumulated sufficient soil and air humidity for effective stomatal O_3 flux to vegetation also during dry growing season (Bičárová and Pavlendová, 2015). Further research using both experimental and modelling tools is needed for analysing of interactions among deposition fluxes, stomatal conductance, soil water, air humidity and PODy related to different dry/wet events. In this work, DO$_3$SE model simulation and validation of soil water parameters for selected different dry/wet events in year 2014 are presented.

MATERIALS AND METHODS

Study area

Research plot Stará Lesná is situated at the foothills of the High Tatra Mts. (49°09´N, 20°17´E, 810 m a.s.l.). Forest is dominant vegetation type and Norway spruce (*Picea abies* (L.) Karst.) is absolutely prevailing tree species. Climate of this location is moderately cool with average annual air temperature 5.9 °C that seasonally varies from -3.5 °C (DJF) to 15.2 °C (JJA). Extreme air temperatures range between -26.5 and 34.2 °C. Growing season length is about 195 days. Mean annual sum of precipitation is 744 mm.Wet periods last from 5 to 13 consecutive wet days; substantially longer are dry periods which last usually from 14 to 39 days (Bičárová et al., 2014).

Ozone monitoring

The measurement of O_3 is done by Slovak Hydrometeorological Institute (SHMI) that is national participating institute in EMEP project. Monitoring station measures O_3 concentration by analyzer Horiba APOA360 with evidence of hourly average values.

Meteorological characteristics

Automatic meteorological station operated from 2014 records 10 minute data (average, sum, maximum). Weather station is equipped by datalogger ProLog-Physicus and following sensors: air temperature - Pt100; air humidity -Prove-HumiAir9; precipitation - rain gauge Meteoservis MR3H; soil water – Virrib; air pressure - PressAir; wind speed and direction – Wind Transmitter compact 4.35 A. Thies; global radiation - pyranometer CMP6 140134 Kipp& Zonen; radiation balance - Net Radiometer NR Lite 2 Kipp& Zonen. Beside this, ground water level by sounding device and soil water potential by Datalogger MicroLog SP3 with Gypsum block were monitored.

DO₃SE model has been developed to estimate the risk of O_3 damage to European vegetation and is capable of providing flux-modelling estimates according to UNECE LRTAP (Long-Range Transboundary Air Pollution) methodologies for effects-based risk assessment. Interfaced version of the model (DO3SE_INTv2.0) is provided for users to estimate total and stomatal O_3 flux on a site-specific basis according to local meteorological and O_3 concentration data.

PODy - Phytotoxic ozone dose is accumulated value of hourly mean stomatal O_3 fluxes exceeding the threshold Y nmol.m^{-2}.s^{-1}, during vegetation season. In this work Y value for forest trees was 1.6 nmol.m^{-2}.s^{-1}. The critical level of POD$_Y$ is proposed to 8 mmol.m^{-2} PLA for spruce (evergreen coniferous) with expected biomass increment reduction 2 % (Mills et al. 2011).

RESULTS

Precipitation course of daily sums in 2014 (Fig. 1) highlights both dry (May/June) and wet (July/August) events. Dry event lasted 38 days from 22th May to 28th June with very low precipitation total 18.6 mm. Wet event started 29th June and continued for next 34 days. During this time, the total amount of precipitation reached high value of 295.4 mm.

Air and Soil Moisture characteristics (Fig. 2) show increase of Vapour Pressure Deficit (VPD) in air and rapidly decrease of water in soil (Soil Water – SW, Soil Water Potential – SWP, Ground Water Level – GWL) during dry event. Comparison of measured and modeled values of soil water content (Fig. 3) suggests similar course for SW with greater smoothing in the case of model output. SWP measurement is more consistent with SWP modeled results considered for measurement depth than model values without specification of ground depth. In spite of this, model values for SWP as well as for ASW (Available Soil Water) decreased during dry event (Fig. 4) without relevant influence on Gsto (stomatal conductance).

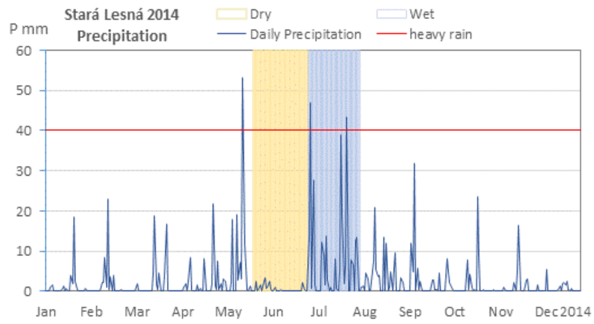

Fig. 1. Precipitation - P (mm) at research plot Stará Lesná, 2014.

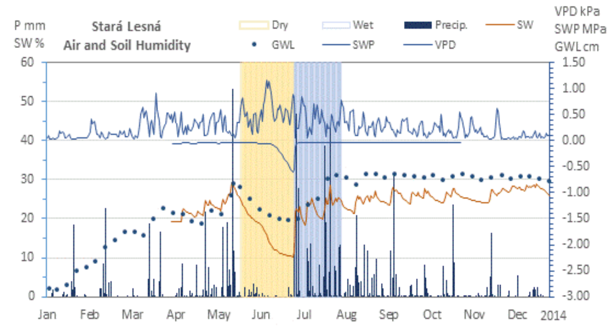

Fig. 2. Air and soil water components according measurement at research plot Stará Lesná, 2014.

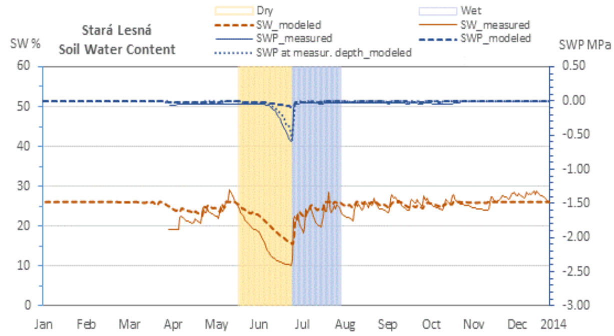

Fig. 3. Measurement and DO$_3$SE model output for SW and SWP.

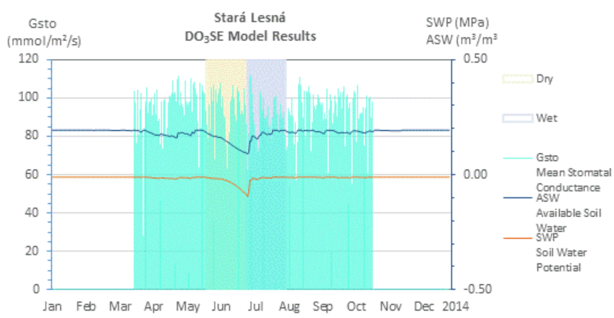

Fig. 4. DO$_3$SE model results for Gsto, SWP and ASW.

Total and Stomatal Ozone Fluxes, PODy

DO_3SE model output shows difference between total (F_{tot}) and stomatal (F_{sto}) O_3 fluxes (Fig. 5). Upper leaf stomatal O_3 flux F_{sto} comprises approximately 20 – 25 % of F_{tot}. Stomatal O_3 uptake by forest vegetation was not disturbed relevantly during dry event. However dry conditions in the first part of growing season resulted to decrease of available water for forest vegetation, POD0 gradually increased. We assume that both prolongation of dry event with higher air temperatures might have a greater impact on stomatal control of water loss. In addition, abundant precipitation amounts before and after dry event could positively influence content of water in soil and groundwater level. Although dry weather in June, PODy exceeded threshold limit at the end of June. Value of PODy continued to increase until the end of growing season. Totally, PODy reached value of 14.2 mmol.m^{-2} PLA that is almost two times more than threshold limit.

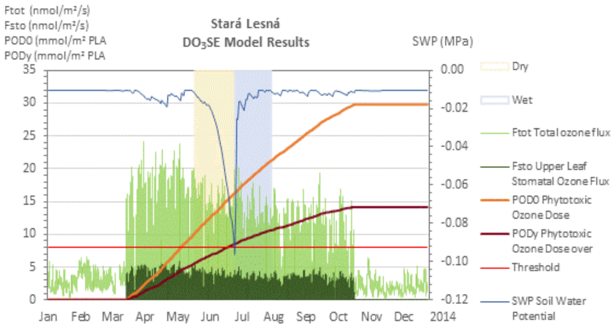

Fig. 5. Model estimations of O_3 fluxes and PODy, Stará Lesná, 2014.

CONCLUSION

Direct phytotoxic response of O_3 on forest vegetation is hardly distinguishable. Deposition models such as DO_3SE that simulate the total and stomatal O_3 fluxes are enable to estimate the risk of O_3 damage to European vegetation. Measurement and DO_3SE model results linked to stomatal flux and PODy indicate no crucial influence of soil water deficit on stomatal O_3 uptake during dry event at research plot Stará Lesná in 2014. Selected dry (May/June, low precipitation amount 18.6 mm) and wet (July/August, high precipitation amount 295.4 mm) events lasted more than 30 days. Especially during dry event, relevant decrease of SW and SWP were recorded. According to model results, this deficit did not affect substantially stomatal conductance and consequently the stomatal flux and POD0. PODy gradually increased during growing season, the threshold limit of 8 mmol.m^{-2} PLA was exceeded at the end of June. In October, at the end of the main growing season, PODy reached value of 14.2 mmol.m^{-2} PLA that indicate high phytotoxicity of O_3 for forest vegetation in the High Tatra Mts. region.

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