Effects of Ozone on Plant Health and Environment: A Mini Review

Sumitra Pal Karmakar, Anushree Baul Das,
Cyaria Gurung and Chandra Ghosh

Research Journal of Agricultural Sciences
An International Journal

P- ISSN: 0976-1675
E- ISSN: 2249-4538

Volume: 13
Issue: 03

Res. Jr. of Agril. Sci. (2022) 13: 612–619

CARAS

Res. Jr. of Agril. Sci. (May-Jun 2022)
13(3): 612–619

www.rjas.org

ISSN: 0976-1675 (P)
ISSN: 2249-4538 (E)

Research Review

Effects of Ozone on Plant Health and Environment: A Mini Review

Sumitra Pal Karmakar[1], Anushree Baul Das[2], Cyaria Gurung[3] and Chandra Ghosh*[4]

Received: 20 Feb 2022 | Revised accepted: 15 Apr 2022 | Published online: 17 May 2022

ABSTRACT

Ozone, a pale blue gas is an inorganic molecule with the chemical formula O_3. Tropospheric ozone is a secondary air pollutant and it is formed due to photochemical reaction of hydrocarbons mainly Volatile Organic Compounds (VOC) and Nitrogen Oxides (NOx) emitted from industrial units and transport services and causes a variety of health problems, damages vegetation and environment. The primary objective of this paper is to review different types of research works undertaken on the effects of tropospheric ozone on different plants, forest, agricultural crops including microflora. This review paper also focuses on the impacts on environmental due to ozone pollution. Vegetations are the important sink of tropospheric ozone which enters into the plant through stomata and oxidize plant tissues during respiration producing many oxidizing compounds and affecting various physiological and biochemical processes of plants. Several damages are noticed on plants including accurate signs of damage like necrotic lesions, chlorosis, stunted plant growth, reddening, bronzing, mottling etc. many of which have been analyzed in this review. Tropospheric ozone as a greenhouse gas is one of the factors of global warming, which leads to climate change and it is also a component of photochemical smog. The information and data regarding consequences of ozone emission at ground level on environment and vegetations are compiled as a review paper from various published articles of reputed journals, e-books and internet sources. The current situation of harmful impacts of ozone emission needs urgent remedial measures to protect the environment. At the end of the review paper, emphasis has been laid on the limited number of research data presently available in this field and necessity for carrying out more researches to meet the current need.

***Key words*:** Ozone, Ecosystem, Environment, Plants, Biodiversity

German scientist Christain Friedrich Schonbein discovered ozone in 1840. He named the gas ozone which is derived from a Greek word ozein; meaning "smell". Swiss chemist J.L. Soret worked out its chemical structure as being a molecule consisting of three bonded oxygen atoms (O_3) [1]. Ozone is categorised as both "good" ozone and "bad" ozone. Good ozone is natural stratospheric ozone and it protects life on Earth by absorbing harmful ultraviolet (UV) radiation from the sun. Bad ozone is tropospheric or ground-level ozone and severely harmful to living systems and environment. It emits from anthropogenic sources and it originates due to the series of cyclic reactions between Nitrogen (N_2), Oxygen (O_2), Nitrogen dioxide (NO_2) and Nitric oxide (NO) About 90% of the atmospheric ozone resides in the lower to middle stratosphere between about 15 and 35 km altitude (often referred to as the "ozone layer"), while only ~ 10% are found in the troposphere [2].

Dry deposition of ozone is influenced by the weather conditions such as temperature, radiation, and air stagnation and uptake at the surface in particular by vegetation [59]. As per National Ambient Air Quality Index, CPCB (Central Pollution Control Board), India, the permissible limit of O_3 is 100 μg/m^3 for 8 hours and 180 μg/m^3 for 1 hour. Warm sunny days are usually favorable condition for increasing the ozone levels in the atmosphere. Global climate change through creating favorable atmospheric conditions aggravate ozone production in the atmosphere and thus ozone level is increasing continuously in many parts of the world [60]. Though O3 is a short-lived chemical species in the atmosphere, it is a potent greenhouse gas with Global Warming Potential (GWP) between 918 - 1022 and it is also one of the major constituents of photochemical smog. Photochemical smog contains anthropogenic air pollutants, mainly ozone, nitric acid, and organic compounds, which are trapped near the ground by temperature inversion [61]. Elevated exposures to ozone can

* **Chandra Ghosh**
✉ chandraghosh19@nbu.ac.in

[1-2] Department of Environmental Science, Siliguri College, Siliguri - 734 001, West Bengal, India

[3] Department of Botany, Siliguri College, Siliguri - 734 001, West Bengal, India

[4] Department of Tea Science, University of North Bengal. P.O. N.B.U., Raja Rammohunpur, Siliguri - 734 013, West Bengal, India

affect human health, sensitive vegetation, wildlife and the environment. However, as a sink of ground level ozone, vegetations, especially ozone sensitive vegetations are highly affected due to ozone exposure.

Under favorable meteorological conditions, O_3 may accumulate in troposphere and reach a level that causes significant decrease in growth and yield of O_3 - sensitive plant species [3]. Ground-level ozone causes more damage to plants than all other air pollutants combined [4]. It has been reported that elevated O_3 not only induces visible tissue injury, inhibits photosynthesis, reduces plant biomass and crop yields [5]. Systematic injury surveys demonstrate that foliar injury occurs on sensitive species throughout the globe [1]. However, deleterious impacts on plant carbon, water and nutrient balance can also occur without visible injury [6]. Elevated ozone levels appear to have detrimental effects on soybean plant roots, their relationship with symbiotic microorganisms in the soil and the ways the plants sequester carbon [7]. High proportions of ozone sensitive species were found in the families Myrtaceae, Salicaceae and Onograceae, while low proportions of ozone sensitive species were found in the families Brassicaceae, Boraginaceae and Plantaginaceae [8]. The legume family is widely accepted as containing some of the most ozone-sensitive species like peas and beans are the most sensitive crops to O_3. Horticulture crops like Tomato, Potato and lettuce were recognized to have high sensitivity to O_3-induced oxidative stress [9]. The effects of ozone on the enormous number of herbaceous and shrubby, annual and perennial species that are not deliberately or intensively cultivated have also been reported [10]. All alterations caused by O_3 lead to high losses in both quality and yield of commercial crops, which are already facing the challenge of producing 60% more food by 2050 [11]. To evaluate the risk posed by ozone, it is necessary to quantify the potential effects of O_3 on different plant species and to identify the most sensitive vegetations to O_3. With the aim of understanding how tropospheric ozone affects different vegetations, ecosystem and environment, this review paper has compiled the research studies presently available in this field.

Formation of tropospheric ozone

The most important mechanism for formation of tropospheric ozone is a photochemical cycle, which is driven by sunlight. Two major precursors of this cyclic reaction are Volatile Organic Compounds (VOCs) and the oxides of nitrogen (NOx), which are produced by natural biological processes, however their contribution is much less important than that from fossil fuel combustion [12]. The photochemical cycle begins with the photolysis of nitrogen dioxide (NO_2) into Nitric oxide (NO) and O. The NO formed then reacts with the O_3 to produce O_2 and NO_2, resulting in series of cyclic reactions between N_2 – NO - NO_2 - O_3 [13]. This photochemical reaction can be illustrated by the following series of equation [81].

$$N_2 + O_2 \;\ldots\ldots\ldots\ldots 2NO$$

$$2NO + O_2 \ldots\ldots\ldots 2NO_2$$

Where hμ represents a photon with wavelength λ<0.39 μm.

$$O + O_2 + M \ldots\ldots\ldots O_3 + M$$

Where M represents a molecule, whose presence is necessary to absorb excess energy from the reaction. Without M the ozone would have too much energy to be stable, and it would dissociate back to O and O_2.

$$O_3 + NO \ldots\ldots\ldots\ldots NO_2 + O_2$$

The diurnal pattern of O_3 concentration in an urban area is not steady. It increases rapidly between 1200 and 1500h during afternoon when the intensity of solar radiation is at a maximum and the NO_2:NO ratio is large. The rate of O_3 formation may then decline, reaching a steady state during the late afternoon to early evening hours. After that period, O_3 concentrations fall as NO_2 breakdown diminishes and as fresh emissions of NO deplete the O_3 [82].

O_3 concentration levels tend to be higher in rural areas. The transport of pollutants from the urban region over long distances is an observed fact in the North America, Europe [89]. The Indian Ocean Experiment (INDOEX) results have shown a pollution haze over the Arabian Sea and the Indian Ocean as a result of transport of pollutants from the Indian subcontinent [83].

Occurrence of ground level ozone

Atmospheric ozone (O_3) is an integral part of global climate change. Although ozone at the ground level is a “greenhouse gas,” it plays a minor role in regulating our air temperature, contributing only about 7% to the total warming effect as reported by Sagar Krupa *et al.* [19]. There is also a naturally occurring beneficial O_3 layer in the upper atmosphere (between 15and 50 km above the surface) that strongly absorbs harmful ultraviolet radiation (about 210 to 290 nm: radiation <280 nm is UV-C and 280 to 315 nm is UV-B). In contrast, there are both natural and human made sources of O_3 at ground level. Because of these natural sources, there is a background average O_3 concentration of roughly 20 to 30 nl/liter (ppb) everywhere. There is no place on earth that has not been influenced by human activity, and ozone is found almost everywhere with varying concentrations.

Impacts of trpospheric ozone on environment and ecosystem

Ozone is a potent greenhouse gas with global warming potential GWP 918-1022 and one of the major responsible components for global warming and climate change. Tropospheric O_3 impacts the radiation budget and may cause climate change because it is a greenhouse gas with a strong absorption band centered at 9.6 micro m in the atmospheric window region [62]. An atmospheric window is the portion of the electromagnetic spectrum that can be transmitted through the atmosphere. Tropospheric ozone absorbs solar ultraviolet radiation and infrared radiation emitted by the earth surface and therefore effectively traps heat and cause global warming and climate change. Tropospheric ozone levels have shown significant global or regional responses to meteorological/climatic changes (e.g., changes in the Brewer-Dobson Circulation, the Hadley Circulation, and El Niño–Southern Oscillation) [64].

Ozone, (O_3) is the most abundant photochemical oxidants of photochemical smog [12]. Photochemical smog is a brownish-gray haze caused by the action of solar ultraviolet radiation on atmosphere polluted with hydrocarbons and oxides of nitrogen [63]. O_3 is responsible for many of the undesirable properties of photochemical smog and causes chest constriction, irritation of the mucous membrane, damage to vegetation. The other components of photochemical smog, principally formaldehyde (HCHO), peroxybenzoyl nitrate (PB_ZN), peroxyacetyl nitrate (PAN) and acrolein (CH_2CHCOH) cause eye irritation [12].

Tropospheric ozone affects the climate beyond increased warming, having impacts on evaporation rates, cloud formation, precipitation levels, and atmospheric circulation. These impacts mainly occur within the regions where tropospheric ozone precursors are emitted, and so disproportionally affect the Northern Hemisphere [61]. These environmental effects impact on the ecosystems and the services provided by these ecosystems.

Tropospheric ozone (O_3) is an important stressor in natural ecosystems, with well documented impacts on soils, biota and ecological processes [61]. And it continues to be of major concern in the field of air pollution effects on terrestrial ecosystem. The potential effects of elevated ozone (O_3) along with climate variability, increasing CO_2, and land use change, 4.5% reduction in NPP (Net Primary Production) and 0.9% reduction in total carbon storage net primary productivity (NPP) and carbon storage in China's terrestrial ecosystems for the period 1961–2000 is well documented [67]. O_3 is more sensitive to plants and vegetations and it is responsible for widespread effects on crops, trees and native plant species. Effects of O_3 on vegetation may lead to long-term effects on ecosystem structure and function. It can indirectly affect soil processes and affect water cycling through shifting in plant species composition and its effect on stomata respectively and can alter overall ecosystem productivity [64]. Tropospheric ozone is involved in a complex web of interactions with other atmospheric gases and particles, and through ecosystem interactions with the N-cycle and climate change [65]. O_3 also impose harmful impact on biodiversity. Plants are growing in a highly competitive environment - a slight loss of vitality of a plant species due to ozone can result in a more vigorously growing but less ozone-sensitive species out competing the affected species for light, nutrients and water resulting in a shift in species balance and potential loss of the more sensitive species at a sub-lethal ozone concentration. All of the component species of the plant community would potentially be impacted, including the animals, fungi, bacteria and insects that live in close association with plants or in nearby soils [66]. For example, changes in leaf chemistry will impact on herbivorous insects and plant pathogens, while changes in root exudation will impact on mycorrhizal associations and microbial soil processes. In so doing, ozone induced changes in species diversity or shifts in species balance will impact on many ecological processes, thereby impacting on ecosystem services, flows, goods and values [66].

General effects of tropospheric ozone on plants

United Nations Economic Commission for Europe has defined ozone critical levels for three vegetation categories: crops, forests and semi-natural vegetation [10]. It is critical to measure O_3 concentrations in the air near the leaf, plant, stand or ecosystem of interest. O_3 exposure is used on a qualitative level, both in terms of range and experimental exposure relative to ambient concentrations in the agricultural or unmanaged ecosystem of the investigated species. The terms 'low (roughly 20–70 nl O_3 l^{-1}) 'moderate' (70–150 nl O_3 l^{-1}) and 'high' exposure (>150 nl O_3 l^{-1}) is assumed [14].

A number of experimental studies have been conducted on the effect of ozone on different type of vegetations. Primary producers of all types, in agricultural as well as natural settings, are sensitive to elevated levels of atmospheric ozone, resulting in foliar injury, pigment loss, premature senescence, and decreased photosynthetic/growth rates [27]. Plants act as a sink for ozone, through stomatal and non-stomatal processes [14]. Stomatal conductance to ozone is the inverse of the sum of an array of resistances that ozone meets in specific locations along the path from the outside of the leaf to the reaction site inside the apoplast [15]. Non-stomatal uptake leads to ozone deposition in soil, stems, and cuticles. These sources are considered of minor importance unless in conditions of surface wetness [16].

After entering the stomata, ozone reacts with the liquid components of the apoplast to create reactive oxygen species (ROS, mainly H_2O_2, but also OH radicals) that can oxidize the cell walls to start a cascade of reactions which lead, at the final stage, to cellular death [14]. The most significant direct effects of O_3 are on plant growth and leaf physiology [17]. There are two modes of action of O_3 within the leaf. At high exposure to O_3, the flux overwhelms the detoxification capacity and most of the O_3 is not detoxified, causing direct damage to the leaf. At a low exposure of O_3, it can induce the defense reactions and gene expression in the plants, which require energy to regenerate antioxidants and de novo synthesis (synthesizing complex molecules from simple molecules), ultimately resulting in a decreased carbon assimilation rate for plant growth [18]. In sensitive species O_3 may affect visual attraction traits important for pollination, and spectral reflectance [19]. Non visible effects of ozone exposure include reduced photosynthesis [20] damage to reproductive processes [21], increased dark respiration [22], lowered carbon transport to roots [23], and reduced decomposition of early successional communities [24].

Fig 1 Healthy (top) and ozone-injured (bottom) tulip tree (yellow poplar) foliage [18]

Effects on lower plants

Algae, Fungi, Lichen, Bryophyta are categorised as lower plants and they are non-vascular plants. Algae and bacteria were grown in three different ozone atmospheres (0, 80, and 250 ppb) [25]. Lichens may be considered as rather ozone-tolerant organisms [29]. At sufficiently high ozone concentrations, algae cells are "oxidized to death" and even their by-products may be destroyed [26]. There are differences in the way that certain algae respond to ozone, and different concentrations and exposures times are necessary to eliminate different species [27-28]. In (Table 1) effects of ozone pollution on different lower plants are shown:

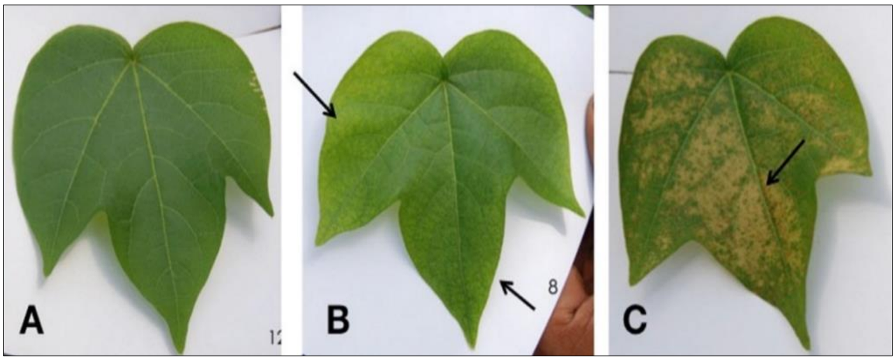

Fig 2 O_3 exposure effects in primary cotton leaves. (A) No exposure; (B) 15-min exposure to 1200 nl $O_3.l^{-1}$ caused chlorosis (C) 15-min exposure to 2400 nl $O_3.l^{-1}$ caused necrosis [7].

Fig 3 Changes in color of petals due to O_3 in *Erodium paularense* [19]

Table 1 Effects of ozone pollution on lower plants

Lower plants	Effects of ozone	Reference
Lichens	Precipitous declines in species richness loss of chlorophyll a reduction of photosynthetic rate	[30-32]
Cyanobacteria	Growth and nitrogen fixation severely inhibited heterocyst formation when exposed to ozone concentrations characterized as being "below" ambient" for semi-urban condition	[33]
Sphagnum moss species in boreal and subarctic peatlands and tundra	Significant changes of chlorophyll content, membrane damage leading to leakage, reduction in photosynthesis and growth have been observed	[34]

Effects on agricultural and horticultural species

The productivity, product quality and competitive ability of important agricultural and horticultural plants in many regions of the world may be adversely affected by current and anticipated concentrations of ground level ozone (O_3) [38]. Ozone sensitive crop and horticultural species include alfalfa, bean, clover and other forages, cotton, grape (*Vitis vinifera* L.), lettuce, oat (*Avena sativa* L.), peanut, potato (*Solanum tuberosum* L.), rape (*Brassica napus* L.), rice, soybean, spinach (*Spinacia oleracea* L.), tobacco, tomato, watermelon (*Citrullus lanatus* (Thunb.) Matsum. & Nakai) and wheat [35-41]. A detailed account of the effects of ozone in different agricultural and horticultural crops is discussed below from various research papers:

Rice

i) Reduction in dry mass and grain yield [42].
ii) Rice grain, protein and iron yield tended to decrease in plants exposed to high ozone [43].
iii) O_3 caused generation of polymorphic DNA bands affecting genome template stability. O_3 reductions in yield and change in the quality of grains [50].
iv) Ozone exposure affected the nitrogen distribution in rice, as indicated by altered foliar activity of the enzymes involved in nitrogen metabolism, such as glutamine synthetase and glutamine -2-oxoglutarate aminotransferase [51].

Wheat

i) Chlorophyll (a + b) and carotenoid loss, and membrane leakage [44]
ii) Lipids were immediately oxidized by ozone (12 ppm) [45]
iii) Visible leaf injury on seedling plants (three-leaf stage) was observed after fumigation with 160 or 240 (g m^{-3} O_3) [46].
iv) O_3 can potentially promote oxidation and/or degradation of the chemical constituents of grains [47].
v) There was a strong negative effect on grain weight, volume weight and on starch concentration [48].
vi) Elevated O_3 decreased wheat grain yield by 29%, and above ground biomass by 18%. O_3 range was between 31 and 59 ppb (average 43 ppb), there was a significant decrease in the grain yield (18%) and biomass (16%). Elevated O_3 significantly decreased the grain protein yield (−18%), photosynthetic rates (−20%), stomatal conductance (−22%), and chlorophyll content (−40%). For the whole plant, rising O_3 induced a larger decrease in below ground (−27%) biomass than in above ground (−18%) biomass [49].

Vegetables and fruit crops

i) Ozone concentrations affected both the photosynthetic and respiratory processes in blueberry, broccoli, carrot [56]
ii) Greatest impacts in fruit and vegetable crops may occur from changes in carbon transport, which causes lower quality in such important crops as potatoes, sweet potatoes, carrots, onions and garlic [53].
iii) Elevated concentrations of atmospheric ozone can induce external and internal disorders, which can lower the post-harvest quality of fruit and by causing such symptoms as yellowing (chlorosis) in leafy vegetables, alterations in starch and sugars contents of fruits and in underground organs [54].
iv) Elevated levels of ozone can induce visual injury and physiological disorders in different species, as well as significant changes in dry matter, reducing sugars, citric and malic acid, among other important quality parameters [54].
v) Elevated atmospheric ozone can result in the decline of the photosynthetic rate, growth, biomass accumulation and

potential reduction in volatile ester emissions in strawberries [55].

Ornamental plants

i) Reductions of photosynthetic activity were observed in all the species; they were associated to stomatal closure and/or mesophyll limitations [56].
ii) Increased tropospheric ozone effects on photo physiological mechanism in urban ornamental plants [57].
iii) The exposure of the seedlings of *Pinus armandi* Franch to O_3 caused the reductions in dry weight, root dry weight relative to the whole plant dry weight, net photosynthetic rate, transpiration rate in light, water-use efficiency and root respiration activity, and increases in shoot/root ratio, and leaf dry weight [58].

Effects on forest tree

i) Vegetation exposure to ozone decreases photosynthesis, growth, and other plant functions [70].
ii) Reduced carbon sequestration of temperate forests [70].
iii) Noticeable injury symptoms like chlorophyll degradation, chlorotic molting and untimely ageing [67-68].
iv) It also effects physiology as well as photosynthesis and can quicken leaf ageing and foliar loss that effects the whole tree growth and productivity [67-68].
v) Ozone can raise forest susceptibility to drought, wind in addition with insect and pest attack (e.g., bark beetle, wood borer, fungal infection) [67], [69].
vi) It can reduce root: shoot ratio, leaf area, Rubisco and chlorophyll content, transpiration rates, tree height and stem diameter [67], [70-71].

Impacts on plant community and biodiversity

Several plant species are known to exhibit foliar injury to ambient O_3 exposure. Plants like white ash (*Fraxinus americana* L.), jack pine (*Pinus banksiana* Lamb.), big-leaf aster (*Aster macrophyllus* L.), and spreading dogbane (*Apocynum cannabinum* L.) have been found to be very sensitive. Similarly, widespread O_3 induced foliar injury was reported in native black cherry and tall milkweed (*Asclepias exaltata* L.). How these foliar responses translate to other issues such as competitive sustainability of a given species within the native plant communities are yet to be fully understood. Nevertheless, tests conducted to determine the effects of O_3 on the competitive relationships between native plants showed, that the rate of blackberry: broom-sedge (*Andropogon virginicus* L.) litter decomposition was reduced with increasing O_3 concentrations, with implications for altering nutrient cycling and biological diversity. Remarkable reductions in flowering and fruiting were observed when species fitness or reproductive capacity was used as a parameter for assessing biological diversity. Experimental O_3 exposures reduced growth and flowering of the butterfly bush (*Buddleja* spp.) [9]. Similarly, exposures to O_3 reduced flowers and fruits in spreading dogbane. Another very important finding was that foliar injury was not necessarily associated with negative effects on sexual reproduction and thus changes in biological diversity as reported by Sagar Krupa [19].

Effects of tropospheric ozone on microflora

Bacteria and microscopic algae and fungi, especially those living in a particular site or habitat are microflora. The effect of ozone gas is particularly noticeable on microflora also. They include mesophilic bacteria, lactic acid bacteria, coliforms, yeasts and moulds [72]. Changes in the ratio of fungal to bacterial biomass induced by plant's exposure to ozone effect on the biomass of fungi and bacteria have been reported in *Pinus ponderosa* Douglas ex C. Lawson [73]. A shift in the overall community structure of microbes in response to ozone has been found in beech trees (*Fagus sylvatica* L.) [74]. The quality of litter from *Fagus sylvatica* L. and *Picea abies* L. was changed due to elevated ozone, which influenced the structure of litter-colonizing microbial communities [75]. Several studies described effects on mycorrhizal abundance for tree species when exposed to ozone [76]. There are several studies on ozone-induced reduction in carbon allocation in fungal symbiont in a mycorrhizal association [77], impacting on mycorrhizal species composition in *Betula pendula* Roth [78] and *Fagus sylvatica* L. [79]. A three years experiment conducted in meadow soil, provided evidence that elevated ozone is able to modify the structure of the microbial community and decreased the biomass of bacteria and fungi [80]. Thus, it is clear that microbial communities are influenced due to elevated ozone in terms of both the dynamic of nutrient cycling processes and the community composition.

Ozone and disease incidence

Ozone is reported to influence the development of plant diseases. But the factors affecting the underlying processes are not well understood. O_3 is reported to decrease the incidence of diseases caused by obligate parasites, while increasing the problems associated with facultative parasites. However, Ozone is unlikely to have direct effects on fungal pathogens; rather, the effects are believed to be host plant mediated. Conversely, altered foliar responses to O_3 have been reported due to occurrence of diseases. Much of this knowledge is based on empirical field observations and experimental studies conducted in controlled environment, greenhouse, or field exposure chambers. There is no information on the combined effects of O_3 and disease on plant growth and yield under field conditions.

CONCLUSION

Ozone is a "criteria air pollutant." and is well known to have documented adverse effects on people, plants, or materials at high concentrations, or approaching those, found in polluted air. A number of experimental studies have been conducted on the effect of ozone on different type of vegetations. All types of vegetations have been found to be sensitive to elevated levels of atmospheric ozone, resulting in foliar injury, pigment loss, premature senescence, and decreased photosynthetic growth rates. Overall, it has been concluded that tropospheric ozone impacts on whole life system including the environment. However, researches on impacts of ozone have been mainly carried out on plants grown in controlled environments and field chambers and not in open fields. Thus, more researches on the impact of ozone pollution on plants in field grown conditions and on other living objects with long-term observations are necessary to understand the effects of ozone on biodiversity, ecosystems and environment fully.

LITERATURE CITED

1. Britannica T. 2021. *Encyclopedia Britannica*. https://www.britannica.com/biography/Christian-Friedrich-Schonbein
2. Langematz U. 2019. Stratospheric ozone: down and up through the anthropocene. *ChemTexts* 5(2): DOI:10.1007/s40828-019-0082-7.

3. Bhatia A, Tomer R, Kumar V, Singh SD, Pathak H. 2012. Impact of tropospheric ozone on crop growth and productivity–a review. *Journal of Scientific and Industrial Research* 71(2): 97-112.
4. Anonymous. 2016. Effect of ozone air pollution on plants. plant science research: https://www.ars.usda.gov/southeast-area/raleigh-nc/plant-science-research/docs/climate-changeair-quality-laboratory/ozone-effects-on-plants/.
5. Chen Z, Cao J, Yu H, Shang H. 2018. Effects of Elevated ozone levels on photosynthesis, biomass and non-structural, carbohydrates of phoebe Bournei and phoebe Zhennan in subtropical China. *Frontiers in Plant Science* 9: 1764. https://doi.org/10.3389/fpls.2018.01764
6. Grulke NE, Heath RL. 2019. Ozone effects on plants in natural ecosystems. *Plant Functioning in a Changing Global Atmosphere* 22(1): 12-37. https://doi.org/10.1111/plb.12971.
7. Kulikowski M. 2021. Elevated warming, ozone has detrimental effects on plant roots, promote soil carbon loss. *Science Daily*. www.sciencedaily.com/releases/2021/07/210709193531.htm
8. Bergmann E, Bender J, Weigel HJ. 2017. Impact of tropospheric ozone on terrestrial biodiversity: A literature analysis to identify ozone sensitive taxa. *Journal of Applied Botany and Food Quality* 90: 83-105. DOI:10.5073/JABFQ.2017.090.012.
9. Montenegro LJ, Fernandez LJ, Gimenez E. 2021. Worldwide research on the ozone influence in plants. *Agronomy*. Available online 11:1504. https://doi.org/10.3390/ agronomy11081504.
10. Davison AW, Barnes JD. 1998. Effects of ozone on wild plants. *New Phytology* 139: 135-151.
11. Maity D. 2015. Literature on ozone (2000-2015): A bibliometric analysis. *International Journal of Library and Information Science* 7(2): 71-79.
12. Finlayson-Pitts BJ, Pitts JN. 1999. Chemistry of the upper and lower atmosphere. E-Book ISBN: 9780080529073. Academic Press, New York.
13. McKee David J. 1994. *Tropospheric Ozone: Human Health and Agricultural Impacts*. Boca Raton: Lewis Publishers.
14. Vitale M, Salvatori E, Loreto F, Fares S, Manes F. 2008. Physiological responses of *Quercus ilex* leaves to water stress and acute ozone exposure under controlled conditions. *Water, Air, and Soil Pollution* 189(1): 113-125.
15. Altimira N, Touvinen J P, Vesala T, Kulmala M, Hari P. 2004. Measurements of ozone removal by Scots pine shoots: calibration of a stomatal uptake model including the non-stomatal component. *Atmospheric Environment* 38(15): 2387-2398.
16. Zhang L. 2002. On ozone dry deposition - With emphasis on non-stomatal uptake and wet canopies. *Atmospheric Environment* 36(30): 4787-4799.
17. Fares S, Goldstein A, Loreto F. 2010. Determinants of ozone fluxes and metrics for ozone risk assessment in plants. *Journal of Experimental Botany* 61(3): 629-633. https://doi.org/10.1093/jxb/erp336.
18. Anonymous. 2020. Ozone Effects on Plants - Air (U.S. National Park Service) (nps.gov), https://www.nps.gov/ subjects/air/nature-ozone.htm
19. Percy EK, Legge HA, Krupa VS. 2003. Troposphere ozone: a continuing threat to global forests? DOI:10.1016/S1474-8177(03)03004-3. pp 85-118.
20. Chappelka AH. 2002. Reproductive development of blackberry (*Rubus cuneifolius*), as influenced by ozone. *New Phytologist* 155: 249-255. https://doi.org/10.1046/j.1469-8137.2002.00464.x
21. Grulke NE, Miller PR. 1994. Changes in gas exchange characteristics during the life span of giant sequoia: implications for response to current and future concentrations of atmospheric ozone. *Tree Physiology* 7(9): 659-668.
22. Cooley DR, Manning WJ. 1987. The impact of ozone on assimilates partitioning in plants: a review. *Environmental Pollution* 47(2): 95-113.
23. Kim JS, Chappelka AH, Miller Goodman MS. 1998. Decomposition of blackberry and broom sedge bluestem as influenced by ozone. *Journal of Environmental Quality* 27(4): 953-960.
24. Bermejo V, Gimeno BS, Sanz J de la Torre, D Gil JM. 2003. Assessment of the ozone sensitivity of 22 native plant species from Mediterranean annual pastures 27based on visible injury. *Atmospheric Environment* 37(3): 4667-4677.
25. Heinlein J. 2013. Where the water meets the sky: The effects of atmospheric ozone pollution on aquatic algal and bacterial communities. Michigan State University.
26. Yun YS, Lim SR, Cho KK, Park JM. 1997. Variations of Photosynthetic activity and growth of fresh-water algae according to ozone contact time in ozone treatment. *Biotechnology Letters*19(9): 831-833. DOI10.1023/A:1018317132450.
27. Hoeger SJ, Dietrich DR, Hitzfeld BC. 2002. Effect of ozonation on the removal of cyanobacterial toxins during drinking water treatment. *Environmental Health Perspectives* 110(11): 1127-1132. https://doi.org/10.1289/ehp.021101127.
28. Paralkar A, Edzwald JK. 1996. Effect of ozone on EOM and coagulation. *American Water Works Association* 88(4): 143-154. https://doi.org/10.1002/j.1551-8833.1996.tb06540.x
29. Bertuzzi S, Davies L, Power SA, Tretiach M. 2013. Why lichens are bad bio monitors of ozone pollution? *Ecological Indicators* 34: 391-397. doi: 10.1016/j.ecolind.2013.05.023.
30. Avnery S, Mauzerall DL, Liu J , Horowitz LW. 2011. Global crop yield reductions due to surface ozone exposure: 1. Year 2000 crop production losses and economic damage. *Atmospheric Environment* 45(13): 2284-2296.
31. Canas MS, Pignata ML. 1998. Temporal variation of pigments and peroxidation products in the lichen *Parmotrema uruguense* (Kremplh.) Hale transplanted to urban and non-polluted environments. *Symbiosis* 24: 147-162.
32. Zambrano A, Nash III TH. 2000. Lichen responses to short-term transplantation in Desierto de los Leones, Mexico City. *Environmental Pollution* 107(3): 407-412. https://doi.org/10.1016/S0269-7491(99)00169-4.
33. Hur JS, Wellburn AR. 1994. Effects of atmospheric O_3 on Azolla-Anabaena symbiosis. *Annals of Botany* 73(2): 205-209. https://doi.org/10.1006/anbo.1994.1024
34. Rinnan R, Holopainen T. 2004. Ozone effects on the ultrastructure of peatland plants: *Sphagnum* mosses, *Vaccinium oxycoccus*, *Andromeda polifolia* and *Eriophorum vaginatum*. *Annals of Botany* 94(4): 623-634.
35. Muntifering R, McGrath M, Burkey K. 2009. The ozone component of global change: Potential effects on agricultural and horticultural plant yield, product quality and interactions with invasive species. *Journal of Integrative Plant Biology* 51(4): 337-351. https://doi.org/10.1111/j.1744-7909.2008.00805.x

36. Heagle AS, Miller JE, Chevone BI, Dreschel TW, Manning WJ, McCool PM, Rebbeck J. 1995. Response of a white clover indicator system to tropospheric ozone at eight locations in the United States. *Water, Air, and Soil Pollution* 85(3): 1373-1378.
37. Feng Z, Kobayashi K, Ainsworth EA. 2008. Impact of elevated ozone concentration on growth, physiology and yield of wheat (*Triticum aestivum* L.): a meta-analysis. *Global Change Biology* 14(11): 2696-2708.
38. Synder RG, Simon JE, Reinert RA, Simini M, Wilcox GE. 1991. Effects of air quality on growth, yield and quality of watermelon. *Hort Science* 26(8): 1045-1047.
39. Krupa SV, Nosal M. 1989. Application of spectral coherence analysis to describe the relationships between ozone exposure and crop growth. *Environmental Pollution* 60: 319-330.
40. Benton J, Fuhrer J, MBS, Skarby L, Palmer-Brown D, Ball G. 2000. An international cooperative programme indicates the widespread occurrence of ozone injury on crops. *Agriculture Ecosystem and Environment* 78: 19-30.
41. Morgan PB, Ainsworth EA, Long SP. 2003. How does elevated ozone impact soybean? A meta-analysis of photosynthesis, growth and yield. *Plant, Cell and Environment* 26(8): 1317-1328.
42. Kobayashi K, Okada M, Nouchi I. 1995. Effects of ozone on dry matter partitioning and yield of Japanese cultivars of rice (*Oryza sativa* L.). *Agriculture, Ecosystem and Environment* 53(2): 109-122.
43. Frei M, Kohno Y, Tietze S. 2012. The response of rice grain quality to ozone exposure during growth depends on ozone level and genotype. *Environmental Pollution* 163: 199-206
44. Ekmekci Y, Terzioglu S. 2005. Effects of oxidative stress induced by paraquat on wild and cultivated wheats. *Pesticide Biochemistry and Physiology* 83: 69-81.
45. Wootton M, Voraputhaporn W. 1997. Effect of ozone on chemical and functional properties of wheat flour. *In*: *Thailand International Temperate Cereals Conference 1997: Production and Utilization,* Chiang Mai (Thailand). pp 11-13.
46. Sah DN, Tiedemann AV, Fehrmann H. 1993. Effects of ozone exposure on resistance of wheat genotypes to *Pyrenophora tritici-repentis*. *Journal of Phytopathology* 138(3): 249-256.
47. Goze P, Rhazi L, Lakhal L, Jacolot P, Pauss A, Aussenac T. 2017. Effects of ozone treatment on the molecular properties of wheat grain proteins. *Journal of Cereal Science* 75: 243-251.
48. Broberg MC, Feng Z, Xin Y, Pleijel H. 2015. Ozone effects on wheat grain quality–A summary. *Environmental Pollution* 197: 203-213.
49. Feng Z, Kobayashi K, Ainsworth EA. 2008. Impact of elevated ozone concentration on growth, physiology and yield of wheat (*Triticum aestivum* L.): a meta-analysis. *Global Change Biology* 14(11): 2696-2708.
50. Sarkar A, Singh AA, Agrawal SB, Ahmad A, Rai SP. 2015. Cultivar specific variations in antioxidative defense system, genome and proteome of two tropical rice cultivars against ambient and elevated ozone. *Ecotoxicology and Environmental Safety* 115: 101-111.
51. Jing L, Dombinov V, Shen S, Wu Y, Yang L, Wang Y, Frei M. 2016. Physiological and genotype-specific factors associated with grain quality changes in rice exposed to high ozone. *Environmental Pollution* 210: 397-408. https://doi.org/10.1016/j.envpol.2016.01.023.
52. Fan L, Forney CF, Jordan MA, Hildebrand PD, Kalt W, Ryan DAJ, Song J. 2001. Effect of ozone treatment and controlled atmosphere storage on quality and phytochemicals in highbush blueberries. *In*: *VIII International Controlled Atmosphere Research Conference* 600: 417-423.
53. Vorne V, Ojanpera K, De Temmerman L, Bindi M, Hogy P, Jones MB, Persson K. 2002. Effects of elevated carbon dioxide and ozone on potato tuber quality in the European multiple-site experiment 'CHIP-project'. *European Journal of Agronomy* 17(4): 369-381.
54. Moretti CL, Mattos LM, Calbo AG, Sargent SA. 2010. Climate changes and potential impacts on postharvest quality of fruit and vegetable crops: A review. *Food Research International* 43(7): 1824-1832.
55. Mattos LM, Moretti CL, Jan S, Sargent SA, Lima CEP, Fontenelle MR. 2014. Climate changes and potential impacts on quality of fruit and vegetable crops. *In*: *Emerging Technologies and Management of Crop Stress Tolerance*. Academic Press. pp 467-486.
56. Lorenzini G, Nali C, Ligasacchi G, Ambrogi R. 1997. Effects of ozone on photosynthesis of Mediterranean urban ornamental plants. *In*: *International Symposium on Urban Tree Health* 496: 335-338.
57. Yang N, Wang X, Cotrozzi L, Chen Y, Zheng F. 2016. Ozone effects on photosynthesis of ornamental species suitable for urban green spaces of China. *Urban Forestry and Urban Greening* 20: 437-447.
58. Shan Y, Feng Z, Izuta T, Aoki M, Totsuka T. 1996. The individual and combined effects of ozone and simulated acid rain on growth, gas exchange rate and water-use efficiency of *Pinus armandi* Franch. *Environmental Pollution* 91(3): 355-361.
59. Lu X, Zhang L, Shen L. 2021. Tropospheric ozone interacts with weather and climate. *Air Pollution, Climate and Health* 15-46.
60. Lu X, Zhang L, Shen L. 2019. Meteorology and climate influences on tropospheric ozone: a review of natural sources, chemistry, and transport patterns. *Current Pollution Reports* 5(4): 238-260.
61. Tropospheric ozone. https://www.ccacoalition.org/en/slcps/tropospheric-ozone.
62. Ren W, Tian HQ. 2007. Effects of ozone pollution on terrestrial ecosystem productivity. *Chinese Journal of Plant Ecology* 31(2): 219.
63. Ren W, Tian H, Liu M, Zhang C, Chen G, Pan S, Xu X. 2007. Effects of tropospheric ozone pollution on net primary productivity and carbon storage in terrestrial ecosystems of China. *Journal of Geophysical Research: Atmospheres* 112(D22).
64. Weigel HJ, Bergmann E, Bender J. 2015. Plant-mediated ecosystem effects of tropospheric ozone. *In*: *Progress in Botany* 395-438.
65. Simpson D, Arneth A, Mills G, Solberg S, Uddling J. 2014. Ozone—the persistent menace: interactions with the N cycle and climate change. *Current Opinion in Environmental Sustainability* 9: 9-19.

66. Felzera BS, Cronin T, Reilly JM, Melillo JM, Wang X. 2007. Impacts of ozone on trees and crops Impacts de l'ozone sur les arbres et les récoltes *Comptes Rendus Geoscience* 339: 784-798.
67. Emberson L. 2020. Effects of ozone on agriculture, forests and grasslands. *Philosophical Transactions of the Royal Society* A. https://doi.org/10.1098/rsta.2019.0327
68. Percy KE, Nosal M, Heilman W, Dann T, Sober J, Legge AH, Karnosky DF. 2007. New exposure-based metric approach for evaluating O_3 risk to North American aspen forests. *Environmental Pollution* 147: 554-566
69. Sun G, McLaughlin SB, Porter JH, Uddling J, Mulholland PJ, Adams MB, Pederson N. 2012. Interactive influences of ozone and climate on streamflow of forested watersheds. Global Change Biology 18 (11): 3395-3409.
70. Karnosky DF, Skelly JM, Percy KE, Chappelka AH. 2007. Perspectives regarding 50 years of research on effects of tropospheric ozone air pollution on US forests. *Environmental Pollution* 147: 489-506. doi: 10.1016/j.envpol.2006.08.043.
71. Proietti C, Anav A, De Marco A, Sicard P, Vitale M. 2016. A multi-sites analysis on the ozone effects on Gross Primary Production of European forests. *Science of the Total Environment* 556: 1-11.
72. Akhtar T, Rahman MR, Biswas S, Perveen R, Alam, MS, Khanum FA, Manirujjaman M. 2016. Identification of microbial contamination of popular fruits of Bangladesh and assessment the effects of alternative preservatives instead of formalin. *American Journal of Microbiological Research* 4(5): 138-142.
73. Olszyk DM, Johnson MG, Phillips DL, Seidler RJ, Tingey DT, Watrud LS. 2001. Interactive effects of CO_2 and O_3 on a ponderosa pine plant/litter/soil mesocosm. *Environmental Pollution* 115(3): 447-462.
74. Esperschutz J, Pritsch K, Gattinger A, Welzl G, Haesler F, Buegger F, Schloter M. 2009. Influence of chronic ozone stress on carbon translocation pattern into rhizosphere microbial communities of beech trees (*Fagus sylvatica* L.) during a growing season. *Plant and Soil* 323(1): 85-95.
75. Alexou M, Hofer N, Liu X, Rennenberg H, Haberer K. 2007. Significance of ozone exposure for inter-annual differences in primary metabolites of old-growth beech (*Fagus sylvatica* L.) and Norway spruce (*Picea abies* L.) trees in a mixed forest stand. *Plant Biology* 9(2): 227-241.
76. Andersen CP. 2003. Source–sink balance and carbon allocation below ground in plants exposed to ozone. *New Phytologist* 157(2): 213-228.
77. Andersen CP, Rygiewicz PT. 1995. Allocation of carbon in mycorrhizal Pinus ponderosa seedlings exposed to ozone. *New Phytologist* 131(4): 471-480.
78. Kasurinen A, Biasi C, Holopainen T, Rousi M, Maenpaa M, Oksanen E. 2012. Interactive effects of elevated ozone and temperature on carbon allocation of silver birch (*Betula pendula*) genotypes in an open-air field exposure. *Tree Physiology* 32(6): 737-751.
79. Matyssek R, Wieser G, Ceulemans R, Rennenberg H, Pretzsch H, Haberer K, Haberle KH. 2010. Enhanced ozone strongly reduces carbon sink strength of adult beech (*Fagus sylvatica*)–Resume from the free-air fumigation study at Kranzberg Forest. *Environmental Pollution* 158(8): 2527-2532.
80. Kanerva T, Palojärvi A, Ramo K, Manninen S. 2008. Changes in soil microbial community structure under elevated tropospheric O_3 and CO_2. *Soil Biology and Biochemistry* 40(10): 2502-2510.
81. Masters GM. 2006. Introduction to Environmental engineering and Science. Second edition.
82. Krupa SV. 1997. *Air pollution, people, and plants: An introduction* (No. 04; QH545. A3, K7.). St. Paul, Minnesota, USA: APS Press.
83. Ramanathan VCPJ, Crutzen PJ, Kiehl JT, Rosenfeld D. 2001. Aerosols, climate, and the hydrological cycle. *Science* 294(5549): 2119-2124