https://doi.org/10.17221/129/2019-JFS

The impact of drought on total ozone flux in a mountain Norway spruce forest

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Citation: Agyei T., Juráň S., Kwakye K. O., Šigut L., Urban O., Marek M.V. (2020): The impact of drought on total ozone flux in a mountain Norway spruce forest. J. For. Sci., 66: 280–287.

Abstract: In order to understand the impact of summer drought on dry deposition of tropospheric ozone (O_3), we compared severe and mild drought periods of summer 2018 in a mountain Norway spruce forest at Bílý Kříž, Beskydy Mts. An eddy covariance technique was applied to measure diurnal courses of the ecosystem O_3 and CO_2 fluxes. Low O_3 deposition was recorded in the morning and evening, while the highest CO_2 and O_3 fluxes were recorded during the central hours of the day. Total O_3 deposition during severe drought (soil humidity 13%) was significantly higher than the deposition during the mild drought period (soil humidity 19%). Our data indicate that high vapour pressure deficit and low soil humidity during severe drought led to the stomatal closure, while non-stomatal O_3 deposition, associated with chemical reactions of O_3 with NO and volatile organic compounds, are responsible for higher total O_3 deposition during the severe drought period. Therefore, we assume that under severe drought stomatal O_3 uptake decreases but non-stomatal depositions to forest ecosystems substantially increase.

Keywords: forest ecosystem; eddy covariance; temperature; photosynthetically active radiation; dry deposition

Climate change projections predict an increased occurrence of frequency, duration, and severity of drought and heatwave periods in Central Europe (Seneviratne et al. 2006). Low precipitation, soil water deficit, and high air temperatures associated with drought usually lead to a decrease in stomatal conductance, photosynthetic CO_2 uptake and annual forest production. Such negative effects can be further amplified by tropospheric ozone (O_3) penetrating the leaves via stomatal pores (Emberson et al. 2007).

O_3, a secondary photochemical pollutant, and greenhouse gas, is formed under high intensities of ultraviolet (UV) radiation by reactions of precursors such as nitrogen oxides (NO_x) and volatile organic compounds (VOCs). Favourable conditions for O_3 production are especially in suburban areas where NO_x-rich air from upwind urban agglomerations mixes with VOCs emitted from trees, and high altitudes due to enhanced UV radiation (Monks et al. 2009). Particularly in the Northern Hemisphere, an average concentration of O_3 in the troposphere has increased in the last 30 years over 40 ppbv (Cooper et al. 2014), which is considered as the threshold of an oxidative stress for terrestrial vegetation (Langer et al. 2005). On the global scale, dry deposition of O_3 is estimated to account for 25% of the total O_3 deposition (Lelieveld, Dentener 2000).

Supported by Ministry of Education, Youth and Sports of the Czech Republic within CzeCOS ProCES (CZ.02.1.01/0.0/0.0/16_013/0001609) and Mobility CzechGlobe (CZ.02.2.69/0.0/0.0/16_027/0008137).

https://doi.org/10.17221/129/2019-JFS

Dry deposition of O_3 to terrestrial ecosystems includes chemical reactions of O_3 molecules particularly with NO and VOCs, the non-stomatal deposition to plant surfaces (cuticle, bark), soil and standing water, and the deposition into leaves through plant stomata leading to oxidative damage. Such stomatal uptake accounts for 30–90% of the total dry O_3 deposition (Cieslik 2004) and is responsible for the declines of photosynthetic CO_2 uptake and forest productivity (Juráň et al. 2018). The openness of stomatal pores is particularly controlled by the intensity of photosynthetically active radiation (*PAR*), vapour pressure deficit (*VPD*), water availability in the soil, and wind velocity (Emberson et al. 2000). Accordingly, one may hypothesize that severe drought conditions leading to stomatal closure will result in reduced O_3 deposition to ecosystems.

Episodes of high O_3 concentrations and drought occur often together during summer months. Drought stress has been shown as a major limiting factor reducing stomatal conductance and subsequently CO_2 uptake in Norway spruce (Kronfuß et al. 1998). Drought is also known to have the potential to reduce dry deposition of O_3 (Pio et al. 2000), which is probably caused by stomatal closure and increased stomatal resistance under water limiting conditions (Mills et al. 2011). However, drought and high temperatures often alter emissions of NO (Schindlbacher, Zechmeister-Boltenstern 2004) and VOCs (Fall 1999) from forest ecosystems having thus the impact on chemical O_3 removal from the atmosphere and consequently changes in total O_3 deposition.

Due to these uncertainties and a prediction of increasing severity and frequency of drought periods in Central Europe, it is crucial to better understand the variability in O_3 deposition under different growth conditions including drought. Moreover, it is important to evaluate potential risks of combined drought and O_3 impacts on spruce forests, as spruce is a widely spread tree species in the Czech Republic and temperate zone. Understanding the impacts of drought on O_3 deposition is also necessary to predict future changes in air quality and atmospheric chemistry at the regional as well as global level.

Accordingly, the main aim of this study was to investigate diurnal changes in O_3 uptake in a mountain Norway spruce forest and to investigate how these courses are influenced by different levels of drought. The measurements were done at the experimental research site Bílý Kříž in the Beskydy Mts. from June to August 2018.

MATERIAL AND METHODS

Site description. The investigated forest stand is located at the Bílý Kříž experimental research site (Beskydy Mountains, 49°33' N, 18°32' E, northeastern Czech Republic, 908 m a.s.l.) and forms part of many international research networks such as CzeCOS (Czech Carbon Observation System), ICOS (Integrated Carbon Observation System), and AnaEE (Analysis and Experimentation on Ecosystems). The experimental forest was described in detail in previous studies (e.g. Juráň et al. 2018). As of 2018, the forest stand (6.2 ha) comprised *Picea abies* (L.) Karst (99%) and *Abies alba* Mill. (1%) with the mean stand slope of 13° to the SSW orientation. This site has a cool (annual mean air temperature 6.8 °C) and humid (annual mean relative air humidity 84%) climate with high annual precipitation (annual mean precipitation 1 318 mm; 1998–2018).

For a period of 35 summer days (June 29 to August 2),the total amount of precipitation recorded at the site was 5.8 mm, mean temperature was 16.6 °C, soil water content was 14% and mean relative air humidity was 74%. The average daily CO_2 concentration was 398 $\mu mol \cdot mol^{-1}$ during both drought periods. In 2018, the year of the investigation, the stand density was 1 428 $trees \cdot ha^{-1}$, average stand height was 13 m, average stem diameter at breast height was 15.9 cm, spruce trees were 38 years old and hemi-surface leaf area index was 9.6 $m^2 \cdot m^{-2}$. During summer months, the area usually records a low concentration of nitrogen oxides (below 10 ppbv) and high O_3 concentrations (above 80 ppbv) (Zapletal et al. 2011).

To analyse effects of drought on processes of CO_2 and O_3 uptake, two successive 10-day periods during the growing season (June – August) were used for the present analysis. In the first period (29.06. to 08.07. 2018) severe drought was characterised by soil moisture of 13–14% at a depth of 15 cm whereas in the second period (24.07. – 02.08. 2018) mild drought was characterised by soil moisture of 16–20%. The periods were classified based on the long-term time series of soil moisture at the experimental site and drought trends of the last decade (Trnka et al. 2016). These two periods were interrupted by a period of three days when precipitation

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amounted to 155 mm in total. See Figures 1 and 2 for detailed meteorological variables.

Eddy covariance measurement of CO_2 and O_3 fluxes. Measurement of CO_2 fluxes between the forest stand and the atmosphere was performed with the eddy covariance system comprising a Gill R3® ultrasonic anemometer (Gill Instruments, Hampshire, UK) and an inbuilt infrared gas analyser LI-7200® (LI-COR Biosciences, Lincoln, NE, USA) placed on the tower at 25 m above the soil surface. EddyPro, the post-processing software (LI-COR, Nebraska, USA), was used to process high-frequency data (20 Hz) according to recent guidelines by Aubinet et al. (2012) and produced half-hourly estimates. Spike removal and quality check of the raw signals, rotation of wind velocity components into the planar fit coordinate system and spectral corrections of calculated fluxes were all included in the procedure. Based on the quality checking scheme, the excluded and missing data are gap-filled according to the marginal distribution sampling method as described by Reichstein et al. (2005).

In 2018, ecosystem CO_2 fluxes were measured together with O_3 flux using the eddy covariance technique placed at the same height of 25 m above the soil surface. The wind components were measured by a 3D anemometer (Young 81000, Transverse City, MI, USA). Changes in O_3 concentration were detected by a fast chemiluminescence O_3 detector (Enviscope, Frankfurt am Main, Germany). Regular re-calibration of O_3 concentrations was performed against O_3 concentrations measured by a slow-response O_3 analyser APOA 370 (Horiba, Kyoto, Japan), which was regularly calibrated by 306 O_3 calibration source (2B Technologies, Boulder, CO, USA). The high-frequency data were processed by EddyPro, resulting in 30-min estimates of O_3 flux. The average O_3 concentrations during the severe and mild drought periods were 40.01 and 39.14 ppbv, respectively.

O_3 flux was calculated as follows Equation (1):

$$F = \overline{w'C'} \tag{1}$$

where:
F – flux measured in nmol m^{-2}·s^{-1},
w – vertical wind component (m·s^{-1}),
C – measured O_3 concentration (ppbv).

The prime (') refers to the fluctuations and the overbar indicates an average over the time period.

Measurement of environmental variables. The eddy covariance measurements were complemented with a detailed measurement of meteorological variables through the canopy profile. The meteorological tower was equipped with a set of sensors for the measurement of relative air humidity (*RH*) and air temperature (*Tair*) (EMS33 Rotro® sensor; EMS, Brno, Czech Republic), intensity of incoming *PAR* (EMS12, EMS, Czech Republic) and a 386 C precipitation gauge (Met One Instruments, Grants Pass, OR, USA). In addition, soil moisture was measured by an ML3 ThetaProbe sensor (Delta-T Devices, UK). The signals from all meteorological sensors were recorded at 30 s intervals and stored in 30-min averages using a data logger (Delta-T®, Burwell, Cambridgeshire, UK).

Vapour pressure deficit (*VPD*) expressed in kPa was calculated as Equation (2):

$$VPD = (100 - RH)/100 \times 610.7 \times 7.5\ Tair/(237.3 + Tair) \tag{2}$$

where:
RH – air humidity,
$Tair$ – air temperature.

Description of statistical test used. ANOVA analyses (The MathWorks, Natick, MA, USA) were used to test the effect of drought conditions (mild and severe drought periods) on daily sums of O_3 deposition during the period of investigation. Significant differences between means were tested ($p < 0.05$).

RESULTS

Daily sum of precipitation during the investigated period ranged between 0 mm in June and 101.2 mm in July (Figure 1). The highest values of soil water content (16.7–19.9%) were observed in late July and early August (mild drought period) and the lowest in June and early July (13.3–13.8%; severe drought period). Soil water content during severe drought had a stable pattern, whereas the mild drought period was characterised by constant soil desiccation (Figure 1).

VPD values ranged from 0.2 to 1.2 kPa and from 0.4 to 1.3 kPa during the mild and severe drought period, respectively (Figure 2). Although we noticed typical diurnal courses of *VPD* values, daily maxima were reached later in the afternoon during severe drought than during the mild drought

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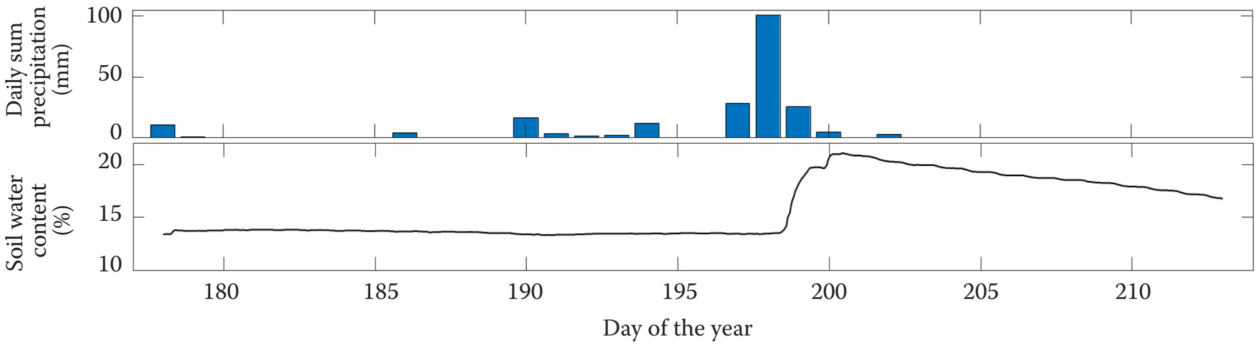

Figure 1. Figure 1. Daily sum of precipitation and soil water content at Bílý Kříž (Beskydy Mts.) during the investigated period from June 29 to August 2, 2018

period. Average air temperature during the severe drought period was 14.9 °C, while it amounted to 19.9 °C during the mild drought period. Daily temperature maxima ranged from 11 to 26 °C and from 22 to 26 °C during the severe and mild drought period, respectively.

Diurnal courses of CO_2 and total O_3 fluxes (Figures 2C, D) followed diurnal changes in *PAR* intensity (Figure 2A) amounting to the maximum values during the noon hours of both the investigated periods. Positive flux values represent a release of gases from the ecosystem, while negative values indicate their uptake by the ecosystem. During the mild drought period, the maximum nocturnal CO_2 flux was 10.73 $\mu mol \cdot m^{-2} \cdot s^{-1}$, it amounted up to –27.25 $\mu mol \cdot m^{-2} \cdot s^{-1}$ during the day. Similarly, these CO_2 fluxes were 6.15 and –26.18 $\mu mol \cdot m^{-2} \cdot s^{-1}$ during the severe drought period. The highest and the lowest O_3 fluxes during the severe drought period were –0.82 (nocturnal) and –11.68 $nmol \cdot m^{-2} \cdot s^{-1}$

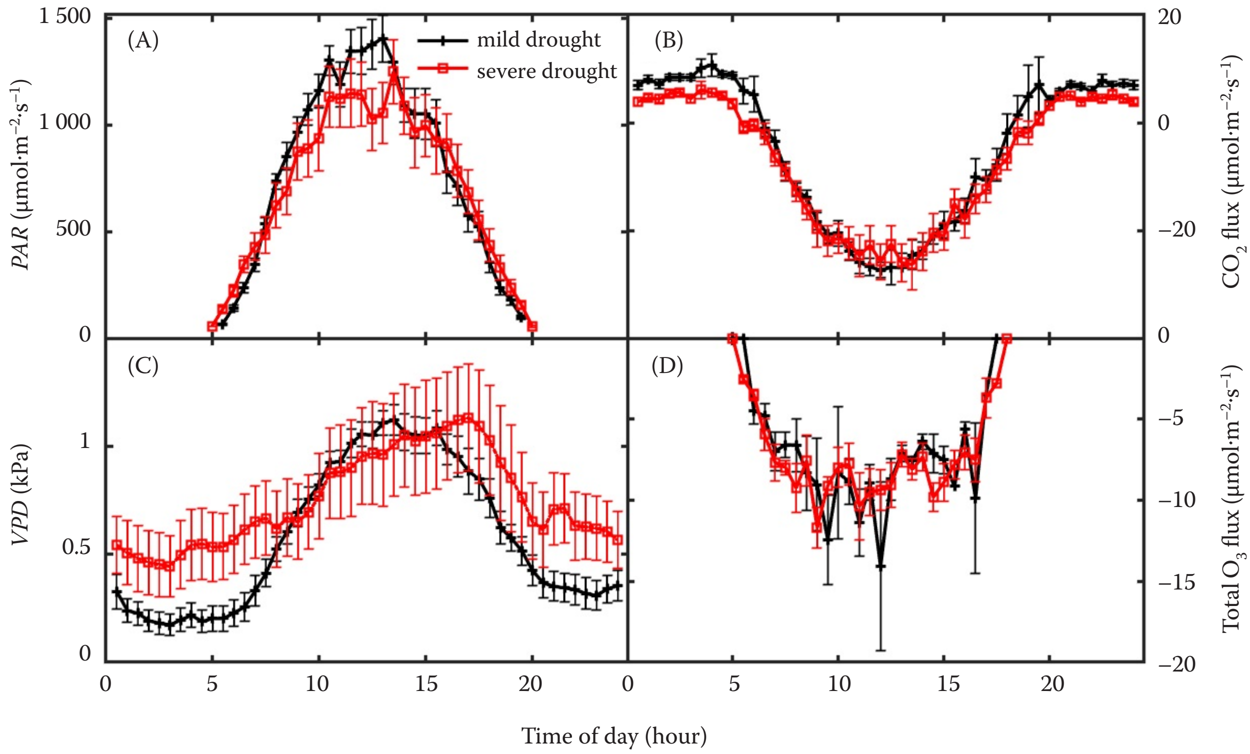

Figure 2. Diurnal courses of photosynthetically active radiation (*PAR*) (A), vapour pressure deficit (*VPD*) (B), CO_2 flux (C), and total O_3 flux (D) during the 10-day periods of mild (black lines) and severe (red lines) drought observed in June – August 2018 (negative values of CO_2 and total O_3 fluxes represent deposition, the symbols represent 30-min averages; error bars are standard error of the means, *N* (days) = 10)

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(diurnal), respectively, while these fluxes amounted to –3.46 and –14.01 nmol·m^{-2}·s^{-1} during the mild drought conditions.

Based on these diurnal courses, daily (24-hour) sums of CO_2 and O_3 depositions were subsequently calculated. Daily sum of CO_2 depositions for the mild and severe drought period were 53 ± 15 and 46 ± 7 mol·m^{-2} (mean ± SD, n = 10), respectively. Although CO_2 deposition during the mild drought period is higher than deposition in the severe drought period, there is no significant difference between them in daily sums (p = 0.2295). The sum of daily O_3 depositions for the severe and mild drought period was 179 ± 126 and 101 ± 77 mmol·m^{-2} (mean ± SD, n = 10), respectively. Statistical analysis showed a significant difference between the two drought periods (p = 0.0318). Daily sum of O_3 depositions during the severe drought period ranged between 81 and 383.54 mmol·m^{-2}, while it was between 17.78 and 246.42 mmol·m^{-2} during the mild drought period.

DISCUSSION

Plant responses to phytotoxic O_3 are well documented by manipulative experiments (Matyssek et al. 1995); however, the direct measurements of O_3 fluxes and responses of whole ecosystems under natural conditions are still insufficient (Ducker et al. 2018). Therefore, we tested the hypothesis that drought conditions may substantially influence total O_3 deposition in a mountain spruce forest and may thus modify ecosystem responses to tropospheric O_3. Indeed, we have found significantly higher O_3 deposition under severe drought conditions than under mild drought characterised by lower soil humidity. This result is in contradiction with the observed reduction of CO_2 uptake under severe drought conditions caused by reduced stomatal conductance to gas diffusion. Accordingly, such contradictory patterns in CO_2 and O_3 uptakes imply a significant contribution of non-stomatal O_3 uptake.

Generally, total O_3 deposition is the summation of stomatal and non-stomatal uptake. It is estimated that less harmful non-stomatal uptake, deposition on cuticles, bark, soil, and/or water, accounts for 30–70% of total deposition during the daytime (Kurpius, Goldstein 2003; Cieslik 2004; Gerosa et al. 2005) and may increase up to 90% during the night when the stomata are closed (Juráň et al. 2019). Moreover, chemical reactions of O_3 with other gases emitted by the ecosystem are considered as a substantial chemical sink of O_3 that can lead to an enhanced total O_3 deposition (Wildt et al. 1997; Li et al. 2018). It has been shown that emission of nitric oxide (NO) from the soil contributes substantially to non-stomatal O_3 uptake (Farmer, Cohen 2008; Fares et al. 2012) depending on the availability of soil water (Schindlbacher, Zechmeister-Boltenstern 2004; Meixner, Yang 2006). Similarly, emissions of VOCs from vegetation, increasing with increasing drought and temperatures of biological surface (Schade, Goldstein 2001; Juráň et al. 2017), are considered as a substantial chemical sink. These examples indicate that the complex evaluation of the atmospheric chemistry is required for the proper quantification of non-stomatal O_3 uptake. It is very likely that severe drought conditions led to a high release of NO and particularly VOCs from the spruce forest studied. Facilitated by VOCs, NO reacted with O_3 forming NO_2 (Leighton 1961) and thus contributed to an increase in total O_3 deposition during the severe drought period.

Even though the aim of this study was not partitioning of total O_3 flux into stomatal and non-stomatal uptake, it is assumed that greater part of the total O_3 flux is represented by non-stomatal deposition. This assumption is based on earlier findings that summer drought, characterised by soil moisture deficit, high air temperatures and *VPD*, reduces the openness of stomata and thus increases stomatal resistance to O_3 diffusion into the leaves (Solberg et al. 2008). In our earlier study on the same forest, we have shown that the stomatal component never exceeded 43.5% of total O_3 flux under dry conditions of clear sky days (Juráň et al. 2019). However, there is a major discrepancy in the relative contributions of stomatal and non-stomatal O_3 uptake depending on the plant/ecosystem functional types, ecosystem structure, chemistry of the atmosphere, and climatic conditions. For instance, Tuzet et al. (2011) and Rannik et al. (2012) reported that non-stomatal uptake can reach 20–63% of total O_3 deposition.

Application of the eddy covariance technique allowed us to determine diurnal courses of O_3 flux in 30-minute intervals (Figure 2). The total O_3 flux to the spruce forest peaked around noon, when also *PAR* intensities were the highest. Similar diurnal courses were reported for deciduous (Finkelstein et al. 2000) as well as coniferous forests (Goldstein

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et al. 2004; Gerosa et al. 2005). Zero or near-zero O_3 depositions in the morning and night hours are likely associated mainly with closed stomatal pores and reduced O_3 production from photo-oxidative reactions. Even a small stomatal uptake during the night is crucial as it has been shown that nighttime O_3 uptake is more toxic to plants than daytime O_3 uptake (Matyssek et al. 1995).

In accordance with our findings, Hogg et al. (2007) reported a strong diurnal O_3 flux in a northern mixed hardwood forest during summer, with maximum values of about 14–28 $nmol \cdot m^{-2} \cdot s^{-1}$ occurring at midday and zero or near-zero flux in the nighttime. Stomatal conductance for O_3 increases with increasing light intensity, but decreases with increasing *VPD* and/or air temperature. Stomatal closure, as a result of persisting drought (low soil moisture) and high temperatures during the summer months, is responsible for generally low total O_3 deposition detected in both drought periods. Panek and Goldstein (2001) reported a reduction of O_3 uptake in a ponderosa pine forest by 40% during summer drought, which was attributed to low soil water content and high *VPD*. Moreover, soil moisture recovery led to an increase of stomatal conductance and subsequently to an increase of O_3 uptake by ponderosa pine.

As compared to pine, spruce is a drought sensitive species due to shallow roots (Spiecker 2000) although its foliage is typically xeromorphic. Spruce trees have an isohydric strategy (Lyr et al. 1992) characterized by the fast closure of stomata at early stages of soil drought or high *VPD* in order to reduce water losses via transpiration and to maintain plant water balance and water potential. Such 'drought avoider' characteristics may have contributed to low total O_3 fluxes under severe and mild drought conditions.

CONCLUSION

We confirmed the hypothesis that drought conditions may substantially influence total O_3 deposition. Investigating the mature mountain Norway spruce forest, we have found significantly higher O_3 deposition under severe drought conditions than under mild drought with higher soil humidity. Although further direct field eddy-covariance measurements of O_3 flux are necessary, our data indicate an important role of non-stomatal O_3 uptake under severe drought conditions and the necessity to investigate complex atmospheric chemistry for the proper understanding of the mechanisms behind the O_3 deposition in forest ecosystems.

ACKNOWLEDGEMENT

We thank Karel Staník and Jiří Mikula for the technical support.

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Received: November 9, 2019
Accepted: June 27, 2020