UNIVERSITÀ DEGLI STUDI DI PADOVA
Dipartimento Territorio e Sistemi Agro-forestali

Corso di laurea magistrale (MSc)
In Scienze Forestali

Assorbimento di ozono troposferico in condizioni di siccità - Un caso di studio degli alberi urbani a Vienna, Austria

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2019-2020

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Department of Land, Environment Agriculture and Forestry

Second Cycle Degree (MSc)
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Tropospheric ozone uptake under drought conditions - A case study of the Urban Trees in Vienna, Austria

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2019-2020

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Acknowledgement

I wish to express my gratitude to my family and friends, for their love and care. To Andreas and family, Eva, Oma, Maria, Alicia, Julia, Denisse, and Cynthia, which I meet during my time in Europe; you enriched my experience and supported me always with your friendship. Furthermore, special thanks to the professors, administrative personnel, students, and everyone involved in this Master Program, especially to the European Commission for supporting professionals coming to Europe and granting them scholarships to widen their knowledge and perception of the world.

Lastly, thanks to Prof. Sitzia, Hans, Anne for their guidance in the master thesis development, and the Institute of Forest Ecology of the University of Life Science, BOKU, Vienna.

Abstract (Italian)

L'ozono troposferico è un inquinante dell'aria che negli ultimi decenni ha acquisito grande importanza, in quanto rappresenta conseguenze forti e talvolta irreversibili per la salute umana e ambientale. La sua formazione, rimozione e importanza sono descritte in questa tesi di laurea basata su una revisione della letteratura degli ultimi 20 anni con particolare attenzione alle interazioni che le piante e la loro fisiologia hanno sul ciclo dell'ozono, come l'emissione di composti organici volatili biogenici (BVOC, per il suo acronimo in inglese), conduttanza stomatica e loro relazione idrica. Un esperimento in condizioni di laboratorio è stato sviluppato presso l'Istituto di ecologia forestale dell'Università di Scienze della vita, BOKU, Vienna, utilizzando cuvette per lo scambio di gas. Consisteva nel testare l'effetto dello stress da sale e siccità nella capacità di assorbire ozono troposferico su quattro specie con diversi tipi di emissione BVOC o e strategie per la difesa dallo stress. Da loro solo *B. pendula* ha diminuito in modo significativo la sua assunzione di ozono sotto stress da siccità, *F. sylvatica* ha presentato le prestazioni più basse e *C. betulus* e *Q. robur* le più grandi.

Inoltre, è stata fatta una raccolta del tipo di BVOC e del grado di tolleranza allo stress da siccità per ogni specie della foresta urbana di Vienna, che compromette 202214 individui che crescono in parchi, bordi stradali e altri boschi, e sono equivalenti a più di 299 specie e 76 generi. È stato sviluppato un elenco delle specie che si consiglia di non utilizzare più; che rappresentano oltre il 29% della foresta urbana totale, con 39 generi e 77 specie. Gli alberi inclusi nell'elenco sono sensibili allo stress da siccità o ad alti emettitori di mono e isoprene (BVOC); queste caratteristiche migliorano direttamente e indirettamente la formazione di ozono.

Keywords: BVOC, foresta urbana, assorbimento dell'ozono troposferico

Abstract (English)

Tropospheric ozone is an air pollutant that in the last decades has gained relevance, as it causes strong and sometimes irreversible consequences to human and environmental health. Its formation, removal, and importance are described in this master thesis based on a literature review from the last 20 years with special attention to the interactions plants and their physiology have on the ozone cycle, like emission of biogenic volatile organic compounds (BVOC), stomatal conductance and their water relationship. An experiment under laboratory conditions was developed in the Institute of Forest Ecology of the University of Life Science, BOKU, Vienna, using gas exchange cuvettes. It consisted of testing the effect of salt and drought stress in the capacity to uptake tropospheric ozone on four species with different types of BVOC emission or and strategies toward stress defense. From these trees only *B. pendula* significantly decreased its ozone uptake under drought stress, *F. sylvatica* presented the lowest performance, and *C. betulu*s and *Q. robur* the largest one.

Additionally, a compilation of the type of BVOC and degree of drought stress tolerance was done for each specie of the urban forest in Vienna, which compromises 202214 individuals growing in parks, roadsides, and other wooded, and are equivalent to more than 299 species and 76 genera. A list of the species, which are recommended not-to-be used anymore, was developed. They represent more than 29% of the total urban forest, with 39 genera and 77 species. The included trees are either sensitive to drought stress or high mono- and isoprene emitters (BVOC); these characteristics enhance directly and indirectly to ozone formation.

Keywords: BVOC, urban-forest, tropospheric-ozone-uptake

1. Introduction

Tropospheric ozone (O_3) generates significant and irreversible damages to humans and plants. The World Health Organization has recommended a maximum exposition of 50 ppb (150 µg/m³) for eight continuous hours or 80 ppb (160 µg/m³) during short exposures for humans (World Health Organization, 2006). Nevertheless, between 2006 and 2016 more than 95% of the European population was exposed to a higher concentration than recommended, during extremely hot summers where the levels of ozone are extremely higher (EEA, 2019).

Ozone can be reduced or increased indirectly by the vegetation. Ozone is taken up through the stomata, deposited on the leaf cuticle or ozone is indirectly degraded or increased by the emission of biogenic volatile organic compounds (BVOC). Some BVOCs form second organic aerosols (SOA) when in contact with ozone which may additionally either worsen or enhance global warming (Fowler et al., 2008). Trees naturally emit species-specific BVOCs as a metabolic reaction to different stages in a tree life. The function of BVOCs are to defend the plants from different abiotic and biotic stresses, or for communication with neighboring trees (Peñuelas and Staudt, 2010). Many BVOC reactions happening between the biosphere and atmosphere are complex (Velikova et al., 2005; Fares et al., 2006). Therefore, latest studies regarding BVOC biogeochemistry and its interplay with environmental influences within urban settings has been appointed as imperative for deciding future policies against air pollution, as plants are both sinks and sources of ozone (Calfapietra et al., 2016).

Climate predictions for 2100 estimate hotter conditions with heatwaves occurring more often and lasting longer. Nonetheless, due to legislations to deaccelerate, it is expected that the greenhouse gas (GHG) emissions decrease at some point within a range of scenarios in which an increment in temperature could range from 1 to 4°C (IPCC, 2014). As urban areas are recording higher temperatures compared to rural regions (urban heat islands-UHI REF), vegetation's plays a major role to improve urban microclimate. Especially in cities the interaction between BVOCs and NO_x, emitted by traffic or industry, becomes interesting, since a ratio between $4 < VOC/NOx < 15$ increases ozone levels drastically (Calfapietra et al., 3013; Young et al., 2013).

A few tools to study these complex interactions is the use of measurements of stomatal conductance (g_s) and stem water potential (SWP) in plants. It is known that since the industrial revolution ozone concentration has raised around 30ppb causing a decline of around 13% of g_s and a significant reduction on ozone removal, as stomatal uptake counts to 45% of the total ozone removal made by plants (Witting, Ainsworth and Long, 2007; Clifton et al., 2020). As well, SWP is a reliable measurement of the water availability within the plant, which considers the plant's ability to transport water from the soil in exchange for obtaining CO_2 from the atmosphere. SWP can easily estimate how the general health status of the plant (Shackel, 2011).

Lastly, to select the best trees for a specific environment the creation of Tree Selection Guides has been widely spread. They provide a direction in which urban forest can develop. Relevant studies in this area, like the ones made by Samson et al. (2017) and Barwise and Kumar (2020), recompile tree traits and responses to diverse factors interacting with the vegetation, even including BVOC emissions. Nevertheless, the present study attempts to provide guidance based on studies in which trees are drought or salt-stressed, which is the predicted condition trees will be facing shortly. And to signal if the trees that are being used nowadays in the Vienna urban forests will be suitable for the future climatic conditions and will behave as a sink or as a promoter of tropospheric ozone.

1.1. Objective

- To evaluate in four model-species ozone assimilation, according to two types of stress: salinity and drought, in laboratory conditions using gas exchange cuvettes.
- To indicate potential species already being used in Vienna that could adequately perform as net ozone sinks, especially under drought stress, using as parameter their BVOC emissions.

1.2. Hypotheses

The species to be measured in the laboratory conditions emit different types of BVOC (Karl et al., 2009; Fitzky et al., 2019). I hyopthesize, that ozone uptake is species-specific and will be deposited differently in each specie, being larger in *Betula pendula* > *Fagus sylvatica* > *Carpinus betulus* > *Quercus robur* (See Table 1). Additionally, species that perform well under drought stress take up more ozone: with high stomatal conductance and high stem water potential, as the ozone would have a better chance to be deposited. Lastly, the study hypothesizes ozone uptake will be significantly lower in species under drought, being this stress stronger than ozone uptake.

2. Background

2.1. Global Tropospheric Ozone importance, formation, removal and future trend

Ozone is an atmospheric highly reactive second pollutant that affects human health and the environment. It has a high impact on vegetation, like decrease in yield and nutritional quality of major crop species like wheat, rice and soybean, threatening the food security in regions like South Asia; and it leads to long-term effects on ecosystem structure and the terrestrial carbon sink (Fowler at al., 2008).

O_3 concentration has a mean day-time ambient background of 41.1±20 ppb but it can scope up to 200-400 ppb in the troposphere, as seen in metropolitan areas of Latin America, Asia, and the USA during extremely hot summer days (Fowler at al., 2008; Derwent, 2020). The World Health Organization has recommended a maximum exposition of 50 ppb (150 $\mu g/m^3$) for eight continuous hours or 80 ppb (160 $\mu g/m^3$) during short exposures (World Health Organization, 2006). Nevertheless, between 2006 and 2016 more than 95% of the European population has been exposed to a concentration above recommended during extremely hot summers (EEA, 2019).

The mean tropospheric ozone burden (TOB, the total mass of ozone) for 2013 was estimated as 337±23 Tg/yr representing an increment of 30% in comparison to 1850, in which the concentration $[O_3]$ was less than 10ppb. Being tropospheric ozone not directly emitted its budget depends on the balance between Chemical Production (P) and Influx from the Stratosphere (S) minus Chemical Loss (L) and Deposition to the Surface (D). The annual budget for 2013 was valued as following: $P = 5110 \pm 606$ Tg/yr, $S = 552 \pm 168$ Tg/yr, $L = 4668 \pm 727$ Tg/yr and $D = 1003 \pm 200$ Tg/yr (Young et al., 2013).

Non-urban surface ozone can be seen in Figure 1 for the months of December-January-February on the upper part; and for June-July-August on the lower part. As represented, the observations are concentrated in North America, Europe, and East Asia; beyond those regions, measurements are quite scarce but still it is considered that ozone concentrations are much lower in the Southern hemisphere (SH) than in the Northern Hemisphere (NH), presenting peaks, $[O_3] > 40$ppb, mostly in the months from September until February, which coincides with the spring and summertime in the hemisphere. For the NH elevated ozone concentrations occur in summer (Gaudel et al., 2018).

Many studies have predicted an increment in the tropospheric ozone burden due to the high population/high fossil fuel growth scenario happening in the future. Even with the increasing tendency to contemplate the use of revolutionary and efficient technologies and the solid compliance of the legal framework controlling global change and air quality that could result in a decrease or maintenance of the concentration of many greenhouse gases (GHG), the increment of tropospheric ozone is still predicted to occur (Akimoto, Sano, and Tomoda, 2018; Meul et al., 2018; Fu and Tian, 2019).

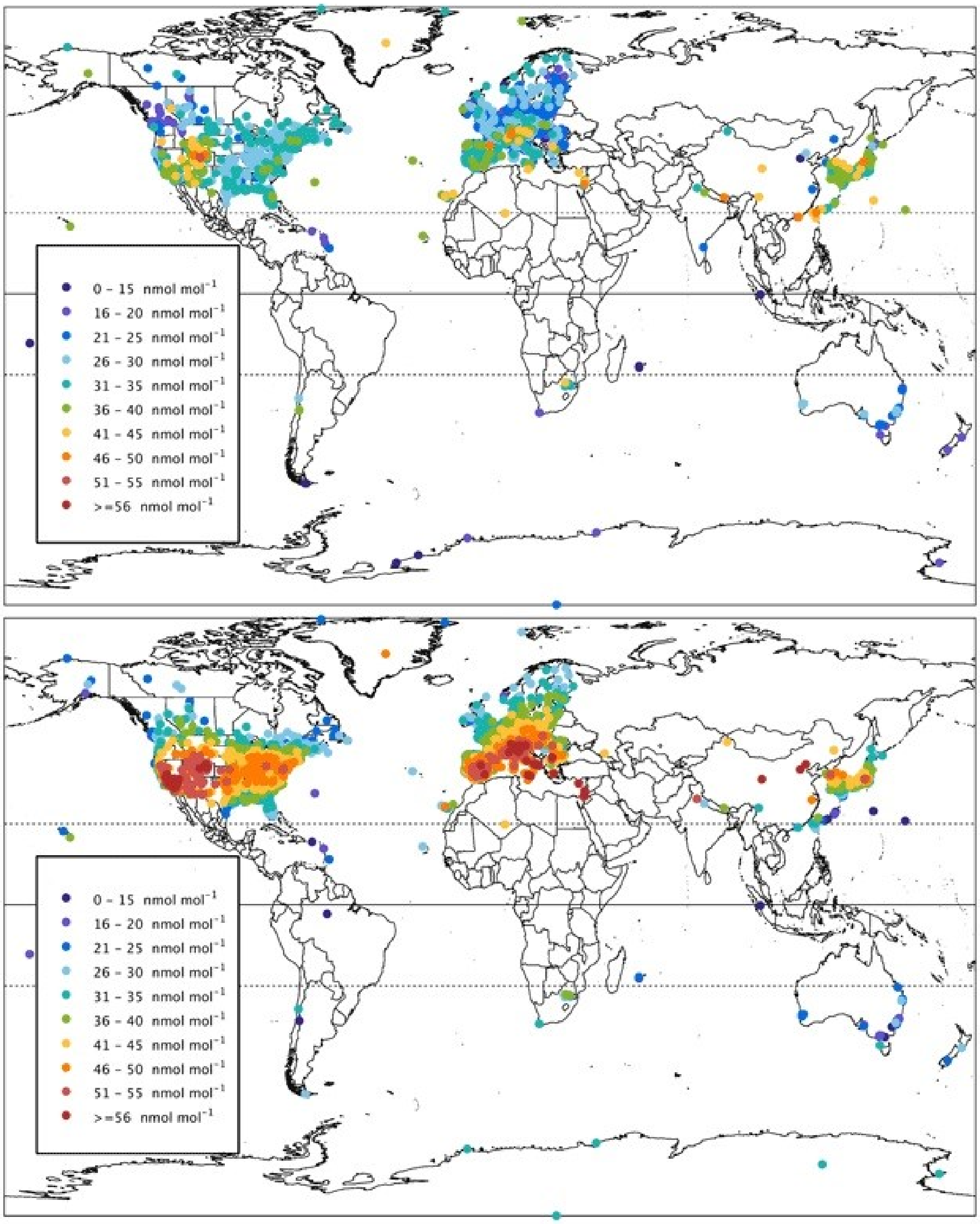


Figure 1. Daytime Ozone Average (nmol/mol) (Gaudel et al., 2018)

Consequently, tropospheric ozone can be transported from the stratosphere or can be formed under warm conditions and radiation. Nitrogen oxides (NOx) are its main catalyzers and Volatile Organic Compounds (VOC) its source of oxidation (Samson, et al., 2017). VOCs are a broad range of gaseous hydrocarbons and methane emitted by the industry, biomass burning, plants, or animals. They can be classified as biogenic -BVOC- (from forests, wetlands, lightning), anthropogenic -AVOC- (from transport, fossil fuels, solvents), non-methane -NMVOC-, among others.

In the tropospheric ozone cycle (Figure 2) there is a constant recycling of NO_X compounds via the RO_X-NO_X interaction which at the end potentializes tropospheric ozone formation. See equation from 1 to 4. When VOC-O_X (compounds with a high potential of photochemical O_3 formation as isoprene) are present in the troposphere they react with hydroxides (OH) forming new radicals, ROH· and R·

$$VOC - OX + OH \rightarrow R \cdot + ROH \cdot \tag{1}$$

They with oxygen molecules making peroxide radicals, $R(OH)O_2\cdot$.

$$R \cdot + O_2 \rightarrow \ RO_2 \cdot \tag{2}$$

$$ROH \cdot + O_2 \rightarrow \ R(OH)O_2 \cdot$$

This peroxide radicals react with nitric oxide (NO) producing nitrogen dioxide (NO_2).

$$RO_2 \cdot \ + NO \rightarrow RO \cdot + NO_2 \tag{3}$$

$$R(OH)O_2 \cdot + NO \rightarrow R(OH)O \cdot \ NO_2$$

Under a light dependent reaction nitrogen dioxide forms oxygen atoms that are highly reactive with molecules of oxygen forming finally ozone.

$$NO_2 + hv \rightarrow NO + O \cdot \tag{4}$$

$$O \cdot + O_2 \rightarrow O_3$$

Accordingly, O_3 formation or removal is determined by the ratio between VOC and NOx; three conditions can be differentiated according to Calfapietra et al. (2013):

- VOC-limited zone ($VOC/NOx < 4$): Situation happening in urban areas where the levels of NO_X are too high and there is not enough VOC to react with the nitrates to form O_3. Still, this stage is highly dependable on the type and quantity of BVOC available, as reactivities variety. If BVOC increase, the ratio moves toward the optimum O3 production condition.
- Optimum O3 production ($4 < VOC/NOx < 15$): Seen in the transition zone from urban to rural areas, in which the presence of vegetation and its BVOC emission are considerable. It is also referred to in the literature as Titration Effect and has been seen in cities in which NO_X controls laws have been imposed, for example in China or UK, presenting more often peeks of ozone formation after

the antipollution measurements have been established. The formation of intense limited-time-period episodes occurs, usually in days of extremely hot temperatures (Li et al., 2013; Calfapietra et al. 2013).

- NO_X-limited zone (VOC/NOx >15): Usually seen in rural areas or remote regions in which NO_X is relatively low, as the transport of contaminated air masses from the cities and industry locations is not possible. Characterized by a net O_3 removal happening at a small rate in a large proportion of the troposphere. In marine environments, the rate tends to be more rapid as a result of the participation of other agents like halogen atoms and radicals

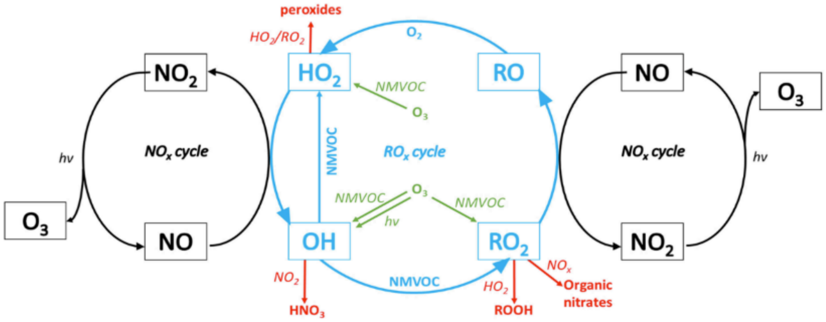


Figure 2. Formation ozone cycle.

Ozone creation through NO_X-cycle (black) interacting with RO_X-cycle (blue). Removal of ozone via methane (not displayed) or NMVOC (green) forming hydroxyl and peroxyl radicals for the terminating reactions of peroxides, organic nitrates, and nitric acid (red); hv, light. (Fitzky et al., 2019).

As well, ozone removal can happen via chemical loss or dry deposition. Chemical loss accounts to be four times bigger than dry deposition (4100 Tg y-1 against 1000 Td y-1) and it is mostly associated to the photolysis of O_3 and water vapor forming hydrogen peroxyl -HOX- and hydroxyl radicals -OH- (Stevenson et al., 2006), in the specific case of interaction with plants, it is referred as non-stomatal uptake or adsorption (Fares et al. 2007).

Terrestrial or marine deposition limits the lifetime of the ozone on the troposphere and happens as a reaction on the quasi-laminar boundary layer of a given surface, like leaf cuticles, leaf stomata, snow, man-made surface, and soil, among others (Zhang, Brook and Vet, 2002). Both surfaces with high-destruction rates (like vegetation due to the presence of humidity) and spatially extensive surfaces with low destruction rates are relevant to the global tropospheric ozone budget and air pollution (Clifton, 2018).

It has been accounted that stomatal uptake represents 45% of the total dry deposition on vegetation, presenting variation depending on the time of the year or the type of vegetation (Clinton et al., 2020). Despite this, other studies have reported nonstomatal uptake to play a minor role at least when they leave surfaces are not wet (Altimir et al. 2006; Calfapietra et al., 2009). Likewise, dry deposition on vegetation increases with stomata conductance, size of the canopy, and presence of waxes and salts and decreases with wind speed (Feng et al., 2017; Sun et al., 2016). In Figure 2 the processes contributing to dry deposition and its relation to the tropospheric chemistry, air pollution, the climate can be appreciated.

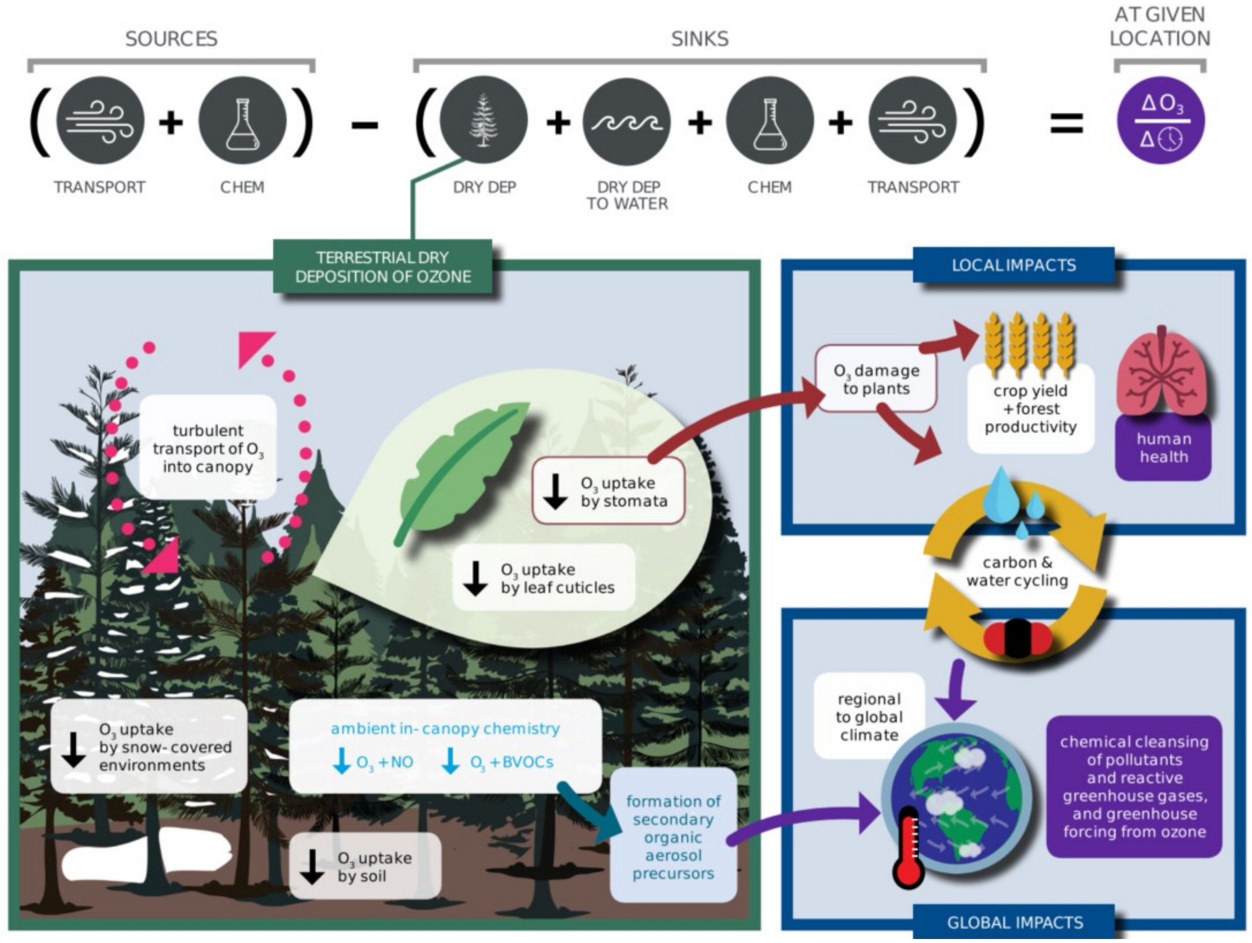


Figure 3. Dry deposition processes.

Dry deposition directs (red and blue) and indirect (purple boxes and arrows) impacts; downward black arrows represent ozone deposition pathways and blue ones represent intermediate stages (Clinton et al., 2020).

Turnock et al in 2018 calculated the changes in tropospheric ozone across 16 regions around the globe using a parameterization of several models used in the Task Force on Hemispheric Transport of Air Pollutants (TF-HTAP) using as precursors NO_X, CO, VOC, and CH_4. They found an arise between 1 to 8 ppb for 2050 at a global scale with special attention to titration effects processes that cannot be well modeled for possible future occurrences for example in regions like South Asia. The study made predictions based on the climatic estimates of the Intergovernmental Panel on Climate Change, in which climate will tend to be hotter with heatwaves occurring more often and lasting longer and with an increase in temperatures ranging from 1 to 4°C. Additionally, considering all Representative Concentration Pathways (RCP) which vary from very conservative to more optimistic future scenarios (IPCC, 2014).

2.2. BVOC emissions

Plants release more than 30.000 different types of BVOC consisting of terpenoids, green leaf volatiles, phenylpropanoids, benzenoids, and methyl esters trough leaves, roots, and flowers (Trowbridge and Stoy, 2013). They have several functions like **plant reproduction**, pollination, and fruit dispersal; **plant-plant interaction**, communication, and allelopathy; **plant defense**, indirect and direct against pathogens and herbivores; and **plant protection** against stress, thermotolerance, photoprotection, and antioxidant capacity -reducing the damage caused by ozone- (Peñuelas and Staudt, 2010; Fineschi and Loreto, 2012).

Their releases are influenced by complex and specie-specifics responses depending on physiological, functional, and stress factors, like biomass, leafage, drought, herbivory, pathogens, among others (Fowler et al., 2008). UV-B, temperature, drought, water scarcity, and species migration to northern latitudes or higher altitudes have been reported to be positively related to BVOC releases. Moreover, ozone has been stated as a positive factor for BVOCs emissions as it plays an important role in protecting the plants from oxidative stress, proving tolerance and detoxification abilities (Tiwari et al., 2016). Still, this response has demonstrated to be highly species-specific and multiple comebacks have been observed (Figure 4).

Temperature is one of the variables that sharply affects BVOC emissions. An increase of 30 to 35% is predicted to occur if global temperature rises 2-3°C; as this means not only warmer temperature with an effect on water pressure and resistance to diffusion at the leaf level but an extension in plant activity season and changes in the land cover resulting in even more BVOCS production. It is then expected that due to global change and the rising in temperature, isoprene emissions increase and not only during summer periods. (Peñuelas and Llusià, 2003; Pachauri et al., 2014).

Drought, like many other variables, affects emissions depending on the level of intensity; reducing production on severe events or increasing it on mild drought stress for isoprene and monoterpene

(Niinemets, 2004; Loreto and Schnitzler, 2010). Responses depending on the [CO2] have been negatively related to BVOC, as a response to the inhibition effect, in which at the leaf level emissions are uncoupled from the photosynthesis processes. Nevertheless, it is unknown if this is a direct response or if is there an underlying factor taking part (Velikova et al., 2009; Hantson et al., 2017). However, on a European Project intending dilucidated the roll BVOC would have on the European context, taking into account global change, the findings suggest a double in CO_2 concentrations will increase CO_2 fixation by photosynthesis, but this won't have an increasing effect on isoprenoids, which would remain unchanged or reduced (Scholefield et al., 2004).

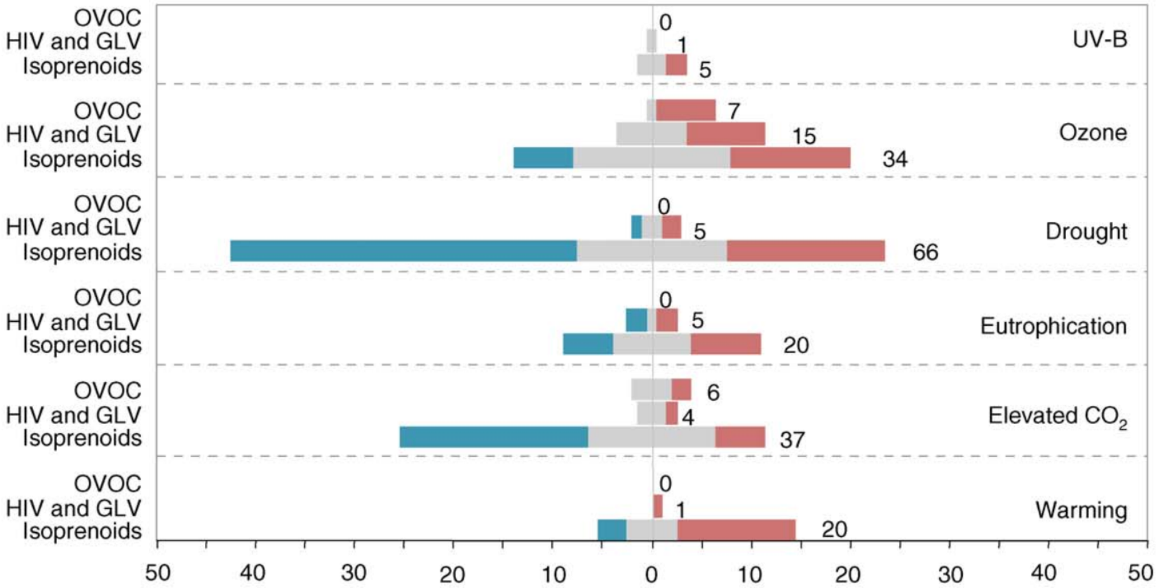


Figure 4. Long-term effects of factors related to BVOC.

The horizontal axis represents the number of publications reporting negative (blue), positive (red), or no significant (gray) change in emissions. Isoprenoids are isoprene, 2-methyl-3-butenol, monoterpenes and sesquiterpenes; HIVs and GLVs, herbivore-induced volatiles, and green leaf volatiles; and OVOCs, short-chained oxygenated BVOCs (Peñuelas and Staudt, 2010).

The most common way of classifying BVOC are in isoprenoids, which contains isoprene (C_{15}), monoterpene(C_{10}) and sesquiterpene(C_{15}), herbivore-induced volatiles (HIVs), green leaf volatiles (GLVs, C_6 aldehydes, and alcohols), and oxygenated volatile organic compounds (OVOCs), a heterogeneous group comprising various alcohols, aldehydes, ketones and specialized released by (stressed) plants and anthropogenic sources (Fitzky et al., 2019). Also, monoterpenes can be divided into light-dependent and light-independent. The most studied BVOC are isoprenoids as its abundance and OFP is bigger than the rest of BVOCs (Peñuelas and Staudt, 2010).

Sindelarova et al (2014) estimated the global present BVOC emission in 760 TgC/yr consisting of isoprene (70%), monoterpenes (11%), methanol (6%), sesquiterpenes (2.5%) and other BVOC species each contributing less than 10.5%. On the other hand, Hanson et al (2017) estimated isoprene and monoterpene in 400 TgC/yr and 30 TgC/yr, respectively. Ozone and BVOC have a cyclical process, as explained in Section 1.1, in which O_3 enhance VOC emissions to the atmosphere and in return ozone can be either again increased, as VOC take part of the reactions that form ozone, or decreased as they can be deposited via stomatal or non-stomatal uptake (Atkinson and Aray, 2013).

BVOCs differ in grade of reactivity and ozone-forming potential (OFP), being isoprene (largely released by vegetation) 22 times more effective than benzene (the most important AVOC), followed by monoterpene and higher terpenoids like sesquiterpenes and oxygenated VOC, being the last one the less frequent and reactive (Atkinson, 2007; Wagner and Kuttler, 2014). OFP is described as the grams of ozone produced per gram of VOC molecule and its formula was first developed by Benjamin and Winer in 1998, considering a biomass factor, the specific emission rate and the reactivity factor of monoterpenes (3.9 g O_3/g_{BVOC}) and isoprene (9 g O_3/g_{BVOC}) in 308 tree and shrub species in the California South Coast Air Basin.

According to Fares et al (2007), it is possible to classify BVOCs emission as high (above 20 µg /g h), medium (between 3 and 20 µg /g h), and low (between 0,1 and 3 µg /g h). Nevertheless, there can be many scale sin in which BVC can be classified, for example, Fitzky et al (2019) proposed additionally for monoterpenes and OVOCs, low < 2 and high > 5; for sesquiterpenes, low < 0.5 and high > 1.1; with medium categories in between. As well, Karl et al in 2009 presented a plant-specific emission of BVOC inventory at the European level for the use of this information in atmospheric transport models. There are therefore standardized conditions, 30°C leaf temperature, and 1000 $\mu mol/m^2 s$ photosynthetic photon flux density (PPFD) in which species are tested and its emissions are measured.

Isoprene presents the biggest size of the BVOCs which implies that in the gas phase of the ozone destruction reaction its rate of reaction is low, therefore it does not interact with O_3 and does not destroy it. Contrary to what happened to the other isoprenoid compounds (monoterpenes and sesquiterpenes), which in laboratory conditions, were the air is well mixed, the high-speed and the resident time is around minutes, there is a non-stomatal reaction around 46-25%. For monoterpene and sesquiterpenes the rate of reaction in the presence of ozone is around seconds and milliseconds, respectively due to their smaller size; implying the destruction of ozone that does not depend only on the stomatal conductance as is the case for isoprene-emitter species in which the non-stomatal reaction was around 5% (Fares et al., 2007).

Many tropical and subtropical species like eucalyptus (*Eucaliptus spp.*), most of the poplars (*Popolus spp.*) and oaks (*Quercus spp.*) have been identified as high isoprene emitters, corresponding to fast-growing plantations highly distributed worldwide (Laothawornkitkul et al., 2009; Fares et al., 2010). Monoterpenes have a lower reactivity factor than isoprene (3.3 g O_3/g VOC and 9.1 g O_3/g VOC, respectively) and have been found to destruct ozone jointly with sesquiterpenes and oxygenated compounds outside the leaves (Bonn and Moortgat, 2003). It is well-known monoterpenes and sesquiterpenes are main components of floral odors and hence related to the urban environment and parks (Farré-Armengol et al., 2013). Numerous woodland coniferous are considered higher monoterpenes emitters including Fagus sylvatica L., Quercus ilex, and several pines (Aydin et al, 2014; Kramer et al., 2010; Calfapietra et al., 2013). Likewise, Fraxinus excelsior, and *Tilia platyphyllos* are reported to be non-monoterpene and -isoprene emitters (Holopainen and Gershenzon, 2010).

Hanston et al (2017) modeled at the global scale the future isoprene and monoterpene release with special care of the emission-inhibit-effect high [CO_2] have at the leaf level. There was an overall decrement in emissions but still, the model was carried out without considering the implication it would take on the atmospheric chemistry, like transportation of ozone and second organic aerosols. At least for isoprene, the main driver of decrease was the anthropogenic land cover, as the pastures and agricultural expansions have typically low emission in comparison to woody plants.

However, at the regional or local level, where the presence of woody plants is representative for example is tropical forested areas or urban forests and where there is a large presence of big industrial cities, BVOCs can increase due to global change, specifically as a response to temperature, UV-B, intense heat and the related interactions (Pommier et al., 2018). Like Calfapietra et al described in 2013, an addition of BVOC to the urban environment, mostly of high OFP (isoprene), can change the ratio between VOC and NO_X and trigger ozone development; reinforced by strong oxidative stress conditions that are quite common in city trees.

After BVOC particles are emitted into the atmosphere they split producing intermediate products, via ozonolysis, called secondary organic aerosols (SOAs), that can be either deposited, condensed, or oxidize to CO_2 (Niu et al., 2017). They are in liquid, solid, or semisolid phase depending on its chemical composition, the relative humidity, and temperature, differing greatly. SOAs influence cloud formation and the reflectivity of the atmosphere; resulting in an alleviation of global warming due to the impact on the global energy balance (Shiraiwa et al., 2017).

Though, an increase in BVOC emissions can also worsen global warming as SAOs indirectly increase the concentration of other important GHG, namely methane, by depleting the level of hydroxyl radicals (OH), therefore, reducing the atmospheric oxidation capacity. Additionally, BVOC degradation indirectly entails tropospheric ozone formation, as O_3 is a sub-component of the interaction between oxides, peroxides, and nitrogen compounds. (Nishimura et al., 2015).

2.3. Stomatal conductance

Plant stomata are microscopic turgor-driven valves on the leaf surfaces of most land plants that regulate gas exchange between the leaf interior and the atmosphere. They are sensitive to the surrounding environment and internal reactions; therefore, their opening is related to the general plant status (Chater et al., 2017). Since their appearance more than 410 years ago they accelerated the hydrological cycle and the expansion of favorable climate zones for plant life as the plants could control the rate of evaporation from their photosynthetic structures (Berry et al., 2010).

Stomata are formed for two symmetric guard cells that allow CO_2 to be absorbed while regulating internal water loss and temperature with a big influence in continental climate and hydrology (Blatt et al., 2017). Furthermore, stomata are a key point for pathogen entry but also plant protection (Gudesblat et al., 2009).

Stomatal conductance (g_s) is regulated by the size of stomatal opening, stomata density, and by the capacity of water transport of the guard cells, which is intermediated through ion transport and regulation (Gamage et al., 2018). Stomata opening happens when guard cells accumulate mainly K+, Cl- and Mal salts solute as well as sugars; this promoted by light, temperature, breakdown of starch, and lipids (urban et al., 2017). In contrast, when closing the pores guard cells reverse this process by metabolizing or transporting the components to the apoplast, all this with the presence of ABA and changes in the pH. Other stimuli that can trigger closure include darkness, high CO_2 partial pressures, and the presence of pathogens (Linder and Raschke, 1992; Jezek and Blatt, 2017).

Besides, when plants detect stressor factors like O_3, drought, or salinity stress, among others, the stomata conductance diminish causing less transpiration and less CO_2 absorption for photosynthesis (Gimenez et al., 2013). Nonetheless, regarding stomata sensitivity toward CO_2, as the response is sensitive to pH, it is believed HCO_3- in solution is a ligand to it rather than CO_2 by itself (Bown, 1985). Many studies have demonstrated coniferous and in general specie with the complex foliar system have a higher stomatal capacity and therefore major potential to deposit pollutants (Freer-Smith et al., 2005).

As enlightened by Jezek and Blatt (2017), when trying to improve water efficiency and cope with water drought stress, manipulation of stomatal conductance seems to be an understandable goal, even being a complex problem in which carbon gain is a cost. Similarly, this could be translated to other kinds of stress, like ozone uptake, having as cost damage in the cellular structure (Loreto and Fares, 2007).

2.4. Plant-Water Relations

Water content in woody plants represents almost 50% of fresh weight; from this between 60 to 90% is located inside the cells and the rest on the cell walls. Even though plants transpire large amounts of water daily, to absorb CO_2 for photosynthesis which translates into growth, development, and productivity, it could be insufficient to buffer transpiration on sunny warm days. The water inside the cells have several direct and indirect functions and represents the general robustness of plants: cell and tissue turgor, transport of solutes, leaf cooling, participation in metabolic tasks like CO_2 reduction in photosynthesis, the solvent of many organic and mineral solutes (Gimenez et al., 2005).

The plant water status is the sum of the interaction of atmosphere, plant and soil factors, like soil water availability, atmospheric demand (influenced by climatic conditions), root system capacity for water absorption, stomatal responses, among others. It is usually characterized as Water Potential (ψ) which varies from zero to negative values and represents the water tension a plant experiences; the more stress a plant presents the more negative the value. Therefore, ψ is the free energy of water status which allows water movements in the soil-plant-atmosphere continuum (Neumann, 2011).

Under abiotic stress, the plant is exposed to sub- or supra-optimal levels of environmental conditions for example solutes, temperature, light, or water. Many of these conditions result in a decrease in metabolic functions with a clear decline in transpiration, photosynthesis, and growth if the stress is severe enough. As explained in section 1.3 under drought or ozone stress water potential presents similar metabolism reactions as the one stomata endure: the presence of ROS, ABA, and ethylene (Wilkinson and Davies, 2010). Consequently, any abiotic stress has a relation to water content as embolism can occur, and the malfunctioning in the xylem cause a reduction in water transport with the before named consequences (McDowell et al., 2008).

Stem Water Potential (SWP) is cited as a fit parameter to determine water status in plants, mostly in cultivars with big economic importance like wine or Fruit trees (Zhang et al., 2013). As the minimal water status in the plants is usually reached between 12:00 and 14:00 on sunny days, this measurement, usually called midday leaf water potential (ψMD) is highly used as an indicator of drought stress. Moreover, to reduce the effect of changing weather conditions, ψMD can be measured in leaves covered by darkened bags after a period of acclimation, usually, 30 min, which is called stem or stem xylem water potential in the literature (SWP or ψST). It is proposed to replace ψMD as it reveals more accurately differences in water status when soil condition is dryer and additionally, it has presented more correlation to stomatal conductance (Naor, 2004; Santesteban et al, 2019; Van Leeuwen et al., 2009).

In vineyards of Cabernet Sauvignon a scale of water constraint was published with the next values (Myburgh et al., 2016): none: SWP ≥ -0.60; mild: -0.60 ≥ SWP ≥ -0.85; moderate -0.85 ≥ SWP ≥-1.15; high: -1.15 ≥ SWP ≥ -1.40; and severe: SWP < 1.40.

2.5. Tropospheric Ozone at the leaf level

When ozone enters the leaf through stomata reactive oxygen components (ROS) are generated trigging a controlled programmed cell death, like the one happening on a pathogen infestation, called a hypersensitive response. Initially, there is an increase in Ca+ in the cytosol, and the formation of hormones like salicylic acid (SA), ethylene (ET), and jasmonic acid (JA) shoots up. It is well known that SA and JA signal defenses response in plants, including VOC emission (Pinto et al., 2010; Kangasjärvi et al., 2005). Consequently, SA triggers the programmed cell death, ET secures its propagation and continuing ROS formation and JA participates in the containment of cell death, as seen in Figure 5. Also, ROS impair photosynthetic enzyme activities, enhance respiration, and interfere with carbon allocation (Ainsworth et al., 2012).

At the functional level, O3 drops the photosynthesis capacity in plants by inhibiting almost every step of photosynthesis, declines the capacity of assimilate transport, and modifies carbon allocation directed to organs and buds. As it causes a reduction in stomatal conductance and the amount of intracellular CO2 the decrease at the global scale of gross primary production and carbon stock in plants and the increase in surface ozone is projected (Li et al., 2018; Zhou et al., 2018).

Ozone uptake can be made either by the stems, cuticles, and other external surfaces (called non-stomatal adsorption) and as reactions inside the apoplast after entering the leaf trough stomata (called stomatal absorption) (Fares et al., 2007). Both processes are affected by BVOCs emissions as they can destroy O3 in the immediate air of the leaf and reduce the volume of ozone that could enter the leaf. This alters the waxes and moisture content in the leaf boundary layer and thus increases non-stomatal adsorption. As well BVOCs can destroy ozone inside the leaf jointly with other antioxidant complexes. This is affected by stomatal conductance and the individual antioxidant capacity of each component, implying plant detoxification, indicating that plants can recover from oxidative stress (Calfapietra et al., 2013; Jardine et al., 2012). (Loreto et al., 2004).

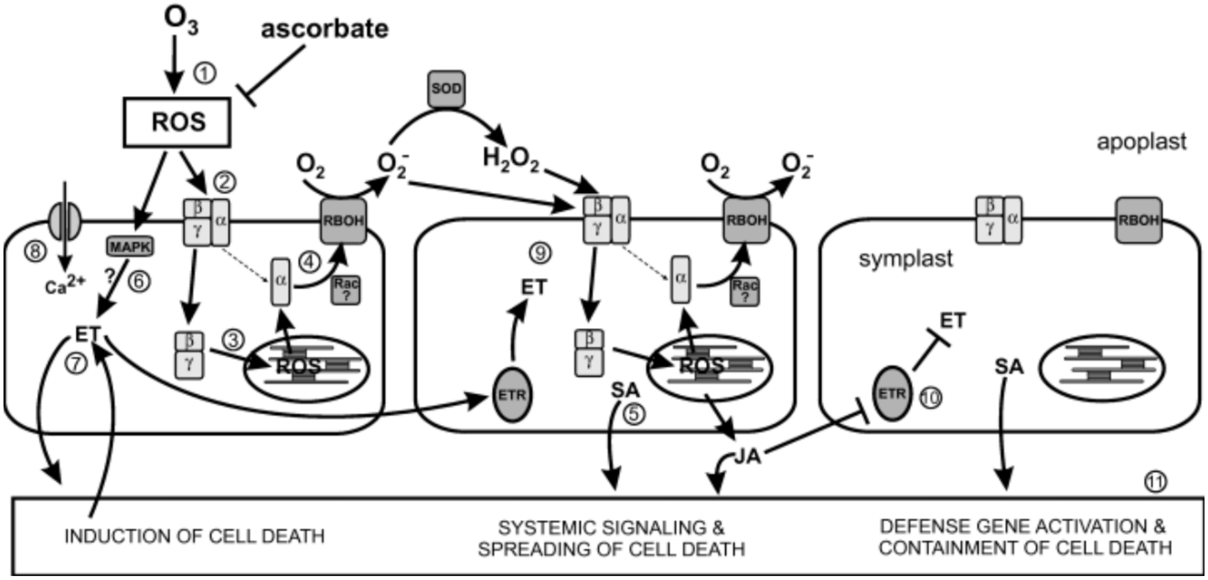


Figure 5. Ozone degradation in the apoplast (Kangasjärvi et al., 2005).

Besides, in 2018 Feng et al. suggested another easy-to-measure functional trait that is related to ozone uptake in plants: leaf dry mass per unit leaf area (LMA) (R^2 = 0.56). The team suggests three possible explanations for these results. The first one, plants with higher LMA have usually thick palisade mesophyll layers which could influence a dilution effect, in which the ozone load per unit leaf mass is lower as in plants with small LMA. Second, a cross-protection could be in place, as species presenting high LMA are associated to be more tolerant to different biotic and abiotic stress, there could be an overall capacity in plants to tolerate oxidative stress, being ozone uptake a part of this. Thirdly, this finding could indicate a dilution effect in which plants with higher LMA have more available space in the apoplast for ozone uptake, where the stomatal absorption occurs.

For instance, the increment in [O_3] from less than 10 ppb to more than 40 ppb after the industrial revolution has decreased gs by 13% and light-saturated photosynthetic CO_2 uptake (Asat) by 11%. Younger trees showed less sensibility to damage than older ones, and the possible cause is due to a cumulative effect of tropospheric O_3 uptake into the leave, which is the product of ozone concentration and time of exposure. Younger trees have not had the opportunity to remove ozone for a long period and therefore the damage inside the leave would not be harsh enough. This theory proposes that more important than the dose is the cumulative effect that trees endure when [O_3] > 40 ppb (Matyssek et al., 2007).

Likewise, it has been suggested cumulative ozone damage in gymnosperms is lower in comparison to angiosperms due to three factors: a lower average of gs in gymnosperms in comparison to angiosperms, 100 mmol/m²s, and 185 mmol/m²s, respectively; secondly, the faster water loss in angiosperms as their leaves are thinner, implying thickness is analogous to the water-bearing tissue; and the specific time of taxa diversification in angiosperms that coincide with a decreased atmospheric CO_2 (Klein and Ramon, 2019). Consequently, independent the environmental damage is related to gs; ozone damage is lessened if there is already another stress, like drought, as the stomata conductance decreases and therefore ozone uptake rate will be slowed down (Witting et al., 2007).

All studies presented in this section have been done under laboratory conditions, this is the case as ozone is a highly reactive molecule, that can be better understood firstly in controlled conditions, where the causation of factors can be discovered. Calfapietra et al 2016 discussed the use of two other methods that are used for ozone measurements, eddy covariance technique, and modelling approaches. The first one measures ozone fluxes at the ecosystem level over surface layers and is based on the turbulent movement of the air that transport mass and energy. Even if has been important for understanding tropospheric ozone movement and real interactions, it is suitable for the measurements of urban trees, as they are highly diverse and cannot specify interaction from individuals. The modeling approaches have the advantage of modelling different factors and scenarios but need to be either parameterized by laboratory or eddy covariance measurements and it usually tends to scarce attention to the physiological status of plants, are is highly diverse and not yet broadly understood.

2.6. Tropospheric Ozone in the cities

Environmental Services -ES- support, directly and indirectly, human's survival and lifestyle. Urban forests are considered to provide many ES, e.g., carbon sequestration, thermoregulation, water regulation, biodiversity, n, education, among others (Samson, 2017). Nonetheless, urban vegetation tends to have a harsher lifecycle compared to other natural forested areas like planted or natural forest and are perceived as a source of conflict, due to its multifunctionality. Accordingly, municipalities need to invest considerable amounts of money for their planning and management and all related activities (Ottitsch and Krott, 2005).

Urban trees are chosen by urban planners to select the most suitable species that can perform well under stress conditions like drought, de-icing, heat waves, air pollutants, small root volumes, among others (Sæbø et al., 2005). Contradictory, practitioners, municipalities and planners of urban spaces do not always select species considering scientific-research aspects like climatic adaptation or disease resistance, but on other aspects like type of ornamentation, origin (native vs. exotic), (lack of) supply from nurseries and demand from the customers (Conway and Vecht, 2015).

Because of climate change and several policies to deaccelerate it, the climatic conditions within urban environments will tend to be hotter, with longer drought periods, and with less presence of NO_X compounds. As explained in section 1.1 the before mentioned conditions create a ratio of $4 < VOC/NOx < 15$ that leads to ozone formation deeply dependable from other NMVOC sources, like BVOC from urban trees (Young et al., 2013).

On top, with an additional presence of BVOC with high OFP like isoprene (section 1.2), it is possible that due to all kind of stress urban trees endure daily ecological services, like mitigation of urban heat island and the absorption of air, soil and water pollutants, be diminished (Calfapietra et al., 2016). Policymakers are invited to make use of different tools to select species more adaptable with features like high O_3 removal capacity, O_3-tolerant, resistant to pests and diseases, tolerant to drought, salinity and non-allergenic (Chang et al., 2012; Manes et al., 2012; Novak et al., 2008; Novak et al., 2014; Sicard et al., 2018; Simpson and McPherson, 2011). This may help answer the question of whether the benefits of BVOC emission outweigh its potential to increase ozone in the atmosphere, with special concern in ozone uptake under drought conditions (Büker et al., 2012; Dunn-Johnston et al., 2016).

2.6.1. Species used in the Experiment

The selected species (Table 1) are commonly used in urban areas and they were selected to represent different types of BVOC emitter (Karl, 2009).

Table 1. Selected species for the experiment

Specie	**Type of BVOC**
Carpinus betulus	Low monoterpene and sesquiterpene emitter
Betula pendula	High sesquiterpene emitter
Fagus sylvatica	High monoterpene emitter
Quercus rubra	High isoprene emitter

2.6.1.1. Carpinus betulus L.

Also called European or common hornbeam, it is a common deciduous specie in the temperate Europe and Asia Minor region as a natural element of the understory of oak forests. In the germination and seedling phase, it requires enough amounts of light but in its adult state is shade tolerant. It has economic importance as its hardwood can be used for firewood, charcoal, and tool making. It can withstand coppicing and pollarding, but it is usually used either as an ornamental tree or cultivated ad coppice understory (Coart et al., 2005). It is a small-medium tree with a high of 20-25m that is known for leaving its brown leaves in winter and drop them in spring when the new one comes. It requires abundant soil and is tolerant of a range of soil types. Its altitudinal range varies from sea level to 700m, in Central Europe, 1000m in the Alps, and 1800m in Iran (Sikkema et al., 2016).

Stojnić et al (2016) studied the effect of drought stress in urban conditions for hornbeam and the English oak, *Q. robur*, in six-years-old individuals during August 2012 in Novi Sad, Serbia. The city has an annual mean temperature during the vegetation period of 18,3°C and annual precipitation of 647mm. The experiment counted with two sites that had a well-installed irrigation system and had a soil moisture content of 38.1 to 61.0% for the well-irrigated site and 12.9 and 13.8% for the non-irrigated one. Net photosynthesis and stomatal conductance were reduced under drought stress but only with statistical significance for the last one (40 mmol/m^{2}s vs 12 mmol/m^{2}s, for Q. robur; and 25 mmol/m^{2}s vs. 0.5 mmol/m^{2}s, for *C. betulus*), which denote stomatal conductance is more sensitive to drought stress, but still, the plant can continue photosynthesizing under mild and moderate drought stress.

Li et al (2016) also studied the response to drought stress on *C. betulus* and other four European species in an experiment in Germany carried out in June 2014 by withholding water from the plants over a variable number of days (from 7 to 56). The average temperature was 17.9°C. They reported a 1:1 relationship between xylem water potential at the onset of embolism and stomatal closure. It was found hornbeam is an embolism resistance specie with P50 = -3.79 MPa (a vulnerability value of xylem water potential at 50% loss of hydraulic conductivity due to embolism formation), with a high photosynthetic capacity. In which its max net photosynthesis (Amax) was 11.12 µmol CO_2/m^2s, maximal stomatal conductance (g_s *max*) was 160 $mmol/m^2s$, xylem water potential at 50% of maximum stomatal conductance (ψg_{s50}) was -2.18 Mpa, and Xylem Water potential at stomatal closure (ψg_{se}) was -3.27 Mpa. These characterize the specie as drought-tolerant, reaching a water stress response after 53 days of treatment, in comparison to 25 and 47, from the other tolerant species studied, *F. excelsior* and *A. campestre*, respectively.

Considering salinity, Zhou et al (2018) studied two-years-old *C. betula* trees, as in recent years the species has been introduced to China as it shows a strong adaptation in several European landscapes. The authors compared their performance under six salinity ranges (from 0 to 85 mM of NaCl concentrations) during 14, 28, and 42 days. In Nanjing, China. The city counts with an average annual temperature of 15.7°C and an annual rainfall of 1047 mm. It was found hornbeam was significantly affected under 51-85 mM treatments for its growth and gas exchange parameters, chlorophyll content, and relative water content. However, for the low salinity stresses (17-34 mM) the specie did not present significant changes, showing tolerance for these levels of stress. Additionally, the number of osmotic adjustment substances and the antioxidant capacity of the tree increase after 14 and 28 days, but later decrease with increasing salinity gradients afterward. Relevant variables ranged from 0mM to 85mM in the next way: gs from 76,67 $mmol/m^2s$ to 44.67 $mmol/m^2s$, respectively; A from 6.47 $mmol/m^2s$ to 0.50 $mmol/m^2s$, respectively; and Na content in the leaves from 0.27 to 5.92 mg/g, respectively.

Regarding ozone uptake, the study by Marzuoli et al (2018) described hornbeam as highly tolerant for ozone. The experiment consisted in 4 levels of ozone (-40% ambient O_3, -5% ambient O_3, +30% ambient O_3 and +75% ambient O_3, which had an annual average in 12 h [O_3] ppb of 26, 41, 50 and 59, respectively for 2012) plus two levels of nitrogen fumigation (none and +70 Kg N/ha yr) to explain the relationship between this two factors. Ambient ozone concentrations varied between 2-70 ppb. Trees growing in the highest ozone concentration increased their stem biomass while their root biomass presented no change. On the other hand, the interaction between O_3 (75% fumigation of O_3) and nitrogen showed a significant decrease in 11% growth and a non-significant decrease in gs. Additionally, N showed an increase in g_s for all treatments, even with the biggest [O_3], representing and alleviation to ozone stress in the specie.

Conforming to Karl et al (2009) C. betulus is a low monoterpene and OVOC, and low sesquiterpene emitter, with 0.1 $\mu g/g_{DW}h$, 2.0 $\mu g/g_{DW}h$ and 0.1 $\mu g/g_{DW}h$, respectively (Karl et al., 2009). In 2014, Aydin et al., measured the BVOC emission from 31 tree species in Turkey. They found the European hornbeam a low emitter from all BVOC types, with a BVOC average of only 0.16 ± 0.14 $\mu g/g_{DW}h$ (based on dry foliage) and 12.5 ± 11.5 $\mu g/m^2h$ (based on leaf area).

2.6.1.2. *Betula pendula* Roth

A deciduous species that belongs to the Betulaceae family with distribution throughout the northern temperate region and a clear climatic tolerance, bearing for example snow and mean winter temperatures of 20°C but not droughts of the Mediterranean region. Birch is highly used as a source of hardwood in northern Europe (Beck et al., 2016). Moreover, it is a pioneer in the forest recently cleared, in gaps left by canopy trees and in habitats climatically unsuitable for other tree species. It usually grows until 20 m high but can have a max of 30 m with a life expectancy from 90 to 100 years. It needs soil with pH variation from 5.5 to 8 (Atkinson, 1992).

Vaz Monteiro et al (2016) classified the *B. pendula* as a moderate drought-tolerant specie, as after two induced drought and recovery cycles, within 3 months, it could rapidly (6 days) recover from non-watering conditions. Additionally, Christensen-Dalsgaard and Ennos (2012) found that the tree under cyclically droughted conditions presented a stronger, stiffer stem and changes associated with mechanical properties as a response to drought acclimation. As well, Thitz et al (2017) found B. pendula presented an increase in glandular trichomes production under drought stress implying an adaptation of the water economics with effects on nonstomatal transpiration.

Aspelmeier and Leuschner (2004) reported that after 11 weeks of drought-stress birch trees reduced their stomatal conductance between 70 and 90%, but these decreases were not immediately followed by a decrease in leaf water potential nor by a decrease in net photosynthesis. Midday leaf water potential was significant after the fourth week of drought with a range between -1.6 and -1.9 MPa.

Regarding, salinity, Zhao et al (2014) reported intra-variation in response (basic stem diameter, tree high, and mortality) from *B. pendula*. Showing a significant resistance and adaptability to salinity from salt-tolerant populations coming from Kazakhstan established in China. Besides, Percival and Henderson (2002) stated *B. pendula* showed a recovery period after 4 weeks for chlorophyll fluorescence and 6 weeks for CO_2 assimilation after a salinity induced stress of 6% of NaCl applied to the foliar system. This tendency was no different from the other 6 studied urban tree species.

Łukowski et al (2020) recommended birch as a specie that can help to mitigate air pollution, as it was the specie that absorbed the most particulate matter (PM) inside the leave followed by *Q. robur* and *Tilia cordata*. Additionally, the authors speculate the PM for *Q. robu*r and *B. pendula* was mainly accumulated in the denser trichome layer and along the venation, as in *T. cordata*, which presented the lower rate of absorption, presented a smooth leaf surface with only small clusters of hair in the abaxial side of the leaf blade.

When exposed to elevated ozone levels trees are reported to experience different responses depending on the concentration and duration of exposure. For example in a 10 weeks experiment under concentration ranging from 60 to 120 ppb there is a general stimulation of growing in foliage area and stem area but under concentrations above or 240 ppb, there is a decrease in leaf, aboveground, root and total biomass and photosynthetic rates and an increase in leaf thickness; this experiment was done under laboratory conditions in 2-year-old trees with fumigation of 10 h/d, 7 d/wk (Wittmann et al., 2007). Additionally, Yamaji et al. (2003) report an increase in growth, a decrease in stomatal conductance, late-season photosynthesis, and a foliar imbalance, among others, for ozone of 1.5-1.7 x ambient ozone. Results supporting a decrease in the general functions of B. pendula has been described by Hartikainen et al., (2020) and Manninen, et al., (2009).

Likewise, Dai et al. (2019) reported that under non-stressed conditions, stomatal conductance was positively stimulated by N but not affected by O_3. Additionally, no effect on stem cross-sectional was found. The authors studied the effect of N on the ozone flux in birch in a two-year experiment in three-year-old individuals. The study was done using solar domes located in Bangor, UK, where the fumigation was done only in the growing season, the 24 mean ozone concentration ranged from 53-66ppb, the average air temperature was 19.1°C and mean daylight 528 PAR.

Moreover, in 2004 Uddling et al. found that in birch juvenile relative biomass fluctuation, as a response to ozone, was more related to stomatal uptake (stomatal conductance) than to external ozone concentrations. The maximal stomatal conductance they reported for birch varied between 160 and 220 mmol/m^{2}s.

An increase in 0.8-1°C in temperature and 1.3-1.4x ambient O_3 concentration shown to decrease gs and increase BVOC emissions in B. pendula under the growing season. However, an effect due to an increase in O_3 solely did not provide an increase in BVOC, which is in line with a previous study of Vuorinen et al (2005). On the contrary, only an increase in temperature accounted to greatly increase sesquiterpene from 0.01 to 0.06 ng/cm^2 h. This BVOC increase seems to be independent of stomatal conductance but as a partial consequence of available substrates due to improved photosynthesis, as a response to an elevation in temperature. (Hartikainen et al., 2012).

In line with Karl et al (2009), birch is a medium monoterpene and OVOC and a high sesquiterpene emitter, with the next values: 3.0 µg/g_{DW} h 2.0 µg/g_{DW} h and 2.0 µg/g_{DW} h. Moreover, a study in which birch trees were fumigated with TiO 2 to check the ability of the specie to remove pollutants from the atmosphere described a high BVOC emission (monoterpenes, 1.4±0.3 ng/cm^2 h; and sesquiterpenes, 1.2±0.2 ng/cm^2 h), a g_s reduction (from 0.45 ± 0.21 mol/cm^{2}s to 0.11 ± 0.02 mol/cm^{2}s) and an intracellular presence of the pollutant (Räsänen et al., 2017).

***2.6.1.3. Fagus sylvatica* L.**

The European beech is a deciduous broadleaf tree that belongs to the natural vegetation in European forests. Under moist conditions is very competitive and can displace other species, like oaks (*Quercus spp.*). On average *F. sylvatica* reaches 30-35 m height and lives up to 250 years. Its wood is vastly used for furniture in Europe and it is usually harvested at the age of 80-120 years (Von Wuehlisch, 2008).

However, under drier conditions, in the south of Europe for example, or middle Europe during extremely hot summers, the specie is replaced for other drought-tolerant species or it presents a decrease in performance, respectively. For instance, under summer drought episodes in Germany from 1990-1994, beech presented a decrease in gs, around 100 mmol/m^{2}s vs 300 mmol/m^{2}s, for the non-stressed vs drought stress episodes; a lower average in midsummer gs in comparison to *Quercus petrea*, 256 mmol/m^{2}s and 352 mmol/m^{2}s, respectively; and a leaf water potential of -2.2 MPa as threshold representing a loss of hydraulic conductivity (Backes and Leuschner, 2000).

As explained before, *F. sylvatica* is susceptible to drought stress, waterlogging and flooding, presenting embolism, a decrease in growth and reduction in nutrient uptake capacity, as a response to a decrease in gs and soil water potential. These conditions under a global change scenario may predict an unfavorable adaptation capacity of beech, which also does not benefit especially from an increase in Carbon Dioxide concentrations, as is the case of other species (Geßler et al., 2006).

Nevertheless, Leuschner et al. (2019) reported European beech to be a specie that faces drought by adapting biochemical and physical internal process, besides stomatal conductance. For example, it can adjust osmotic concentrations, not depending entirely on CO_2 stomatal uptake. However, the authors stated that it also has stiffer walls which make the specie less tolerant to stress than other species, like for example *C. betulus*.

Matyssek et al. (2010) found a reduction of 44% in whole stem growth in adult beech trees exposed for eight years to elevated O_3 (2x and 1x ambient ozone) in a free-air study in Germany. They found that at the leaf level the impact of O_3 on trees was reduced as a response to stomatal closure induced by drought stress in 2004, meaning a slightly decrease in ozone uptake, even though even if in that year ozone levels were 41% greater than the rest of the humid years.

Regarding the interaction between ozone uptake and drought stress on the field, Kühn et al (2015) reported growth on *F. sylvatica* was more affected by drought than by ozone in nine forests across Germany from 2010 to 2012, with a significant reduction on the radial stem increment. This study considered the ozone concentration present and did not induce it. Additionally, Nunn et al (2005) did an experiment in the lab and the field and found trees in the lab show more sensitivity to ozone, with higher uptake and slower flux detoxification capacity, while the older trees on the field showed lower stomatal conductance but more ability to detoxify ozone inside the leaves.

Pearson and Mansfield in 1993 stated that under 50 days induced drought stress ozone fumigation decreased the response in stomatal resistance, in comparison with well-watered trees. Additionally, on well-watered trees, ozone fumigation showed an increase in stomatal resistance. Nevertheless, this means, difficulties in the water economy for the ozone-drought stressed but may have more ozone uptake capacity. Regarding the non-drought but ozone stressed trees, there was a reduction in CO_2 uptake. The experiment lasted 50 days and the trees were fumigated with concentration from 60 to 120 ppb.

However, in 2008, Gerosa et al also studied the interaction between ozone and drought in beech and pedunculate oak (*Q. robur*) in a south Alpine region with the treatment of three levels of ambient ozone (50%, 95% and 100%) and water stress (watered vs. non-watered). They found beech to be more ozone sensitive with earlier and heavier decreases in growth, performance, and leaf injuries, for the 100% ambient O_3 levels, magnified in the non-watered treatment. The study was developed in 2004 and 2005 and the maximum O_3 and accumulated ozone over a threshold of 40ppm in 2005 were 153 ppb (in June) and 8636 ppb/h (in July). The species presented water vapor deficit (VPD), which determines the progressive closure of stomata, of 1.8 Kpa for *F. sylvatica* and 2.1KPa for *Q. robur*, and a seasonal ozone uptake of 33.63 mmol O_3/m^2 and 78.40mmol O_3/m^2, respectively for 2005.

According to Karl et al (2009), the standard emission potential for beech is 21.1 $\mu g/g_{DW}$ h for monoterpenes, 2.0 $\mu g/g_{DW}$ h for OVOC, and 0.1 $\mu g/g_{DW}$ h for sesquiterpene, meaning it is a high monoterpene emitter and a low OVOC and sesquiterpene emitter. Likewise, Šimpraga et al (2011) reported BVOC emissions for beech under an 18 days drought stress in the growing season, in which monoterpene increase sharply (up to 410 $\mu g/m^2h$) coinciding with a decrease in net photosynthesis and stem growth, and then a decrease as the stress progressed, coinciding with no more growth of the stem, therefore not having enough resources for the allocation of BVOCs (95 $\mu g/m^2h$).

2.6.1.4. Quercus robur L.

Also called pedunculate or English oak, it is a common deciduous broadleaf tree species in Europe with a distribution from Scandinavia to the Iberian Peninsula. It has a great similarity, overlapping their distributions with *Q. petrea*. The tree has an immense cultural significance for people through Europe, as since ancient times its timber, bark, fruits have been used for fuel, livestock, tanning, and construction. It can reach 1000 years old and can be managed in a plantation as coppice or as high forest. Its natural habitat temperate deciduous mixed forests where they show a large ecological amplitude in which it can behave as a pioneer species and when it reaches maturity leaves enough light to pass through its canopy for other species to colonize the understory. It can reach 30m height and 1m diameter. Recently it has been used also as an ornamental tree (Eaton et al., 2016).

Laffray et al (2018) studied the effect of salinity in *Q. robur* and found that seedlings presented a decrease in leaf biomass of 55 and 75% when growing under treatments of salinity conditions of 50 and 100 mM

NaCl concentrations respectively and a reduction in stem length and root biomass of 84 and 175%, respectively for the 100 mM treatment. Also, non-significant decrease in water content with changes in ion balance was recorded.

Concerning drought stress, Früchtenicht et al (2018) found English Oak to show the earliest and strongest response to drought regarding leaf water content (lower than 76.25%), sap flow and predawn water potential (below -3 MPa) against *Q. ilex* and *Q. pubescens* in field conditions in Frankfurt, Germany. Measurements were done on 9 years-old individuals during the summer months in 2014 and 2015. Additionally, the authors reported a significant diminution in net photosynthesis and stomatal conductance of almost 0 µmol/m^{2}s and 10.08 mmol/m^{2}s, respectively, in severe drought. Gieger and Thomas (2002) reported a midday leaf water potential of -3.5 Mpa for *Q. robur*, with a resulting loss of 33% hydraulic conductance in trees under drought stress, which was equivalent in maximal stomatal conductance to ~290 vs ~100 mmol/m^{2}s, for control and drought stress, respectively. Moreover, Vaz Monteiro et al (2016) classified *Q. robur* as low drought tolerant as after drought stress, it could not recover and achieve a normal performance.

The English Oak is high isoprene and low monoterpene, OVOC and sesquiterpene emitter with 70 µg/g$_{DW}$h, 0.1 µg/g$_{DW}$h, 0.2 µg/g$_{DW}$h, and 0.1 µg/g$_{DW}$h, respectively under standard conditions (Karl et al., 2009). In a study of Van Meening et al (2016), genetical identical Q. robur individuals were measured in 3 different places in Europe, Slovenia, Denmark, and Germany, during the vegetative phase (May to July, with a monthly average temperature in those months of 11.7-21.3°C) with the purpose to identify differences in BVOC emissions depending on the site. It was found BVOC decreased in the trees that endured damage by frost events. Emissions of isoprene were significantly smaller than in other studies, 0.65-10.38 µg/g$_{DW}$h, with gs and A ranging from 83-730 mmol/m^{2}s and 2.5-7.0 µmol CO$_2$/m^{2}s, respectively.

As explained in Section 3.1.1.3, Gerosa et al (2008) found the English oak to be ozone resistance under ambient ozone concentrations and non-watered conditions. Another studied in this direction was made in 2017 for *Q. robur* along with other oak species, *Q. ilex* and *Q. pubescens*. Two-year-old-seedlings were fumigated ~12 h/day with 1, 1.2 and 1.4 x normal ozone concentration (35.1 ± 1.0, 43.0 ± 1.2, and 49.0 ± 1.3 ppb) for 5 months (June to October 2015) in ozone free-air controlled exposure facility, under other water availability treatments (water stress -WS-, mid-watered -WM-. and well-watered -WW- consisting in 1.2, 0.6 and 0.12 L water/day, respectively). The English oak showed a significant diminution in biomass growth (a critical level was recorded as a 5% decrease) for the WS treatment (35 g vs. 20 g, for WW vs. WS) under normal average ozone conditions with a sharp decline in g_s, as expected, as under drought stress the specie prefers to close stomata before dealing with low water potentials (Hoshika et al 2017).

3. Experiment

3.1. Materials and Methods

Twelve individuals of four tree species were potted in May 2019 in 7-liter pots with well-drained soil in the greenhouse in Tulln, Austria. Two weeks before enclosing the trees in the gas chambers the trees were moved to a nearby greenhouse in Vienna. Drought and salt treatments were started 10 days before the gas measurements. Drought stressed trees (d) were kept at 5% volumetric water content, whereas the control (c) was held well-watered at 100% field capacity with 13.4% volumetric water content. Salt stressed trees (s) were infused with 5L of 50mM NaCl two and one week before the gas measurement and re-watered every second day. 24h before enclosing the trees into the gas chambers, they were rinsed wioth water to remove dust and finger-prints and moved to a climate chamber (Fitotron, Weiss Gallenkamp, UK) at 25°C, 60% rH and 300µmol/m²s PAR (photo…etc.) to adapt to the air temperature inside the gas chamber.

3.2. Data collection

The measuring campaign took place in June and July 2019. We measured O_3 and CO2/H2O gas fluxes, SWP and Na and Cl leaf content. The trees were enclosed in gas exchange cuvettes of 10 L capacity. Each tree was pre-fumigated with $[O_3]$ between 75 -170 ppb for 30 min before measurement. Three of the cuvettes were used for plant measurement and the one left was used as a reference, remained empty. Each day six trees were measured, three in the morning and three in the afternoon, one tree per chamber. For avoiding selection bias, the tree species were randomized. After being fumigated and monitored in the chambers, the tree leaves were cut off and their fresh weight, leaf area, dry weight, and chloride content, were examined individually. The following variables were measured:

- Leaf Temperature – LT (° C)was measured using a thermocouple directly on the underside of a leaf located in the middle of the tree during the gas exchange measurements.
- Transpiration rate - E (mmol/m²s): Using the *CIRAS-3 SC CO_2/H_2O Gas Analyzer*, it was calculated from the next equation:

$$E = \left[\frac{W \times (e_{out} - e_{in})}{(P - e_{out})}\right] \tag{5}$$

Where *W* is the mass flow of air entering the cuvette per unit leaf area, *e_{in}* is the partial pressure of water vapor of reference air supplied to the cuvette, *e_{out}* is the partial pressure of water vapor in the air inside the cuvette, and *P* is atmospheric pressure (PP Sytems, 2018).

- Stomatal Conductance – gs (mmol/m²s): Using the *CIRAS-3 SC CO2/H2O Gas Analyzer*, it was calculated from the next equation:

$$g_s = \frac{1}{r_s} \times 10^3 \left(\frac{mmol}{mol}\right) \tag{6}$$

Where r_s represents stomatal resistance and is explained in the next equation, e_{leaf} is saturated water vapor pressure inside the leaf at a reference temperature, e_{out} is the partial pressure of water vapor in the air inside the cuvette, E is transpiration rate, *P* is atmospheric pressure, and r_b is the boundary layer resistance to water vapor (PP Sytems, 2018).

$$r_s\ (m^2\ s\ mol^{-1}) = \left[\frac{(e_{leaf} - e_{out})}{(E\ \times (P - \ (e_{leaf}\ +\ e_{out})/2))}\right] - r_b \tag{7}$$

- Ozone conductance - g_{O_3}(mmol/m^{2}s): It was calculated according to Fares et al (2008) where ozone conductance represents the deposition of ozone in the plant (R1), the ozone loss on the walls of the chamber (R2), and the product of the gas-phase reactions of ozone with BVOC (R3). These last two depositions were removed from the calculation as R2 was not considered in the experiment: ozone uptake was obtained from the difference of outgoing ozone from a chamber with a tree inside and the outgoing ozone from a chamber without plant inside. As well, R3 was not considered, as there was no measurement of BVOC in this study. Additionally, as found by Fares et al (2008), gas-phase reaction would only be significant for F. sylvatica and B. pendula, as they are mono- and sesquiterpene emitters.

$$g_{O_3} = \left[\frac{F}{LA} \times \frac{O_{in} - O_{out}}{O_{in}} - R_2 - R_3\right] \tag{8}$$

Where *F* represents air flow, *LA* is the leaf area, O_{in} represents O_3 concentration entering the cuvette and O_{out} represents O_3 concentration exiting the cuvette (BMT MESSTECHNIK GMBH, 2014). Ozone was generated using a the *Certizon C25* ozonizer from Sander (Erwin Sander Elektroapparatebau GmbH, 2016).

- Net Photosynthesis – A (µmol/m²s): Using the *CIRAS-3 SC CO2/H2O Gas Analyzer*, it was calculated from the next equation:

$$A = -\big[\big((C_{out} - C_{in}) \times W\big) + (C_{out} \times E)\big] \tag{9}$$

Where C_{out} represents CO_2 concentration exiting the cuvette, C_{on} represents CO_2 concentration entering the cuvette, W is the mass flow of air entering the cuvette per unit leaf area, and E is transpiration (PP Sytems, 2018).

- Stem water potential – SWP (MPa): After gas exchange measurements, one leaf was selected from the tree, was covered with aluminum foil and left in a plastic bag for 30 minutes. Later SWP was measured using a pressure bomb as explained in Williams and Araujo (2002).
- Leaf area – LA (cm^2): After gas exchange measurements were done, all leaves of the tree were cut, excluding the brown ones, and scanned. Posterior, the images were analyzed using the software *WinFOLIA 2014a*.
- Ozone uptake - ΔO_3 ($\mu g/m^3$): Using the *Ozone Monitor BMT 932* it was calculated from the next equation:

  $$\Delta O_3 = [O_{in} - O_{out}] \tag{10}$$

  Where O_{in} represents O_3 concentration entering the cuvette and O_{out} represents O_3 concentration exiting the cuvette (BMT MESSTECHNIK GMBH, 2014).
- Ozone uptake per leaf area - ΔO_3 ($\mu g/m^3 cm^2$): As appreciated in equation 9 but corrected with the leaf area of each tree (LA):

  $$\Delta O_3 = \left[\frac{O_{in} - O_{out}}{LA}\right] \tag{11}$$
- Ozone losses - ΔO_3 (%): Taken from Fares et al. (2007) where ozone is displayed as the percentage of uptake:

  $$\Delta O_3 = \left[\frac{O_{in} - O_{out}}{O_{in}}\right] \tag{12}$$
- Chloride Content – Cl (mg/g_{DW}): After gas exchange and leaf area measurements were done, 0,5 g of fresh weight leaves where shredded using liquid nitrogen in a hand mortar. Later, the powder was added to a 25 ml distilled water and left for 1 h on a shaker. Subsequently, it was filtrated through a filter paper following a final analysis in an ion chromatograph, *881 Compact IC pro – Anion*, and this supplement: *Autosampler: 858 Professional Sample Processor*.

3.2.1. **Gas exchange cuvette**

The chamber was a 10 L oven bag which can maintain the gas inside an was easy to manipulate. For avoiding low irradiance, the lamps that were located on the top of the chambers were covered with an aluminum layer of 50 lengths, to improve reflection also on the sides of the plants. Furthermore, the system was constructed with tubes and connectors made of inert material, like Polytetrafluoroethylene

(PTFE), and all the surfaces that could react with O_3 or VOC within the track in which the ozonated air was flowing were covered with Teflon tape. All measurements were performed at 1000 µmol/m² s.

As explained in section 3.2, one chamber was not used for tree measurements but as an ozone reference, and before connected to the BMT, a 1L/min valve was previously installed. Additionally, as four outlets were connected to the *CIRAS* a relay module was used with four mechanic valves in which every 20 minutes one of the valves was opened and the rest closed. See Figure 7.

Firstly, an 80 L/min pump vacuumed air from the exterior of the building. This air was dehumidified at 5°C and later cleaned in a charcoal filter. After, the air was divided into two channels, one of them with a 1L/min flow valve connected to the ozone generator (which function properly with a maximal flow of (L/min) and the other one linked afterward again to this fumigated air and separated into five channels, one directed to the *CIRAS-3 SC CO2/H2O Gas Analyzer* as a reference with a valve of 1L/min previously installed, and the four remaining to the four chambers, also with valve previously installed (with a max. flow of 10L/min but a real one of 7.88L/min, see below), each of them with four outlets: one for overflow, one for temperature, one for ozone measurements directed to the *Ozone Monitor BMT 932* and the other aimed to the *CIRAS* for CO_2 and H_2O measurements.

Each chamber counted with a flow of 7,88 L/min flow and the safety O_3 channel with 1,65 L/min. The chamber flushing time was calculated using the following equation from Niinemets et al. (2011), where a time of $4\tau_c$ is needed for 94% of full system response, in this case: 3 minutes and 30 seconds.

$$\tau_c(minutes) = \frac{\ln 2}{F/V} \tag{13}$$

Where τ_c is the chamber flushing half-time, F is the flow rate through the system and V is the chamber volume. This equation is based on ideal turbulent mixing in the chamber without the plant, nevertheless, as the volume of each chamber was 10 L, a relatively small one in comparison with other studies, the steady conditions should be reached on this time (Calfapietra et al., 2016).

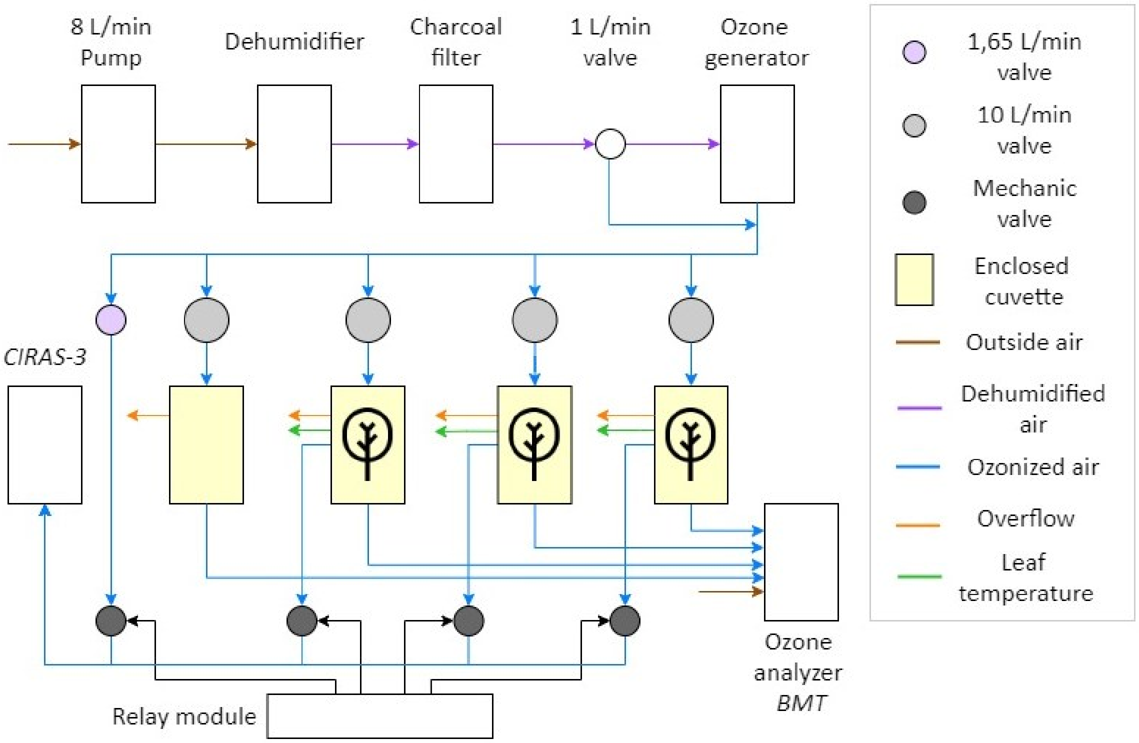


Figure 6. Enclosed system for gas exchange measurements

3.3. Data analysis

In each specie, an Analysis of Variance (ANOVA) followed by Tukey's test was performed contrasting drought and salinity treatments against control treatment. Additionally, the analysis of correlation was performed between ΔO_3 and *gs, gO₃,* and *SWP* individually for all species. The analysis was done in *R*, for linear, logarithmic and exponential relations, and choosing the one with a significance p_value < 0,05 and the bigger R^2.

4. Results

4.1. Gas exchange and related measurements

From Table 2, it can be appreciated that trees growing under salinity and drought stress presented lower performance in comparison with the control treatment, as expected. Nevertheless, the statistical significance difference for the variables within the drought vs. control comparison were: SWP and $\Delta O_3(\%)$ lower for all species. Additionally, g_s was lower for all species but *C. betulus,* g_{O_3} and *A* only for *B. pendula* und *F. sylvatica*, and ΔO_3 (µg/m^{3}cm^2) only for *B. pendula*. For the comparisons regarding only salinity and control, *Cl content* was lower in all species but Q. robur, SWP only in *C. betulus,* and ΔO_3 *(%)* in *F. sylvatica*.

It is important to mention that the species per treatment measured in the experiment varied, between 4 and 2, with less individuals from F. sylvatica, as many individuals died under the drought stress treatment. For a better understanding, a graphical representation of the variables is also displayed in Figure 8; however even if no statistical differences were found between treatments x species, when compared all data together, the graphical representation could show important trends.

4.2. Correlations for Ozone Uptake

In order to identify if the before mentioned variables showed a relation among ozone uptake for the comparison of drought vs. control, that resulted more significant according to data shown in Table 2, individual correlations of ΔO_3 (µg/m^{3}cm^2) against *gs,* g_{O_3}, *SWP* were done for each specie and can be appreciated in Table 3 with the respective function, constant, intercept, R^2 and p_value. All variables showed a positive relation between to ozone uptake, with an R^2 ranging from 0.613 and 0.93, except for g_s in *C. betulus* and *SWP* in *F. sylvatica.*

Interestingly, for *C. betulus* gs was not significative but g_{O_3} was, being the biggest R_2 of all analysis. The correlation function that were compared were linear, exponential and functional, presenting the data only for the comparison that presented a p_value < 0.05. In Figure 9 the clear patterns of treatment can be appreciated.

Table 2. Mean ± sd for relevant variables.

Bold represents a significant difference between treatments (drought (d) or salinity (s) contrasted against control (c)); Anova and Tukey with p_value<0.05

Species	T	n	SWP (Mpa)	Cl (mg/g DW)	g_s (mmol/m^2s)	g_{O_3} (mmol/m^2s)	E (mmol/m^2s)	A (µmol/m^2s)	ΔO_3 (µg/m^3cm^2)	ΔO_3 (%)
Betula pendula	c	4	-0.2 ± 0.06	0.16 ± 0.06	85.83 ± 18.68	41.11 ± 1.84	1.3 ± 0.05	5.81 ± 0.69	0.13 ± 0.05	43.35 ± 8.65
	d	4	**-1.09 ± 0.21**		**25.57 ± 24.87**	**15.13 ± 13.97**	0.57 ± 0.38	**2.88 ± 1.73**	**0.04 ± 0.04**	**17.86 ± 15.26**
	s	4	-0.4 ± 0.1	**1.37 ± 0.52**	74.44 ± 30.46	28.87 ± 8.88	0.96 ± 0.2	4.57 ± 0.87	0.09 ± 0.04	41.09 ± 12.72
Carpinus betulus	c	4	-0.19 ± 0.05	0.94 ± 0.34	79.13 ± 34.27	32.45 ± 7.09	1.35 ± 0.24	4.15 ± 0.75	0.12 ± 0.02	24.4 ± 8.67
	d	3	**-0.77 ± 0.15**		39.42 ± 14.74	17.35 ± 13.44	1.03 ± 0.21	4.06 ± 1.2	0.06 ± 0.05	**11.95 ± 8.97**
	s	3	**-0.18 ± 0.06**	**3.53 ± 1**	80.96 ± 25.74	43.34 ± 19.15	1.29 ± 0.12	3.86 ± 0.33	0.17 ± 0.11	30.12 ± 10.28
Fagus sylvatica	c	2	-0.23 ± 0.04	0.25 ± 0.02	81.94 ± 6.41	30.92 ± 3.37	1.36 ± 0.26	4.46 ± 0.84	0.07 ± 0.01	29.84 ± 3.24
	d	5	**-1.91 ± 0.7**		**19.75 ± 13.16**	**9.12 ± 7.6**	0.6 ± 0.34	**1.53 ± 1.26**	0.03 ± 0.03	**5.34 ± 4.21**
	s	3	-0.4 ± 0.05	**4.17 ± 0.53**	60.61 ± 15.39	23.8 ± 9.07	1.26 ± 0.37	3.29 ± 0.98	0.07 ± 0.04	**12.72 ± 2.87**
Quercus robur	c	3	-0.32 ± 0.1	0.43 ± 0.43	105.31 ± 30.71	42.75 ± 16.26	1.24 ± 0.39	7.17 ± 1.8	0.17 ± 0.11	51.09 ± 2.95
	d	4	**-1.61 ± 0.56**		**27.89 ± 26.11**	17.92 ± 18.94	0.61 ± 0.41	2.75 ± 2.67	0.04 ± 0.03	**18.99 ± 18.91**
	s	3	-0.47 ± 0.06	1.61 ± 0.65	73.26 ± 18.7	26.74 ± 3.91	0.88 ± 0.23	4.4 ± 0.99	0.09 ± 0.01	42.46 ± 10.14

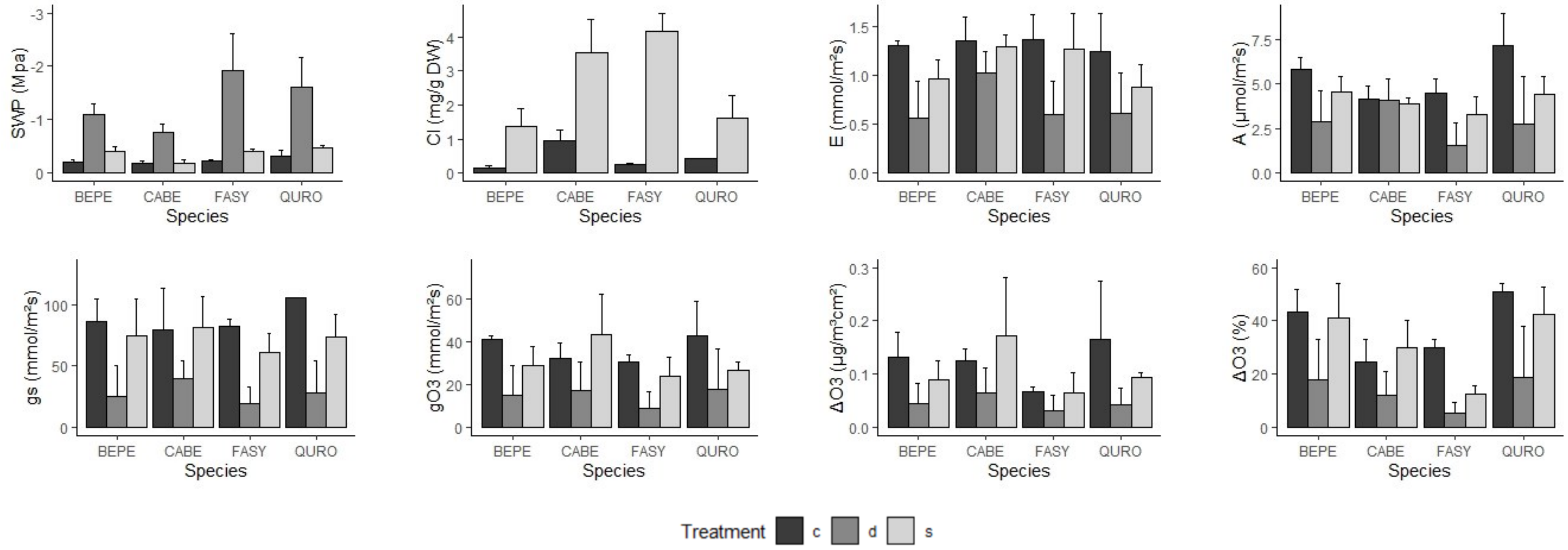
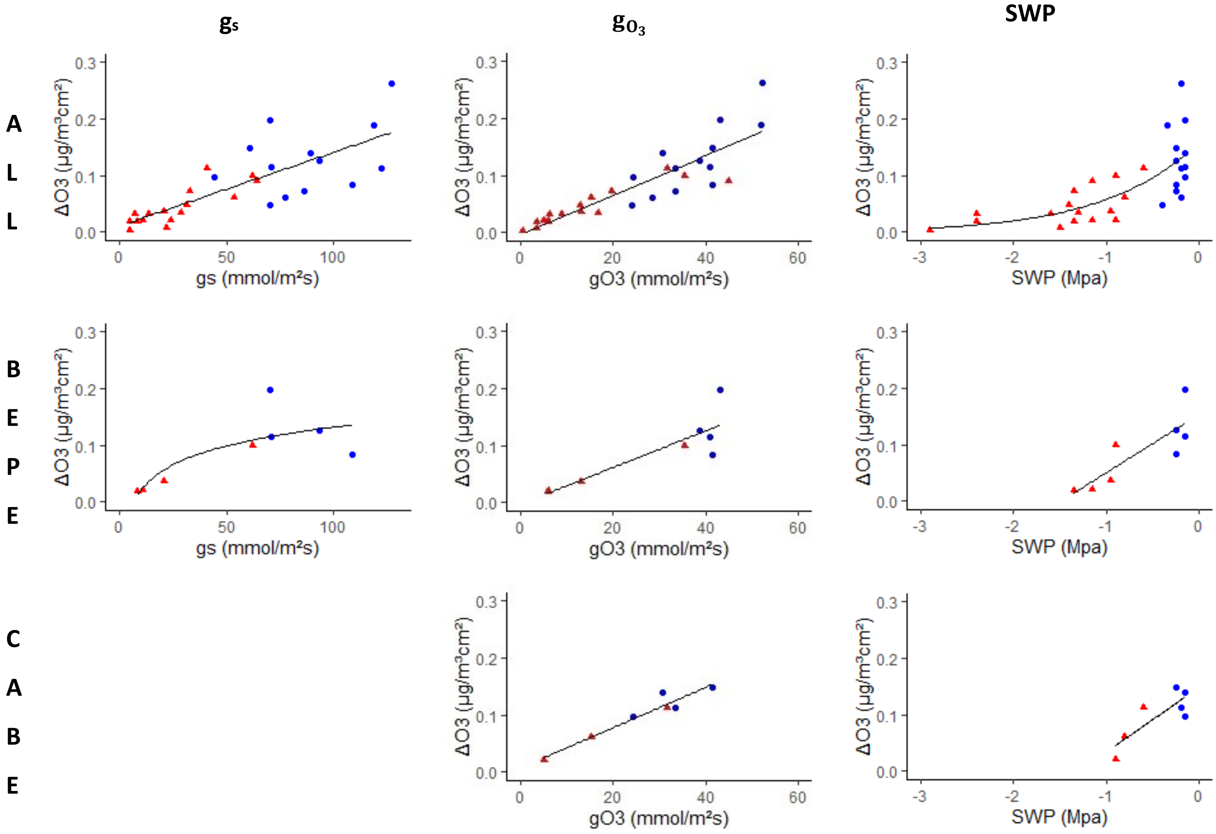


Figure 7. Response from the relevant variables

Table 3. Correlations of ΔO_3

Against g_s, g_{O_3}, and *SWP* individually for c and d treatments

Species	Variable	Function	Constant	Intercept	R²	p_value
All	g_s	Linear	0.001	0.011	0.613	**< 0.001**
	g_{O_3}	Linear	0.003	-0.004	0.799	**< 0.001**
	SWP	Exponential	0.162	-0.002	0.529	**< 0.001**
Betula pendula	g_s	Logarithmic	0.048	-0.089	0.620	**0.02**
	g_{O_3}	Linear	-0.003	0.003	0.762	**0.005**
	SWP	Linear	0.103	0.154	0.694	**0.01**
Carpinus betulus	g_s	Linear				> 0.05
	g_{O_3}	Linear	0.004	0.007	0.930	**< 0.001**
	SWP	Linear	0.114	0.149	0.675	**0.023**
Fagus sylvatica	g_s	Logarithmic	0.021	-0.025	0.613	**0.037**
	g_{O_3}	Linear	0.002	0.010	0.822	**0.005**
	SWP	Linear				> 0.05
Quercus robur	g_s	Linear	0.002	-0.013	0.853	**0.003**
	g_{O_3}	Linear	0.004	-0.015	0.763	**0.01**
	SWP	Exponential	0.267	-0.021	0.658	**0.027**



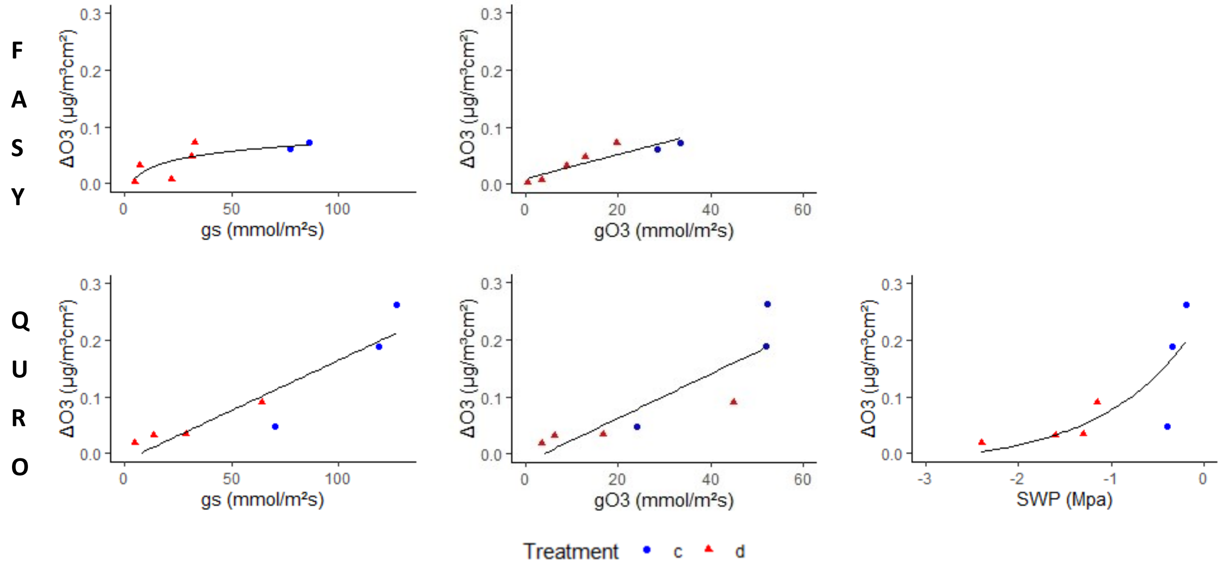


Figure 8. Correlations of ΔO₃

Where BEPE is *Betula pendula*, CABE is *Carpinus betulus*, FASY is *Fagus sylvatica* and QURO is *Quercus robur*.

5. Species used in Vienna

5.1. Methodology

An inventory of the Viennese Urban Forest was taken from the Open Data Austria Portal, in which the Austrian Government provides public and transparent access to relevant data. The last update was performed on the 15 of April 2020 (Stadt Wien, 2020). This inventory includes 202214 trees growing in parks, on roadsides, and other wooded areas in Vienna, which are equivalent to 299 species and 76 genera. The data set was grouped by species and for each of them, a BVOC emission was recorded from previous studies. The complete list is in the Annex.

The BVOC emissions were classified as isoprene (IS), monoterpenes (MO), sesquiterpenes (SE), and other BVOCs (OT). Additionally, the degree of tolerance to drought stress was classified as tolerant (t), moderate tolerant (mt), moderately sensitive (ms), and sensitive (s). A group named *Others* was created with the trees without an identified scientific name or the species from which no BVOC emission register was found (described in the table as *NA*). This category represents 3,5% of the Viennese urban forest corresponding to 1021 individuals jointly with trees that did not count with a specie name in the inventory itself as it was the case of fruit- (*Obstbaum,* 4 individuals), unknown- (*Baumgruppe*, 4; *nicht bekannt*, 8; and *unknown*, 4) and small-to-be-planted trees (*Jungbaum wird gepflanzt*, 6041 individuals). The category named as *Others* represents 3.5% of the total urban forest.

BVOC emissions are recorded in µg/g_{DW} h and the measurements were done under standardized environments, which means under a temperature of 30°C and a PAR of 1000 µmol/m^2 s. For the report of the BVOC emissions, when more than one register was found, an average of the measurements was made. Additionally, the emissions were classified as high, medium, low and none (*H*, *M*, *L* and *N* in the table): IS as high (above 20 µg/g h), medium (between 3 and 20 µg/g h), and low (between 0.1 and 3 µg /g h); MO and OT as high (above 5 µg/g h), medium (between 2 and 5 µg/g h), and low (between 0.1 and 2 µg/g h); SES as high (above 1.1 µg/g h), medium (between 0.5 and 1.1 µg/ g h), and low (between 0.1 and 0.5 µg/g h); and all emissions below 0.1 µg/g h, as none (Calfapietra et al., 2009; Fitzky et al., 2019).

5.2. Results

It was found that 17.3% of the urban forest was represented by high isoprene emitters, from 18 genera and 59 species, from which *Platanus x acerifolia, Robinia pseudoacacia, Pinus nigra, Sophora japónica,* and *Quercus robur* represent individually more than 1% of abundance. High monoterpenes emitters represent 2.47% with 14 genera and 37 species with *Acer negundo, Ginkgo biloba, Fagus sylvatica, Pinus Sylvestris,* and *Acer saccharinum* having an individual abundance ranging 0.65-0.13%. Likewise, sensitive to drought stress trees represents 18 genera and 36 species with 11.75% of the urban forest and *Fraxinus excelsior, Fraxinus ornus, Betula pendula*, and *Prunus avium* represent individually more than 1% of abundance.

The species with the three variables valued as high or sensitive (high isoprene, high monoterpene and sensitive to drought) denote 29.44%, with 39 genera and 77 species (Table 9, Annex); and the only species which comply with all three of them were the *Fagus* genera with 722 individuals representing 0.36% of the urban forest. Data are shown in Tables 4, 5, 6, and 9. Reference for each specie is in Table 10 (Annex).

Table 4. High isoprene emitters of the Viennese Urban Forest
IS in µg/gh

Species	N	%	IS
Platanus x acerifolia	6909	3.42	73.6
Robinia pseudoacacia	6087	3.01	30.0
Populus nigra	6030	2.98	70.0
Sophora japonica	3208	1.59	37.9
Quercus robur	2505	1.24	115.5
Koelreuteria paniculata	1668	0.82	40.0
Populus alba	1461	0.72	131.0
Populus x canadensis	847	0.42	52.4
Populus x canescens	798	0.39	52.4
Picea abies	765	0.38	77.5
Fagus sylvatica	710	0.35	100.0
Platanus spec.	641	0.32	36.3
Salix alba	510	0.25	37.2
Platanus orientalis	388	0.19	36.3
Populus simonii	388	0.19	52.4
Morus alba	366	0.18	39.3
Populus spec.	237	0.12	52.4
Quercus spec.	183	0.09	91.7
Salix spec.	160	0.08	39.4
Populus tremula	115	0.06	52.4
Metasequoia glyptostroboides	111	0.05	181.0
Morus nigra	110	0.05	39.3
Quercus rubra	98	0.05	91.7
Quercus frainetto	82	0.04	153.0
Liquidambar styraciflua	82	0.04	57.5
Populus balsamifera	59	0.03	52.4

Species	N	%	IS
Salix matsudana	58	0.03	37.2
Broussonetia papyrifera	52	0.03	83.0
Robinia spec.	45	0.02	30.0
Cercidiphyllum japonicum	45	0.02	32.9
Quercus petraea	40	0.02	72.0
Albizia julibrissin	39	0.02	32.9
Robinia hispida	25	0.01	30.0
Quercus pubescens	21	0.01	105.5
Quercus coccinea	21	0.01	153.9
Koelreuteria spec.	17	0.01	40.0
Sophora spec.	15	0.01	37.9
Rhamnus cathartica	12	0.01	36.9
Fagus spec.	12	0.01	94.9
Populus lasiocarpa	9	0.00	52.4
Picea breweriana	9	0.00	77.3
Euonymus europaeus	8	0.00	189.8
Quercus macrantheram	5	0.00	91.7
Ficus carica	5	0.00	130.0
Robinia x slavinii	4	0.00	30.0
Salix babylonica	3	0.00	88.0
Quercus ilex	3	0.00	189.9
Salix fragilis	2	0.00	37.2
Picea engelmannii	2	0.00	124.7
Quercus x turneri	2	0.00	91.7
Liquidambar spec.	2	0.00	57.5
Rhamnus frangula	1	0.00	36.9
Robinia x margaretta	1	0.00	30.0
Quercus dentata	1	0.00	72.5
Salix aurita	1	0.00	37.2
Populus deltoides	1	0.00	146.3
Quercus libani	1	0.00	91.7
Quercus x kewensis	1	0.00	91.7
Quercus hispanica	1	0.00	91.7
Total	**34982**	**17.30**	

Table 5. High monoterpene emitters of the Viennese Urban Forest

MO in µg/gh

Species	N	%	MO
Acer negundo	1316	0.65	25.3
Ginkgo biloba	1269	0.63	35.6
Fagus sylvatica	710	0.35	21.1
Pinus sylvestris	419	0.21	30.4
Acer saccharinum	268	0.13	25.3
Quercus spec.	183	0.09	23.6
Metasequoia glyptostroboides	111	0.05	46.0
Pseudotsuga menziesii	110	0.05	28.2
Quercus rubra	98	0.05	23.6
Magnolia spec.	96	0.05	53.3
Magnolia kobus	61	0.03	53.3
Acer rubrum	50	0.02	31.6
Abies concolor	44	0.02	26.2
Taxodium distichum	36	0.02	76.7
Sequoiadendron giganteum	31	0.02	76.7
Acer palmatum	29	0.01	25.3
Magnolia grandiflora	28	0.01	53.3
Magnolia x soulangiana	22	0.01	53.3
Quercus coccinea	21	0.01	39.5
Tsuga canadensis	21	0.01	26.2
Pinus ponderosa	12	0.01	31.6
Fagus spec.	12	0.01	21.1
Euonymus europaeus	8	0.00	23.8
Magnolia stellata	8	0.00	53.3
Magnolia	6	0.00	53.3
Quercus macrantheram	5	0.00	23.6
Acer glabrum	4	0.00	25.3
Quercus ilex	3	0.00	43.2
Pinus aristata	2	0.00	31.6
Quercus x turneri	2	0.00	23.6
Picea engelmannii	2	0.00	30.7
Quercus hispanica	1	0.00	23.6
Magnolia liliiflora	1	0.00	53.3
Quercus x kewensis	1	0.00	23.6
Magnolia tripetala	1	0.00	53.3
Quercus libani	1	0.00	23.6
Pinus flexilis	1	0.00	31.6
Total	**4993**	**2.47**	

Table 6. Sensitive species to drought stress of the Viennese Urban Forest

Species	N	%
Fraxinus excelsior	10299	5.09
Fraxinus ornus	3328	1.65
Betula pendula	2847	1.41
Prunus avium	2252	1.11
Populus x canadensis	847	0.42
Populus x canescens	798	0.39
Fagus sylvatica	710	0.35
Ulmus minor	517	0.26
Salix alba	510	0.25
Fraxinus pennsylvanica	506	0.25
Liriodendron tulipifera	276	0.14
Ulmus glabra	238	0.12
Thuja occidentalis	157	0.08
Larix decidua	100	0.05
Magnolia kobus	61	0.03
Prunus cerasus	46	0.02
Cornus spec.	37	0.02
Amelanchier spec.	36	0.02
Betula papyrifera	31	0.02
Magnolia grandiflora	28	0.01

Species	N	%
Magnolia x soulangiana	22	0.01
Tsuga canadensis	21	0.01
Amelanchier arborea	16	0.01
Fagus spec.	12	0.01
Alnus incana	12	0.01
Amelanchier lamarckii	10	0.00
Picea breweriana	9	0.00
Magnolia stellata	8	0.00
Betula ermanii	8	0.00
Magnolia	6	0.00
Betula pubescens	3	0.00
Salix babylonica	3	0.00
Aesculus pavia	2	0.00
Betula utilis var. utilis	2	0.00
Aesculus parviflora	1	0.00
Abies veitchii	1	0.00
Total	**23760**	**11.75**

The 10 more abundant species in the Viennese Urban Forests, which account for 54.1% of it, are listed in Table 7. From them, the high isoprene or monoterpene emitters are *Platanus x acerifolia*, *Robinia pseudoacacia*, and *Populus nigra.* As well*, Fraxinus excelsior* was classified as drought sensitive as it cannot cope with drought stress.

Table 7. The most abundant urban tree species used in Vienna with their BVOC emission and drought tolerance

Species	n	%	IS	MO	SE	OT	DT
Acer platanoides	27406	13.55	M	L	L	M	mt
Tilia cordata	12180	6.02	N	L	L	L	ms
Aesculus hippocastanum	11851	5.86	M	M	L	H	ms
Fraxinus excelsior	10299	5.09	L	N	L	M	s
Acer pseudoplatanus	8371	4.14	M	N	N	N	ms
Acer campestre	8080	4.00	L	L	L	M	mt
Platanus x acerifolia	6909	3.42	H	L	L	L	mt
Carpinus betulus	6091	3.01	M	L	H	M	ms
Robinia pseudoacacia	6087	3.01	H	L	M	M	t
Populus nigra	6030	2.98	H	N	L	M	ms
Celtis australis	5994	2.96	M	L	N	M	mt
Total	**109298**	**54.1**					

The most abundant genera in Vienna are listed in Table 8 and account for 76.3% of the total urban forest. The most relevant ones regarding ozone formation are *Populus* and *Platanus* as both are high isoprene emitters and the first one contains many species that are sensitive to drought.

Table 8. The most abundant genera used in Vienna with their BVOC emission and drought tolerance

Genera	N	%	IS	MO	SE	OT	DT
Acer	46329	22,91	L	M	L	L	ms
Tilia	23837	11,79	M	L	L	L	ms
Fraxinus	15180	7,51	N	N	L	L	ms
Aesculus	14328	7,09	L	M	L	N	ms
Populus	9945	4,92	H	L	L	L	ms
Pinus	9558	4,73	L	M	L	L	ms
Prunus	8494	4,20	L	L	L	L	ms
Platanus	7938	3,93	H	N	L	L	mt
Celtis	7041	3,48	N	L	L	M	mt
Robinia	6162	3,05	H	L	N	M	t
Carpinus	6140	3,04	N	L	L	L	ms
Total	**154952**	**76.63**					

6. Discussion

6.1. Experiment

The species selected for the experiment differ in their BVOC emission but also in their strategies to deal with ozone, drought, and salinity stress. As explained in Section 2.2, isoprene has the biggest ozone formation potential, followed by monoterpene, sesquiterpene, and the rest of the BVOC. Nevertheless, as founded by Fares et al (2010), BVOC also participate in the gas phase of the ozone destruction, and the mono- and sesquiterpenes have bigger rates of participation when airflow is high, as is the case of experiments using cuvettes; as its size is smaller than isoprene, these two can rapidly interact with the ozone molecules in seconds or minutes, while for isoprene takes hours.

On one hand, *C. betulus* is a low emitter species that is known to be drought, ozone, and salt (mild) tolerant, to be part of the understory of the natural forest in Europe, non-needing big quantities of light and being tolerant to a variable range of soil pH. Under drought stress, this specie showed negative *SWP* and the biggest ΔO_3(μg/m^{3}cm^2), g_s, *E*, and *A*; being only statistically significant the first one. Nevertheless, there is a clear tendency showing that this specie is robust and tolerant to the harsh urban environment; being its *SWP* -0.77 ± 0.15 Mpa, it is categorized under mild stress under the findings of Myburgh et al. (2016). For its ozone uptake, even if there is no statistical difference between control and drought, the results were highly correlated to g_{O_3}(R^2: 0.93) and *SWP* (R^2: 0.675); and the significance for g_s was not enough having a p_value very close to 0.05.

As well, *B. pendula* is a pioneer European specie known to tolerate a wide range of climatic conditions including snow and frost but not harsh drought periods. It is a high sesquiterpene and medium monoterpene emitter from which an increase in temperature is expected to increase its emissions, as was demonstrated in an experiment from Hartikainen et al (2012). Under mild drought stress, the specie has been recognized to be tolerant, tending to close its stomata rapidly and to generate adaptability strategies like, stiffer, stronger stems, or more density of trichomes in the leaf, to improve non-stomata transpiration. It is known to be mild salt and ozone tolerant showing only a decrease in performance after extreme ozone fumigations which are highly dependent on its stomatal conductance. This specie under drought presented medium *SWP* (-1,09 ± 0,21 which is classified as moderate stress (Myburgh et al., 2016)), g_s, and ΔO_3(μg/m^{3}cm^2). It was the only specie in which ozone uptake was statistically significant lower showing a relationship between ozone uptake and *gs,* g_{O_3}, and *SWP*, as expected.

F. sylvatica, on the other hand, is a specie that under moisty conditions is very competitive, nonetheless, it is known to be affected by drought, watering, and flooding, presenting decrease in stomatal conductance, embolism, reduction in growth and nutrient uptake; which has been predicted will decrease its abundance under global change. However, it has been reported the specie can adjust biochemical and physical processes to deal with stresses. About ozone, it is identified as sensitive to it with a marked difference between young seedlings (laboratory conditions) and old trees (field conditions), with high ozone rate uptake and low detoxify capacity from the former and the opposite from the latter ones. Considering the BVOC, it is a high monoterpene emitter which under the first stages of drought heavily increases its emissions until the stress is too high that emissions stop totally (Šimpraga et al., 2011). In the experiment, the specie displayed the lowest *SWP* (-1.91 ± 0.7Mpa, classified as severe stress by the study of Myburgh et al., 2016), g_s, g_{O_3}, A, and ΔO_3 of all species under drought stress, being significantly different in the specie all but ΔO_3 ($\mu g/m^3cm^2$). Interestingly the variables that had a significant relationship with ozone uptake are g_s and g_{O_3}; showing that its performance under drought limited as reported.

Lastly, *Q. robur*, which counts with an enormous traditional and cultural meaning in the European context is a pioneer specie with a lifespan of 1000 years. Even if it has a big geographic distribution of its medium salinity and sensitive to drought stress. When stress is perceived, it rapidly closes its stomata. Still, in the literature is described as ozone resistant and air pollution alleviator. In the study by Gerosa et al (2008) the specie had bigger rates of ozone uptake than *F. sylvatica* under drought stress. The specie presented, in the experiment, a significant decrease in g_s and *SWP* (-1.61 ± 0.56Mpa, classified as severe stress by the study of Myburg et al., 2016) and a non-significant decrease in g_{O_3}, A, and ΔO_3 in the comparison between control and drought treatment, which goes in line with the literature findings. Additionally, its ozone uptake was significantly related to g_s g_{O_3}, and *SWP*.

Respecting ozone uptake, it is interesting to notice that the decrease in performance when the calculations do not involve leaf area are statistically significant for the comparison between control and drought in all species. And that the contrary happens when the calculation does discriminate against the ozone uptake per leaf area, leaving only *B. pendula* to have a significant decrease, which heavily depends on its water relationship.

It was hypothesized that ozone uptake would be greater in species with no emissions or monoterpene and sesquiterpene emissions, as the last two would participate in the atmospheric phase of ozone destruction. However, even if not statistically significant, the specie with the biggest (non-significant) ozone uptake (µg/m^{3}cm^2) under ozone + drought stress was *C. betulus* (the non-emitter but highly tolerant specie); additionally, under ozone + salt stress, this specie had the biggest (non-significant) ozone uptake, displaying maybe a boost in production as a response to mild salt stress. The specie that under control treatment presented the best ozone uptake was *Q. robur* (high isoprene emitter and the one with the biggest *A* and the second biggest g_s), maybe exhibiting the ozone stress exposition was not strong enough, a subject that is discussed above.

This high ozone uptake from *Q. robur* coincides with another hypothesis the study proposed: ozone uptake would be bigger in species that under stress perform well, with open stomata and less negative SWP. And that is precisely what occurred in the experiment, there was a marked tendency to destroy ozone from the species that perform better. On the contrary, the specie with the biggest difficulty to deal with drought, *F. sylvatica,* was the one that non-significant destroyed less ozone, even if its monoterpene emissions could interact and remove it. Moreover, Fares et al (2013) found a reduction in carbon assimilation in three different types of trees was more related to stomatal ozone deposition (g_{O_3}) than to ozone concentration and that decoupling between carbon assimilation and stomatal aperture increased with the amount of ozone pollution. And those finding are heavily related to the water relationship plants may have.

The experiment had some methodological disadvantages in its execution: the low duration of the ozone fumigation, only during two hours per plant, in comparison with studies that fumigate the individuals for several, days, months or years or that have an intensity of 12h/d of fumigation (Witting et al., 2007). Additionally, the ozone fumigation was not so stable as desired, as the capacity of the employed ozone generator was bigger than needed. Nevertheless, the analysis of the data was done with the good faith that the results showed the reality. Furthermore, the variability in individuals per treatment was high and that could alter the results as the number of individuals per treatment is in some treatments too small and maybe a bigger number of them would reduce the variability in the response. Finally, the individuals used in the experiment were seedling which is easy to measure and secure a homogenous group; but as studied by Bagard et al in 2008 the developmental stage of the leaves influences the impact of ozone on the primary carbon metabolism. The authors studied in young poplar trees (*Populus tremula* x *Populus alba*) the effect of ozone on three types of leaves (newly formed, young, and mature leaves) and found expanding leaves showed an apparent resistance to ozone but mature leaves showed a marked reduction in photosynthetic parameters. Even if all species are deciduous and measurements started at the same time when all tress had mature leaves, it can also happen that a species develops more abundant young leaves. Nevertheless, for practicality reasons this kind of error it is almost unavoidable.

To finish, as ozone impact on trees is done on the long term, during days, months or years, there are corresponding variables that are used for valuing its impact: ones related to ozone flux (duration of fumigation times level of fumigation) and the others related to ozone threshold. IN this study the calculation of certain measurements is not significant as the time of exposure is only from two hours and the threshold of ozone pretends to simulate concentrations happening during heat waves, max. 200ppb. However, the data used in this master thesis makes part of a project called *Urban trees and air pollution: Effect of drought and salt stress on the production of VOC and absorption of ozone by different city trees* funded by the *Vienna Science and Technology Fund,* which plans not only to developed a similar experiment, with a more constant ozone concentration, but also measure BVOC exchange.

6.2. Vienna Case Study

Regarding ozone formation it was discussed in Section 2, it is enhanced by BVOC when the presence of other NO_x are in a certain ratio in comparison to BVOC ($4 < VOC/NO_x < 15$) and that high temperature, coinciding with the ones happening during heat waves, are the perfect conditions for its boost (Calfapietra et al., 2013). Additionally, that not all BVOC have the same ozone-forming potential and that isoprene is the most effective ones for forming ozone with a product of 9 g per each g of isoprene in comparison with monoterpene, which can form in average 3.9 g of ozone per g of monoterpene (Benjamin and Wiener, 1998). And lastly that perhaps temperature is the most decisive factor for the increase in emissions, with findings like more production of isoprene and monoterpenes (11 vs 8 and 108 vs 83 Kton, respectively for the comparison between predictions from 1998 vs. the end of the 21st century, using the Guenther 93 algorithm) for an increase in 3°C hourly temperature (Steinbrecher et al., 2001).

Moreover, in a study released by Rennenberg et al., (2006), the effect of heat weaves on BVOC emissions was studied having as scenario the events of Summer 2003 in Europe also using the Guenther algorithm. In North Italy, an extreme and prolonged heatwave was endured like in the rest of Central Europe. On the contrary, Central Italy experienced a shorter and less intense heatwave but in general with higher temperatures than Central Europe, as the Mediterranean Region is characterized by this condition.

Researchers found that in Northern Italy BVOC emissions were lower than expected, with bare emission during stress and boost after the drought wave, which maybe is related to recovery of the stress that is independent from temperature (one of the functions of BVOCs). In the case of Central Italy, in which only high temperatures but no additional drought stress was studied, there was a large increase in emissions when compared with previous years. This experiment concludes that it is necessary to directly measure emissions for having more accurate results but that one prediction from severe drought stress is that BVOC emissions will be reduced, also, as a response to a reduction in leaf area index and duration.

Considering the before mentioned information, this study proposes that even if considering the possible fluctuations in emissions under a global change scenario, high isoprene emitters do have an impact of ozone formation. Additionally, that species which cannot deal with drought stress, either have faster rates of mortality under this condition or its relationship with water is not enough for enhancing ozone destruction. Nevertheless, it is important to clarify that the optimal species that could enhance ozone destruction are the ones that can deal with drought stress, not entirely closing their stomata and maintaining high leaf stem water potentials, as was the case of *Carpinus betulus* in the experiment detailed in this master thesis. Even If our experiment does not show mono- and sesquiterpenes do enhance ozone formation, literature reported otherwise. Nevertheless, to correctly name which tree species comply with this task, it is imperative to have real data from each urban specie: BVOC emission, stem water potential, and stomatal conductance under drought stress. Therefore, this study does not list species that enhance ozone destruction, only the no favorable ones which are in Table 9 in the Annex (that enhance ozone formation), because these data for all 299 species Vienna has, is not available.

Curiously, many studies propose some species that alleviate air pollution in cities like the study of Donovan in 2005 which considers attributes love O_3, NO_x, HNO_3, and PAN alleviation and high BVOC emissions. Nevertheless, two species ranked as desired on the top 10, *Larix decidua, Betula pendula,* and *Pinus nigra*, are not desirable as the two first are sensitive to drought tolerance and the third one is high monoterpene emitter, and as explained before, from the physiological point of view they cannot enhance pollution when they cannot endure drought stress, which is stated in our experiment tacking as reference *B. pendula*, or when the BVOC emission rate is high.

In the study by Barwise and Kumar (2020), a list of 61 desirable species that can act as vegetation barriers for urban pollution abatement using as decision variables biophysical traits like leaf area, presence of trichomes, and ridges, also stomatal characteristics and BVOC emissions. However, authors admit studies dealing with the stomatal characteristic for urban air pollution mitigation are species with wanted characteristics but high BVOC emissions could be also used if other non-emitting plants surround them. In this order of ideas, species like *Ginko biloba*, *Koelreuteria pandiculata, Liquidambar styracifilia, Robinia pseudoacacia*, *Populus nigra,* among others are inside the list being high isoprene or monoterpene emitters.

7. Conclusion

Differences in ozone uptake from four different BVOC type of emitters was only significantly lower in *Betula pendula* when contrasting control and drought conditions, even if there is a strong trend in all used species for reducing ozone uptake up to 50%. The species whit better water relationship and response stress performance were *Carpinus betulus*, a robust, stress-tolerant species which during normal conditions do not present high stomatal conductance or photosynthetic rate, but that on harsh conditions do not diminish its performance and where their physiological responses maintain a constant rate.

According to a literature review, ozone-forming species are high isoprene and monoterpene emitters, and species that cannot deal with drought stress, which indirectly diminish ozone destruction. Therefore, a list with the non-favorable urban tree species for Vienna was developed considering the before stated variables, which represents almost two-thirds of the total urban forest.

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Annex

List of urban tree species used in Vienna, Austria, with the corresponding BVOC emissions classified as isoprene (IS), monoterpenes (MO), sesquiterpenes (SE), and other BVOCs (OT) and their drought tolerance (DT) degree as tolerance (t), moderate tolerant (mt), moderately sensitive (ms) and sensitive (s). There was a total of 202214 individuals from 298 genera. A group named *Others* was created with the trees without an identified scientific name or the species from which no BVOC emission register was found (described in the table as *NA*); this category represents 3,5% of the Viennese urban forest. BVOC emissions are recorded in µg/g$_{DW}$ h and the measurements were done under standardized environments, which means under a temperature of 30°C and a PAR of 1000 µmol/m^2 s. When more than one register was found for BVOC an average of the measurements was made; this was also the case for drought tolerance. Additionally, the emissions were classified as high, medium, low and none (*H*, *M*, *L* and *N* in the table; which are located in the columns named with the final _*c* addition): IS and Mo as high (above 20 µg/g h), medium (between 3 and 20 µg/gh), and low (between 0.1 and 3 µg /g h); OT as high (above 5 µg/g h), medium (between 2 and 5 µg/g h), and low (between 0.1 and 2 µg/g h); SES as high (above 1.1 µg/g h), medium (between 0.5 and 1.1 µg g h), and low (between 0.1 and 0.5 µg/g h); and all emissions below 0.1 µg/g h, as none (Calfapietra, 2009; Fitzky et al., 2019).

Table 9. Non-favorable species used in the Viennese Urban Forest

Species	n	%	IS	MO	DT
Abies concolor	44	0.0	M	H	t
Abies veitchii	1	0.0	M	M	s
Acer glabrum	4	0.0	N	H	ms
Acer negundo	1316	0.7	N	H	ms
Acer palmatum	29	0.0	N	H	ms
Acer rubrum	50	0.0	N	H	ms
Acer saccharinum	268	0.1	N	H	ms
Aesculus parviflora	1	0.0	M	M	s
Aesculus pavia	2	0.0	M	M	s
Albizia julibrissin	39	0.0	H	M	ms
Alnus incana	12	0.0	N	L	s
Amelanchier arborea	16	0.0	N	N	s
Amelanchier lamarckii	10	0.0	N	N	s
Amelanchier spec.	36	0.0	N	N	s
Betula ermanii	8	0.0	M	M	s
Betula papyrifera	31	0.0	M	M	s
Betula pendula	2847	1.4	M	L	s
Betula pubescens	3	0.0	M	L	s
Betula utilis var. utilis	2	0.0	M	M	s
Broussonetia papyrifera	52	0.0	H	L	mt
Cercidiphyllum japonicum	45	0.0	H	M	ms
Cornus spec.	37	0.0	M	L	s
Euonymus europaeus	8	0.0	H	H	mt
Fagus spec.	12	0.0	H	H	s
Fagus sylvatica	710	0.4	H	H	s
Ficus carica	5	0.0	H	N	mt

Species	n	%	IS	MO	DT
Fraxinus excelsior	10299	5.1	L	N	s
Fraxinus ornus	3328	1.6	L	N	s
Fraxinus pennsylvanica	506	0.3	N	N	s
Ginkgo biloba	1269	0.6	N	H	mt
Koelreuteria paniculata	1668	0.8	H	N	t
Koelreuteria spec.	17	0.0	H	N	t
Larix decidua	100	0.0	N	L	s
Liquidambar spec.	2	0.0	H	M	ms
Liquidambar styraciflua	82	0.0	H	M	ms
Liriodendron tulipifera	276	0.1	M	N	s
Magnolia	6	0.0	N	H	s
Magnolia grandiflora	28	0.0	N	H	s
Magnolia kobus	61	0.0	N	H	s
Magnolia liliiflora	1	0.0	N	H	ms
Magnolia spec.	96	0.0	N	H	ms
Magnolia stellata	8	0.0	N	H	s
Magnolia tripetala	1	0.0	N	H	ms
Magnolia x soulangiana	22	0.0	N	H	s
Metasequoia glyptostroboides	111	0.1	H	H	ms
Morus alba	366	0.2	H	M	ms
Morus nigra	110	0.1	H	M	ms
Picea abies	765	0.4	H	M	ms
Picea breweriana	9	0.0	H	M	s
Picea engelmannii	2	0.0	H	H	ms
Pinus aristata	2	0.0	N	H	mt
Pinus flexilis	1	0.0	N	H	t
Pinus ponderosa	12	0.0	N	H	mt
Pinus sylvestris	419	0.2	M	H	mt
Platanus orientalis	388	0.2	H	N	mt
Platanus spec.	641	0.3	H	N	mt
Platanus x acerifolia	6909	3.4	H	L	mt
Populus alba	1461	0.7	H	L	ms
Populus balsamifera	59	0.0	H	L	ms
Populus deltoides	1	0.0	H	N	ms
Populus lasiocarpa	9	0.0	H	L	ms
Populus nigra	6030	3.0	H	N	ms
Populus simonii	388	0.2	H	L	ms

Species	n	%	IS	MO	DT
Populus spec.	237	0.1	H	L	ms
Populus tremula	115	0.1	H	L	mt
Populus x canadensis	847	0.4	H	L	s
Populus x canescens	798	0.4	H	L	s
Prunus avium	2252	1.1	N	L	s
Prunus cerasus	46	0.0	M	L	s
Pseudotsuga menziesii	110	0.1	M	H	ms
Quercus coccinea	21	0.0	H	H	ms
Quercus dentata	1	0.0	H	N	ms
Quercus frainetto	82	0.0	H	N	mt
Quercus hispanica	1	0.0	H	H	t
Quercus ilex	3	0.0	H	H	mt
Quercus libani	1	0.0	H	H	ms
Quercus macrantheram	5	0.0	H	H	ms
Quercus petraea	40	0.0	H	L	mt
Quercus pubescens	21	0.0	H	L	t
Quercus robur	2505	1.2	H	L	ms
Quercus rubra	98	0.0	H	H	ms
Quercus spec.	183	0.1	H	H	ms
Quercus x kewensis	1	0.0	H	H	ms
Quercus x turneri	2	0.0	H	H	mt
Rhamnus cathartica	12	0.0	H	N	ms
Rhamnus frangula	1	0.0	H	N	ms
Robinia hispida	25	0.0	H	L	t
Robinia pseudoacacia	6087	3.0	H	L	t
Robinia spec.	45	0.0	H	L	t
Robinia x margaretta	1	0.0	H	L	t
Robinia x slavinii	4	0.0	H	L	t
Salix alba	510	0.3	H	N	s
Salix aurita	1	0.0	H	N	ms
Salix babylonica	3	0.0	H	N	s
Salix fragilis	2	0.0	H	N	ms
Salix matsudana	58	0.0	H	N	ms
Salix spec.	160	0.1	H	N	ms
Sequoiadendron giganteum	31	0.0	N	H	mt
Sophora japonica	3208	1.6	H	M	t
Sophora spec.	15	0.0	H	M	t

Species	n	%	IS	MO	DT
Taxodium distichum	36	0.0	N	H	mt
Thuja occidentalis	157	0.1	N	M	s
Tsuga canadensis	21	0.0	M	H	s
Ulmus glabra	238	0.1	M	N	s
Ulmus minor	517	0.3	M	N	s
Total	**595542**	**29.5**			

Table 10. Urban Tree Species used in Vienna and their BVOC emissions and drought stress degree

Species	n	%	IS	IS_c	MO	MO_c	SE	SE_c	OT	OT_c	BVOC Source	DT
Abies alba	39	0,0	0,60	M	0,46	L	0,15	L	2,00	M	a,h,p,z	mt
Abies cephalonica	22	0,0	18,40	M	0,76	L	0,15	L	2,00	M	a,z,k	t
Abies concolor	44	0,0	10,70	M	26,20	H	0,00	N	0,00	N	d	t
Abies grandis	6	0,0	10,70	M	13,36	H	0,10	L	2,00	M	z,d	ms
Abies nordmanniana	29	0,0	2,63	M	2,43	M	0,36	L	0,19	L	a	mt
Abies pinsapo	36	0,0	10,70	M	13,36	H	0,10	L	2,00	M	z,d	mt
Abies spec.	29	0,0	30	M	3,00	M	0,00	N	0,00	N	ze	mt
Abies veitchii	1	0,0	10,70	M	13,36	H	0,10	L	2,00	M	z,d	s
Abies x vilmorinii	4	0,0	10,70	M	13,36	H	0,10	L	2,00	M	z,d	mt
Acer buergerianum	11	0,0	30	L	1,99	L	0,10	L	2,54	M	z,s	mt
Acer campestre	8080	4,0	0,01	L	1,99	L	0,10	L	2,54	M	z,s	mt
Acer capillipes	10	0,0	0,01	L	1,99	L	0,10	L	2,54	M	z,s	ms
Acer cappadocicum	18	0,0	0,01	L	1,99	L	0,10	L	2,54	M	z,s	mt
Acer cappadocicum lobelii	3	0,0	0,01	L	1,99	L	0,10	L	2,54	M	z,s	mt
Acer carpinifolium	1	0,0	0,01	L	1,99	L	0,10	L	2,54	M	z,s	ms
Acer cissifolium	11	0,0	0,01	L	1,99	L	0,10	L	2,54	M	z,s	ms
Acer davidii	4	0,0	0,01	L	1,99	L	0,10	L	2,54	M	z,s	ms
Acer davidii subsp. grosseri	2	0,0	0,01	L	1,99	L	0,10	L	2,54	M	z,s	ms
Acer glabrum	4	0,0	0,00	N	25,30	H	0,00	N	0,00	N	d	ms
Acer griseum	53	0,0	0,01	L	1,99	L	0,10	L	2,54	M	z,s	ms
Acer hyrcanum	9	0,0	0,01	L	1,99	L	0,10	L	2,54	M	z,s	ms
Acer japonicum	3	0,0	0,01	L	1,99	L	0,10	L	2,54	M	z,s	ms
Acer monspessulanum	164	0,1	0,00	N	1,50	L	0,10	L	2,00	M	z	t
Acer negundo	1316	0,7	0,00	N	25,30	H	0,00	N	0,00	N	d	ms
Acer opalus	75	0,0	0,10	M	1,50	L	0,10	L	2,00	M	z	ms
Acer palmatum	29	0,0	0,00	N	25,30	H	0,00	N	0,00	N	d	ms
Acer platanoides	27406	13,6	0,10	M	1,50	L	0,10	L	2,00	M	z	mt

Species	n	%	IS	IS_c	MO	MO_c	SE	SE_c	OT	OT_c	BVOC Source	DT
Acer pseudoplatanus	8371	4,1	3,90	M	0,00	L	0,00	N	0,00	N	zc	ms
Acer rubrum	50	0,0	0,00	N	31,60	H	0,00	N	0,00	N	d	ms
Acer saccharinum	268	0,1	0,00	N	25,30	H	0,00	N	0,00	N	d	ms
Acer saccharum	2	0,0	0,01	L	0,07	L	0,01	M	0,01	L	f	mt
Acer spec.	89	0,0	0,01	L	1,99	L	0,10	L	2,54	M	z,s	ms
Acer tataricum	132	0,1	0,01	L	1,99	L	0,10	L	2,54	M	z,s	mt
Acer truncatum	59	0,0	0,01	L	1,99	L	0,10	L	2,54	M	z,s	ms
Acer x freemanii	159	0,1	0,01	L	1,99	L	0,10	L	2,54	M	z,s	mt
Aesculus flava	154	0,1	0,14	M	16,50	H	0,44	L	11,20	H	f,k	ms
Aesculus hippocastanum	11851	5,9	0,14	M	16,50	H	0,44	L	11,20	H	f,k	ms
Aesculus parviflora	1	0,0	0,14	M	16,50	H	0,44	L	11,20	H	f,k	s
Aesculus pavia	2	0,0	0,14	M	16,50	H	0,44	L	11,20	H	f,k	s
Aesculus spec.	70	0,0	0,14	M	16,50	H	0,44	L	11,20	H	f,k	ms
Aesculus x carnea	2249	1,1	0,14	M	16,50	H	0,44	L	11,20	H	f,k	ms
Aesculus x neglecta	1	0,0	0,14	M	16,50	H	0,44	L	11,20	H	f,k	ms
Ailanthus altissima	1314	0,6	0,01	L	1,60	L	0,00	N	0,00	N	w	t
Ailanthus spec.	2	0,0	0,01	L	1,60	L	0,00	N	0,00	N	w	t
Albizia julibrissin	39	0,0	32,90	H	12,60	H	0,00	N	0,00	N	d	ms
Alnus cordata	30	0,0	0,00	N	1,50	L	0,10	L	2,00	M	z	ms
Alnus glutinosa	92	0,0	0,02	L	0,00	L	0,00	N	0,06	L	a	ms
Alnus incana	12	0,0	0,00	N	1,50	L	0,10	L	2,00	M	k	s
Alnus spaethii	24	0,0	0,02	L	0,00	L	0,00	N	0,06	L	a	mt
Alnus spec.	9	0,0	0,02	L	0,00	L	0,00	N	0,06	L	a	ms
Amelanchier arborea	16	0,0	0,00	N	0,00	L	0,00	N	0,00	N	w	s
Amelanchier lamarckii	10	0,0	0,00	N	0,00	L	0,00	N	0,00	N	w	s
Amelanchier spec.	36	0,0	0,00	N	0,00	L	0,00	N	0,00	N	w	s
Araucaria araucana	3	0,0	0,10	M	1,50	L	0,00	N	0,00	N	w	mt
Betula ermanii	8	0,0	0,91	M	5,63	H	0,00	N	0,00	N	a,k,zd	s
Betula nigra	6	0,0	0,91	M	5,63	H	0,00	N	0,00	N	a,k,r	ms
Betula papyrifera	31	0,0	0,91	M	5,63	H	0,00	N	0,00	N	a,k,s	s
Betula pendula	2847	1,4	0,91	M	1,63	L	2,00	H	0,06	L	a,k,u	s
Betula pubescens	3	0,0	0	M	2,3	M	2,00	H	2,00	M	i,z	s
Betula spec.	89	0,0	0,91	M	5,63	H	0,00	N	0,06	L	a,k,u	ms

Species	n	%	IS	IS_c	MO	MO_c	SE	SE_c	OT	OT_c	BVOC Source	DT
Betula utilis var. utilis	2	0,0	0,91	M	5,63	H	0,00	M	1,06	L	a,k,x	s
Broussonetia papyrifera	52	0,0	83,00	H	0,40	L	0,00	N	0,00	N	n	mt
Buxus sempervirens	10	0,0	10,00	M	0,00	L	0,10	L	2,00	M	z	ms
Calocedrus decurrens	17	0,0	0,00	N	7,20	H	0,00	N	0,00	N	d	t
Carpinus betulus	6091	3,0	0,07	M	0,20	L	0,11	L	2,02	M	z,zf,a	ms
Carpinus spec.	49	0,0	0,00	N	0,00	L	0,00	N	0,20	L	k	ms
Carya ovata	1	0,0	3,15	M	0,00	L	0,00	N	0,00	N	d	mt
Castanea sativa	115	0,1	0,38	M	14,20	H	0,03	M	0,28	L	a	ms
Catalpa bignonioides	727	0,4	0,00	N	0,09	L	0,00	N	0,00	N	q	ms
Catalpa erubescens	1	0,0	0,00	N	0,09	L	0,00	N	0,00	N	q	ms
Catalpa ovata	16	0,0	0,00	N	0,09	L	0,00	N	0,00	N	q	ms
Catalpa spec.	9	0,0	0,00	N	0,09	L	0,00	N	0,00	N	q	ms
Cedrus atlantica	86	0,0	0,00	N	5,90	H	0,10	L	2,00	M	d,k	mt
Cedrus deodara	7	0,0	0,00	N	2,90	M	0,10	L	2,00	M	z,d,k	t
Cedrus libani	3	0,0	0,01	L	0,48	L	0,03	M	0,34	L	a	mt
Celtis australis	5994	3,0	0,12	M	0,33	L	0,00	N	2,84	M	e,s	mt
Celtis occidentalis	992	0,5	0,01	L	0,33	L	0,20	L	0,01	L	f	mt
Celtis reticulata	3	0,0	0,12	M	0,33	L	0,00	N	2,84	M	e,s	mt
Celtis spec.	51	0,0	0,12	M	0,33	L	0,00	N	2,84	M	e,s	mt
Celtis tournefortii	1	0,0	0,12	M	0,33	L	0,00	N	2,84	M	e,s	mt
Cercidiphyllum japonicum	45	0,0	32,90	H	12,60	H	0,00	N	0,00	N	d	ms
Cercis siliquastrum	114	0,1	0,00	N	0,00	L	0,10	L	2,00	M	z	mt
Chamaecyparis lawsoniana	212	0,1	0,00	N	7,20	H	0,00	N	0,00	N	d	ms
Chamaecyparis nootkatensis	29	0,0	0,00	N	7,20	H	0,00	N	0,00	N	d	ms
Chamaecyparis obtusa	1	0,0	0,00	N	3,48	M	0,00	N	0,00	N	c	ms
Chamaecyparis pisifera	4	0,0	0,00	N	3,48	M	0,00	N	0,00	N	c	ms
Chamaecyparis spec.	97	0,0	0,00	N	3,48	M	0,00	N	0,00	N	c	mt
Chamaecyparis thyoides	1	0,0	0,00	N	3,48	M	0,00	N	0,00	N	c	mt
Cornus mas	95	0,0	0,10	M	1,60	L	0,00	N	0,00	N	w	ms
Cornus spec.	37	0,0	0,10	M	1,60	L	0,00	N	0,00	N	w	s
Corylus colurna	2873	1,4	0,01	L	1,30	L	0,01	M	0,01	L	f,zc	ms
Corylus spec.	27	0,0	0,01	L	1,30	L	0,01	M	0,01	L	f,zc	ms
Cotinus coggygria	24	0,0	0,20	M	15,00	H	0,00	N	0,00	N	n	t

Species	n	%	IS	IS_c	MO	MO_c	SE	SE_c	OT	OT_c	BVOC Source	DT
Crataegus laevigata	246	0,1	0,00	N	0,00	L	0,02	M	0,00	N	b	mt
Crataegus monogyna	242	0,1	0,00	N	0,00	L	0,02	M	0,00	N	b	mt
Crataegus spec.	105	0,1	0,00	N	0,00	L	0,02	M	0,00	N	b	ms
Crataegus x lavallei	92	0,0	0,00	N	0,00	L	0,02	M	0,00	N	b	ms
Cupressus arizonica	9	0,0	0,05	L	0,79	L	0,06	M	1,18	L	a,z,d	mt
Cupressus sempervierens	7	0,0	0,05	L	0,79	L	0,06	M	1,18	L	a,z,d	mt
Euonymus europaeus	8	0,0	189,80	H	23,84	H	0,10	L	0,10	L	z,d	mt
Fagus spec.	12	0,0	94,91	H	11,15	H	0,10	L	2,00	M	zf,d	s
Fagus sylvatica	710	0,4	100,00	H	12,35	H	0,00	N	0,00	N	zf,d	s
Ficus carica	5	0,0	130,00	H	0,00	L	0,00	N	0,00	N	x	mt
Fraxinus americana	188	0,1	0,01	L	0,01	L	0,10	L	2,01	M	z,zf,a	ms
Fraxinus angustifolia	443	0,2	0,01	L	0,06	L	0,10	L	2,98	M	k,s	ms
Fraxinus excelsior	10299	5,1	0,01	L	0,01	L	0,10	L	2,01	M	z,zf,a	s
Fraxinus ornus	3328	1,6	0,02	L	0,07	L	0,05	M	1,01	L	a,z,k	s
Fraxinus pennsylvanica	506	0,3	0,00	N	0,00	L	0,00	N	0,00	N	d	s
Fraxinus spec.	416	0,2	0,01	L	0,01	L	0,10	L	2,01	M	z,zf,a	ms
Ginkgo biloba	1269	0,6	0,00	N	35,60	H	0,00	N	9,91	H	d,s	mt
Gleditsia spec.	49	0,0	0,00	N	5,30	H	0,00	N	0,00	N	b	t
Gleditsia triacanthos	3492	1,7	30	N	5,30	H	0,00	N	0,00	N	b	t
Gymnocladus dioicus	256	0,1	0,10	M	0,10	L	0,00	N	0,00	N	w	mt
Ilex aquifolium	60	0,0	0,00	N	0,00	L	0,10	L	2,00	M	n	ms
Ilex x meserveae	1	0,0	0,00	N	0,00	L	0,10	L	2,00	M	z	mt
Juglans microcarpa	2	0,0	0,00	N	16,30	H	0,10	L	2,00	M	z	ms
Juglans nigra	188	0,1	0,00	N	16,30	H	0,10	L	2,00	M	z,d	ms
Juglans regia	1777	0,9	0,00	N	16,30	H	0,10	L	2,00	M	z,d	ms
Juglans spec.	10	0,0	0,00	N	16,30	H	0,10	L	2,00	M	z,d	ms
Juniperus chinensis	13	0,0	0,00	N	5,40	H	0,00	N	0,00	N	z,d	t
Juniperus communis	28	0,0	0,03	L	0,55	L	0,06	M	1,04	L	d	t
Juniperus drupacea	1	0,0	0,03	L	0,55	L	0,06	M	1,04	L	a,z	t
Juniperus scopulorum	1	0,0	0,03	L	0,55	L	0,06	M	1,04	L	a,z	t
Juniperus virginiana	57	0,0	0,03	L	0,55	L	0,06	M	1,04	L	a,z	t
Koelreuteria paniculata	1668	0,8	40,00	H	0,00	L	0,00	N	0,00	N	a,z	t
Koelreuteria spec.	17	0,0	40,00	H	0,00	L	0,00	N	0,00	N	d	t

Species	n	%	IS	IS_c	MO	MO_c	SE	SE_c	OT	OT_c	BVOC Source	DT
Laburnum anagyroides	32	0,0	0,10	M	0,20	L	0,00	N	0,00	N	d	mt
Larix decidua	100	0,0	0,00	N	2,50	M	0,10	L	2,00	M	w	s
Larix kaempferi	1	0,0	0,00	N	2,50	M	0,10	L	2,00	M	z,k	ms
Larix spec.	4	0,0	0,10	M	0,10	L	0,00	N	0,00	N	z	ms
Liquidambar spec.	2	0,0	57,50	H	3,50	M	0,00	N	0,00	N	ze	ms
Liquidambar styraciflua	82	0,0	57,50	H	3,50	M	0,00	N	0,00	N	w	ms
Liriodendron tulipifera	276	0,1	4,10	M	0,00	L	0,00	N	0,00	N	w	s
Magnolia	6	0,0	0,00	N	53,30	H	0,00	N	0,00	N	w	s
Magnolia grandiflora	28	0,0	0,00	N	53,30	H	0,00	N	0,00	N	d	s
Magnolia kobus	61	0,0	0,00	N	53,30	H	0,00	N	0,00	N	d	s
Magnolia liliiflora	1	0,0	0,00	N	53,30	H	0,00	N	0,00	N	d	ms
Magnolia spec.	96	0,0	0,00	N	53,30	H	0,00	N	0,00	N	d	ms
Magnolia stellata	8	0,0	0,00	N	53,30	H	0,00	N	0,00	N	d	s
Magnolia tripetala	1	0,0	0,00	N	53,30	H	0,00	N	0,00	N	d	ms
Magnolia x soulangiana	22	0,0	0,00	N	53,30	H	0,00	N	0,00	N	d	s
Malus	109	0,1	0,00	N	0,00	L	0,10	L	2,00	M	d	ms
Malus floribunda	12	0,0	0,00	N	0,00	L	0,10	L	2,00	M	k	ms
Malus hybrida	52	0,0	0,00	N	0,00	L	0,10	L	2,00	M	k	ms
Malus hybride	72	0,0	0,00	N	0,00	L	0,10	L	2,00	M	k	ms
Malus spec.	796	0,4	0,00	N	0,00	L	0,10	L	2,00	M	k	ms
Malus spectabilis	7	0,0	0,00	N	0,00	L	0,10	L	2,00	M	k	ms
Malus sylvestris	66	0,0	0,00	N	0,00	L	0,10	L	2,00	M	k	ms
Malus toringo	5	0,0	0,00	N	0,00	L	0,10	L	2,00	M	k	ms
Malus tschonoskii	42	0,0	0,00	N	0,00	L	0,10	L	2,00	M	k	ms
Malus x purpurea	86	0,0	0,00	N	0,00	L	0,10	L	2,00	M	k	ms
Metasequoia glyptostroboides	111	0,1	181,00	H	46,00	H	0,00	N	0,00	N	k	ms
Morus alba	366	0,2	39,30	H	18,50	H	0,00	N	6,95	H	n	ms
Morus nigra	110	0,1	39,30	H	18,50	H	0,00	N	6,95	H	a,d,x	ms
Morus spec.	75	0,0	0,00	N	14,40	H	0,00	N	0,00	N	a,d,x	ms
Parrotia persica	78	0,0	0,00	N	0,00	L	0,00	N	0,00	N	d	mt
Phellodendron amurense	4	0,0	0,00	N	0,00	L	0,00	N	0,00	N	w	mt
Photinia x fraseri	10	0,0	0,01	L	0,90	L	0,00	N	0,00	N	w	t
Picea abies	765	0,4	77,45	H	7,50	H	0,10	L	2,30	M	w	ms

Species	n	%	IS	IS_c	MO	MO_c	SE	SE_c	OT	OT_c	BVOC Source	DT
Picea breweriana	9	0,0	77,30	H	17,20	H	0,00	N	0,00	N	d	s
Picea engelmannii	2	0,0	124,70	H	30,70	H	0,00	N	0,00	N	z,zf,d	ms
Picea omorika	165	0,1	2,37	M	3,69	M	0,07	M	0,43	L	d	ms
Picea orientalis	36	0,0	2,37	M	3,69	M	0,07	M	0,43	L	d	mt
Picea pungens	596	0,3	0,00	N	3,48	M	0,15	L	0,00	N	a	ms
Picea spec.	64	0,0	2,37	M	3,69	M	0,07	M	0,43	L	a	ms
Picea torano	1	0,0	2,37	M	3,69	M	0,07	M	0,43	L	j	ms
Pinus aristata	2	0,0	0,00	N	31,60	H	0,00	N	0,00	N	a	mt
Pinus cembra	7	0,0	0,00	N	2,50	M	0,10	L	2,00	M	a	mt
Pinus flexilis	1	0,0	0,00	N	31,60	H	0,00	N	0,00	N	d	t
Pinus leucodermis	60	0,0	0,00	N	6,00	H	0,10	L	2,00	M	k	mt
Pinus nigra	5589	2,8	30	L	7,92	H	0,14	L	2,19	M	d	mt
Pinus nigra laricio	2	0,0	0,05	L	7,92	H	0,14	L	2,19	M	k	mt
Pinus nigra nigra	3245	1,6	0,05	L	7,92	H	0,14	L	2,19	M	z,a,k	mt
Pinus parviflora	4	0,0	0,05	L	7,92	H	0,14	L	2,19	M	z,a,l	mt
Pinus ponderosa	12	0,0	0,00	N	31,60	H	0,00	N	0,00	N	z,a,m	mt
Pinus spec.	131	0,1	0,00	N	4,50	M	0,00	N	0,00	N	z,a,m	mt
Pinus strobus	35	0,0	0,00	N	2,50	M	0,10	L	2,00	M	d	ms
Pinus sylvestris	419	0,2	0,78	M	30,43	H	0,07	M	1,71	L	d,ze	mt
Pinus uncinata	5	0,0	0,10	M	5,00	H	0,10	L	2,00	M	z	mt
Pinus wallichiana	46	0,0	0,05	L	7,92	H	0,14	L	2,19	M	a,v,z,d	ms
Platanus orientalis	388	0,2	36,25	H	0,03	L	0,07	M	1,10	L	z,k	mt
Platanus spec.	641	0,3	36,25	H	0,03	L	0,07	M	1,10	L	z,a,m	mt
Platanus x acerifolia	6909	3,4	73,59	H	0,15	L	0,11	L	1,11	L	a,z	mt
Platycladus orientalis	139	0,1	0,00	N	7,20	H	0,00	N	0,00	N	a,z	t
Populus alba	1461	0,7	131,00	H	0,50	L	0,10	L	10,64	H	f,e,w	ms
Populus balsamifera	59	0,0	52,40	H	0,22	L	0,06	M	1,03	L	d	ms
Populus deltoides	1	0,0	146,32	H	0,07	L	0,02	M	0,02	L	z	ms
Populus lasiocarpa	9	0,0	52,40	H	0,22	L	0,06	M	1,03	L	a,t,z	ms
Populus nigra	6030	3,0	70,00	H	0,00	L	0,10	L	2,00	M	a,d	ms
Populus simonii	388	0,2	52,40	H	0,22	L	0,06	M	1,03	L	a,t,z	ms
Populus spec.	237	0,1	52,40	H	0,22	L	0,06	M	1,03	L	z	ms
Populus tremula	115	0,1	52,40	H	0,22	L	0,06	M	1,03	L	a,t,z	mt

Species	n	%	IS	IS_c	MO	MO_c	SE	SE_c	OT	OT_c	BVOC Source	DT
Populus x canadensis	847	0,4	52,40	H	0,22	L	0,06	M	1,03	L	a,t,z	s
Populus x canescens	798	0,4	52,40	H	0,22	L	0,06	M	1,03	L	a,t,z	s
Prunus armeniaca	108	0,1	0,00	N	0,90	L	0,00	N	0,00	N	a,t,z	ms
Prunus avium	2252	1,1	0,00	N	0,90	L	0,10	L	2,00	M	a,t,z	s
Prunus cerasifera	2187	1,1	1,00	M	1,90	L	0,00	N	0,00	N	d	ms
Prunus cerasus	46	0,0	1,00	M	1,90	L	0,00	N	0,00	N	z,d	s
Prunus domestica	187	0,1	1,00	M	1,90	L	0,00	N	0,00	N	d,u	t
Prunus domestica subsp. insititia	81	0,0	1,00	M	1,90	L	0,00	N	0,00	N	d,u	t
Prunus dulcis	51	0,0	1,00	M	1,90	L	0,00	N	0,00	N	d,u	t
Prunus eminens	40	0,0	1,00	M	1,90	L	0,00	N	0,00	N	d,u	ms
Prunus incisa	2	0,0	1,00	M	1,90	L	0,00	N	0,00	N	d,u	ms
Prunus maackii	5	0,0	1,00	M	1,90	L	0,00	N	0,00	N	d,u	ms
Prunus mahaleb	188	0,1	1,00	M	1,90	L	0,00	N	0,00	N	d,u	ms
Prunus padus	332	0,2	0,00	N	0,00	L	0,10	L	2,00	M	d,u	ms
Prunus persica	6	0,0	0,00	N	0,90	L	0,00	N	0,00	N	d,u	ms
Prunus persica var. nucipersica	1	0,0	1,00	M	1,90	L	0,00	N	0,00	N	z	ms
Prunus sargentii	24	0,0	1,00	M	1,90	L	0,00	N	0,00	N	d	ms
Prunus serrulata	2251	1,1	1,00	M	1,90	L	0,00	N	0,00	N	d,u	ms
Prunus spec.	577	0,3	0,00	N	0,90	L	0,00	N	0,00	N	d,u	ms
Prunus spinosa	19	0,0	1,00	M	1,90	L	0,00	N	0,00	N	d,u	ms
Prunus subhirtella	98	0,0	1,00	M	1,90	L	0,00	N	0,00	N	d	ms
Prunus virginiana	14	0,0	0,00	N	0,90	L	0,00	N	0,00	N	d,u	ms
Prunus x schmittii	4	0,0	1,00	M	1,90	L	0,00	N	0,00	N	d,u	mt
Prunus x yedoensis	21	0,0	1,00	M	1,90	L	0,00	N	0,00	N	d	ms
Pseudotsuga menziesii	110	0,1	11,20	M	28,20	H	0,05	M	1,00	L	d,u	ms
Pterocarya fraxinifolia	119	0,1	0,00	N	0,00	L	0,00	N	0,00	N	d,u	ms
Pterocarya spec.	19	0,0	0,00	N	0,00	L	0,00	N	0,00	N	d	ms
Pyrus calleryana	3297	1,6	0,00	N	0,00	L	0,00	N	0,00	N	w	t
Pyrus communis	135	0,1	0,00	N	0,00	L	0,10	L	2,00	M	w	ms
Pyrus nivalis	5	0,0	0,00	N	0,00	L	0,10	L	2,00	M	d	ms
Pyrus salicifolia	14	0,0	0,00	N	0,00	L	0,10	L	2,00	M	k	ms
Pyrus spec.	98	0,0	0,00	N	0,00	L	0,00	N	0,00	N	k	ms
Quercus cerris	299	0,1	0,14	M	0,32	L	0,06	M	1,06	L	k	mt

Species	n	%	IS	IS_c	MO	MO_c	SE	SE_c	OT	OT_c	BVOC Source	DT
Quercus coccinea	21	0,0	153,85	H	39,45	H	0,05	M	2,00	M	d	ms
Quercus dentata	1	0,0	72,50	H	0,00	L	0,10	L	2,00	M	o,a,z,k	ms
Quercus frainetto	82	0,0	153,00	H	0,00	L	0,10	L	2,00	M	d,k	mt
Quercus hispanica	1	0,0	91,65	H	23,60	H	0,15	L	2,00	M	zb,z	t
Quercus ilex	3	0,0	189,85	H	43,20	H	0,10	L	15,47	H	o,k	mt
Quercus libani	1	0,0	91,65	H	23,60	H	0,15	L	2,00	M	z,d	ms
Quercus macrantheram	5	0,0	91,65	H	23,60	H	0,15	L	2,00	M	za,z,e,d	ms
Quercus petraea	40	0,0	72,00	H	0,16	L	0,06	M	1,04	L	z,d	mt
Quercus pubescens	21	0,0	105,50	H	0,45	L	0,10	L	0,54	L	z,d	t
Quercus robur	2505	1,2	115,50	H	1,12	L	0,15	L	2,00	M	a,z	ms
Quercus rubra	98	0,0	91,65	H	23,60	H	0,15	L	2,00	M	o,g	ms
Quercus spec.	183	0,1	91,65	H	23,60	H	0,15	L	2,00	M	z,s	ms
Quercus x kewensis	1	0,0	91,65	H	23,60	H	0,15	L	2,00	M	z,d	ms
Quercus x turneri	2	0,0	91,65	H	23,60	H	0,15	L	2,00	M	z,d	mt
Rhamnus cathartica	12	0,0	36,90	H	0,00	L	0,00	N	0,00	N	z,d	ms
Rhamnus frangula	1	0,0	36,90	H	0,00	L	0,00	N	0,00	N	z,d	ms
Rhus spec.	4	0,0	0,00	N	0,00	L	0,00	N	0,00	N	w	t
Rhus typhina	11	0,0	0,00	N	0,00	L	0,00	N	0,00	N	w	mt
Robinia hispida	25	0,0	30	H	0,12	L	0,06	M	3,20	M	d	t
Robinia pseudoacacia	6087	3,0	30	H	0,12	L	0,06	M	3,20	M	d	t
Robinia spec.	45	0,0	30	H	0,12	L	0,06	M	3,20	M	a,z,e,d	t
Robinia x margaretta	1	0,0	30	H	0,12	L	0,06	M	3,20	M	a,z,e,d	t
Robinia x slavinii	4	0,0	30	H	0,12	L	0,06	M	3,20	M	a,z,e,d	t
Salix alba	510	0,3	37,20	H	0,00	L	0,10	L	2,00	M	a,z,e,d	s
Salix aurita	1	0,0	37,20	H	0,00	L	0,10	L	2,00	M	a,z,e,d	ms
Salix babylonica	3	0,0	88,00	H	0,00	L	0,00	N	0,00	N	z	s
Salix caprea	25	0,0	18,90	M	0,00	L	0,10	L	2,00	M	z	ms
Salix fragilis	2	0,0	37,20	H	0,00	L	0,10	L	2,00	M	d	ms
Salix matsudana	58	0,0	37,20	H	0,00	L	0,10	L	2,00	M	z	ms
Salix spec.	160	0,1	39,35	H	0,00	L	0,10	L	2,00	M	z	ms
Sambucus nigra	329	0,2	0,00	N	0,00	L	0,00	N	0,00	N	z	ms
Sambucus nigra var. laciniata	1	0,0	0,00	N	0,00	L	0,00	N	0,00	N	z,zc	ms
Sambucus spec.	3	0,0	0,00	N	0,00	L	0,00	N	0,00	N	w	ms

Species	n	%	IS	IS_c	MO	MO_c	SE	SE_c	OT	OT_c	BVOC Source	DT
Sassafras albidum	1	0,0	0,00	N	3,60	M	0,00	N	0,00	N	w	mt
Sequoiadendron giganteum	31	0,0	0,00	N	76,70	H	0,00	N	0,00	N	w	mt
Sophora japonica	3208	1,6	37,90	H	12,65	H	0,00	N	0,00	N	d	t
Sophora spec.	15	0,0	37,90	H	12,65	H	0,00	N	0,00	N	d	t
Sorbus aria	156	0,1	0,00	N	0,00	L	0,10	L	2,00	M	d,ze	t
Sorbus aucuparia	134	0,1	0,00	N	0,00	L	0,10	L	2,00	M	d,ze	ms
Sorbus domestica	14	0,0	0,00	N	0,00	L	0,10	L	2,00	M	k	t
Sorbus intermedia	122	0,1	0,00	N	0,00	L	0,10	L	2,00	M	k	ms
Sorbus spec.	33	0,0	0,00	N	0,00	L	0,10	L	2,00	M	k	mt
Sorbus torminalis	27	0,0	0,00	N	0,00	L	0,10	L	2,00	M	k	t
Sorbus x thuringiaca	9	0,0	0,00	N	0,00	L	0,10	L	2,00	M	k	mt
Tamarix spec.	29	0,0	0,00	N	1,15	L	0,00	N	0,00	N	k	mt
Tamarix tetrandra	19	0,0	0,00	N	1,15	L	0,00	N	0,00	N	k	t
Taxodium distichum	36	0,0	0,00	N	76,70	H	0,00	N	0,00	N	q	mt
Taxus baccata	1303	0,6	0,00	N	1,10	L	0,00	N	0,00	N	q	mt
Thuja occidentalis	157	0,1	0,00	N	7,20	H	0,00	N	0,00	N	d	s
Thuja plicata	20	0,0	0,00	N	7,20	H	0,00	N	0,00	N	q	ms
Thuja spec.	85	0,0	9,00	M	0,60	L	0,05	M	1,00	L	d	ms
Tilia americana	425	0,2	0,02	L	1,50	L	0,01	M	0,01	L	d	ms
Tilia cordata	12180	6,0	0,00	N	0,71	L	0,18	L	1,15	L	k	ms
Tilia mongolica	2	0,0	12,56	M	0,07	L	0,01	M	0,10	L	f	ms
Tilia platyphyllos	5784	2,9	12,56	M	0,07	L	0,01	M	0,10	L	f,k	ms
Tilia platyphyllos var. vitifolia	30	0,0	12,56	M	0,07	L	0,01	M	0,10	L	a,w	ms
Tilia spec.	1944	1,0	12,56	M	0,07	L	0,01	M	0,10	L	a,w	ms
Tilia tomentosa	1694	0,8	12,56	M	0,07	L	0,01	M	0,10	L	a,w	mt
Tilia x euchlora	535	0,3	12,56	M	0,07	L	0,01	M	0,10	L	a,w	ms
Tilia x europaea	616	0,3	12,56	M	0,07	L	0,01	M	0,10	L	a,w	ms
Tilia x vulgaris	627	0,3	12,56	M	0,07	L	0,01	M	0,10	L	a,w	ms
Tsuga canadensis	21	0,0	10,70	M	26,20	H	0,00	N	0,00	N	a,w	s
Ulmus	762	0,4	0,02	L	0,05	L	0,00	N	1,66	L	a,w	mt
Ulmus glabra	238	0,1	0,10	M	0,00	L	0,10	L	2,00	M	d	s
Ulmus laevis	125	0,1	0,10	M	0,00	L	0,10	L	2,00	M	d	mt
Ulmus minor	517	0,3	0,10	M	0,00	L	0,10	L	2,00	M	z	s

Species	n	%	IS	IS_c	MO	MO_c	SE	SE_c	OT	OT_c	BVOC Source	DT
Ulmus pumila	5	0,0	0,01	L	0,96	L	0,01	M	0,01	L	z	mt
Ulmus pumila var. arborea	4	0,0	0,01	L	0,96	L	0,01	M	0,01	L	z	Ms
Ulmus spec.	506	0,3	0,01	L	0,96	L	0,01	M	0,01	L	f	Mt
Ulmus x hollandica	106	0,1	0,01	L	0,96	L	0,01	M	0,01	L	f	mt
Zelkova carpinifolia	3	0,0	0,01	L	0,42	L	0,11	L	0,01	L	f	mt
Zelkova serrata	97	0,0	0,01	L	0,42	L	0,11	L	0,01	L	f	mt
Zelkova spec.	8	0,0	0,01	L	0,42	L	0,11	L	0,01	L	f,d	mt
Others	7082	3,5	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Total	202214	100										

IS, MO, SE and OT in µg/gh. BVOC Soruce: a, Aydin et al. (2014); b, Baghi et al. (2012); c, Bao et al (2008); d, Benjamin and Winer (1998); e, Calfapietra et al. (2013); f, Curtis et al. (2014); g, Genard-Zielinski et al (2015); h, Geron et al. (1994); i, Hakola et al (1999); j, Helmig et al (2013); k, Karl et al (2009); l, König et al., (1995); m, Lamb et al (1987); n, Li et al (2017); o, Lim et al. (2011); p, Moukhtar et al. (2006); q, Noe et al. (2008); r, Owen et al. (1997); s, Paoletti et al. (2011); t, Portillo-Estrada et al. (2015); u, Préndez et al. (2013); v, Rinne et al., (2000); w, Scholz, (2019); x, Singh et al., (211); z, Steinbrecher et al. (2009); za, Street et al. (1997); zb, Tani and Kawata (2008); zc, Tiwary et al. (2013); zd, van Meeningen et al. (2016); ze, Wang et al. (2007); zf, Zemankova and Brechler (2010); and zg, Guenther,et al. (1996).

DT source: Department of Environmental Horticulture at the University of Florida, 2020; EUFORGEN, 2020; Hirons and Sjöman, 2018; Samson et al, 2017.