



HAL
open science

Impact of air pollution on terrestrial ecosystems

Maria Kanakidou, Maria Sfakianaki, Anne Probst

► **To cite this version:**

Maria Kanakidou, Maria Sfakianaki, Anne Probst. Impact of air pollution on terrestrial ecosystems. François Dulac, Stéphane Sauvage, Eric Hamonou. Atmospheric Chemistry in the Mediterranean: From Air Pollutant Sources to Impacts, Springer, 2022, 978-3-030-82384-9. 10.1007/978-3-030-82385-6_24 . hal-03377002

HAL Id: hal-03377002

<https://hal.science/hal-03377002>

Submitted on 13 Oct 2021

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Atmospheric Chemistry in the Mediterranean: Vol. 2, From Air Pollutant Sources to Impacts

François Dulac, Stéphane Sauvage, and Eric Hamonou Eds.

MANUSCRIPT OF PART X (vol. 2)

Impacts of air pollution on human health and ecosystems

*Coordinated by **Maria Kanakidou** (UOC, Heraklion, Greece)*

*Section reviewed by **Semia Cherif** (ISSBAT, University of Tunis El Manar, Tunisia)*

Abstract This section reviews current knowledge on the impacts of air pollution on human health as well as marine and terrestrial ecosystems in the Mediterranean. The first chapter summarizes the human health studies in the region, with special focus on the impact of dust and biomass burning events. The last two chapters concentrate on the impact of air quality on the marine and terrestrial ecosystems summarizing relevant knowledge from studies performed in the Mediterranean.

Content

total 76 pp.

- Air quality and health impacts 2
- Impact of atmospheric deposition on marine chemistry and biogeochemistry 28
- Impact of air pollution on terrestrial ecosystems 48

Impact of air pollution on terrestrial ecosystems

Maria Kanakidou¹, Maria Sfakianaki¹, and Anne Probst²

¹ Environmental Chemical Processes Laboratory, Department of Chemistry, University of Crete, 70013 Heraklion, Greece

² Laboratoire Ecologie Fonctionnelle et Environnement, Observatoire Midi-Pyrénées, Université de Toulouse, CNRS, Toulouse, France

* Corresponding author: mariak@uoc.gr

Reviewed by **Panayiotis Nektarios** (School of Agricultural Sciences, Department of Agriculture, Hellenic Mediterranean University), as part of the book Section X also reviewed by **Semia Cherif** (ISSBAT, University of Tunis El Manar, Tunisia)

Abstract This chapter summarizes the current state of knowledge on the impacts of air pollution on terrestrial vegetation in general and in the Mediterranean region in particular. These impacts occur either indirectly through changes in the physical state of the atmosphere, such as increase in the temperature (caused by greenhouse gases), and in the diffuse radiation (caused by aerosols) that reaches vegetation, or directly through phytotoxicity resulting from ozone, sulfur, nitrogen and other pollutants stomatal and non-stomatal uptake by the plants, nutrient balance modification by atmospheric deposition, transfer of plant diseases by aerosols, and pollution by persistent pollutants and metals. These impacts are summarized and plant physiological responses and deposition mode of action in excess of critical nutrient levels are presented and discussed.

1 Introduction

Mediterranean Basin is among the world's regions hosting the highest biodiversity of both marine and terrestrial ecosystems. The Mediterranean's flora is highly diverse with 15,000 to 25,000 species, among which 60% are native and endemic species unique to the region (Vlachogianni et al. 2012). Globally, terrestrial vegetation is responsible for more than half of the atmospheric oxygen production. Regionally, vegetation interacts with the atmospheric water cycle through photosynthesis, respiration and transpiration. In urban regions, vegetation has the capacity to partially counterbalance the heat island effect, and improve microclimate through the reduction of both noise and intensity of atmospheric ionization. Furthermore, vegetation is an efficient recycling energy source and plant products provide raw material for various constructions, clothing as well as nutrients for humans and fauna.

Due to the mild weather conditions and the fertility of most soils, agriculture has always been an integral part of human activities and an important contributor to the economy of the Mediterranean countries. However, vegetation in the region is at risk due to land use changes and the occurrence of environmental stresses and, in particular, air pollution combined with climate change. Mediterranean vegetation is known to be highly resilient to disturbances, which is tentatively attributed to its historical evolution under various stresses and to its increased biodiversity, although the mechanisms associated with the resilience of ecosystems remain to be understood (Lavorel 1999). Severe man-driven land use changes, like urban extension, agricultural abandonment and afforestation, have

led to flora redistribution within the Mediterranean region and to the increase of invasive alien plant species (Vilà et al. 2003; Mosher et al. 2009). In addition, human interference to nature, has resulted to several side effects such as extreme climatic events, including prolonged droughts, increased occurrence of wildfires, along with elevated ozone (O₃) and particulate matter levels (Avila et al. 1997; Kanakidou et al. 2011).

Air pollutants affect the physiology of the plants in several ways and through different pathways: a) by absorption through the leaf stomata or epidermis (Hill 1971; Heath 2008), b) through the root system after air pollutant deposition onto the soils (Gandois and Probst 2012; Cataldo and Wildung 1978), c) by adsorption of aerosols onto the leaves thus reducing the penetrating light and blocking the opening of stomata (Gheorghe and Ion 2011) d) by changing the Photosynthetically Active Radiation that reaches the plant (Rap et al. 2015). Air pollutants can also cause acute damage to the vegetation whenever absorption of high pollutant concentrations is performed in a relatively short time interval, while chronic injuries occur due to long-term absorption of pollutants at sub-lethal concentrations (Gheorghe and Ion 2011). Mills et al. (2018) estimated a global loss in wheat yields due to exposure to O₃ of 6% to 9% on average in the south and north hemisphere, respectively, that results in actual total grain losses of approximately 85 Tg per year.

In the 80's acid rain emerged as a major problem for European forests (Grennfelt et al. 2020). The acid rain facilitated solubilisation and leaching of mineral elements, like Calcium (Ca), Potassium (K) and Magnesium (Mg), from the soil and led to the removal of vital minerals and nutrients for plant growth resulting in profound yellowing of the leaves due to deficiencies (Landmann and Bonneau, 1995). The applied legislation for air pollution abatement, resulted in the reduction of pollutants' emissions (Lamarque et al. 2013) that subsequently led to substantial decrease of sulfate concentrations in atmospheric aerosols over the past 30 years (Aas et al. 2019) and reduced atmospheric deposition to distant forests (Pierret et al. 2019). However, deposition fluxes of reactive nitrogen remain high and affect ecosystems health (Markaki et al. 2010; Ochoa-Hueso et al. 2011; Aguilhaume et al. 2016; Im et al. 2013; Kanakidou et al. 2020). Nevertheless, eutrophication and acidification issues persist and they are of high concern since they affect biodiversity leading to a loss of species richness (Duprè et al. 2010). Analyzing 70 years of species richness in acidic grasslands of Northern Europe, Duprè et al. (2010) found that changes in vegetation species spatial distribution were mainly related to soil acidity, which affects solubilisation of metal oxides and releases toxic metal ions, and to the cumulative amounts of Nitrogen (N) and Sulfur (S) deposition. It is worth noting that N atmospheric deposition has been proposed to be the main driver for variation in plant species richness (Stevens et al. 2004), phytocommunity composition (Bobbink et al. 2010) and relative plant species abundance (Gilliam, 2006). The interaction between N deposition and air temperature increase under climate change, has been predicted to impact soil functioning and to cause vegetation species and spatial changes for the next decades (Gaudio et al. 2015; Rizzetto et al. 2016).

Furthermore, aerosol pollution also affects vegetation by scattering light and thus increasing the fraction of diffuse radiation and the efficiency of photosynthesis (Rap et al. 2015) and by providing nutrients and/or toxic substances to the ecosystem through dry or wet deposition (Ochoa-Hueso et al. 2011; Kanakidou et al. 2018). Adsorption of aerosols on the leaf surface causes negative effects to the plants since aerosols cover the leaves

surface, reduce the penetrating light and block the opening of stomata (Gheorghe and Ion 2011). The vicinity of the Mediterranean Basin with the African desert, results in frequent dust outbreaks that increase aerosol levels and nutrient deposition over the Mediterranean (Kanakidou et al. 2020). In addition, dust outbreaks can also carry pathogens to Mediterranean (Polymenakou et al. 2008) and other ecosystems causing them to degrade as has been suggested for Caribbean ecosystems (Garrison et al. 2003 and 2006).

Finally, intensification of agriculture activities so as to cover human needs for nutrition, has led to soil contamination through the excessive use of fertilizers and pesticides. Spraying of several pesticides in the atmosphere against insects, plant pathogens or other pests, in order to improve product quality and to increase the yields of various crops has contributed to air pollution of agricultural regions. Pesticides include a wide range of compounds: insecticides, herbicides, fungicides, plant growth regulators and others (Aktar et al. 2009). They are sprayed on the crops and thus they partially remain in the atmosphere, transported by the wind and deposited to the nearby soils, thus expanding contamination and providing an additional pathway for pesticides to penetrate into the plants through the soil. Toxic metals consist another category of important air pollutants present in the atmosphere in low concentrations, which are deposited to and can accumulate in the soils (Hernandez et al. 2003), sediments (N'Guessan et al. 2009) and organisms (Kabata-Pendias 2010; EMEP 2018). Persistent organic compounds and toxic metals tend to accumulate in plants, resulting in an increase of their concentration within the tissues of organisms at successively higher levels, entering into the food chain (Liu et al. 2005). Metal enrichments of soils in agricultural and urban areas of Greece (Kelepertzis. 2014) and Spain (Acosta et al. 2011) have been attributed to accumulation processes resulting from prolonged applications of large amounts of fertilizers and pesticides–fungicides (copper (Cu), zinc (Zn), cadmium (Cd), lead (Pb) and arsenic (As)), as well as from industrial activities, and metal deposition due to the high volume of vehicular traffic (Pb and Cd). Pollution of vegetation both by metals and pesticides can be harmful to human health since these pollutants can penetrate in the food chain (Nasreddine and Parent-Massin 2002). Finally, more or less biodegradable detergents that are discharged into the sea, can then be transported to the atmosphere through the production of sea-spray leading to air pollution. The deposition of sea spray loaded with detergent on the leaves of the plants, promotes the penetration of salt into the plants causing their death. Impacts of the aforementioned pollution can be observed on certain coastal forests around the Mediterranean Sea (Garrec 2020).

In this chapter, we first outline general information regarding the mechanisms of air pollutants pathways into the plants and the phytotoxicity effects caused by the most common atmospheric pollutants. Subsequently, we discuss the impact of the major pollutants, namely, ozone, sulfur, nitrogen and metals on the vegetation, spanning from forests to crops in the Mediterranean Region.

2 Pollutant uptake by the plants

Penetration of air pollutants into the plant occurs either from the aerial or from the underground organs of the plants. From the aerial organs, air pollutant absorption into plants occurs mainly through the leaves, although a slight absorption through stems and trunk might also be possible (Kabata-Pendias 2010; Garrec 2020). Air pollutants can also be

absorbed by the roots of the plants after being deposited onto the soil in their deposited chemical form or after being chemically transformed. Before reaching the cuticle of the leaf, the pollutant passes through a thin zone of calm air that surrounds each leaf, the atmospheric interfacial leaf/atmosphere sub-layer. The resistance to air pollution absorption through the interfacial atmospheric layer varies according to numerous parameters, such as leaf size, shape and orientation, presence and shape of trichomes, and wind speed ([Heath et al. 2009](#); [Gupta 2016](#); [Garrec 2020](#)).

The interfacial leaf/atmosphere layer, contains three phases: a) The gas phase, where the air pollutants reaching the plant are present together with the emissions of the leaf; b) the aqueous phase, which contains the water film located at the surface of the leaf and water that is bound to the cuticle through its polar groups; and c) the lipid phase, which contains the waxes that are located on the surface of or inside the cuticle. The pollutant may react in one of these phases and could produce additional secondary phytotoxic products to the initial pollutant itself ([Percy et al. 1994](#)). Organic matter exudation by the leaves can lead to a complete dissolution of dry deposition of metals at the leaf surface and make them easier to be absorbed by the leaves ([Hou et al. 2005](#)).

The air pollutants can be transported into the plant following various pathways (**Fig. 1**): penetration mainly by stomata (**gases**), which are present in the leaf surface ([Gupta 2016](#)), surface deposits (aerosols), and trapping in epicuticular waxes (lipophilic and high molecular weight gases). Following dry and wet atmospheric deposition, **metals** can be found in wax and inside the coniferous needles depending on the metal and its particulate or dissolved form ([Gandois and Probst 2012](#)). The main route that **organic pollutants** will be absorbed by the plant is via the lipid structure of the cuticle. However, from the pollutant concentration found in the interfacial leaf/atmosphere layer, only a small portion will finally enter into the plant. There, they will react within the different plant compartments, both in the outer and the inner sides of the plasma membrane (apoplast and symplast) ([Oparka 2005](#); [Kundu et al. 2018](#); [Faulkner 2018](#); [Garrec 2020](#)). Meteorological conditions such as amount of sun irradiance, wind and rain, as well as leaf microstructure and vegetation macrostructure, influence the characteristics of **aerosol deposition** on the surface of the leaves ([Leonard et al. 2016](#)). Moreover, O₃ absorption by stomata depends on water availability during the growing season, plant morphological characteristics such as the existence and the shape of the leaf trichomes and also on the sensitivity of the plants, which may vary strongly according to both the species and the varieties ([Lombard et al. 2015](#); [Saitanis and Karandinos 2002](#); [Saitanis et al. 2014](#)). The physiological response of plants to air pollutants after their absorption, will depend on both the characteristics of the plant and the nature of the air pollutant ([Wolfenden and Mansfield 1990](#)).

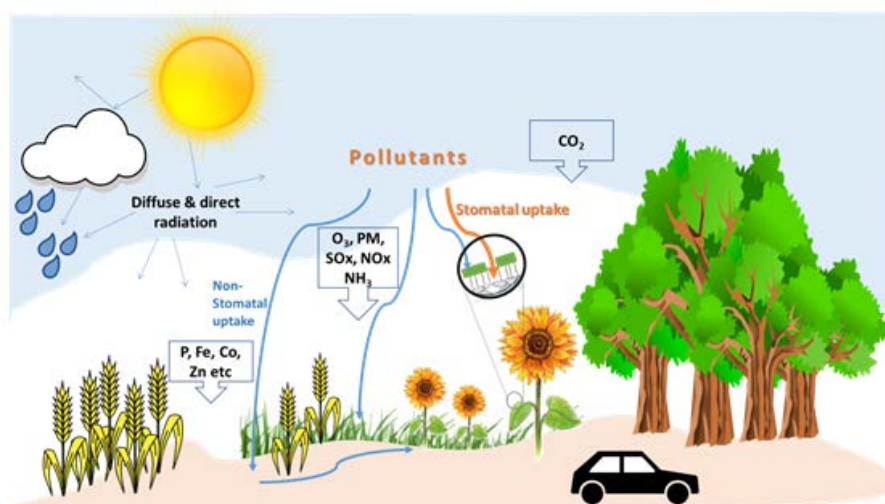


Fig. 1 Gaseous and particulate atmospheric pollutants are transported in the plants through stomatal and non-stomatal uptake by the leaves as well as via deposition onto the soil and subsequent uptake by the roots

3 Pollutant reactions inside the plant

Once the pollutant enters the plant, it causes an oxidative stress producing reactive oxygen species (ROS), including free hydroxyl radicals, which can cause damage to the plants at different levels. ROS induce oxidative damage to lipids, proteins and DNA (Sharma et al. 2012). The pollutant will cause specific stress to the plant depending on its physicochemical characteristics (Table 1).

Ozone enters the plants through stomatal and non-stomatal uptake from the leaf cuticle via thermal decomposition or aqueous reactions in water-films on plant surfaces (Heath 2008; Fowler et al. 2009). Inside the plant, O_3 contributes to ROS production but since it is very short-lived, it is quickly converted to more stable ROS, such as hydrogen peroxide, superoxide and hydroxyl radical (Health 2008). If O_3 concentration exceeds the detoxification capacity of the apoplastic antioxidants, it will negatively affect plant's physiological processes, such as photosynthesis and/or respiration (Musselman et al. 2006; Emberson et al. 2018).

Nitrogen dioxide (NO_2) dissolved in cells produces nitrite ions (NO_2^-), which are toxic at high concentrations and nitrate ions (NO_3^-) that enter into nitrogen metabolism. Nitrogen dioxide pollution is detectable on leaves and seedlings and is more profound in conifer older needles where tip burn is observed. It forms crystalloid structures in the stroma of chloroplasts and bloats the thylakoid membrane within the plant cells, resulting in the reduction of photosynthetic activity (Gheorghe and Ion 2011).

Sulfur enters the leaves as sulfur dioxide (SO_2) through the stomata. Sulfur, at low concentrations, is used by the plant in protein synthesis, but at high concentrations it interferes with electron transport chain, leading to stomatal opening reduction, water stress and oxygen replacement in cellular material (Mudd 1975). It also affects structural proteins in the cell membrane leading to alterations in the permeability of the membranes (Nieboer et al. 1976). In high concentrations, SO_2 will lead to chlorophyll's degradation (Brahmachari and Kundu 2017).

Halogens (Cl₂, HCl, HF) enter the plants through the stomata and move to the margins and edges of the leaves, where they tend to accumulate. Inside the plants, fluorides interfere with the activity of many enzymes, by inhibiting the functioning of proteins through combination with the metal components of the proteins or otherwise (Gheorghe and Ion 2011). It is worth mentioning that hydrofluoric acid (HF) pollution is also inducing a disruption of the cellular metabolism of calcium (Garrec 2020).

The phytotoxicity of the various pollutants depends on their chemical identity (Table 1). The main air pollutants have been classified by laboratory experiments according to their decreasing phytotoxicity impact as follows:

Hydrofluoric acid (HF) > ozone (O₃) > sulfur dioxide (SO₂) > nitrogen dioxide (NO₂)

However this trend is only indicative, since different plants have different sensitivity to the various pollutants (Smith et al. 1989; Yu and Tsunoda 2004). In addition to the phytotoxic potential of the pollutant, the plant's response depends on the cumulative amount of the pollutant that entered the plant. Furthermore, the time period over which a certain amount of pollutant is transported into the plant, is also important for its phytotoxic response. For the same amount of pollutant, a shorter transportation time will result in a greater pollutant impact. The so-called “peak effect” is usually explained by the fact that, over short periods of time, the plant does not have adequate time to acclimatize, adapt and initiate its defense systems response.

Table 1. Main categories of atmospheric pollutants, the pathways through which they enter into the plants and their main effects on the plants

Pollutant	Transport pathway	Effect on plant
Ozone (O ₃)	Stomata, Non-stomatal pathway, Deposition on leaves	<ul style="list-style-type: none"> · Increase in reactive oxygen species · Changes in plant's physiological processes · Reduced photosynthesis · Reduced crop yields
Reactive nitrogen (N) (mainly NO _x , NH ₃ , HNO ₃ , ammonium and nitrate)	Stomata, Deposition on leaves	<ul style="list-style-type: none"> · Low levels → amino acids/protein synthesis · High levels → Reduced photosynthetic activity · Changes in plant and soil stoichiometry (N/P) · N-induced P-limitation · Soil and water eutrophication leading to plant toxicities or deficiencies and biodiversity losses
Sulfur (S) (mainly SO ₂ , H ₂ SO ₄ , sulfate)	Stomata, Deposition on leaves	<ul style="list-style-type: none"> · Low levels → Protein synthesis · High levels → Stomata opening reduction, water stress, O₂ replacement in cellular material · Chlorophyll degradation · Acidification after deposition to plants and soils · Soil acidification/nutrient losses
Acid deposition (mainly N, S)	Deposition on leaves and soil	<ul style="list-style-type: none"> · Acidification of soil- nutrient losses through leaching of plant growth minerals and nutrients, resulting in yellowing of leaves, increase vulnerability of plants, dying trees and solubilisation of toxic metals ; loss of plant diversity

Aerosols (also containing S, N and metals)	Deposition on leaves and soil	<ul style="list-style-type: none"> · Diffuse radiation, closing of stomata · Acidification of soils à leaching of minerals à mineral and nutrient deficiency · Accumulation of pollutants into plants · Carriers of plant diseases
Trace metals	Deposition on leaves and soil, with uptake by the roots	<ul style="list-style-type: none"> · Accumulation into plants and leave edges · Disturbance of plant's physiological processes depending on metal · Contamination of food chains
Pesticides	Deposition on leaves and soil, with uptake by roots	<ul style="list-style-type: none"> · Accumulation into plants · Contamination of food chains
Halogens (Cl ₂ , HCl, HF)	Stomata, Deposition on leaves	<ul style="list-style-type: none"> · Interfere with enzymes activity · Damage cell membranes of plants · Disruption of the cellular metabolism of calcium · Necrosis, Plant death

The large number of pollutants (e.g., HF, O₃, SO₂, NO₂, aerosols, metals) that affect plants, can also be classified according to the extent of their impact zone, which depends on their lifetime in the atmosphere and thus on the distance in which they can affect vegetation after emission or formation and transport in the atmosphere (Garrec 2020). Short-lived pollutants, like nitrogen oxides and ammonia, with lifetimes of a few hours to a day, exhibit impacts on the plants within a radius of a few tens of kilometres from their emission sources. Nitrogen oxides (NO_x) are mainly originated from transport and other combustion sources, while ammonia (NH₃) is mainly originated from agriculture and transport. In contrast, pollutants with atmospheric lifetimes ranging from few days to weeks can have impacts over several hundred kilometres around their emission sources. These include mainly acidic compounds, such as sulfuric acid (H₂SO₄) and nitric acid (HNO₃), deposited by dry or wet removal processes. Since these acids are formed via the oxidation of primary pollutants (SO₂ and NO₂) by oxidants like ozone, hydroxyl radicals and nitrate radicals, they are considered as secondary pollutants (Graedel and Crutzen 1993).

Pollutants with lifetime of several years have global impacts and mainly include carbon dioxide (CO₂), which is linked to the massive use of fossil fuels by transport and industry. Carbon dioxide has direct beneficial effects on plant growth via its essential role in photosynthesis, while at the same time, it has indirect harmful effects on plants through enhancing the greenhouse effect that results in climate change (Farquhar 1997). Other global pollutants, which have an indirect effect on vegetation via their contribution to the greenhouse effect, include: methane (CH₄), a gas component of natural gas, which is also produced by ruminants and in anaerobic environments such as wetlands and rice fields and which has phytotoxic effects on plants whenever its concentration is increased such as in the case of landfills (Peer et al. 1993); nitrous oxide (N₂O), resulting from the massive use of fertilizers in agriculture; halocarbons, having several applications such as solvents, refrigerants and in insulation materials; or even soil disinfectants such as methyl bromide which was in use until the beginning of the century. Halocarbons are also ozone-depleting gases with the possibility of an additional negative impact on plants as a result of the increased UV-B solar flux that reaches Earth's surface due to their contribution to the enlargement of the ozone hole.

4 Plant's response to pollution exposure

Plants respond to air pollution by developing different defensive mechanisms through anatomical, morphological and physiological changes (Darrall 1989; Gravano et al. 2003; Dineva 2004), aiming to limit the uptake of the pollutant and thus increase plant's tolerance to the pollutant. Such mechanisms can be physiological (i.e. falling leaves, closing stomata) or chemical and biochemical (i.e. production of insoluble precipitates, emission of reduced forms of pollutant (e.g., H₂S, NH₃), enzymatic degradations or on-enzymatic antioxidant compounds) (Heck et al. 1988). When the plant confronts pollution stress, these additional defense mechanisms are activated and added to the existing ones, in an effort to strengthen the plant's tolerance to imposed pollution stress.

Damages caused by air pollution can be irreversible, such as cell death and leaf necrosis of the plant which correspond to the so-called 'visible injury'. In contrast the injuries could be 'invisibles' whenever the defense system of the plants manages to limit the damage or the pollution impact is low. In those cases, either a physiological plant change is observed, such as decreases in size and yield (Guderian 1985; Garrec 2020) or changes in phenology (Honour et al. 2009).

Wang et al. (2003) suggested that the impact of abiotic stresses related to climate and air pollution, such as heat, drought, cold, salinity and nutrient deficiencies or toxicity, can cause a reduction on worldwide agriculture average yields by >50% for most major crop plants. Imposition of stress conditions may also alter the emissions of biogenic volatile compounds from the vegetation (Rinnan et al. 2014; Guenther et al. 2012). Each emitted compound has a specific role in the plant tolerance and defense. For instance, isoprene emissions from plants were found to attribute an antioxidant role in particular in the presence of high O₃ levels (Loreto et al. 2001) and to contribute to the thermotolerance of the plants (Hanson et al. 1999; Velikova and Loreto 2005). Tiiva et al. (2007) also found that exposure of subarctic fens to high UV-B radiation resulting from stratospheric O₃ depletion, was leading to isoprene emissions increase.

5 Symptomatology of plants affected by air pollution

Upon air pollution imposition, a variety of symptoms are induced and expressed by plants. Therefore, the symptomatology, which is the analysis of such symptoms, could serve as the basis of air quality bio-monitoring methods by utilizing plants' responses to pollutants.

5.1 Symptoms

Depending on the plant species and the type of pollutant, the injury symptoms are different. Generally, air or soil pollution by pesticides have similar symptoms on vegetation, which are mainly expressed on foliage in the form of chlorosis, necrosis, burns and twisting of leaves (Sharma et al. 2018). Reactive nitrogen species, in the form of nitrate (NO₃⁻) and ammonium (NH₄⁺), act as fertilizers promoting plant's growth. However, they can also have a negative impact on vegetation (and fauna) when they accumulate inducing ecosystems eutrophication, acidification and mineral deficiencies. The latter affects biodiversity and leads to a decrease in resilience resistance to various stresses (European Commission 2013; European Environment Agency 2019; Garrec 2020). In most cases, injury by NO₂ is shown as burn at the edge of the conifer needle and chlorosis in the leaves of angiosperms. Leaves

first exhibit water-soaked areas that at later stages become necrotic (Gheorghe and Ion 2011). Injury by halogens is commonly visible on conifers by chlorosis, which later on is changing to red/brown discoloration and burns of the edges of the needles, eventually evolving to necrosis of the entire needle. Similar symptoms are common in the leaves of angiosperms (Gheorghe and Ion 2011). In most cases, plants' injury by SO₂ is initially seen by the appearance of water-soaked leaves, which later become necrotic, changing into brown spots (Gheorghe and Ion 2011). Yellowing of conifer needles and decrease in tree vitality are the impacts of acid deposition on plants (Altshuller and Linthurst 1984). This is mainly an indirect effect of acid atmospheric deposition on soil acidification, which leads to soil base cation depletion and consequently, to needle magnesium deficiency evidenced by needle yellowing (Landmann and Bonneau 1995). Acidity is mainly induced by HNO₃ and H₂SO₄ acids and releases soluble forms of metals into the environment, which may be in toxic forms. For instance, Cu toxicity is increased in acidic environments and affects primarily the plant roots leading to growth reduction and chlorosis of mature leaves (Alva et al. 1995). Finally, Pb and Cd affect the biodiversity of soil fauna species and microorganisms and reduce plant growth (European Environment Agency 2019).

Injury due to exposure to elevated concentrations of O₃, is commonly expressed by necrotic spots on the leaves of the plants that have irregular shape and are often tan, brown or black colored. Some of the leaves change their color to bronze or red, which is usually a precursor sign to necrosis. Ozone is the most worrying pollutant currently affecting vegetation and ecosystems, since it is well established that it causes leaf necrosis and results in yield losses reaching 5%–19% (Feng and Kobayashi 2009). Ozone also has indirect effects on vegetation since it is a greenhouse gas linked to climate change (see discussion Chapter 9.2). Holland et al. (2006) estimated that ozone is responsible for 90% of the plants yield losses related to air pollution. However, the negative effects of ozone are very often masked by the positive effects on photosynthesis due to CO₂ increase in the atmosphere.

5.2. Biotic and abiotic Indicators and biomonitoring of air quality

Due to this significant role of O₃, a number of indicators have been developed in order to describe the sensitivity of plants to O₃ in different natural or anthropogenic environments (forests, grasslands, field crops, etc.), depending on the climatic zones (Western and Central Europe, Mediterranean coast of Europe, and other). The most commonly used indicator for plant's exposure to O₃ is AOT40, which is a measure of the accumulated daylight ozone concentrations in excess above a threshold of 80 µg m⁻³ (40 ppbv), using only the daily O₃ levels per hour between 8:00 and 20:00 (CET). This is also used for legislation purposes in European Union (EU Directive 2008/50/EC). Other O₃ metrics include the daylight average ozone concentrations during the growing season (M7 for 7 hours daylight period or M12 for 12 hours daylight period) or cumulative exposure indexes over the growing season with weights on hourly average O₃ concentrations that favor the higher hourly average concentrations, while retaining the mid and lower concentrations (Emberson et al. 2018).

Plants can also be used as indicators of metals air pollution. Riga-Karandinos and Saitanis (2004) suggested that trace metal concentration measurements in the leaves of Laurel (*Laurus nobilis* L.) could be used as indicators of urban traffic in Athens. Riga-Karandinos et al. (2006) have further found high concentrations of Platinum (Pt) and Pb,

known to be used in catalytic converters, together with other traffic metals (Pb, Cu and Zn) at roadside topsoil in the greater Athens area where pollutants can penetrate the plants through their roots. Furthermore, [Rodríguez Martín et al. \(2018\)](#) suggested that metal content in tree rings could be used as a pollution registry.

Biomonitoring is using both the visible (by observing necroses) or invisible (by biochemical analyses) disturbances of the plants caused by air pollution to deduce air pollutant levels ([De Temmerman et al. 2004](#); [Garrec and Van Haluwyn 2002](#)). The use of bioindicators might be complicated by the non-linear response of ecosystems to air pollution and climate change. In addition, it requires an unambiguous relationship between the cause and the bioindicator symptom.

Cryptogams (lichens and bryophytes), which are important components of the Mediterranean vegetation, are often used as indicators of air pollution and climate change relative to a set of contaminants ([Agnan et al. 2015](#); [Gandois et al. 2014](#); [Loppi et al. 1997](#)). Due to their high sensitivity to environmental changes, they are often employed as early-warning indicators of such impacts in particular for N ([Ochoa-Hueso et al. 2017](#)). In addition, the potential utility of the N content in mosses as an indicator of total N deposition has been demonstrated by [Munzi et al. \(2012\)](#) and they have also been used as critical load indicators for nitrogen ([Geiser et al. 2010](#)). However, cryptogams in the Mediterranean are not effective biomarkers for changes in water availability induced by climate change because they are affected by several stress factors in similar ways ([Pirintsos et al. 2011](#)). Lichens have been efficiently used to identify local sources of atmospheric contamination in urban or highly contaminated industrial sites of the Mediterranean countries ([Paoli et al. 2006](#); [Llop et al. 2017](#); [Ratier et al. 2018](#)). More rarely used in distant areas, lichen and mosses were successfully used as metal biomonitors in various environmental situations in France and over the last century. This allowed identification of present-day and past sources of contaminants and dust, and their variation in time and space ([Agnan et al. 2014 and 2015](#)), revealing a regional atmospheric signal, including both soils derived and industrially influenced atmospheric deposition. Moreover, in three different mountainous forest sites in France, lichens and mosses content in trace metals, of which Rare Earth Elements, were compared to various compartments of the forest ecosystem (bulk deposition and throughfall, soil and bedrock) ([Gandois et al. 2014](#)). The different accumulation of trace metals as monitored by lichens and mosses indicated a different influence of forest ecosystems. Mosses were representative of local throughfall content, since they were enriched in elements from the accumulation of dry deposition inside the canopy, either due to leaching (Mn), direct uptake (Ni), or dry deposition dissolution (Pb, Cu, Cs) contrary to lichens growing on tree barks where transfer was observed only for major elements. [Agnan et al. \(2017\)](#) has improved the bioindication scale using lichens collected in eight distinct French and Swiss forest areas. This also enabled the evaluation of the metal resistance or sensitivity of lichens. Furthermore, the index of atmospheric purity and the lichen diversity value were calculated based on the estimation of various ecological variables (including lichen diversity and abundance) and average ecological features for each site and variable (light, temperature, humidity, substrate pH, and eutrophication) that corresponded to lichen communities. Furthermore, tobacco plant varieties have been used as O₃ bioindicators in Greece ([Saitanis et al. 2003](#); [Saitanis 2008](#)) and have shown high injuries in all studied regions indicating high phytotoxicity by O₃ levels.

5.3. Eutrophication, acidification, critical loads

Eutrophication refers to ecosystem conditions with an excess in nutrients (often referring to N compounds) resulting from increased input rates. Nitrate and ammonium inputs through atmospheric deposition are of particular interest in the present section. In concern to air pollution, eutrophication is related to the ability of an ecosystem to optimally use the reactive nitrogen atmospheric deposition fluxes for its growth. Eutrophication happens when the ecosystem is saturated in N and thus additional N input is not leading to further growth optimization but instead is leading to N and biodiversity losses (Bobbink et al. 2010; Schmitz et al. 2019). Acidification is related to eutrophication and refers to the lowering of the soil pH due to deposition of acidic compounds, such as HNO₃ and H₂SO₄ that are produced from the oxidation of NO_x and SO_x emissions. Under the Convention of Long-range Transboundary Air Pollution (LRTAP) within the United Nations the critical loads of S and N have been used as indicators for ecosystem sensitivity to acidification and eutrophication (Reinds et al. 2008). Thus, critical N load levels are the threshold values above which damage occurs to the ecosystem (Hettelingh et al. 2001). These thresholds were initially determined using mass balance steady-state models or from empirical models. The latter are experimentally derived models studying different types of vegetation and are specific to habitat classes. Ammonia and NO_x critical levels are based on the response of vegetation types like lichens and bryophytes (Ochoa-Hueso et al. 2017), often based on very little information. Thus, for European-Mediterranean habitats, empirical critical N loads have been proposed to vary between 3 and 25 Kg N ha⁻¹ yr⁻¹ for four different ecosystems with the highest values corresponding to xeric grasslands and the lowest ones to the *Pinus* woodlands (Bobbink and Hettelingh 2011).

Recently, it was stated that while steady-state models are compatible with the critical loads concept (CLRTAP 2015), they are not suitable for simulating temporal air pollutant changes, particularly for nitrogen. Therefore, dynamic biogeochemical-ecological coupled models have been developed (Rowe et al. 2015; de Vries et al. 2010; Wallman et al. 2005), based on the impact of atmospheric deposition of S and N on soil functioning and in cascade to forest underground vegetation, using the loss of biodiversity as an indicator of change (Belyazid et al. 2011; Probst et al. 2015). However, the adequacy of critical loads as indicators of N deposition effects, has been recently questioned by Payne et al. (2019), who proposed that the cumulative deposition over a thirty-year window should be considered as the metric for the ecological damage caused by nitrogen deposition. This suggestion was further supported by the observed slow recovery of ecosystems from N deposition effects (Schmitz et al. 2019). Similarly, although N deposition has decreased in several regions over Europe due to declined NO_x and NH₃ emissions (>50% and <30%, respectively, between 1990 and 2015), the required timescale to observe the effect of these changes on the ecosystems is uncertain. Dirnböck et al. (2018) investigated 23 European forest research sites, including sites in Italy and the Balkans, and they concluded that reduction of NO_x and NH₃ emissions have to be significantly higher than projected under current legislation scenarios to allow recovery from chronically high N deposition. Thus, current reduction in N deposition is expected to lead only to limited species recovery in European forests.

6 Interactions and covariates between plants, air pollutants and environment

Air pollution and climate have concurrent impacts on vegetation. Temperature increases accelerate the dryness of vegetated soils, which retain less water for evapotranspiration, and, thus, cannot effectively contribute to the cooling of the atmosphere. In a warmer and dryer environment, plants close their stomata in order to reduce their water losses, thus minimizing the entrance of O₃ within the plant, therefore, reducing O₃ uptake and subsequent reactive oxygen species formation. [Gao et al. \(2017\)](#) suggested that accounting for water stress effects on stomatal O₃ flux can better explain biomass losses on poplar (*Populus deltoides* Marsh) than without consideration of such effects. [Lin et al. \(2020\)](#) pointed out the significant O₃/vegetation/climate interactions since reduced O₃ absorption or uptake by vegetation is increasing surface O₃ concentrations, leading to further atmosphere warming through escalation of greenhouse effect by O₃. They further discussed the importance of soil moisture effect on O₃ reduction by stomatal uptake and its consequent increase for the overall O₃ dry deposition. These effects are currently not taken into account in O₃ deposition modeling although they could help to improve our understanding of the observed O₃ concentration trends. [Lin et al. \(2020\)](#) have used measurements of O₃ fluxes by eddy correlation and derived O₃ deposition velocities over an oak forest in Italy, Mediterranean and over a spruce dominated forest in Denmark. These observations were performed for two different study periods; one year characterized by heatwave and drought and a second year with normal precipitation events. They reported significant decreases in O₃ deposition velocity during the year characterized by heatwaves and drought periods. More specifically, in the Mediterranean study site, a 70% reduction in O₃ deposition velocity was reported and was attributed to plants' stomatal response to the reduced soil moisture, suggesting that vegetation response is expected to worsen peak O₃ episodes during mega-droughts periods. However, multiple stresses on vegetation do not result in additive effects since, for instance, the signaling pathways of biotic and abiotic stresses can act antagonistically as reported by [Atkinson and Urwin \(2012\)](#). Therefore, understanding the mechanisms of the interactions of the responses to various stress factors at a molecular level is fundamental for future development of stress tolerant crop plants ([Atkinson and Urwin 2012](#)).

[Ainsworth \(2008\)](#) meta-analysis of vegetation response to combined increases in temperature, CO₂ and O₃, showed that high temperature negated any yield benefits resulting from elevated CO₂. A large number of studies have been conducted in major food crops (potato, barley, wheat, rice, bean and soybean) to study concurrent effects of drought and ozone on vegetation (see [Feng and Kobayashi \(2009\)](#) for a comprehensive review). Such studies have exhibited that the positive impact of O₃ limitation by stomata closing was often outweighed by the damages on yield due to drought stress ([Fangmeier et al. 1994](#)). High temperatures induce faster maturation and hence a shorter grain fill period, reducing the overall yield ([Erda et al. 2005](#)), and can induce floret sterility in cereals such as rice ([Matsui et al. 2014](#)), wheat and maize ([Wheeler et al. 1996](#); [Craufurd and Wheeler 2009](#)). However, physiological responses differ among crops ([Eyshi Rezaei et al. 2015](#)). Yield losses varied from 5.3% for potato to 19% for beans and soya beans when exposed to O₃ concentrations between 30–50 ppbv compared to 26 ppbv or less ([Feng and Kobayashi 2009](#)). [Avnery et al. \(2011\)](#) evaluated crop losses reaching up to 15% for the year 2000 due to O₃ exposure, corresponding to an annual loss of 79–121 million metric tons of global crop yields or 11–18 billion dollars annually; while [Mills et al.](#)

(2018) estimated that exposure to O₃ led to wheat grain losses to cost 24.2 billion dollars annually for the period 2010-2012.

In addition to O₃, climate is affecting other pivotal air pollutants (such as SO₂, N reactive species and aerosols), due to their temperature dependent photochemical production or depletion and their deposition dependence on precipitation and wind patterns. In particular, atmospheric N deposition due to the semi-volatile character of NH₄NO₃, is strongly dependent on relative humidity and temperature conditions (Nenes et al. 2020; Fowler et al. 2009). Thus, atmospheric deposition of nitrogen is affected by climatic changes and will impact vegetation habitats (Dirnböck et al. 2003). Dynamic biogeochemical-ecological chain models for critical loads have thus tested these covariant effects. They were able to detect the joined influence of climate and nitrogen deposition on biodiversity loss, following scenarios of current legislation or maximum feasible reduction of N emissions or/and temperature increase (Gaudio et al. 2015, Rizzetto et al. 2016).

7 Impacts of air pollutants on terrestrial vegetation of the Mediterranean Region

The natural and semi-natural ecosystems in the Mediterranean Basin have much higher plant biodiversity (hosting 4.3% of the global endemic plants) and biologically-relevant heterogeneity in space and time compared to those in temperate and boreal areas of Europe (Myers et al. 2000; Ochoa-Hueso et al. 2017). The Mediterranean climate, characterized by drought summer periods and mild winter temperatures, plays a critical role in the behavior of plants, allowing their growing season to be extended over the whole course of the calendar year. Therefore, it has been suggested that the entire ecosystem exposure to pollutants should be calculated based on an annual basis, while the actual growing season period is more suitable for determining single species exposure to pollutants (Schenone 1993). These particularities support a separate discussion of air pollution impact on Mediterranean vegetation. This separation is further supported by the existence of multiple plant adaptation mechanisms to the climatic conditions of the Mediterranean Basin, where heat waves and droughts are occurring frequently. Such mechanisms include foliage loss during the water stress periods, physiological responses such as closing of the stomata to limit water losses, changes in the metabolic pathways such as instead of C₃ photosynthesis utilizing the Crassulacean Acid Metabolism (CAM), which is a typical ecophysiological adaptation of plants to arid conditions (Grams and Thiel 2002), and changes in the depth and distribution pattern of the root systems. All the above mechanisms develop plant adaptation and ensure their survival under stressful climatic extremes (Schenone 1993). Furthermore, due to natural evolution and adaptation to their environment, the Mediterranean forests have developed cross-tolerance to the environmental conditions dominating the region (Paoletti 2006).

7.1 Vegetation exposure to ground-level ozone

Due to the sunny and warm weather conditions of the Mediterranean region, there is a potential for high O₃ deposition rates throughout the year (Kanakidou et al. 2011). Similarly, in Mediterranean, higher O₃ stomatal uptake may take place during winter than summer months, in spite of the lower winter ozone concentrations (Gerasopoulos et al. 2006; Cieslik 2009). However, Gerosa et al. (2005) found that in an Italian oak forest, which represented a typical Mediterranean ecosystem, the average O₃ stomatal uptake was less than half of the total O₃ deposition flux and that non-stomatal deposition was increasing with leaf

wetness and air humidity during the fall season. The increased non-stomatal fluxes of O₃ observed in Mediterranean forests (Gerosa et al. 2005 and 2009) and their diurnal and seasonal variations were different in many aspects when compared to those observed in the northern European forests (Fowler et al. 2009). Furthermore, measurements above oak forests in central Italy (Gerosa et al. 2005 and 2009; Cieslik, 2009) and southeastern France (Michou et al. 2005) showed that dry and hot conditions can significantly affect the diurnal variation of O₃ deposition velocity. The Mediterranean vegetation is more tolerant to high O₃ levels than the mesophilic broadleaf trees (Paoletti 2006) because of its better antioxidant defense (Nali et al. 2004), although biomass losses and changes in biomass distribution in the various plant compartments due to exposure to high O₃ cannot be excluded. However, deciduous broadleaf trees are less tolerant to oxidative stress compared to evergreen broadleaf trees due to their physiology with higher stomatal conductance and thinner leaves (Calatayud et al. 2010). Indeed, Calatayud et al. (2007) investigated the sensitivity to O₃ of four maple trees (*Acer campestre*, *A. opalus subsp. granatense*, *A. monspessulanum* and *A. pseudoplatanus*), which are present in humid parts of the Mediterranean. They found differences (e.g. in CO₂ assimilation, stomatal conductance, transpiration rate and water use efficiency), which may be partly related to higher stomatal conductance. On the other hand, Li et al. (2016) examining the O₃ sensitivity of 29 deciduous and evergreen species in China detected correlation to both low leaf mass per area and low leaf area-based antioxidant levels, but not to stomatal conductance. Moreover, Manes et al. (2007) evidenced that O₃ uptake varies within a Holm oak (*Quercus ilex* L.) canopy and attributed this fluctuation to the influence of microclimatic conditions on plants' physiological activity related to stomatal opening, which in turn is affected by internal and external effectors (e.g., plant hormones, water availability, hydraulic conductance). Sanz and Millan (2000) suggested a complex interaction between high radiation, drought and O₃ response in Mediterranean tree species such as Aleppo pine (*Pinus halepensis* Mill.). Tree species sensitivity to O₃ as revealed by functional leaf traits has to be considered (Calatayud et al. 2011). Saitanis et al. (2003) observed stomatal conductance in leaves of tobacco, grape vines and needles of Aleppo pine at various locations in Greece and found them peaking in midday hours when O₃ was high. They also observed injuries due to O₃ air pollution which were more severe at the high altitude location. Fumagalli et al. (2001) performed studies with open-top chambers in 24 agricultural and horticultural crops grown in commercial fields in the Mediterranean. They reported that ambient O₃ resulted in 17–39% yield loss in crops such as wheat, bean, watermelon and tomato. Nitrogen fixing legumes were also found to be less tolerant to O₃ exposure compared to grasses, which could eventually reduce their economic value (Sanz et al. 2007).

7.2 Vegetation exposure to nitrogen oxides

Dry deposition onto the ecosystems can contribute up to 58%–67% of the total N deposition in the Mediterranean Basin (Rodà et al. 2002). Due to the difficulty of measuring the actual dry deposition, this flux is commonly inferred from observations of atmospheric concentrations from representative stations (Sanz et al. 2002) coupled with deposition modeling (García-Gómez et al. 2018). Nitrogen is deposited in the forms of reduced or oxidized, inorganic or organic N. The contribution of organic N was found to vary between 34%–56% of total deposition (Mace et al. 2003; Violaki et al. 2010; Im et al. 2013; Izquieta-Rojano et al. 2016; Kanakidou et al. 2020) and can be a substantial contributor to N critical

loads in Mediterranean agricultural areas. Several studies have been performed in the Mediterranean to investigate the impact of N deposition on individual plants, lichens and soil properties as reviewed by [Ochoa-Hueso et al. \(2017\)](#). Few studies, such as NitroMed ([Ochoa-Hueso and Manrique 2011](#)), investigated the integrated responses at the ecosystem level using statistical methods. Their results indicate that N availability in soils is increased by N deposition but concurrently soil becomes more acidic, which affects the microbial community by reducing the fungi to bacteria ratio, and impact the overall enzymatic activity ([Ochoa-Hueso et al. 2017](#)). Changes in the stoichiometry of the plants (higher N/P ratio of the leaves) ([Sardans et al. 2016](#)) as well as changes in biomass partitioning and allometric ratios ([Cambui et al. 2011](#)) have been observed as a response to the increased N deposition. Furthermore, the effect of concurrent O₃ and N deposition in the Mediterranean can change composition and reproductive structure of the annual pastures ([Gonzalez-Fernandez et al. 2013](#)).

7.3 Accumulation of toxic metal air pollutants on vegetation and soil

Only limited number of studies have investigated metals in agricultural soils in the Mediterranean region ([Stanners and Bourdeau 1995](#)), and mainly at regional level in some countries such as Greece ([Stalikas et al. 1997](#)), Italy ([Facchinelli et al. 2001](#); [Abollino et al. 2002](#)) and Spain ([Boluda et al. 1988](#); [Andreu and Gimeno-García 1996](#)). [Riga-Karandinos et al. \(2006\)](#) measurements of trace metals at roadside topsoil in the greater Athens area indicated the penetration of pollution metals into the soils, from where they can be potentially transferred to the plants ([Gandois et al. 2010](#)). Evergreen shrubs were tested for their capacity to accumulate a large set of metals on the surface of their current season leaves in a Mediterranean environment. The results showed a common temporal pattern with elements increasing from early summer to mid-summer and then decreasing to early autumn. Deposition was also linked to meteorological parameters; in particular rain decreased the accumulation of metals on leaves, while increasing wind speed was enhancing the presence of elements on leaves ([Mori et al. 2015](#)).

Furthermore, [Rodríguez Martin et al. \(2018\)](#) have found significant enrichments of metals in Aleppo pine wood compared to the natural environment. More specifically, they measured 2.5 times higher Pb in tree wood close to burning power plants and 25 times higher Cd near mining areas compared to natural areas. Based on measurements of aerosols deposited on the leaves of *Platanus acerifolia* tree from 23 European cities over 20 countries, [Baldacchini et al. \(2017\)](#) concluded that this tree could be used to monitor aerosols, using the morphology and elemental composition of leaf deposited particles, together with the leaf magnetic content, i.e. in ferromagnetic minerals coming from dust deposited on the leaves ([Leng et al. 2018](#)).

7.4 Plant nutrient uptake limitations induced by air pollution

[Ochoa-Hueso et al. \(2011\)](#) suggested that the effect of N deposition inputs and the susceptibility of the Mediterranean ecosystems to exotic plant invasion may be controlled by P availability. In their study, [Herut et al. \(1999\)](#) indicated that atmospheric inputs of bioavailable N and P represent an imbalanced contribution to the new carbon production and reinforce the unusual N:P ratios (27) and possible P limitation in the southeast Mediterranean Sea. [Ochoa-Hueso and Manrique \(2013\)](#) and [Ochoa-Hueso et al. \(2017\)](#) reported a shift from N to P limitation in the terricolous moss *Tortella squarrosa* in the

Iberian Peninsula due to increased N deposition. In addition, the epiphytic lichen communities in Portugal and Spain have shifted from oligotrophic-dominated to nitrophytic-dominated species (Pinho et al. 2008; Aguilhaume 2016). The impact of anthropogenic N emissions on these shifts is supported by the ^{15}N isotopic signature of the N composition of mosses, which is shifted to more positive $\delta^{15}\text{N}$ values, while the agricultural activities are reducing $\delta^{15}\text{N}$ (e.g. Delgado et al. 2013). Human-induced imbalance in N and P deposition has been also reported for other regions and ecosystems, like the Chinese forests, leading to P-limitation of the forest ecosystem (Du et al. 2016).

8 Conclusions and Perspectives

Air pollution has significant direct (after uptake by the plant) and indirect (through changes in climate and diffuse solar radiation) effects on terrestrial vegetation that lead to visible and invisible vegetation damages. These effects, mostly from exposure to high O_3 , have been observed to reduce crop yields thus, affecting agriculture effectiveness and its ability to feed the Earth's population. Plant phenology, functional type and the seasonality of O_3 have to be taken into account when evaluating the impact of air pollution on the Mediterranean vegetation. Understanding of the interaction between the various stress factors in particular, climate (temperature, droughts and other extremes) and air pollution (O_3 , aerosol, CO_2), and how these factors combined affect vegetation, is critical for the definition of actions in order to preserve biodiversity and sustain agricultural production.

Atmospheric deposition of pollutants provides nutrients and toxic compounds or their products to the vegetation via either direct uptake by the foliage or by indirect uptake through plants' roots. Accumulation of pollutants in the environment has long term effects on vegetation and soil, thus it demands long recovery periods after the accumulation has stopped. This is particularly true for N deposition, which leads to N accumulation in excess of the optimal ecosystem levels in the soils, implies soil acidification and leads to biodiversity reduction and change the composition of phytocommunities. Indeed, changes in nutrient stoichiometry have been observed in plants exposed to excessively high N levels in the soil resulting from deposition of anthropogenic reactive nitrogen. As in other locations, human-induced P limitation has been observed in Europe and the Mediterranean due to anthropogenic N deposition. Such alterations of the ecosystem's composition have to be carefully evaluated, particularly under conditions of climate change that are potentially increasing the occurrence of severe drought events. Indeed, interactive effects between climate change and N deposition on vegetation have been shown and predicted.

Finally, plants' response to air pollution is expressed by symptoms that are different depending on the plant species and variety and the type of pollutant. Thus, plant disturbances caused by air pollution can be utilized to deduce air pollution levels, through the so-called biomonitoring procedure. However, since the use of bioindicators requires an unambiguous relationship between the cause and the plant response, this approach becomes complicated by the non-linear response of ecosystems to air pollution and climate change. Despite this complexity, the power of biomonitoring to reconstruct past pollution influence, by using for example well-preserved herbariums compared with present-day situations, can contribute to the effort to obtain a spatial view of the impact of atmospheric pollution around the Mediterranean regions.

Further research is needed in all above mentioned fields. Observatories for long term monitoring of all compartments of the environment and key drivers are essential to understand and evaluate the impact of air pollution to Earth's vegetation. This need is specifically urgent for the Mediterranean region, due to its susceptibility to various stresses induced either by climate change or air pollution or by other expressions of human activities footprint on the environment.

Acknowledgments We acknowledge support of this work by the project "PANhellenic infrastructure for Atmospheric Composition and climate change" (MIS 5021516), which is implemented under the Action "Reinforcement of the Research and Innovation Infrastructure" funded by the Operational Programme "Competitiveness, Entrepreneurship and Innovation" (NSRF 2014–2020) and co-financed by Greece and the European Union (European Regional Development Fund). We also thank the reviewer for his detailed comments that helped improve this chapter significantly.

References

- Aas, W., Mortier, A., Bowersox, V., Cherian, R., Faluvegi, G., Fagerli, H., Hand, J., Klimont, Z., Galy-Lacaux, C., Lehmann C. M. B, Myhre C. L., Myhre, G., Olivié, D., Sato, K., Quaas, J., Rao, P. S. P., Schulz, M., Shindell, D., Skeie, R. B., Stein, A., Takemura, T., Tsyro, S., Vet, R., and Xu, X.: Global and regional trends of atmospheric sulfur, *Sci. Rep.*, 9, 1–11, <https://doi.org/10.1038/s41598-018-37304-0>, 2019.
- Abollino, O., Aceto, M., Malandrino, M., Mentasti, E., Sarzanini, C., and Petrella, F.: Heavy metals in agricultural soils from Piedmont, Italy. Distribution, speciation and chemometric data treatment, *Chemosphere*, 49, 545–557, [https://doi.org/10.1016/S0045-6535\(02\)00352-1](https://doi.org/10.1016/S0045-6535(02)00352-1), 2002.
- Acosta, J. A., Faz, A., Martínez-Martínez, S., and Arocena, J. M.: Enrichment of metals in soils subjected to different land uses in a typical Mediterranean environment (Murcia City, southeast Spain), *Appl. Geochem.*, 26, 405–414, <https://doi.org/10.1016/j.apgeochem.2011.01.023>, 2011.
- Agnan, Y., Séjalon-Delmas, N., and Probst, A.: Origin and distribution of rare earth elements in various lichen and moss species over the last century in France, *Sci. Total Environ.*, 487, 1–12, <https://doi.org/10.1016/j.scitotenv.2014.03.132>, 2014.
- Agnan, Y., Séjalon-Delmas, N., Claustres, A., and Probst, A.: Investigation of spatial and temporal metal atmospheric deposition in France through lichen and moss bioaccumulation over one century, *Sci. Total Environ.*, 529, 285–296, <https://doi.org/10.1016/j.scitotenv.2015.05.083>, 2015.
- Agnan, Y., Probst, A., and Séjalon-Delmas, N.: Evaluation of lichen species resistance to atmospheric metal pollution by coupling diversity and bioaccumulation approaches: A new bioindication scale for French forested areas, *Ecol. Indic.*, 72, 99–110, <https://doi.org/10.1016/j.ecolind.2016.08.006>, 2017.
- Aguillaume, L.: La deposición de nitrógeno en encinares Mediterráneos: Cargas e indicadores, *Ecosistemas*, 25, 110–113, <https://doi.org/10.7818/ECOS.2016.25-2.15>, 2016.
- Aguillaume, L., Rodrigo, A., and Avila, A.: Long-term effects of changing atmospheric pollution on throughfall, bulk deposition and stream waters in a Mediterranean forest, *Sci. Total Environ.*, 544, 919–928, <https://doi.org/10.1016/j.scitotenv.2015.12.017>, 2016.

- Ainsworth, E. A.: Rice production in a changing climate: a meta-analysis of responses to elevated carbon dioxide and elevated ozone concentration, *Global Change Biol.*, 14, 1642–1650, <https://doi.org/10.1111/j.1365-2486.2008.01594.x>, 2008.
- Aktar, W., Sengupta, D., and Chowdhury, A.: Impact of pesticides use in agriculture: Their benefits and hazards, *Interdiscip. Toxicol.*, 2, 1–12, <https://doi.org/10.2478/v10102-009-0001-7>, 2009.
- Altshuller, A. P., and Linthurst, R. A.: Acidic deposition phenomenon and its effects: critical assessment review papers, Volume 1, Tech. Rept. PB-85-100030/XAD, North Carolina State Univ., Raleigh, USA, 1984.
- Alva, A. K., Graham, J. H., and Anderson, C. A.: Soil pH and Copper Effects on Young ‘Hamlin’ Orange Trees, *Soil Sci. Soc. Am. J.*, 59, 481–487, <https://doi.org/10.2136/sssaj1995.03615995005900020031x>, 1995.
- Andreu, V., and Gimeno-García, E.: Total content and extractable fraction of cadmium, cobalt, copper, nickel, lead, and zinc in calcareous orchard soils, *Commun. Soil Sci. Plant Anal.*, 27, 2633–2648, <https://doi.org/10.1080/00103629609369728>, 1996.
- Atkinson, N. J., and Urwin, P. E.: The interaction of plant biotic and abiotic stresses: From genes to the field, *J. Exp. Bot.*, 63, 3523–3544, <https://doi.org/10.1093/jxb/ers100>, 2012.
- Avila, A., Queralt-Mitjans, I., and Alarcón, M.: Mineralogical composition of African dust delivered by red rains over northeastern Spain, *J. Geophys. Res.*, 102, 21977–21996, <https://doi.org/10.1029/97jd00485>, 1997.
- Avnery, S., Mauzerall, D. L., Liu, J., and Horowitz, L. W.: Global crop yield reductions due to surface ozone exposure: 1. Year 2000 crop production losses and economic damage, *Atmos. Environ.*, 45, 2284–2296, <https://doi.org/10.1016/j.atmosenv.2010.11.045>, 2011.
- Baldacchini, C., Castanheiro, A., Maghakyan, N., Sgrigna, G., Verhelst, J., Alonso, R., Amorim, J. H., Bellan, P., Breuste, J., Bühler, O., Cântar, I. C., Cariñanos, P., Carriero, G., Churkina, G., Dinca, L., Esposito, R., Gawronski, S. W., Kern, M., Le Thiec, D., Moretti, M., Ningal, T., Rantzoudi, E. C., Sinjur, I., Stojanova, B., Aničić Urošević, M., Velikova, V., Zivojinovic, I., Sahakyan, L., Calfapietra, C., and Samson, R.: How Does the Amount and Composition of PM Deposited on *Platanus acerifolia* Leaves Change Across Different Cities in Europe?, *Environ. Sci. Technol.*, 51, 1147–1156, <https://doi.org/10.1021/acs.est.6b04052>, 2017.
- Belyazid, S., Kurz, D., Braun, S., Sverdrup, H., Rihm, B., and Hettelingh, J. P.: A dynamic modelling approach for estimating critical loads of nitrogen based on plant community changes under a changing climate, *Environ. Pollut.*, 159, 789–801, <https://doi.org/10.1016/j.envpol.2010.11.005>, 2011.
- Bobbink, R., Hicks, K., Galloway, J., Spranger, T., Alkemade, R., Ashmore, M., Bustamante, M., Cinderby, S., Davidson, E., Dentener, F., Emmett, B., Erisman, J. W., Fenn, M., Gilliam F., Nordin, A., Pardo, L., and De Vries, W.: Global assessment of nitrogen deposition effects on terrestrial plant diversity: a synthesis, *Ecol. Appl.*, 20, 30–59, <https://doi.org/10.1890/08-1140.1>, 2010.
- Bobbink, R., and Hettelingh, J.-P. (Eds.): Review and revision of empirical critical loads response relationships, in Proc. Expert Workshop, Noordwijkerhout, the Netherlands, 23–25 June 2010, Coordination Centre for the Effects, Rijksinstituut voor Volksgezondheid en Milieu, 246 pp., <https://rivm.openrepository.com/bitstream/handle/10029/260510/680359002.pdf>, 2011.
- Boluda, R., Andreu, V., Pons, V., Sánchez, J.: Contenido de metales pesados (Cd, Co, Cr, Cu, Ni, Pb y Zn) en suelos de la comarca La Plana de Requena-Utiel (Valencia), *Anal. Edafol. Agrob.*, 47, 1485–1502, 1988.

- Brahmachari, S., and Kundu, S.: SO₂ stress: Its effect on plants, plant defence responses and strategies for developing enduring resistance, *Int. Adv. Res. J. Sci. Engin. Technol.*, 4, 303–309, <https://doi.org/10.17148/IARJSET.2017.4752>, 2017.
- Calatayud, V., Cerveró, J., Sanz, M. J.: Foliar, physiological and growth responses of four maple species exposed to ozone, *Water Air Soil Pollut.*, 185, 239–254, <https://doi.org/10.1007/s11270-007-9446-5>, 2007.
- Calatayud, V., Marco, F., Cerveró, J., Sánchez-Peña, G., and Sanz, M. J.: Contrasting ozone sensitivity in related evergreen and deciduous shrubs, *Environ. Pollut.*, 158, 3580–3587, <https://doi.org/10.1016/j.envpol.2010.08.013>, 2010.
- Calatayud, V., Cerveró, J., Calvo, E., García-Breijo, F. J., Reig-Arminana, J., and Sanz, M. J.: Responses of evergreen and deciduous *Quercus* species to enhanced ozone levels, *Environ. Pollut.*, 159, 55–63, <https://doi.org/10.1016/j.envpol.2010.09.024>, 2011.
- Cambui, C. A., Svennerstam, H., Gruffman, L., Nordin, A., Ganeteg, U., and Näsholm, T.: Patterns of plant biomass partitioning depend on Nitrogen source, *PLoS ONE*, 6, 1–7, <https://doi.org/10.1371/journal.pone.0019211>, 2011.
- Cataldo, D. A., and Wildung, R. E.: Soil and plant factors influencing the accumulation of heavy metals by plants, *Environ. Health Persp.*, 27, 149–159, <https://doi.org/10.2307/3428874>, 1978.
- Cieslik, S.: Ozone fluxes over various plant ecosystems in Italy: A review, *Environ. Pollut.*, 157, 1487–1496, <https://doi.org/10.1016/j.envpol.2008.09.050>, 2009.
- CLRTAP: Mapping Critical Loads for Ecosystems, Chapter V of Manual on Methodologies and Criteria for Modelling and Mapping Critical Loads and Levels and Air Pollution Effects, Risks and Trends, Umweltbundesamt/German Environment Agency, Berlin, 116 pp., <https://www.umweltbundesamt.de/sites/default/files/medien/4292/dokumente/ch5-mapman-2017-09-10.pdf>, last access 11 June 2020, 2015.
- Craufurd, P. Q., and Wheeler, T. R.: Climate change and the flowering time of annual crops, *J. Exp. Bot.*, 60, 2529–2539, <https://doi.org/10.1093/jxb/erp196>, 2009.
- Darrall, N. M.: The effect of air pollutants on physiological processes in plants, *Plant Cell Environ.*, 12, 1–30, <https://doi.org/10.1111/j.1365-3040.1989.tb01913.x>, 1989.
- de Temmerman, L., Bell, J. N. B., Garrec, J. P., Klumpp, A., Krause, G. H. M., and Tonneijck, A. E. G.: Biomonitoring of air pollutants with plants – considerations for the future, in *Urban Air Pollution, Bioindication and Environmental Awareness*, Klumpp, A., Ansel, W., and Klumpp, G., Eds., Cuvillier Verlag, Göttingen, 337–373, ISBN 978-3736910782, 2004.
- de Vries, W., Wamelink, G. W. W., Van Dobben, H., Kros, J., Reinds, G. J., Mol-Dijkstra, J. P., Smart, S. M., Evans, C. D., Rowe, E. C., Belyazid, S., Sverdrup, H. U., Van Hinsberg, A., Posch, M., Hettelingh, J. P., Spranger, T., and Bobbink, R.: Use of dynamic soil - vegetation models to assess impacts of nitrogen deposition on plant species composition: An overview, *Ecol. Appl.*, 20, 60–79, <https://doi.org/10.1890/08-1019.1>, 2010.
- Delgado, V., Ederra, A., and Santamaría, J. M.: Nitrogen and carbon contents and $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$ signatures in six bryophyte species: Assessment of long-term deposition changes (1980-2010) in Spanish beech forests, *Global Change Biol.*, 19, 2221–2228, <https://doi.org/10.1111/gcb.12210>, 2013.
- Dineva, S. B.: Comparative studies of the leaf morphology and structure of white ash *Fraxinus americana* L. and London plane tree *Platanus acerifolia* Willd growing in polluted area, *Dendrobiology*, 52, 3–8, http://yadda.icm.edu.pl/yadda/element/bwmeta1.element.agro-article-c95f1f7a-69a8-48dd-9331-224b19949fa7/c/52_3_8.pdf, last access 22 May 2020, 2004.

- Dirnböck, T., Dullinger, S., and Grabherr, G.: A regional impact assessment of climate and land-use change on alpine vegetation, *J. Biogeogr.*, 30, 401–417, <https://doi.org/10.1046/j.1365-2699.2003.00839.x>, 2003.
- Dirnböck, T., Pröll, G., Austnes, K., Beloica, J., Beudert, B., Canullo, R., De Marco, A., Fornasier, M. F., Futter, M., Goergen, K., Grandin, U., Holmberg, M., Lindroos, A. J., Mirtl, M., Neiryneck, J., Pecka, T., Nieminen, T. M., Nordbakken, J. F., Posch, M., Reinds, G. J., Rowe, E. C., Salemaa, M., Scheuschner, T., Starlinger, F., Uziębło, A. K., Valinia, S., Weldon, J., Wiegner, G. W., Wamelink, W. G. W., and Forsius, M.: Currently legislated decreases in nitrogen deposition will yield only limited plant species recovery in European forests, *Environ. Res. Lett.*, 13, 125010, <https://doi.org/10.1088/1748-9326/aaf26b>, 2018.
- Du, E., De Vries, W., Han, W., Liu, X., Yan, Z., and Jiang, Y.: Imbalanced phosphorus and nitrogen deposition in China's forests, *Atmos. Chem. Phys.*, 16, 8571–8579, <https://doi.org/10.5194/acp-16-8571-2016>, 2016.
- Duprè, C., Stevens, C. J., Ranke, T., Bleeker, A., Peppler-Lisbach, C., Gowing, D. J. G., Dise, N. B., Dorland, E., and Diekmann, M.: Changes in species richness and composition in European acidic grasslands over the past 70 years: The contribution of cumulative atmospheric nitrogen deposition, *Global Change Biol.*, 16, 344–357, <https://doi.org/10.1111/j.1365-2486.2009.01982.x>, 2010.
- Emberson, L. D., Pleijel, H., Ainsworth, E. A., van den Berg, M., Ren, W., Osborne, S., Mills, G., Pandey, D., Dentener, F., Büker, P., Ewert, F., Koeble, R., and Van Dingenen, R.: Ozone effects on crops and consideration in crop models, *Eur. J. Agron.*, 100, 19–34, <https://doi.org/10.1016/j.eja.2018.06.002>, 2018.
- Erda, L., Wei, X., Hui, J., Yinlong, X., Yue, L., Liping, B., and Liyong, X.: Climate change impacts on crop yield and quality with CO₂ fertilization in China, *Phil. Trans. R. Soc. B*, 360, 2149–2154, <https://doi.org/10.1098/rstb.2005.1743>, 2005.
- European Commission: Science for Environment Policy, IN-DEPTH REPORT, Nitrogen Pollution and the European Environment: Implications for Air Quality Policy, 28 pp., https://ec.europa.eu/environment/integration/research/newsalert/pdf/IR6_en.pdf, last access 23 May 2020, 2013.
- European Environment Agency: Eutrophication of terrestrial ecosystems due to air pollution. Annual Indicator Report Series (AIRS), 1–9, retrieved from <https://www.eea.europa.eu/airs/2016/natural-capital/eutrophication-of-terrestrial-ecosystems>, last access 20 May 2020, 2019.
- EMEP: Transboundary particulate matter, photo-oxidants, acidifying and eutrophying components, European Monitoring and Evaluation Programme Status Report 2018, 1–204, ISSN 1504-6192, https://emep.int/publ/common_publications.html, 2018.
- Eyshi Rezaei, E., Webber, H., Gaiser, T., Naab, J., and Ewert, F.: Heat stress in cereals: Mechanisms and modelling, *Eur. J. Agron.*, 64, 98–113, <https://doi.org/10.1016/j.eja.2014.10.003>, 2015.
- Facchinelli, A., Sacchi, E., and Mallen, L.: Multivariate statistical and GIS-based approach to identify heavy metal sources in soils, *Environ. Pollut.*, 114, 313–324, [https://doi.org/10.1016/S0269-7491\(00\)00243-8](https://doi.org/10.1016/S0269-7491(00)00243-8), 2001.
- Fangmeier, A., Brockerhoff, U., Grütters, U., and Jäger, H. J.: Growth and yield responses of spring wheat (*Triticum aestivum* L. CV. Turbo) grown in open-top chambers to ozone and water stress, *Environ. Pollut.*, 83, 317–325, [https://doi.org/10.1016/0269-7491\(94\)90153-8](https://doi.org/10.1016/0269-7491(94)90153-8), 1994.

- Farquhar, G. D.: Carbon dioxide and vegetation, *Science*, 278, 1411, <https://doi.org/10.1126/science.278.5342.1411>, 1997.
- Faulkner, C.: Plasmodesmata and the symplast, *Curr. Biol.*, 28, R1374–R1378, <https://doi.org/10.1016/j.cub.2018.11.004>, 2018.
- Feng, Z., and Kobayashi, K.: Assessing the impacts of current and future concentrations of surface ozone on crop yield with meta-analysis, *Atmos. Environ.*, 43, 1510–1519, <https://doi.org/10.1016/j.atmosenv.2008.11.033>, 2009.
- Fowler, D., Pilegaard, K., Sutton, M. A., Ambus, P., Raivonen, M., Duyzer, J., D. Simpson, D., Fagerli, H., Fuzzi, S., Schjoerring, J. K., Granier, C., Neftel, A., Isaksen, I. S. A., Laj, P., Maione, M., Monks, P. S., Burkhardt, J., Daemmgen, U., Neiryneck J., Personne, E., Wichink-Kruit, R., Butterbach-Bahl, K., Flechard, C., Tuovinen, J. P., Coyle, M., Gerosa, G., Loubet, B., Altimir, N., Gruenhage, L., Ammannl, C., Cieslik, S., Paoletti, E., Mikkelsen, T. N., Ro-Poulsen, H., Cellier, P., Cape, J. N., Horváth, L., Loreto, F., Niinemets, Ü, Palmer, P. I., Rinne, J., Misztal, P., Nemitz, E., Nilsson, D., Pryor, S., Gallagher, M. W., Vesala, T., Skiba, U., Brüggemann, N., Zechmeister-Boltenstern, S., Williams, J., O’Dowd, C., Facchini, M. C., de Leeuw, G., Flossman, A., Chaumerliac, N., and Erisman, J. W.: Atmospheric composition change: Ecosystems-atmosphere interactions, *Atmos. Environ.*, 43, 5193–5267, <https://doi.org/10.1016/j.atmosenv.2009.07.068>, 2009.
- Fumagalli, I., Gimeno, B. S., Velissariou, D., De Temmerman, L., and Mills, G.: Evidence of ozone-induced adverse effects on crops in the Mediterranean region, *Atmos. Environ.*, 35, 2583–2587, [https://doi.org/10.1016/S1352-2310\(00\)00468-4](https://doi.org/10.1016/S1352-2310(00)00468-4), 2001.
- Gandois, L., Nicolas, M., VanderHeijden, G., and Probst, A.: The importance of biomass net uptake for a trace metal budget in a forest stand in north-eastern France, *Sci. Total Environ.*, 408, 5870–5877, <https://doi.org/10.1016/j.scitotenv.2010.07.061>, 2010.
- Gandois, L., and Probst, A.: Localisation and mobility of trace metal in silver fir needles, *Chemosphere*, 87, 204–210, <https://doi.org/10.1016/j.chemosphere.2011.12.020>, 2012.
- Gandois, L., Agnan, Y., Leblond, S., Séjalon-Delmas, N., Le Roux, G., and Probst, A.: Use of geochemical signatures, including rare earth elements, in mosses and lichens to assess spatial integration and the influence of forest environment, *Atmos. Environ.*, 95, 96–104, <https://doi.org/10.1016/j.atmosenv.2014.06.029>, 2014.
- Gao, F., Calatayud, V., Paoletti, E., Hoshika, Y., and Feng, Z.: Water stress mitigates the negative effects of ozone on photosynthesis and biomass in poplar plants, *Environ. Pollut.*, 230, 268–279, <https://doi.org/10.1016/j.envpol.2017.06.044>, 2017.
- García-Gómez, H., Izquieta-Rojano, S., Aguillaume, L., González-Fernández, I., Valiño, F., Elustondo, D., Santamaría, J. M., Avila, A., Bytnerowicz, A., Bermejo, V., and Alonso, R.: Joining empirical and modelling approaches to estimate dry deposition of nitrogen in Mediterranean forests, *Environ. Pollut.*, 243, 427–436, <https://doi.org/10.1016/j.envpol.2018.09.015>, 2018.
- Garrec, J. P., and Van Haluwyn, C.: *Biosurveillance Végétale de la Qualité de l’Air. Concepts, Méthodes et Applications*, Editions Tec et Doc, Lavoisier, Paris, 116 pp., ISBN 2-7430-0540-8, 2002.
- Garrec, J. P.: What is the impact of air pollutants on vegetation?, in *Encyclopedia of the Environment*, Joyard, J., Moreau, R., and Sommeria, J. Eds., online ISSN 2555-0950, Uni. Grenoble Alpes, Saint-Martin-d’Hères, France, <https://www.encyclopedie-environnement.org/en/life/impact-air-pollutants-on-vegetation/>, last access 22 May 2020, 2020.

- Garrison, V. H., Shinn, E. A., Foreman, W. T., Griffin, D. W., Holmes, C. W., Kellogg, C. A., Majewski, M. S., Richardson, L. L., Ritchie, K. B., and Smith, G. W.: African and Asian Dust : From desert soils to coral reefs, *BioScience*, 53, 469–480, [https://doi.org/10.1641/0006-3568\(2003\)053\[0469:AAADFJ\]2.0.CO;2](https://doi.org/10.1641/0006-3568(2003)053[0469:AAADFJ]2.0.CO;2), 2003.
- Garrison, V. H., Foreman, W. T., Genualdi, S., Griffin, D. W., Kellogg, C. A., Majewski, M. S., Mohammed, A., Ramsubhag, A., Shinn, E. A., Simonich, S. L., and Smith, G. W.: Saharan dust – A carrier of persistent organic pollutants, metals and microbes to the Caribbean? Saharan dust – a carrier of persistent organic pollutants, metals and microbes to the Caribbean?, *Rev. Biol. Trop.*, 54 (Suppl. 3), 9–21, https://www.scielo.sa.cr/scielo.php?script=sci_arttext&pid=S0034-77442006000600007, last access 22 May 2020, 2006.
- Gaudio, N., Belyazid, S., Gendre, X., Mansat, A., Nicolas, M., Rizzetto, S., Harald Sverdrup, H., and Probst, A.: Combined effect of atmospheric nitrogen deposition and climate change on temperate forest soil biogeochemistry: A modeling approach, *Ecol. Model.*, 306, 24–34, <https://doi.org/10.1016/j.ecolmodel.2014.10.002>, 2015.
- Geiser, L. H., Jovan, S. E., Glavich, D. A., and Porter, M. K.: Lichen-based critical loads for atmospheric nitrogen deposition in Western Oregon and Washington Forests, USA, *Environ. Pollut.*, 158, 2412–2421, <https://doi.org/10.1016/j.envpol.2010.04.001>, 2010.
- Gerasopoulos, E., Kouvarakis, G., Vrekoussis, M., Donoussis, C., Mihalopoulos, N., and Kanakidou, M.: Photochemical ozone production in the Eastern Mediterranean, *Atmos. Environ.*, 40, 3057–3069, <https://doi.org/10.1016/j.atmosenv.2005.12.061>, 2006.
- Gerosa, G., Vitale, M., Finco, A., Manes, F., Denti, A. B., and Cieslik, S.: Ozone uptake by an evergreen Mediterranean Forest (*Quercus ilex*) in Italy. Part I: Micrometeorological flux measurements and flux partitioning, *Atmos. Environ.*, 39, 3255–3266, <https://doi.org/10.1016/j.atmosenv.2005.01.056>, 2005.
- Gerosa, G., Finco, A., Mereu, S., Vitale, M., Manes, F., and Denti, A. B.: Comparison of seasonal variations of ozone exposure and fluxes in a Mediterranean Holm oak forest between the exceptionally dry 2003 and the following year, *Environ. Pollut.*, 157, 1737–1744, <https://doi.org/10.1016/j.envpol.2007.11.025>, 2009.
- Gheorghe, I. F., Ion, B.: The effects of air pollutants on vegetation and the role of vegetation in reducing atmospheric pollution, in *The Impact of Air Pollution on Health, Economy, Environment and Agricultural Sources*, Khallaf, M. K., Ed., IntechOpen, Croatia, 241–280, <https://doi.org/10.5772/17660>, 2011.
- Gilliam, F. S.: Response of the herbaceous layer of forest ecosystems to excess nitrogen deposition, *J. Ecol.*, 94, 6, 1176–1191, <https://doi.org/10.1111/j.1365-2745.2006.01155.x>, 2006.
- Gonzalez-Fernandez, I., Gerosa, G., and Bermejo, V.: Ozone effects on vegetation biodiversity in a biodiversity “hotspot” (southern Europe), in *Ozone Pollution: Impacts on Ecosystem Services and Biodiversity*, Mills, G., Wagg, S., and Harmens, H., Eds., NERC Centre for Ecology and Hydrology, Bangor, UK, 38–42, <http://nora.nerc.ac.uk/id/eprint/502675/>, last access 23 May 2020, 2013.
- Graedel, T. E., and Crutzen, P. J.: *Atmospheric Change: An Earth Perspective*, W. H. Freeman & Co. Ltd, ISBN 978-0716723325, 446 pp., 1993.
- Grams, T. E. E., and Thiel, S.: High light-induced switch from C3-photosynthesis to Crassulacean acid metabolism is mediated by UV-A/blue light, *J. Exp. Bot.*, 53, 1475–1483, <https://doi.org/10.1093/jexbot/53.373.1475>, 2002.

- Gravano, E., Giulietti, V., Desotgiu, R., Bussotti, F., Grossoni, P., Gerosa, G., and Tani, C.: Foliar response of an *Ailanthus altissima* clone in two sites with different levels of ozone-pollution, *Environ. Pollut.*, 121, 137–146, [https://doi.org/10.1016/S0269-7491\(02\)00180-X](https://doi.org/10.1016/S0269-7491(02)00180-X), 2003.
- Grennfelt, P., Engleryd, A., Forsius, M., Hov, Ø., Rodhe, H., and Cowling, E.: Acid rain and air pollution: 50 years of progress in environmental science and policy, *Ambio*, 49, 849–864, <https://doi.org/10.1007/s13280-019-01244-4>, 2020.
- Guderian, R. (Ed.): *Air Pollution by Photochemical Oxidants: Formation, Transport, Control, and Effects on Plants*, Springer, ISBN 978-3-642-70118-4, 1985.
- Guenther, A. B., Jiang, X., Heald, C. L., Sakulyanontvittaya, T., Duhl, T., Emmons, L. K., and Wang, X.: The Model of Emissions of Gases and Aerosols from Nature version 2.1 (MEGAN2.1): an extended and updated framework for modeling biogenic emissions, *Geosci. Model Dev.*, 5, 1471–1492, <https://doi.org/10.5194/gmd-5-1471-2012>, 2012.
- Gupta, A.: Effect of air pollutants on plant gaseous exchange process: Effect on stomata and respiration, In *Plant Responses to Air Pollution*, Kulshrestha U., and Saxena P., Eds., Springer, 85–92, https://doi.org/10.1007/978-981-10-1201-3_8, 2016.
- Hanson, D. T., Swanson, S., Graham, L. E., Sharkey, T. D.: Evolutionary significance of isoprene emission from mosses, *Am. J. Bot.*, 86, 634–639, <https://doi.org/10.2307/2656571>, 1999.
- Heath, R. L.: Modification of the biochemical pathways of plants induced by ozone: What are the varied routes to change?, *Environ. Pollut.*, 155, 453–463, <https://doi.org/10.1016/j.envpol.2008.03.010>, 2008.
- Heath, R. L., Lefohn, A. S., and Musselman, R. C.: Temporal processes that contribute to nonlinearity in vegetation responses to ozone exposure and dose, *Atmos. Environ.*, 43, 2919–2928, <https://doi.org/10.1016/j.atmosenv.2009.03.011>, 2009.
- Heck W. W., Taylor O. C., and Tingey D. T.: Assessment of crop loss from air pollutants, *J. Agric. Sci.*, 113, 414–414, <https://doi.org/10.1017/S0021859600070209>, 1988.
- Hernandez, L., Probst, A., Probst, J. L., and Ulrich, E.: Heavy metal distribution in some French forest soils: Evidence for atmospheric contamination, *Sci. Total Environ.*, 312, 195–219, [https://doi.org/10.1016/S0048-9697\(03\)00223-7](https://doi.org/10.1016/S0048-9697(03)00223-7), 2003.
- Herut, B., Krom, M. D., Pan, G., and Mortimer, R.: Atmospheric input of nitrogen and phosphorus to the Southeast Mediterranean: Sources, fluxes, and possible impact, *Limnology and Oceanogr.*, 44, 1683–1692, <https://doi.org/10.4319/lo.1999.44.7.1683>, 1999.
- Hettelingh, J. P., Posch, M., and De Smet, P. A. M.: Multi-effect critical loads used in multi-pollutant reduction agreements in Europe, *Water Air Soil Pollut.*, 130, 1133–1138, <http://doi.org/10.1023/A:1013935907768>, 2001.
- Hill, A. C.: Vegetation: A sink for atmospheric pollutants, *J. Air Pollut. Control Assoc.*, 21, 341–346, <https://doi.org/10.1080/00022470.1971.10469535>, 1971.
- Holland, M., Kinghorn, S., Emberson, L., Cinderby, S., Ashmore, M., Mills, G., and Harmens, H.: Development of a framework for probabilistic assessment of the economic losses caused by ozone damage to crops in Europe, (Natural Environment Research Council) CEH Project C02309NEW Defra Contract EPG, 1, 3–205, 2006.
- Honour, S. L., Bell, J. N. B., Ashenden, T. W., Cape, J. N., and Power, S. A.: Responses of herbaceous plants to urban air pollution: Effects on growth, phenology and leaf surface characteristics, *Environ. Pollut.*, 157, 1279–1286, <https://doi.org/10.1016/j.envpol.2008.11.049>, 2009.

- Hou, H., Takamatsu, T., Koshikawa, M. K., and Hosomi, M.: Copper complexing capacity of throughfall and its environmental effect, *Water Air Soil Pollut.*, 162, 229–245, <https://doi.org/10.1007/s11270-005-6439-0>, 2005.
- Im, U., Christodoulaki, S., Violaki, K., Zampas, P., Kocak, M., Daskalakis, N., Mihalopoulos, N., and Kanakidou, M.: Atmospheric deposition of nitrogen and sulfur over southern Europe with focus on the Mediterranean and the Black Sea, *Atmos. Environ.*, 81, 660–670, <https://doi.org/10.1016/j.atmosenv.2013.09.048>, 2013.
- Izquieta-Rojano, S., García-Gomez, H., Aguilhaume, L., Santamaría, J. M., Tang, Y. S., Santamaría, C., Valiño, F., Lashera, E., Alonso, R., Avila, A., Cape, J. N., and Elustondo, D.: Throughfall and bulk deposition of dissolved organic nitrogen to holm oak forests in the Iberian Peninsula: Flux estimation and identification of potential sources, *Environ. Pollut.*, 210, 104–112, <https://doi.org/10.1016/j.envpol.2015.12.002>, 2016.
- Kabata-Pendias, A.: *Trace Elements in Soils and Plants*, 4th Ed., Taylor and Francis, 550 pp., <https://doi.org/10.1201/b10158>, 2010.
- Kanakidou, M., Mihalopoulos, N., Kindap, T., Im, U., Vrekoussis, M., Gerasopoulos, E., Dermitzaki, E., Unal, A., Koçak, M., Markakis, K., Melas, D., Kouvarakis, G., Youssef, A. F., Richter, A., Hatzianastassiou, N., Hilboll, A., Ebojie, F., Wittrock, F., von Savigny, C., Burrows, J. P., Ladstaetter-Weissenmayer, A., and Moubasher, H.: Megacities as hot spots of air pollution in the East Mediterranean, *Atmos. Environ.*, 45, 1223–1235, <https://doi.org/10.1016/j.atmosenv.2010.11.048>, 2011.
- Kanakidou, M., Myriokefalitakis, S., and Tsigaridis, K.: Aerosols in atmospheric chemistry and biogeochemical cycles of nutrients, *Environ. Res. Lett.*, 13, 063004, <https://doi.org/10.1088/1748-9326/aabcbd>, 2018.
- Kanakidou, M., Myriokefalitakis, S., and Tsagkaraki, M.: Atmospheric inputs of nutrients to the Mediterranean Sea, *Deep Sea Res. II*, 171, 104606, <https://doi.org/10.1016/j.dsr2.2019.06.014>, 2020.
- Kelepertzis, E.: Accumulation of heavy metals in agricultural soils of Mediterranean: Insights from Argolida basin, Peloponnese, Greece, *Geoderma*, 221–222, 82–90, <https://doi.org/10.1016/j.geoderma.2014.01.007>, 2014.
- Kundu, P., Gill, R., Ahlawat, S., Anjum, N. A., Sharma, K. K., Ansari, A. A., Hasanuzzaman, M., Ramakrishna, A., Chauhan, N., Tuteja, N., and Gill, S. S.: Targeting the redox regulatory mechanisms for abiotic stress tolerance in crops, In *Biochemical, Physiological and Molecular Avenues for Combating Abiotic Stress in Plants*, Wani, S. H., Ed., Academic Press, 151–220, <https://doi.org/10.1016/B978-0-12-813066-7.00010-3>, 2018.
- Lamarque, J. F., Shindell, D. T., Josse, B., Young, P. J., Cionni, I., Eyring, V., Bergmann, D., Cameron-Smith, P., Collins, W. J., Doherty, R., Dalsoren, S., Faluvegi, G., Folberth, G., Ghan, S. J., Horowitz, L. W., Lee, Y. H., MacKenzie, I. A., Nagashima, T., Naik, V., Plummer, D., Righi, M., Rumbold, S. T., Schulz, M., Skeie, R. B., Stevenson, D. S., Strode, S., Sudo, K., Szopa, S., Voulgarakis, A., and Zeng, G.: The atmospheric chemistry and climate model intercomparison Project (ACCMIP): Overview and description of models, simulations and climate diagnostics, *Geosci. Mod. Dev.*, 6, 179–206, <https://doi.org/10.5194/gmd-6-179-2013>, 2013.
- Landmann, G., and Bonneau, M. (Eds.): *Forest Decline and Atmospheric Deposition Effects in the French Mountains*, Springer, 461 pp., 1995.
- Lavorel, S.: Ecological diversity and resilience of Mediterranean vegetation to disturbance, *Divers. Distrib.*, 5, 3–13, <https://doi.org/10.1046/j.1472-4642.1999.00033.x>, 1999.

- Leng, X., Qian, X., Yang, M., Wang, C., Huiming Li, H., Wang, J.: Leaf magnetic properties as a method for predicting heavy metal concentrations in PM_{2.5} using support vector machine: A case study in Nanjing, China, *Environmental Pollution*, 242, 922–930, <https://doi.org/10.1016/j.envpol.2018.07.007>, 2018.
- Leonard, R. J., McArthur, C., and Hochuli, D. F.: Particulate matter deposition on roadside plants and the importance of leaf trait combinations, *Urban For. Urban Gree.*, 20, 249–253, <https://doi.org/10.1016/j.ufug.2016.09.008>, 2016.
- Li, P., Calatayud, V., Gao, F., Uddling, J., and Feng, Z.: Differences in ozone sensitivity among woody species are related to leaf morphology and antioxidant levels, *Tree Phys.*, 36, 1105–1116, <https://doi.org/10.1093/treephys/tpw042>, 2016.
- Lin, M., Horowitz, L. W., Xie, Y., Paulot, F., Malyshev, S., Shevliakova, E., Finco, A., Gerosa, G., Kubistin, D., and Pilegaard, K.: Vegetation feedbacks during drought exacerbate ozone air pollution extremes in Europe, *Nature Clim. Change*, 10, 444–451, <https://doi.org/10.1038/s41558-020-0743-y>, 2020.
- Liu, H., Probst, A., and Liao, B.: Metal contamination of soils and crops affected by the Chenzhou lead/zinc mine spill (Hunan, China), *Sci. Total Environ.*, 339, 153–166, <https://doi.org/10.1016/j.scitotenv.2004.07.030>, 2005.
- Llop, E., Pinho, P., Ribeiro, M. C., Pereira, M. J., and Branquinho, C.: Traffic represents the main source of pollution in small Mediterranean urban areas as seen by lichen functional groups, *Environ. Sci. Pollut. Res.*, 24, 12016–12025, <https://doi.org/10.1007/s11356-017-8598-0>, 2017.
- Lombard, L., van der Merwe, N. A., Groenewald, J. Z., and Crous, P. W.: Generic concepts in Nectriaceae, *Stud. Mycol.*, 80, 189–245, <https://doi.org/10.1016/j.simyco.2014.12.002>, 2015.
- Loppi, S., Nelli, L., Ancora, S., and Bargagli, R.: Passive monitoring of trace elements by means of tree leaves, epiphytic lichens and bark substrate, *Environ. Monitor. Assess.*, 45, 81–88, <https://doi.org/10.1023/A:1005770126624>, 1997.
- Loreto, F., Mannozi, M., Maris, C., Nascetti, P., Ferranti, F., and Pasqualini, S.: Ozone quenching properties of isoprene and its antioxidant role in leaves, *Plant Phys.*, 126, 993–1000, <https://doi.org/10.1104/pp.126.3.993>, 2001.
- Mace, K. A., Kubilay, N., and Duce, R. A.: Organic nitrogen in rain and aerosol in the eastern Mediterranean atmosphere: An association with atmospheric dust, *J. Geophys. Res.*, 108, 4320, <https://doi.org/10.1029/2002jd002997>, 2003.
- Manes, F., Vitale, M., Maria Fabi, A., De Santis, F., and Zona, D.: Estimates of potential ozone stomatal uptake in mature trees of *Quercus ilex* in a Mediterranean climate, *Environ. Exp. Bot.*, 59, 235–241, <https://doi.org/10.1016/j.envexpbot.2005.12.001>, 2007.
- Markaki, Z., Loýe-Pilot, M. D., Violaki, K., Benyahya, L., and Mihalopoulos, N.: Variability of atmospheric deposition of dissolved nitrogen and phosphorus in the Mediterranean and possible link to the anomalous seawater N/P ratio, *Mar. Chem.*, 120, 187–194, <https://doi.org/10.1016/j.marchem.2008.10.005>, 2010.
- Matsui, T., Kobayasi, K., Nakagawa, H., Yoshimoto, M., Hasegawa, T., Reinke, R., and Angus, J.: Lower-than-expected floret sterility of rice under extremely hot conditions in a flood-irrigated field in New South Wales, Australia, *Plant Prod. Sci.*, 17, 245–252, <https://doi.org/10.1626/pps.17.245>, 2014.
- Michou, M., Laville, P., Serça, D., Fotiadi, A., Bouchou, P., and Peuch, V. H.: Measured and modeled dry deposition velocities over the ESCOMPTE area, *Atmos. Res.*, 74, 89–116, <https://doi.org/10.1016/j.atmosres.2004.04.011>, 2005.

- Mills, G., Sharps, K., Simpson, D., Pleijel, H., Frei, M., Burkey, K., Emberson, L., Uddling, J., Broberg, M., Feng, Z., Kobayashi, K. and Agrawal, M.: Closing the global ozone yield gap: Quantification and cobenefits for multistress tolerance, *Global Chang. Biol.*, 24, 4869–4893, <https://doi.org/10.1111/gcb.14381>, 2018.
- Mori, J., Sæbø, A., Hanslin, H. M., Teani, A., Ferrini, F., Fini, A., and Burchi, G.: Deposition of traffic-related air pollutants on leaves of six evergreen shrub species during a Mediterranean summer season, *Urban For. Urban Gree.*, 14, 264–273, <https://doi.org/10.1016/j.ufug.2015.02.008>, 2015.
- Mosher, E. S., Silander, J. A., and Latimer, A. M.: The role of land-use history in major invasions by woody plant species in the northeastern north american landscape. *Biol. Invasions*, 11, 2317–2328, <https://doi.org/10.1007/s10530-008-9418-8>, 2009.
- Mudd, J. B.: Sulfur dioxide, in *Responses of Plants to Air Pollution*, Mudd, J. B. and Kozlowski, T. T., Ed., Academic Press New York, 9–22, ISBN 978 0125094504, 1975.
- Munzi, S., Paoli, L., Fiorini, E., and Loppi, S.: Physiological response of the epiphytic lichen *Evernia prunastri* (L.) Ach. to ecologically relevant nitrogen concentrations, *Environ. Pollut.*, 171, 25–29, <https://doi.org/10.1016/j.envpol.2012.07.001>, 2012.
- Musselman, R. C., Lefohn, A. S., Massman, W. J., and Heath, R. L.: A critical review and analysis of the use of exposure- and flux-based ozone indices for predicting vegetation effects, *Atmos. Environ.*, 40, 1869–1888, <https://doi.org/10.1016/j.atmosenv.2005.10.064>, 2006.
- Myers, N., Mittermeyer, R. A., Mittermeyer, C. G., Da Fonseca, G. A. B., and Kent, J.: Biodiversity hotspots for conservation priorities, *Nature*, 403, 853–858, <https://doi.org/10.1038/35002501>, 2000.
- Nali, C., Paoletti, E., Marabottini, R., Della Rocca, G., Lorenzini, G., Paolacci, A. R., Ciaffi, M., and Badiani, M.: Ecophysiological and biochemical strategies of response to ozone in Mediterranean evergreen broadleaf species, *Atmos. Environ.*, 38, 2247–2257, <https://doi.org/10.1016/j.atmosenv.2003.11.043>, 2004.
- Nasreddine, L., and Parent-Massin, D.: Food contamination by metals and pesticides in the European Union. Should we worry?, *Toxicol. Lett.*, 127, 29–41, [https://doi.org/10.1016/S0378-4274\(01\)00480-5](https://doi.org/10.1016/S0378-4274(01)00480-5), 2002.
- Nenes, A., Pandis, S. N., Kanakidou, M., Russell, A., Song, S., Vasilakos, P., and Weber, R. J.: Aerosol acidity and liquid water content regulate the dry deposition of inorganic reactive nitrogen, *Atmos. Chem. Phys. Discuss.*, <https://doi.org/10.5194/acp-2020-266>, in review, 2020.
- Nieboer, N., Richardson, D. H. S., Pukett, K. J., Tomassini, F. D.: The phytotoxicity of sulfur dioxide in relation to measurable responses in lichen, in *Effects of Air Pollution on Plants*, Semin. Ser. Soc. Exp. Biol., Cambridge University Press, ISBN 0521 29039, 61–86, 1976.
- N’Guessan, Y. M., Probst, J. L., Bur, T., and Probst, A.: Trace elements in stream bed sediments from agricultural catchments (Gascogne region, S-W France): Where do they come from?, *Sci. Total Environ.*, 407, 2939–2952, <https://doi.org/10.1016/j.scitotenv.2008.12.047>, 2009.
- Ochoa-Hueso, R., Allen, E. B., Branquinho, C., Cruz, C., Dias, T., Fenn, M. E., Manrique, E., Pérez-Corona, M. E., Sheppard, L. J., and Stock, W. D.: Nitrogen deposition effects on Mediterranean-type ecosystems: An ecological assessment, *Environ. Pollut.*, 159, 2265–2279, <https://doi.org/10.1016/j.envpol.2010.12.019>, 2011.
- Ochoa-Hueso, R., and Manrique, E.: Effects of nitrogen deposition and soil fertility on cover and physiology of *Cladonia foliacea* (Huds.) Willd., a lichen of biological soil crusts from

- Mediterranean Spain, Environ. Pollut., 159, 449–457, <https://doi.org/10.1016/j.envpol.2010.10.021>, 2011.
- Ochoa-Hueso, R., and Manrique, E.: Effects of nitrogen deposition on growth and physiology of *Pleurochaete squarrosa* (Brid.) Lindb., a terricolous moss from Mediterranean ecosystems, Water Air Soil Pollut., 224, <https://doi.org/10.1007/s11270-013-1492-6>, 2013.
- Ochoa-Hueso, R., Munzi, S., Alonso, R., Arróniz-Crespo, M., Avila, A., Bermejo, V., Bobbink, R., Branquinho, C., Concostrina-Zubiri, L., Cruz, C., de Carvalho, R. C., De Marco, A., Dias, T., Elustondo, D., Elvira, S., Estébanez, B., Fusaro, L., Gerosa, G., Izquieta-Rojano, S., Lo Cascio, M., Marzuoli, R., Matos, P., Mereu, S., Merino, J., Morillas, L., Nunes, A., Paoletti, E., Paoli, L., Pedro Pinho, P., Rogers, I. B., Santos, A., Sicard, P., Stevens, C. J., and Theobald, M. R.: Ecological impacts of atmospheric pollution and interactions with climate change in terrestrial ecosystems of the Mediterranean Basin: Current research and future directions, Environ. Pollut., 227, 194–206, <https://doi.org/10.1016/j.envpol.2017.04.062>, 2017.
- Oparka, K. J. (Ed.): Plasmodesmata, ISBN-13 978-14051-2554-3, Oxford Blackwell Publishing Ltd, 303 pp., 2005.
- Paoletti, E.: Impact of ozone on Mediterranean forests: A review, Environ. Pollut., 144, 463–474, <https://doi.org/10.1016/j.envpol.2005.12.051>, 2006.
- Paoli, L., Guttová, A., and Loppi, S.: Assessment of environmental quality by the diversity of epiphytic lichens in a semi-arid Mediterranean area (Val Basento, South Italy), Biologia, 61, 353–359, <https://doi.org/10.2478/s11756-006-0064-2>, 2006.
- Payne, R. J., Campbell, C., Britton, A. J., Mitchell, R. J., Pakeman, R. J., Jones, L., Ross, L. C., Stevens, C. J., Field, C., Caporn, S. J. M., Carroll, J., Edmondson, J. L., Carnell, E. J. Tomlinson, S., Dore, A. J., Dise, N., and Dragosits, U.: What is the most ecologically-meaningful metric of nitrogen deposition?, Environ. Pollut., 247, 319–331, <https://doi.org/10.1016/j.envpol.2019.01.059>, 2019.
- Peer, R. L., and Thorneloe, S. A., Epperson, D. L.: A comparison of methods for estimating global methane emissions from landfills, Chemosphere, 26, 387–400, [https://doi.org/10.1016/0045-6535\(93\)90433-6](https://doi.org/10.1016/0045-6535(93)90433-6), 1993.
- Pierret, M. C., Viville, D., Dambrine, E., Cotel, S., and Probst, A.: Twenty-five year record of chemicals in open field precipitation and throughfall from a medium-altitude forest catchment (Strengbach – NE France): An obvious response to atmospheric pollution trends, Atmos. Environ., 202, 296–314, <https://doi.org/10.1016/j.atmosenv.2018.12.026>, 2019.
- Pinho, P., Augusto, S., Martins-Loução, M. A., Pereira, M. J., Soares, A., Máguas, C., and Branquinho, C.: Causes of change in nitrophytic and oligotrophic lichen species in a Mediterranean climate: Impact of land cover and atmospheric pollutants, Environ. Pollut., 154, 380–389, <https://doi.org/10.1016/j.envpol.2007.11.028>, 2008.
- Pirintsos, S. A., Paoli, L., Loppi, S., and Kotzabasis, K.: Photosynthetic performance of lichen transplants as early indicator of climatic stress along an altitudinal gradient in the arid Mediterranean area, Clim. Change, 107, 305–328, <https://doi.org/10.1007/s10584-010-9989-0>, 2011.
- Percy, K. E., Cape, J. N., Jagels, R., and Simpson C. J. (Eds.): Air Pollutants and the Leaf Cuticle, NATO ASI Series, 236, 398 pp., <https://doi.org/10.1007/978-3-642-79081-2>, 1994.
- Polymenakou, P. N., Mandalakis, M., Stephanou, E. G., and Tselepidis, A.: Particle size distribution of airborne microorganisms and pathogens during an intense African dust event in the eastern Mediterranean, Environ. Health Persp., 116, 292–296, <https://doi.org/10.1289/ehp.10684>, 2008.

- Probst, A., Obeidy, C., Gaudio, N., Belyazid, S., Gégout, J. C., Alard, D., Corket, E., Party, J. P., Gauquelin, T., Mansat, A., Nihlgård, B., Leguédois, S., and Sverdrup, H. U.: Evaluation of plant-responses to atmospheric nitrogen deposition in France using integrated soil-vegetation models, in *Critical Loads and Dynamic Risk Assessments – Nitrogen, Acidity and Metals in Terrestrial and Aquatic Ecosystems*, de Vries, W., Hettelingh, J.-P., and Posch, M., Eds., Springer, Environmental Pollution, 255, 359–379, https://doi.org/10.1007/978-94-017-9508-1_13, 2015.
- Rap, A., Spracklen, D. V., Mercado, L., Reddington, C. L., Haywood, J. M., Ellis, R. J., Phillips, O. L., Artaxo, P., Bonal, D., Restrepo Coupe, N., and Butt, N.: Fires increase Amazon forest productivity, *Geophys. Res. Lett.*, 42, 4654–4662, <https://doi.org/10.1002/2015GL063719>, 2015.
- Ratier, A., Dron, J., Revenko, G., Austruy, A., Dauphin, C. E., Chaspoul, F., and Wafo, E.: Characterization of atmospheric emission sources in lichen from metal and organic contaminant patterns, *Environ. Sci. Pollut. Res.*, 25, 8364–8376, <https://doi.org/10.1007/s11356-017-1173-x>, 2018.
- Reinds, G. J., Posch, M., De Vries, W., Slootweg, J., and Hettelingh, J. P.: Critical loads of sulphur and nitrogen for terrestrial ecosystems in Europe and northern Asia using different soil chemical criteria, *Water Air Soil Pollut.*, 193, 269–287, <https://doi.org/10.1007/s11270-008-9688-x>, 2008.
- Riga-Karandinos A. N., and Saitanis, C.: Biomonitoring of concentrations of platinum group elements and their correlations to other metals, *Int. J. Environ. Pollut.*, 22, 563–579, <https://doi.org/10.1504/IJEP.2004.005910>, 2004.
- Riga-Karandinos, A. N., Saitanis, C. J., and Arapis, G.: First study of anthropogenic platinum group elements in roadside top-soils in Athens, Greece, *Water Air Soil Pollut.*, 172, 3–20, <https://doi.org/10.1007/s11270-005-9016-7>, 2006.
- Rinnan, R., Steinke, M., McGenity, T., and Loreto, F.: Plant volatiles in extreme terrestrial and marine environments, *Plant Cell Environ.*, 37, 1776–1789, <https://doi.org/10.1111/pce.12320>, 2014.
- Rizzetto, S., Belyazid, S., Gégout, J. C., Nicolas, M., Alard, D., Corcket, E., Gaudio, N., Sverdrup, H., and Probst, A.: Modelling the impact of climate change and atmospheric N deposition on French forests biodiversity, *Environ. Pollut.*, 213, 1016–1027, <https://doi.org/10.1016/j.envpol.2015.12.048>, 2016.
- Rodà, F., Avila, A., and Rodrigo, A.: Nitrogen deposition in Mediterranean forests, *Environ. Pollut.*, 118, 205–213, [https://doi.org/10.1016/s0269-7491\(01\)00313-x](https://doi.org/10.1016/s0269-7491(01)00313-x), 2002.
- Rodríguez Martin, J. A., Gutiérrez, C., Torrijos, M., and Nanos, N.: Wood and bark of *Pinus halepensis* as archives of heavy metal pollution in the Mediterranean Region, *Environ. Pollut.*, 239, 438–447, <https://doi.org/10.1016/j.envpol.2018.04.036>, 2018.
- Rowe, E. C., Wamelink, G. W., Smart, S. M., Butler, A., Henrys, P. A., van Dobben, H. F., Reinds, G. J., Evans, C. D., Kros, J., and de Vries, W.: Field survey based models for exploring nitrogen and acidity effects on plant species diversity and assessing long-term critical loads, in *Critical Loads and Dynamic Risk Assessments – Nitrogen, Acidity and Metals in Terrestrial and Aquatic Ecosystems*, de Vries, W., Hettelingh, J.-P., and Posch, M., Eds., Environmental Pollution, 255, 297–326, Springer, Dordrecht, https://doi.org/10.1007/978-94-017-9508-1_11, 2015.
- Saitanis, C.: Tropospheric ozone: a menace for crops and natural vegetation in Greece, *Ital. J. Agron.*, 3, 71–77, <https://doi.org/10.4081/ija.2008.71>, 2008.

- Saitanis, C. J., and Karandinos, M. G. Effects of ozone on tobacco (*Nicotiana tabacum* L.) varieties. *J. Agron. and Crop Sci.*, 188, 51–58, <https://doi.org/10.1046/j.1439-037x.2002.00539.x>, 2002.
- Saitanis, C., Karandinos, M. G., Riga-Karandinos, A. N., Lorenzini, G., and Vlassi, A.: Photochemical air pollutant levels and ozone phytotoxicity in the region of Mesogia-Attica, Greece, *Int. J. Environ. Pollut.*, 19, 197–208, <https://doi.org/10.1504/IJEP.2003.003748>, 2003.
- Saitanis, C. J., Bari, S. M., Burkey, K. O., Stamatelopoulos, D., and Agathokleous, E.: Screening of Bangladeshi winter wheat (*Triticum aestivum* L.) cultivars for sensitivity to ozone, *Environ. Sci. Pollut. Res.*, 21, 13560–13571, <https://doi.org/10.1007/s11356-014-3286-9>, 2014.
- Sanz, M. J., and Millán, M. M.: Ozone in the Mediterranean region: evidence of injury to vegetation, in *Forest Dynamics in Heavily Polluted Regions*, Innes, J. L., Ed., IUFRO Research Series 1, CABI Publishing, Wallingford, UK, 165–192, 2000.
- Sanz, M. J., Carratalá, A., Gimeno, C., and Millán, M. M.: Atmospheric nitrogen deposition on the east coast of Spain: Relevance of dry deposition in semi-arid Mediterranean regions, *Environ. Pollut.*, 118, 259–272, [https://doi.org/10.1016/S0269-7491\(01\)00318-9](https://doi.org/10.1016/S0269-7491(01)00318-9), 2002.
- Sanz, J., Bermejo, V., Gimeno, B. S., Elvira, S., and Alonso, R.: Ozone sensitivity of the Mediterranean terophyte *Trifolium striatum* is modulated by soil nitrogen content, *Atmos. Environ.*, 41, 8952–8962, <https://doi.org/10.1016/j.atmosenv.2007.08.016>, 2007.
- Sardans, J., Alonso, R., Carnicer, J., Fernández-Martínez, M., Vivanco, M. G., Peñuelas, J.: Factors influencing the foliar elemental composition and stoichiometry in forest trees in Spain, *Perspect. Plant Ecol. Evol. Syst.*, 18, 52–69, <http://doi.org/10.1016/j.ppees.2016.01.001>, 2016.
- Schenone, G.: Air pollution and vegetation in the Mediterranean area, *Medit.*, 4, 49–52, 1993.
- Schmitz, A., Sanders, T. G. M., Bolte, A., Bussotti, F., Dirnböck, T., Johnson, J., Peñuelas, J., Pollastrini, M., Prescher, A., Sardans, J., Verstraeten, A., and Vries, W.: Responses of forest ecosystems in Europe to decreasing nitrogen deposition, *Environ. Pollut.*, 244, 980–994. <https://doi.org/10.1016/j.envpol.2018.09.101>, 2019.
- Sharma, P., Jha, A. B., Dubey, R. S., and Pessaraki, M.: Reactive oxygen species, oxidative damage, and antioxidative defense mechanism in plants under stressful conditions, *J. Bot.*, 2012, 1–26, <https://doi.org/10.1155/2012/217037>, 2012.
- Sharma, A., Kumar, V., Kumar, R., Shahzad, B., Thukral, A. K., and Bhardwaj, R.: Brassinosteroid-mediated pesticide detoxification in plants: A mini-review, *Cogent Food Agric.*, 4, 1436212, <https://doi.org/10.1080/23311932.2018.1436212>, 2018.
- Smith, R. I., Fowler, D., and Cape, J. N.: The Statistics of Phytotoxic Air Pollutants, *J. Roy. Stat. Soc. A*, 152, 183–198, <http://doi.org/10.2307/2982914>, 1989.
- Stalikas, C. D., Mantalovas, A. C., and Pilidis, G. A.: Multielement concentrations in vegetable species grown in two typical agricultural areas of Greece, *Sci. Total Environ.*, 206, 17–24, [https://doi.org/10.1016/S0048-9697\(97\)00213-1](https://doi.org/10.1016/S0048-9697(97)00213-1), 1997.
- Stanners, D., and Bourdeau, P.: *Europe's Environment: The Dobris Assessment*, Paperback – 31, Office for Official Publications of the European Communities, Luxembourg, 712 pp., 1995.

- Stevens, C. J., Dise, N. B., Owen Mountford, J., and Gowing, D. J.: Impact of nitrogen deposition on the species richness of grasslands, *Science*, 303, 1876–1879, <http://doi.org/10.1126/science.1094678>, 2004.
- Tiiva, P., Rinnan, R., Faubert, P., Räsänen, J., Holopainen, T., Kyrö E., and Holopainen, J. K.: Isoprene emission from a subarctic peatland under enhanced UV-B radiation, *New Phytol.*, 176, 346–355, <https://doi.org/10.1111/j.1469-8137.2007.02164.x>, 2007.
- Velikova, V., and Loreto, F.: On the relationship between isoprene emission and thermotolerance in *Phragmites australis* leaves exposed to high temperatures and during the recovery from a heat stress, *Plant Cell Environ.*, 28, 318–327, <https://doi.org/10.1111/j.1365-3040.2004.01314.x>, 2005.
- Vilà, M., Burriel, J. A., Pino, J., Chamizo, J., Llach, E., Porterias, M., and Vives, M.: Association between *Opuntia* species invasion and changes in land-cover in the Mediterranean region, *Glob. Chang. Biol.*, 9, 1234–1239, <https://doi.org/10.1046/j.1365-2486.2003.00652.x>, 2003.
- Violaki, K., Zarbas, P., and Mihalopoulos, N.: Long-term measurements of dissolved organic nitrogen (DON) in atmospheric deposition in the Eastern Mediterranean: Fluxes, origin and biogeochemical implications, *Mar. Chem.*, 120, 179–186, <https://doi.org/10.1016/j.marchem.2009.08.004>, 2010.
- Vlachogianni, T., Vogrin, M., and Scoullou, M.: Biodiversity in the Mediterranean, The Regional Activity Centre for Specially Protected Areas (RAC/SPA), 1–10, Retrieved from <http://www.rac-spa.org/publications>, 2012.
- Wallman, P., Svensson, M. G. E., Sverdrup, H., and Belyazid, S.: ForSAFE – an integrated process-oriented forest model for long-term sustainability assessments, *For. Ecol. Manag.* 207, 19–36, <http://doi.org/10.1016/j.foreco.2004.10.016>, 2005.
- Wang, W., Vinocur, B., and Altman, A.: Plant responses to drought, salinity and extreme temperatures: Towards genetic engineering for stress tolerance, *Planta*, 218, 1–14, <https://doi.org/10.1007/s00425-003-1105-5>, 2003.
- Wheeler, T. R., Hong, T. D., Ellis, R. H., Batts, G. R., Morison, J. I. L., and Hadley, P.: The duration and rate of grain growth, and harvest index, of wheat (*Triticum aestivum* L.) in response to temperature and CO₂, *J. Exp. Bot.*, 47, 623–630, <https://doi.org/10.1093/jxb/47.5.623>, 1996.
- Wolfenden, J., and Mansfield, T. A.: Physiological disturbances in plants caused by air pollutants, *Proc. Roy. Soc. Edinburgh B*, 97, 117–138, <https://doi.org/10.1017/s0269727000005315>, 1990.
- Yu, M. H., and Tsunoda, H.: *Environmental Toxicology: Biological and Health Effects of Pollutants*, CRC press, 2nd Ed., ISBN 978-1566706704, 364 pp., 2004.