Climate Change, Ultraviolet-B Radiation and Effects on Plants: A Review

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Abstract—*Climate change induces variations in environmental conditions and severely affects agricultural crop productivity and yield. The gradual depletion of the stratospheric ozone layer in the atmosphere has led to an increase in solar ultraviolet-B radiation (UV-B) reaching the earth's surface. Relatively little information exists on the effects of UV-B radiation on field crops. The aim of this review is to summarize the results of recent studies on the interaction between climate change, in particular the increase in UV-B radiation, and crops, in terms of yield, stress damage, defense and quality. Adaptive mechanisms, such as the increased production of secondary metabolites in leaf tissues under enhanced UV-B radiation, are also described.*

Keywords— Agriculture, secondary metabolites, stress damage, defense.

I. INTRODUCTION

Climate change has occurred mainly due to fossil fuel burning and rise in concentration of harmful greenhouse gases (GHGs) in the atmosphere during post-industrialization era. It induced variation in environmental conditions severely affect agricultural crop productivity and yield. Gradual depletion of stratospheric ozone layer in atmosphere has lead to increase in solar ultraviolet-B radiation (UV-B) that reaches earth surface. Relatively little information exists on the effects of UV-B radiation on field crops. The aim of this review is to summarize the results of recent studies on the interaction between climate change, in particular the increase of UV-B radiation, and crops, in terms of yield, stress damage and defence and quality.

1.1 Climate change

The climate on Earth has always followed natural cycles linked to the variation of solar insolation resulting from changes in some parameters of the Earth's orbit. By now it is incontrovertible that the climatic changes that are currently occurring are different and more dramatic than those that have marked the history of our planet: the greater concentration of greenhouse gases in the atmosphere and the rise in temperature and in consequent sea levels have never been so rapid and had such far-reaching consequences. Extreme climatic events, droughts, storms and catastrophic floods are and will be increasingly intense and frequent. As evidenced by periodic reports from the UN's IPCC (Intergovernmental Panel on Climate Change), the decade 2010-2019 was the warmest on record since reliable and regular records have been kept.

Starting from the 1980s, each subsequent decade has been increasingly hot, with increasingly frequent climatic events.

Human activities are primarily responsible for this problem, with a 147% increase in greenhouse gases in the atmosphere, such as CO_2, compared to pre-industrial levels. Therefore, studies on climate change play an increasingly central role in multidisciplinary scientific research involving researchers from various cultural backgrounds: agronomists, foresters, ecologists, botanists, zoologists, naturalists, geologists, engineers, even physicians and sociologists.

Climate change, recognized all over the world by the scientific community, is already having a strong impact on the world population due to changes in the yields, qualitative characteristics and water requirements of agricultural crops [1,29].

There are two elements to consider when it comes to climate change: the greenhouse effect and the thinning of the ozone layer.

While the former can be considered a normal phenomenon for regulating the temperature of our planet, the problem arises when, with the increase of so-called "greenhouse gases" such as CO_2, CH_4 and N_2O, in the atmosphere, an increasing amount of thermal energy from the sun raises seasonal temperatures.

The temperature of the planet has always reported risen in modern times, starting from 1880 until today, rising by about 1.5° C over the period, a trend that shows no signs of stopping.

The ozone layer is fundamental for the survival of every living species, since it creates a "shield" in the atmosphere against harmful radiation from the sun.

Its gradual decrease in thickness is mainly due to the release into the atmosphere of chlorofluorocarbons (CFCs) [54].

The thinning phenomenon is currently present at the South Pole and is expanding at a rate of 5% every 10 years. This represents a huge risk for survival, since the vanishing of the "shield" effect allows an ever increasing quantity of ultraviolet rays of the types B (UV-B) and C (UV-C) to enter into the atmosphere [35].

Most of our knowledge on the effects of UV-B radiation on plants derives from studies on economically important crops, most of which have emerged as sensitive to UV-B rays. Sensitivity differs between cultivars of the same species [30].

1.2 UV rays and higher plants

Plants are sessile autotrophic organisms that must constantly adapt to changes in the surrounding environment. Plant adaptation to UV rays has been of particular interest to researchers in recent years.

UV rays represent a range of electromagnetic radiation with a well-defined wavelength, divided into 3 specific regions: UV-A, with a wavelength ranging from 315 nm to 400 nm, UV-B, with a wavelength from 280nm to 315 nm, and UV-C, with a wavelength from 200 nm to 280 nm [27].

The global changes in the chemical composition of the atmosphere, with a substantial reduction of the protective ozone layer, have led to an ever more worrying increase in solar radiation on the earth, in particular UV-B rays [2].

Currently, the levels of UV-B reaching the earth during the harvest season are roughly between 2 and 12 kJ m^{-2} per day at the earth's surface, with a 6% to 14% increase in UV-B radiation compared to levels recorded before 1980 [3].

Under normal conditions, only rays included in the UV-A spectrum and a small portion of UV-B rays (0.5%) reach the earth's surface. The changing composition of the atmosphere however is allowing an ever greater passage of the latter rays. Although they are a minor component of sunlight, they may potentially cause biological damage that is a cause for concern, due to the high energy emitted (3.94 - 4.43 eV) [4].

Numerous studies have already shown that the increase in UV-B rays has significant effects on the yield and on the morphological, physiological and biochemical processes of many crops.

Radiative stress has been classified as an abiotic stress.

These notes will briefly examine the various effects found in some herbaceous crops, and the defense mechanisms developed to counteract damage from UV-B rays.

1.3 UVB rays and damage

1.3.1 UV-B and effects on yield

The deleterious effects of enhanced UV-B radiation vary markedly within and among species [36,37].

Zeng et al. [38] showed for winter wheat that the supplemental UV-B can cause a decrease in yield of winter wheat of up to 24% with an 11.4% increase in UV-B.

One species that has been studied extensively is soybean (*Glycine max*). Two soybean cultivars grown with enhanced UVB radiation showed conflicting sensitivities. One of the Essex cultivars showed substantial reductions (20-25%) in yields, while another, the Williams cultivar, was not affected by the increase in UV-B radiation [31].

UV-B rays interfere with the photomorphogenic development of plants and give rise to numerous regulatory effects on the morphology, development, physiology and biochemical composition of plants [5].

II. UV-B RAYS AND MORPHOLOGICAL EFFECTS

The symptoms most visible to the naked eye, referring to stress from overexposure to UV-B rays, are certainly morphological in nature. The appearance of the plant can often differ appreciably from the reference ideotype. Changes in the color and shape of leaves have been observed in several species. The initial appearance of yellow-brown punctate areas, which may be a symptom of chlorosis, necrosis or desiccation of the leaves, may be followed, with prolonged exposure to UV-B rays, , by an involution of the leaves with a classic cupped shape, resulting in a decrease in leaf volume, decrease in the number of stomata, smaller stomata and an increase in axillary branching. Prolonged exposure, after the appearance of the aforementioned symptoms, leads to the drying and fall of the leaf.

The presence of chlorotic and necrotic patches has been attributed to the decrease in the chlorophyll content in the leaves further to exposure to UV-B rays [6].

Chlorotic and necrotic symptoms are not exclusive to UV-B radiation, in various studies they have also been found in plants subjected to both nutritional and mineral deficiencies, in particular sodium, potassium, magnesium, iron, manganese, copper, chlorine and nitrogen [7], and exposed to environmental pollutants.

Among the morphological effects that were found, size reduction was highlighted in various plant species after exposure to UVB rays, for example in the cucumber, [8] after two weeks of exposure to UV-B rays, the stem of the plant had reached only 68% of its normal development in length compared to that of plants not subjected to any radiation treatment.

The decrease in elongation growth was not limited to plant height only; a decrease in the elongation of the petioles was also found.

The effects of UV-B radiation were particularly pronounced for younger leaves, with a decrease in growth of more than 40% compared to the control sample.

Like other visible effects on a morphological level, the length of the hypocotyl decreased in various model species, such as *Arabidopsis thaliana* [38], with a reduction in fresh weight, reduction in root growth and decrease in cell wall thickness.

Furthermore, many studies have reported that UV-B radiation can delay or postpone the development phases of alpine plants and the beginning of flowering of other plants [32,33]. A delay in growth is seen as an advantage in some particular situations [34].

III. UV-B RAYS AND EFFECTS ON PHOTOSYNTHESIS

When it comes to plant metabolism, the main reference process is certainly chlorophyll photosynthesis, one of the metabolic processes most sensitive to the effects of UV-B rays.

Various researches have shown that the photosynthetic apparatus is the main target of damage from UV-B rays, since it is responsible for receiving the light signal to transform it into energy and organic substance useful for the plant [2,12,14,26, 27,28].

There are various negative effects on the photosynthesis process, depending on species and cultivars, experimental conditions of growth, state of growth of the plant, the relationship between PAR and dosage of UV-B rays and finally interaction with other environmental stress factors. (e.g. cold, drought, mineral availability) [2].

The most immediate effects include: damage to proteins and photosynthetic pigments leading directly to an inhibition of the process itself [2], decreasing plant yield in terms of both growth and production. damage to the thylakoid membranes, damage to photosystem II, which can extend to photosystem I [9], reduction in CO_2 fixation, decrease in dry weight, starch and chlorophyll contents [5].

Indirectly, these cascading effects lead to other problems in the plant, such as: the reduction in gas exchange efficiency due to the closure of the stomata; the change in thickness and anatomy of the leaf, which directly modifies foliage, already mentioned among the morphological effects; this also has an effect on the photosynthetic rate and plant yield [39].

The cause of the damage to the photosynthesis process is to be found in the proteins and pigments that are directly related to this process.

Since proteins in plants can absorb UV light, as can pigments, both can be easily damaged.

Marwood and Greenberg [10] reported that exposure to UV-B rays of different wavelengths leads to a selective destruction of chlorophyll, in particular chlorophyll a, with regard to both its biosynthesis and precursors.

Also, Swarna et al. [11] reported that UV-B rays affect the photochemistry of PS II with an attested loss of functionality of 68%; this inhibition is closely related to the extent of lipid peroxidation of thylakoid membranes, studied in maize leaves.

Oxygen evolving complex (OEC) also appears to be sensitive to UV-B rays [12]. Damage to the PS II reaction center occurs mainly in the water oxidizing manganese cluster (Mn), which causes the electron transport chain to be inactivated.

Rubisco (ribulsio-1,5-bisphosphate carboxylase/oxygenase), one of the most abundant enzymes present in the leaves, is particularly vulnerable to exposure to UV-B rays. Increased UV-B radiation causes reductions in both Rubisco activity and content in many crop fields, such as rapeseed (Brassica napus L cv. Topas) or the pea plant (Pisum sativum L., cv. Greenfeast) [13,55,15].

However, the effects of UV-B rays cannot always be seen as negative. Many studies have reported that UV-B radiation can delay or postpone the development phases of alpine plants and the beginning of flowering of other plants, such as Ursiniaanthemoides L., Senecio elegans L., Gladiolus carneus Delaroche and corn (Zea mays L.) [32,33].

IV. UV-B RAYS AND THEIR EFFECTS ON BIOCHEMICAL BEHAVIOR

Finally, the biochemical behavior of plants is influenced both positively and negatively by the activity of UV-B rays.

The biochemical effects of UV-B include the accumulation of flavonoids in the epidermis of the plant organism, providing a shield to protect the plant [16,17].

At low doses of fluency, UV-B stimulates some genes responsible for the production of flavonoids and phenolic compounds [18].

High doses of UV-B radiation produce damage to biomolecules, generating reactive oxygen species (ROS), which can cause the oxidation of lipids and proteins, damage to DNA [19] and enhancement of lipid peroxidation [17,20]. To lessen the impact of ROS, the plant produces antioxidants such as ascorbic acid and alpha-tocopherol [19,20] and antioxidant enzymes such as superoxide dismutase, and ascorbic acid peroxidase, glutathione reductase, and guaiacol peroxidase [16,20,21].

It is interesting to focus on ROS production in plants.

Oxidative stress in plants is the result of an imbalance in the accumulation and removal, within the plant tissues, of oxidizing compounds such as free radicals and reactive oxygen species, which include hydrogen peroxide (H_2O_2), superoxide anion (O_{2-}), hydroxyl radical (OH) and other highly oxidizing molecules. These molecules target membrane lipids, proteins and nucleic acids with their oxidizing action, leading to an accumulation of H_2O_2 in the affected tissues.

The most serious effects can determine more or fewer point mutations, and macroscopically damage the DNA itself by altering the chemical structure of the nitrogenous bases and, by interrupting transcription, influencing gene regulation models, reducing protein synthesis [22,23].

Oxidative damage to DNA is therefore capable of having a profound impact on cell growth and development, which can have serious consequences for the entire organism.

The most common form of protection against reactive oxygen species is that which uses enzymes responsible for the conversion of ROS into less reactive and toxic products for the cell. In the past these ROSs were considered as only harmful to cells, now it is recognized that redox regulation involving oxidative stress products is also an important factor in modulating cellular activity [24].

The accumulation of hydrogen peroxide in plant tissues acts as a signal molecule for the activation of many plant genes, including those defending the plant, programmed cell death, apoptosis and genes for the biogenesis of peroxisomes, very important organelles for the detoxification of toxic molecules [25].

V. CONCLUSIONS

Solar UV-B radiation and its potential effect on global agriculture is a major concern for the future. UV-B radiation has very important photobiological effects, from various points of view. This leads to the assertion that rising UVB radiation will have deleterious effects on chlorophyll photosynthesis and crop productivity on a large geographical scale.

It has been ascertained that UV-B radiation seriously damages the photosynthetic apparatus and membrane of plants, alters protein content and enzymatic activity, damages DNA, and transforms the chemistry of the leaves.

Morphological damage, such as stunted plant growth, discoloration of leaves or reduction of vegetative biomass, must also be taken into consideration. UV-B radiation may directly contain some characteristics of cell division and key growth, which must retard the growth rate of plants. This growth retardation has been recognized as one of the UV-B radiation protection mechanisms.

In the future it will be important to develop study methodologies not only to estimate the effects of exposure to radiation and other abiotic and non-abiotic stresses. This is because environmental stresses act in isolation, but often act in synergy with other similar conditions, such as drought and extreme heat.

Further studies seek to understand the responses of plants to UV-B radiation and other variables of climate change, in particular temperature, ozone, drought conditions and mineral treatments.

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