Effect of Elevated CO₂, O₃, and UV Radiation on Soils

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In this work, we have attempted to review the current knowledge on the impact of elevated CO₂, O₃, and UV on soils. Elevated CO₂ increases labile and stable soil C pool as well as efficiency of organic pollutants rhizoremediation and phytoextraction of heavy metals. Conversely, both elevated O₃ and UV radiation decrease inputs of assimilates to the rhizosphere being accompanied by inhibitory effects on decomposition processes, rhizoremediation, and heavy metals phytoextraction efficiency. Contrary to elevated CO₂, O₃, or UV-B decreases soil microbial biomass, metabolisable C, and soil N content leading to higher C/N of soil organic matter. Elevated UV-B radiation shifts soil microbial community and decreases populations of soil meso- and macrofauna via direct effect rather than by induced changes of litter quality and root exudation as in case of elevated CO₂ or O₃. CO₂ enrichment or increased UV-B is hypothesised to stimulate or inhibit both plant and microbial competitiveness for soluble soil N, respectively, whereas O₃ favours only microbial competitive efficiency. Understanding the consequences of elevated CO₂, O₃, and UV radiation for soils, especially those related to fertility, phytotoxins inputs, elements cycling, plant-microbe interactions, and decontamination of polluted sites, presents a knowledge gap for future research.

1. Introduction

Carbon dioxide, ozone, and ultraviolet radiation are individual climate change factors that have direct biological effects on plant coverage. Elevated CO₂ causes up- and downregulation of genes of primary plant metabolism and N₂ fixation; elevated O₃ significantly diminishes the carbon sink of soil-plant systems [1, 2]. Both rising CO₂ and surface O₃ impact upon plant growth, response of crops to pests and herbivores, and the ability of plants to support decontamination of polluted sites [1]. Decrease in stratospheric O₃ is accompanied by increasing UV radiation of which most attention has been given to UV-B. Elevated UV-B reduces crop yields and tree biomass, plant respiration potential, gas exchange, leaf area, and water-use efficiency and increases the content of amino acids, hormones, and flavonoids [3].

While replacement of current solvents by oxygenates decreases O₃ pollution [4], forest fires increase O₃ concentrations in some countries [5]. Calafipietra et al. [6] also reported formation of O₃ from volatile organic compounds (especially isoprenoids) released from vegetation, which react in the atmosphere with NO₃ to produce O₃ under UV radiation. Many reviews focused on the effects of elevated CO₂, O₃, and UV-B radiation on plant biomass, ecosystems, and human health (e.g., [1, 7]). Nevertheless, only little work has focused upon understanding the consequences for soils. In this paper, we present a review of the current knowledge on the impact of elevated CO₂, O₃, and UV on soils and identify new hypotheses for future research.

2. Effect of Elevated UV Radiation on Soils

2.1. Direct Effect of UV Radiation on Soil Microorganisms

Pigment content, cell oxygen yield, growth, C assimilation, and PSII of cyanobacteria change with increasing UV-B [8]; besides, UV-B also induces synthesis of mycosporine-like amino acids [9]. Soil surface bacteria are more resistant to UV than subsurface bacteria [4]. Nonmotile Gram-positive bacteria isolated from Antarctic soils are tolerant to UV radiation due to synthesis of protective melanins [10]. Also, compost-born thermophilic methanogenic Archaea were proved to be resistant to UV-B, probably due to their attachment to compost material acting as an effective carrier [11]. Growth...
of lichens is not affected by UV-B due to increased phenolics content [12].

Direct effects of UV on soils occur through a shift of the fungal community with an increase in competitive abilities of darkly pigmented fungi [13]. Only some of the soil and phylloplane fungal species are sensitive to UV-B [14]. For example, the entomopathogenic fungus *Tolypocladium* sp. is UV-B tolerant [15]. Peatland amoebae are more abundant in ambient than reduced UV-B and diversity of some species increases under ambient UV-B [16].

2.2. Direct Effect of UV Radiation on Soil Meso- and Macrofauna. UV-B pretreatment decreases rotifers, nematodes and mites population size and increases generation time in soils polluted with heavy metals due to reproductive defects; nevertheless, it protects *Caenorhabditis elegans* from disturbed locomotion [16, 17]. Experiments showed that a large increase in nematode density in Antarctic soils (especially microbivorous genus *Plectus*) resulted from blocking UV with a UV-absorbing perspex cloth [18]. No effect of UV-B on the mass of earthworms feeding on litter was found, and some of the species benefited from UV-B [19]. Low mortality of spider mites due to UV-A, UV-B, and UV-C was reported by Suzuki et al. [20], while inactivation of *Ascaris* eggs was significant only in water [21].

2.3. Release/Degradation of Soil Pollutants by UV Radiation. Elevated UV-B (but not UV-A) directly reduces soil-associated Hg through significant increase of Hg emissions from forest soils [22]. UV-B is also known to increase degradation of pollutants (phenylurea herbicides, *p,p''-DDT*, 2,4-dichlorophenoxyacetic acid, biphenol, Z or PAHs), while PAHs degradation on soil surfaces, in the presence of nanometer anatase TiO$_2$, follows pseudo-first-order kinetics [23]. UV photolysis has been suggested as a suitable treatment for extracts of PAHs contaminated soils, where up to 83% removal was achieved [24].

2.4. Measured Effects of UV-B Radiation on Soils. Elevated UV-B does not substantially influence initial chemical composition of leaf litter [25] and has only little effect on total carbon (C$_t$) and nitrogen (N$_t$) in soils; on average they decrease by 2 and 9%, respectively (Figure 1). On the other hand, elevated UV-B decreases NH$_4^+$-N and NO$_3^-$-N by 46 and 14%, respectively (Figure 3), and reduced UV-B (compared to ambient value) decreases dissolved organic carbon (DOC) and phosphorus content in 0–10 mm of peatland in course of vegetation [16]. Pretreatment of air-dried litter with UV followed by rewetting did not change decomposition rate [26], whereas some researchers found inhibitory effect of UV-B on soil organic matter (SOM) decomposition (reduced by 32% on average) with no effect on Q$_{10}$ (Figure 2). Lower effect later in the season occurs due to increasing crop coverage reducing soil sterilization [27]. Also, N$_2$O fluxes in soils are reduced by elevated UV-B by ca. 22% with no change of diurnal variation patterns (Figure 2). Elevated UV-B equivalent to 15% O$_3$ depletion decreases N$_2$ fixation in tropical leguminous crops due to reduced photosynthesis and nodulation including nitrogenase activity; nevertheless, the molecular basis of this phenomenon is not known yet [28]. Altered gene activity due to elevated UV-B was found to enhance rice allelopathic potential (inhibition and stress of neighbouring plants especially at high density in native environment) including autotoxicity via phytotoxins of root exudates and leaf leachates [29] of which identification presents a knowledge gap for future research.
2.5. Hypotheses on Indirect Effects of UV Radiation on Soils. Plant coverage ameliorates the impact of elevated UV-B on soil microorganisms; nevertheless, indirect effects via altered quality and reduced quantity of plant biomass are hypothesised to inhibit SOM decomposition and heavy metals bioremediation. These include especially accumulation of phenolics, salicylic acid, tannins, cinnamic acid, and flavonoids [3]. Phenolics are involved in stabilization of aggregates and some of them (e.g., gallic acid) decrease cation exchange capacity (CEC) of soils; on the other hand, hydrolysable tannins (e.g., \( \beta \)-1,2,3,4,6-penta-O-galloyl-D-glucose) increase the CEC [42]. Phenolics and flavonoids are inhibitors of decomposition processes including enzymatic activities (sulfatase, phosphatase, \( \beta \)-glucosidase, xylosidase, chitinase, and dehydrogenase) and are also involved in stabilization of xenobiotics and Fe complexation representing a potential constraint in wetland-based acid mine drainage bioremediation, due to low Fe availability (e.g., [43, 44]). Phenolics are also known to support growth of PCB-degrading bacteria [45].

3. Effect of Elevated \( \text{CO}_2 \) on Soils

3.1. Alteration of Soil Properties due to Elevated \( \text{CO}_2 \). Elevated \( \text{CO}_2 \) delays soil water depletion due to partial plant stomatal closure and alters solarization efficiency and heat fluxes [46, 47]. Furthermore, dilution of plant biomass by carbohydrates and increased plant-derived C inputs including rhizodeposition are hypothesised to increase \( C_i \) with no effect on \( N_i \) and reduction of mineral nitrogen content in soils [48]. Nevertheless, recalculation of data from a range of studies showed negligible effect of elevated \( \text{CO}_2 \) on soil \( C_i \) and \( N_i \) (Figure 1). Effect of elevated \( \text{CO}_2 \) on soil \( C_i \) and \( N_i \) is ecosystem- and type of plants-dependent being increased only in sweetgum or cotton plantations, deserts, \( \text{Agrostis capillaris} \) cover, or seminatural grasslands (Table 1). It may also be affected by the initial soil properties, the type of experiment (laboratory versus field), occurrence of \( N_2 \)-fixing species, and the plant C allocation pattern being affected by plant genotypic variation [34]. For example, the effect of elevated \( \text{CO}_2 \) on soils may be diminished in base-rich sites [49]. Contrary to cultivated plants, wild genotypes allocate more C into roots resulting in greater rhizodeposition under elevated \( \text{CO}_2 \) [34, 48].

Proportion of labile to recalcitrant C fraction changes in response to elevated \( \text{CO}_2 \) via increased transfer of C into slow-decay C pool and reduces decay of old C; some works describe rhizodeposition-induced decomposition of stable soil C; quality and quantity of the labile C are altered by increased plant litter and root exudation [34, 35]. Elevated \( \text{CO}_2 \) increases decomposition of metabolisable C only in topsoils with opposite effect in subsoils and no effect on amides degradation [34]. Root biomass and volume of rhizospheric soil including mycorrhizal symbiosis of trees in boreal and temperate zones increase due to elevated \( \text{CO}_2 \) [34, 48]. In some ecosystems (peatlands), growth of root biomass of low decomposability is induced by elevated \( \text{CO}_2 \), and in some cases, decomposition of fine roots is faster [50]. Concentrations of both mineral nitrogen forms (\( \text{NH}_4^+ \)-N and \( \text{NO}_3^- \)-N) in soils are significantly reduced (by >50\% on average) by elevated \( \text{CO}_2 \) (Figure 3), probably due to N dilution in foliage and increased plant-microbes competition for N sources [48]. Furthermore, elevated \( \text{CO}_2 \) may alter the chemistry of groundwater (Ca\(^{2+}\), trace metals and other types of cations and anions) [48] and its effect on bulk density or pH of soil is low (Table 1).

3.2. Elevated \( \text{CO}_2 \) versus Soil Microbial Community and Activity of Enzymes. Elevated \( \text{CO}_2 \) (including transient elevation) changes the structure and physiology of soil microbial community in favour of bacteria due to lower soil nitrogen inputs which are accompanied by reduction of the abundance of taxonomic units within the \textit{Firmicutes} as well as the populations of Gram-positive bacteria in rhizosphere soils [54, 55]. Allocation of \( C \) to soil microorganisms usually depends on the type of ecosystem [34, 56] and is often accompanied by increased \( \text{C}_{\text{MIC}}/C_i \) ratio. An increase of soil microbial N (\( N_{\text{MIC}} \)) as a posttreatment response to elevated \( \text{CO}_2 \) in N-limited ecosystems was found probably due to lower nutrient (nitrogen) competition between microorganisms and plants [57]. Soil respiration increased by 7\% on average due to elevated \( \text{CO}_2 \) (Figure 2) compared to ambient control without change of substrate use efficiency [35] and \( \text{N}_2\text{O} \) fluxes were only slightly changed (1.5\% decrease) (Figure 2). Numbers of archaeal and bacterial 16S rRNA and genes encoding key enzymes of ammonia-oxidation (\textit{amoA}), denitrification (\textit{ nirK, nirS, } and \textit{ nosZ}), and genes of nitrate-reducing bacteria (\textit{narG, napA}) are increased or reduced (or not affected) in the rhizosphere by elevated \( \text{CO}_2 \) depending on inputs of fertilizers (N), soil depth and moisture, type of plant metabolism (\( C_i \) versus \( C_4 \)), time of sampling during
3.3. Effect of Elevated CO\textsubscript{2} on Soil Meso- and Macrofauna. Elevated CO\textsubscript{2} suppresses the role of fauna in litter decomposition due to its dilution by carbohydrates and the effect is ecosystem-dependent being significant especially in tropical forests [60, 61]. Elevated CO\textsubscript{2} modifies the pattern (abundance and diversity) of nematode communities (especially groups of omnivores, saprophagous feeders, and predators), earthworms and enchytraeids, oribatid mites, microarthropods, collemboles, and omnivorous insects as well as the proportion of edaphic groups via changes of plant biomass quality and moisture [61]. Elevated CO\textsubscript{2} has generally been found to have negative impacts on the performance of insect herbivores whose larvae reach smaller size when feeding on elevated CO\textsubscript{2}-grown plants [61]. The hypothesised negative impact of elevated CO\textsubscript{2} on omnivorous bugs via lowering the quality of plants and prey was not proved; on the contrary, the predators may benefit from elevated CO\textsubscript{2} through increased vulnerability of their prey [60, 61].

4. Effect of Ozone on Soils

4.1. Alteration of Soil Properties due to Elevated O\textsubscript{3}. Effect of elevated O\textsubscript{3} on soils is poorly understood. O\textsubscript{3} deposition to soil has been expressed by parameters such as aerodynamic resistance (\(R_{a}\)), quasi-laminar boundary layer resistance (\(R_{bO3}\)), and soil resistance (\(R_{wSoil}\)) being a function of soil water content with daily variations [62]. Ozonation of humic acids or their components (p-hydroxybenzaldehyde, vanillin, syringaldehyde, vanillic acid, and di-n-butylphthalate) leads to formation of mutagenic compounds and O\textsubscript{3} also induces amino acid racemization [63].

Contrary to elevated UV-B or CO\textsubscript{2} which cause N dilution and increased phenolics in plant biomass, elevated O\textsubscript{3} modifies plant biomass via decrease in both N and phenolics [36, 64]. Elevated O\textsubscript{3} increases C\textsubscript{4} and reduces N\textsubscript{t} by 4 and 10%, respectively (Figure 1); NH\textsubscript{4}\textsuperscript{+}-N and NO\textsubscript{3}\textsuperscript{-}-N are also reduced by 17 and 10%, respectively (Figure 3), including humic acids fraction, C\textsubscript{mic}, and pH of soils in different ecosystems (black cherry, milkweed, spring wheat, and beech) [19]. Soil respiration is decreased (by 15% on average) (Figure 2) under O\textsubscript{3} enrichment; the same was found in case of methane emissions from soils of different ecosystems (e.g., temperate lowland peat bog and rice soils) which are reduced by about 25% [65]. On the other hand,
N₂O fluxes are enhanced (by 7% on average) under O₃ enrichment (Figure 2) as it reacts with N₂O emitted from fertilized soils [37]. Elevated O₃ increases Ca²⁺, Mg²⁺, and Mn²⁺ in soil solution and stimulates export of NO₃⁻ from forest sites [19].

4.2. Alteration of Soil Microbial Communities and Fauna by Elevated O₃. Elevated O₃ alters soil microflora structure and physiology with a negative impact on numbers of bacteria and fungi, glutathione content of protozoa, and His⁺ reversion of some bacteria [30]. Especially the numbers of functional microbial genes are lower under O₃ treatment in dependence on plant coverage development and N fertilizers inputs with no effect on amoA and nosZ genes abundance [66]. Increased terpene inputs (especially α- and β-pinene or 3-carene) as a consequence of elevated O₃ are hypothesized to alter soil microbial community, especially via stimulation of bacteria and inhibition of fungi [67]. Roots of forest trees are also a significant source of monoterpenes in soil and over 75% of ectomycorrhizal fungi or 25% of isolated saprotrophic fungi were inhibited by one of the monoterpenes, affecting the structure of the fungal community [67]. On the other hand, monoterpenes supplied to soil increase degradation of polychlorinated biphenyls (PCB), even without increasing the bacterial biomass [68]. Elevated O₃ strongly decreases the abundance rather than genera richness of soil collemobolans compared with ambient atmospheric O₃, probably due to decreased allocation of carbohydrates to roots. However, in the Bt cotton fields, elevated O₃ did not significantly affect the abundance or diversity of soil collemobola suggesting that Bt cotton can buffer the effect of elevated O₃ on soil collemobolans via root-derived ways [69]. Contrary to elevated CO₂ and UV radiation, elevated O₃ is hypothesized not to increase phytotoxicity of soils through inputs of plant phenolics [36]; nevertheless, a direct effect via racemization of low-molecular-weight organic compounds (amino acids) is hypothesized [63].

5. Hypotheses on the Effect of Elevated CO₂, O₃ and UV Radiation on Plant-Microbe Competition for N Sources

Plant communities, especially at low productivity sites with acid soils, are more adapted to organic N uptake; nevertheless, higher proportion of both soil organic as well as mineral N is captured by microorganisms rather than by plants [48]. Management practices including grasslands mowing or grazing or forest stands thinning are thought to reduce plant-microbe competition for N sources, since N-cycling and mineralization rates are increased and are accompanied by lower organic N availability and no effect on kinetics of organic N uptake by microorganisms [48].

O₃ enrichment shifts the N-balance in favour of plants over soil microorganisms, being significant especially in ecosystems with low productivity (grasslands, mountain forests, and tundra communities) where organic N forms the dominant pool [48]. Alterations in plant-microbe competition for N sources may be facilitated by natural fungicides (phenolics) which is hypothesized to be significant in case of elevated CO₂ and UV, but not O₃ [64]. In this case, dominance of the bacterial fraction of the soil microbial community favours microbial competitiveness over plant roots; however, this advantage may be eliminated by fertilization [48]. Also, it is hypothesized that the maximum N acquisition by plants is regulated by intermediate concentrations of phenolics [64]. Elevated O₃ reduces ascorbic acid in plant biomass; its degradation in soils may act to produce an effective sporocide, which plays a role in mitigation of salinity effects on plant growth [70]. Competition between microbes and plants for N sources is regulated by rhizodeposition in terms of exudation rates and qualitative composition of the exudates, both being altered by elevated UV-B, CO₂, and O₃ [48]. Nitrifiers are strong competitors for NH₄⁺ on fertile sites where competition may be reduced due to increased tannins under elevated UV-B or CO₂ [48].

6. Conclusions

Overall, study of the consequences of elevated CO₂, O₃, and UV radiation for soils is significant due to increasing CO₂ concentrations worldwide and also because there is clear evidence that stratospheric O₃ is being depleted which causes increased ground UV radiation. On the other hand, change of air quality due to emissions of hydrocarbons and exhaust gases leads to increasing tropospheric O₃ production. Contrary to elevated CO₂, O₃, or UV-B decreases Cmic, metabolisable C, and soil N₂ content leading to higher C/N of soil organic matter. Mechanism of the CO₂ or O₃ enrichment effects on soils including elevated UV-B radiation differs considerably. Elevated O₃ or UV-B decreases inputs of assimilates to the rhizosphere and has an inhibitory effect on decomposition processes and rhizoremediation of organic pollutants. UV-B shifts soil microbial community and decreases populations of soil meso- and macrofauna directly rather than via induced changes of litter quality and root exudation as in case of elevated CO₂ or O₃. Worldwide increasing CO₂ concentrations stimulate rhizoremediation of organic pollutants due to higher root biomass and volume of rhizospheric soil as well as phytoextraction of heavy metals (contrary to elevated O₃ or UV-B) as a result of increased mycorrhizal colonization and plant biomass. Enhanced C inputs and root mycorrhizal colonization as a consequence of elevated CO₂ are hypothesized to stimulate both microbial and plant N acquisition. UV-B is hypothesized to reduce both plant and microbial competitiveness for soluble soil N whereas O₃ enrichment favours microbial competitive efficiency. Since the effects of elevated CO₂, O₃, and UV radiation on soils are only little understood, it is essential to conduct further studies to understand their consequences for soil fertility, elements cycling, and decontamination of polluted sites.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.
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References

[1] H. Fukayama, M. Sugino, T. Fukuda et al., “Gene expression profiling of rice grown in free air CO₂ enrichment (FACE) and elevated soil temperature,” Field Crops Research, vol. 121, no. 1, pp. 195–199, 2011.

[2] W. J. Manning and A. Tiedemann v., “Climate change: potential effects of increased atmospheric carbon dioxide (CO₂), ozone (O₃), and ultraviolet-B (UV-B) radiation on plant diseases,” Environmental Pollution, vol. 88, no. 2, pp. 219–245, 1995.

[3] B. Harbaum-Piayda, B. Walter, G. B. Bengtsson, E. M. Hubermann, W. Bilger, and K. Schwarz, “Influence of pre-harvest UV-B irradiation and normal or controlled atmosphere storage on flavonoid and hydroxyorganic acid content of pak choi (Brassica campestris L. ssp. chinensis var. commutis),” Postharvest Biology and Technology, vol. 56, no. 3, pp. 202–208, 2010.

[4] A. A. Arrage, T. J. Phelps, R. E. Benoit, A. V. Palumbo, and D. C. White, “Bacterial sensitivity to UV light as a model for ionizing radiation resistance,” Journal of Microbiological Methods, vol. 18, no. 2, pp. 127–136, 1993.

[5] A. Carvalho, A. Monteiro, M. Flannigan, S. Solman, A. I. Miranda, and C. Borrego, “Forest fires in a changing climate and their impacts on air quality,” Atmospheric Environment, vol. 45, no. 31, pp. 5545–5553, 2011.

[6] C. Callafani, S. Fares, and F. Loreto, “Volatile organic compounds from Italian vegetation and their interaction with ozone,” Environmental Pollution, vol. 157, no. 5, pp. 1478–1486, 2009.

[7] N. D. Paul and D. Gwynn-Jones, “Ecological roles of solar UV radiation: towards an integrated approach,” Trends in Ecology and Evolution, vol. 18, no. 1, pp. 48–55, 2003.

[8] M. Zeeshan and S. M. Prasad, “Differential response of growth, photosynthesis, antioxidant enzymes and lipid peroxidation to UV-B radiation in three cyanobacteria,” South African Journal of Botany, vol. 75, no. 3, pp. 466–474, 2009.

[9] R. P. Sinha, M. Klisch, and D. Häder, “Induction of a mycosporine-like amino acid (MAA) in the rice-field cyanobacterium Anabaena sp. by UV irradiation,” Journal of Photochemistry and Photobiology B, vol. 52, no. 1–3, pp. 59–64, 1999.

[10] S. Bhattacharyya, B. Nayak, and N. K. Choudhury, “Response of diatocystrophic cyanobacterium Nostoc carneum under pesticide and UV-B stress,” Chemosphere, vol. 84, no. 1, pp. 131–135, 2011.

[11] K. Thummes, J. Schäfer, P. Kämpfer, and U. Jäckel, “Thermophilic methanogenic Archaea in compost material: occurrence, persistence and possible mechanisms for their distribution to other environments,” Systematic and Applied Microbiology, vol. 30, no. 8, pp. 634–643, 2007.

[12] J. W. Bjerke, D. Gwynn-Jones, and T. V. Callaghan, “Effects of enhanced UV-B radiation in the field on the concentration of phenolics and chlorophyll fluorescence in two boreal and arctic-alpine lichens,” Environmental and Experimental Botany, vol. 53, no. 2, pp. 139–149, 2005.

[13] K. J. Duguay and J. N. Klironomos, “Direct and indirect effects of enhanced UV-B radiation on the decomposing and competitive abilities of saprobiic fungi,” Applied Soil Ecology, vol. 14, no. 2, pp. 157–164, 2000.

[14] S. A. Moody, K. K. Newsham, P. G. Ayres, and N. D. Paul, “Variation in the responses of litter and phylloplane fungi to UV-B radiation (290–315 nm),” Mycological Research, vol. 103, no. 11, pp. 1469–1477, 1999.

[15] M. P. Santos, L. P. Dias, P. C. Ferreira, L. A. A. P. Pasin, and D. E. N. Rangel, “Cold activity and tolerance of the entomopathogenic fungus Tolypocladium spp. to UV-B irradiation and heat,” Journal of Invertebrate Pathology, vol. 108, no. 3, pp. 209–213, 2011.

[16] T. M. Robson, V. A. Pancotto, A. L. Scopel, S. D. Flint, and M. C. Caldwell, “Solar UV-B influences microfaunal community composition in a Tierra del Fuego peatland,” Soil Biology and Biochemistry, vol. 37, no. 12, pp. 2205–2215, 2005.

[17] G. Wang, Z. Hao, R. H. Anken, J. Lu, and Y. Liu, “Effects of UV-B radiation on photosynthesis activity of Wolffia arrhiza as proved by chlorophyll fluorescence transients,” Advances in Space Research, vol. 45, no. 7, pp. 839–845, 2010.

[18] P. Convey and D. D. Wynn-Williams, “Antarctic soil nematode response to artificial climate amelioration,” European Journal of Soil Biology, vol. 38, no. 3–4, pp. 255–259, 2002.

[19] L. Steubing, A. Fangmeier, R. Both, and M. Frankenfeld, “Effects of SO₂, NOₓ, and O₃ on population development and morphological and physiological parameters of native herb layer species in a beech forest,” Environmental Pollution, vol. 58, no. 4, pp. 281–302, 1989.

[20] T. Suzuki, M. Watanabe, and M. Takeda, “UV tolerance in the two-spotted spider mite, Tetranychus urticae,” Journal of Insect Physiology, vol. 55, no. 7, pp. 649–654, 2009.

[21] S. Mun, S. H. Cho, T. S. Kim, B. T. Oh, and J. Yoon, “Inactivation of Ascaris eggs in soil by microwave treatment compared to UV and ozone treatment,” Chemosphere, vol. 77, no. 2, pp. 285–290, 2009.

[22] H. D. Choi and T. M. Holsten, “Gaseous mercury emissions from unsterilized and sterilized soils: the effect of temperature and UV radiation,” Environmental Pollution, vol. 157, no. 5, pp. 1673–1678, 2009.

[23] D. Dong, P. Li, X. Li et al., “Investigation on the photocatalytic degradation of pyrene on soil surfaces using nanometer anatase TiO₂ under UV irradiation,” Journal of Hazardous Materials, vol. 174, no. 1–3, pp. 859–863, 2010.

[24] B. Guieysse, G. Viklund, A. Toes, and B. Mattiasson, “Combined UV-biological degradation of PAHs,” Chemosphere, vol. 55, no. 11, pp. 1493–1499, 2004.

[25] K. K. Newsham, P. Splatt, P. A. Coward, P. D. Greenslade, A. R. McLeod, and J. M. Anderson, “Negligible influence of elevated UV-B radiation on leaf litter quality of Quercus robur,” Soil Biology and Biochemistry, vol. 33, no. 4–5, pp. 659–665, 2001.

[26] M. U. F. Kirschbaum, S. M. Lambie, and H. Zhou, “No UV enhancement of litter decomposition observed on dry samples under controlled laboratory conditions,” Soil Biology and Biochemistry, vol. 43, no. 6, pp. 1300–1307, 2011.

[27] Z. Hu, S. Chen, Q. Li, and S. Shen, “Characteristics of soil CO₂ fluxes and N₂O emission in a winter wheat ecosystem under enhanced UV-B radiation,” African Journal of Agricultural Research, vol. 7, no. 6, pp. 929–936, 2012.

[28] A. Singh, “Increased UV-B radiation reduces N₂-fixation in tropical leguminous crops,” Environmental Pollution, vol. 95, no. 3, pp. 289–291, 1997.
J. H. van Ginkel, A. Gorissen, and D. Polci, “Elevated atmospheric CO₂ and O₃ for three growing seasons,” Soil Biology and Biochemistry, vol. 42, no. 11, pp. 1967–1975, 2010.

G. R. Edwards, H. Clark, and P. C. D. Newton, “Soil development under elevated CO₂ affects plant growth responses to CO₂ enrichment,” Basic and Applied Ecology, vol. 4, no. 2, pp. 185–195, 2003.

D. J. Messenger, S. C. Fry, S. Yamulki, and A. R. McLeod, “Effects of UV-B filtration on the chemistry and decomposition of Praxinus excelsior leaves,” Soil Biology and Biochemistry, vol. 47, pp. 133–141, 2012.

E. E. Austin, H. F. Castro, K. E. Sides, C. W. Schadt, and A. T. Classen, “Assessment of 10 years of CO₂ fumigation on soil microbial communities and function in a sweetgum plantation,” Soil Biology and Biochemistry, vol. 41, no. 3, pp. 514–520, 2009.

M. de Graaff, C. van Kessel, and J. Six, “Rhizodeposition-induced decomposition increases N availability to wild and cultivated wheat genotypes under elevated CO₂,” Soil Biology and Biochemistry, vol. 41, no. 6, pp. 1094–1103, 2009.

M. R. Hoosbeek, J. M. Vos, M. B. J. Meinders, E. J. Velhorst, and G. E. Scarscia-Mugnozza, “Free atmospheric CO₂ enrichment (FACE) increased respiration and humification in the mineral soil of a poplar plantation,” Geoderma, vol. 138, no. 3–4, pp. 204–212, 2007.

S. Chen, Z. Hu, H. Li, Y. Ji, and Y. Yang, “Effects of elevated UV-B radiation on ecosystem and soil respiration in a winter wheat farmland,” European Journal of Soil Biology, vol. 47, no. 1, pp. 16–23, 2011.

N. T. Edwards, “Root and soil respiration responses to ozone in Pinus taeda L. seedlings,” New Phytologists, vol. 118, no. 2, pp. 315–321, 1991.

C. Decock, H. Chung, R. Ventera, S. B. Gray, A. D. B. Leakey, and J. Six, “Elevated CO₂ and O₃ modify N turnover rates, but not N₂O emissions in a soybean agroecosystem,” Soil Biology and Biochemistry, vol. 51, pp. 104–114, 2012.

Y. Liu, S. J. Han, Y. M. Zhou, and X. F. Li, “Soil and root respiration under elevated CO₂ concentrations during seedling growth of Pinus sylvestris var. sylvestrisformis,” Pedosphere, vol. 17, no. 5, pp. 660–665, 2007.

J. H. van Ginkel, A. Gorissen, and D. Polci, “Elevated atmospheric CO₂ and O₃ concentration effects: increased carbon input in a Lolium perenne soil on microorganisms and decomposition,” Soil Biology and Biochemistry, vol. 32, no. 4, pp. 449–456, 2000.

W. E. Holmes, D. R. Zak, K. S. Pregitzer, and J. S. King, “Soil nitrogen transformations under Populus tremuloides, Betula papyrifera and Acer saccharum following 3 years exposure to elevated CO₂ and O₃,” Global Change Biology, vol. 9, no. 12, pp. 1743–1750, 2003.

F. Hagedorn and M. Machwitz, “Controls on dissolved organic matter leaching from forest litter grown under elevated atmospheric CO₂,” Soil Biology and Biochemistry, vol. 39, no. 7, pp. 1759–1769, 2007.

K. Rejsek, V. Vranova, M. Pavelka, and P. Formanek, “Acid phosphomonooesterase (E.C. 3.1.3.2) location in soil,” Journal of Plant Nutrition and Soil Science, vol. 175, no. 2, pp. 196–211, 2012.

R. A. White, C. Freeman, and H. Kang, “Plant-derived phenolic compounds impair the remediation of acid mine drainage using treatment wetlands,” Ecological Engineering, vol. 37, no. 2, pp. 172–175, 2011.

J. S. Fletcher and R. S. Hegde, “Release of phenols by perennial plant roots and their potential importance in bio remediation,” Chemosphere, vol. 31, no. 4, pp. 3009–3016, 1995.

A. W. Al-Kayssi, “Impact of elevated CO₂ concentrations in the soil on soil solarization efficiency,” Applied Soil Ecology, vol. 43, no. 1, pp. 150–158, 2009.

J. A. Bunce and M. Nasyrov, “A new method of applying a controlled soil water stress, and its effect on the growth of cotton and soybean seedlings at ambient and elevated carbon dioxide,” Environmental and Experimental Botany, vol. 77, pp. 165–169, 2012.

K. Rejsek, P. Formanek, and V. Vranova, The Soil Amino Acids: Quality, Distribution and Site Ecology, Nova Science Publishers, New York, NY, USA, 2010.

T. W. Berger, E. Inselsbacher, and S. Zechmeister-Boltenstern, “Carbon dioxide emissions of soils under pure and mixed stands of beech and spruce, affected by decomposing foliage litter mixtures,” Soil Biology and Biochemistry, vol. 42, no. 6, pp. 986–997, 2010.

X. Li, S. Han, Z. Guo, D. Shao, and L. Xin, “Changes in soil microbial biomass carbon and enzyme activities under elevated CO₂ affect fine root decomposition processes in a Mongolian oak ecosystem,” Soil Biology and Biochemistry, vol. 42, no. 7, pp. 1101–1107, 2010.

J. B. Winkler and M. Herbst, “Do plants of a semi-natural grassland community benefit from long-term CO₂ enrichment?” Basic and Applied Ecology, vol. 5, no. 2, pp. 131–143, 2004.

C. W. Wood, H. A. Torbert, H. H. Rogers, G. B. Runion, and S. A. Prior, “Free-air CO₂ enrichment effects on soil carbon and nitrogen,” Agricultural and Forest Meteorology, vol. 70, no. 1–4, pp. 103–116, 1994.

N. M. Clark, M. C. Rillig, and R. S. Nowak, “Arbuscular mycorrhizal fungal abundance in the Mojave Desert: seasonal dynamics and impacts of elevated CO₂,” Journal of Arid Environments, vol. 73, no. 9, pp. 834–843, 2009.

S. D. Frey, E. T. Elliott, K. Paustian, and G. A. Peterson, “Fungal translocation as a mechanism for soil nitrogen inputs to surface residue decomposition in a no-tillage agroecosystem,” Soil Biology and Biochemistry, vol. 32, no. 5, pp. 689–698, 2000.

L. M. Nguyen, M. P. Buttner, P. Cruz, S. D. Smith, and E. A. Robelo, “Effects of elevated atmospheric CO₂ on rhizosphere soil microbial communities in a Mojave Desert ecosystem,” Journal of Arid Environments, vol. 75, no. 10, pp. 917–925, 2011.

E. Kandeler, A. R. Mosier, J. A. Morgan et al., “Transient elevation of carbon dioxide modifies the microbial community composition in a semi-arid grassland,” Soil Biology and Biochemistry, vol. 40, no. 1, pp. 162–171, 2008.

E. Kandeler, A. R. Mosier, J. A. Morgan et al., “Response of soil microbial biomass and enzyme activities to the transient elevation of carbon dioxide in a semi-arid grassland,” Soil Biology and Biochemistry, vol. 38, no. 8, pp. 2448–2460, 2006.

D. M. Nelson, I. K. O. Cann, and R. I. Mackie, “Response of archeal communities in the rhizosphere of maize and soybean to elevated atmospheric CO₂ concentrations,” PLoS ONE, vol. 5, no. 12, Article ID e15897, 2010.

K. Regan, C. Kammann, K. Hartung et al., “Can differences in microbial abundances help explain enhanced N₂O emissions...”
in a permanent grassland under elevated atmospheric CO$_2$?" 
*Global Change Biology*, vol. 17, no. 10, pp. 3176–3186, 2011.

[60] M. F. Cotrufo, B. Drake, and J. R. Ehleringer, "Palatability trials on hardwood leaf litter grown under elevated CO$_2$: a stable carbon isotope study," *Soil Biology and Biochemistry*, vol. 37, no. 6, pp. 1105–1112, 2005.

[61] Z. Lindo and N. N. Winchester, "Oribatid mite communities and foliar litter decomposition in canopy suspended soils and forest floor habitats of western redcedar forests, Vancouver Island, Canada," *Soil Biology and Biochemistry*, vol. 39, no. 11, pp. 2957–2966, 2007.

[62] P. Stella, B. Loubet, E. Lamaud, P. Laville, and P. Cellier, "Ozone deposition onto bare soil: a new parameterisation," *Agricultural and Forest Meteorology*, vol. 151, no. 6, pp. 669–681, 2011.

[63] G. Ohlenbusch, S. Hesse, and F. H. Frimmel, "Effects of ozone treatment on the soil organic matter on contaminated sites," *Chemosphere*, vol. 37, no. 8, pp. 1557–1569, 1998.

[64] M. Ushio, T. Miki, and K. Kitayama, "Phenolic control of plant nitrogen acquisition through the inhibition of soil microbial decomposition processes: a plant-microbe competition model," *Microbes and Environments*, vol. 24, no. 2, pp. 180–187, 2009.

[65] S. Toet, P. Ineson, S. Peacock, and M. Ashmore, "Elevated ozone reduces methane emissions from peatland mesocosms," *Global Change Biology*, vol. 17, no. 1, pp. 288–296, 2011.

[66] Y. Liang, J. D. V. Nostrand, J. Wang, X. Zhang, J. Zhou, and G. Li, "Microarray-based functional gene analysis of soil microbial communities during ozonation and biodegradation of crude oil," *Chemosphere*, vol. 75, no. 2, pp. 193–199, 2009.

[67] K. E. Ludley, C. H. Robinson, S. Jickells, P. M. Chamberlain, and J. Whitaker, "Differential response of ectomycorrhizal and saprotrophic fungal mycelium from coniferous forest soils to selected monoterpenes," *Soil Biology and Biochemistry*, vol. 40, no. 3, pp. 669–678, 2008.

[68] H. Dudášová, L. Lukáčová, S. Murínová, and K. Dercová, "Effects of plant terpenes on biodegradation of polychlorinated biphenyls (PCBs)," *International Biodeterioration and Biodegradation*, vol. 69, pp. 23–27, 2012.

[69] L. Chang, X. Liu, and F. Ge, "Effect of elevated O$_3$ associated with Bt cotton on the abundance, diversity and community structure of soil Collembola," *Applied Soil Ecology*, vol. 47, no. 1, pp. 45–50, 2011.

[70] A. A. Aly, "Biosynthesis of phenolic compounds and water soluble vitamins in culantro (*Eryngium foetidum* L.) plantlets as affected by low doses of $\gamma$ irradiation," *Analele Universității din Oradea—Fascicula Biologie*, vol. 17, no. 2, pp. 356–361, 2010.