Oxygen types that damage crops in extreme weather conditions

By Prof Charlie Reinhardt

Oxygen is best known as a life-giving gas without which life as we know it, would not be possible. Apart from the oxygen (O_2) humans and animals inhale when they breathe and that which plants release during photosynthesis, the air we are exposed to comprises several other forms of oxygen, namely ozone (O_3), nitrous oxide (NO_x) and carbon dioxide (CO_2).

These three gases all contribute to the greenhouse effect and are therefore members of the group of 'greenhouse gases' that accelerate global warming.

The fundamental problem

The release of natural greenhouse gases is not the fundamental problem that threatens the sustainability of the earth's climate as we know it. Instead, it is the impact of the Anthropocene – the epoch that marks the changes humanity has wrought on the earth's natural systems – that poses a threat.

Ozone is mostly brought to our attention when we hear reports on the state of the ozone layer over the poles (*Nature News*, 2020). It plays a protective role in the stratosphere and forms part of the earth's atmosphere that lies above the troposphere. It extends to approximately 50km above the earth's surface.

The troposphere is the lowest level of the earth's atmosphere. It extends from the earth's surface to a height of approximately 10km, with its thickness varying from approximately 7km at the poles to 28km at the equator.

However, relatively little is known about ozone that can injure plants.

The effect of ozone

Ozone (O_3) is the tri-atomic form of oxygen. It is formed in light-dependent reactions of atmospheric oxygen (O_2) with gaseous air pollutants such as nitrous oxides (NO_x) and hydrocarbons such as methane (CH_4). In the stratosphere it acts as a protective 'shield' against damaging ultraviolet (UV) radiation from the sun, but in the troposphere, it is relegated to one of the notorious air pollutants.

The susceptibility of plants, including crops, to relatively low but chronic concentrations of ozone is well documented. The damaging effects of ozone in plants include reduced photosynthesis and general growth, as well as the onset of early senescence.

Other plant responses include lower crop yields, as well as reduced disease tolerance and ability to withstand adverse environmental conditions. The phytotoxic effects of ozone manifest as lesions on plant leaves, which are the result of cell death in plants.

The higher the concentration of air pollutants that react with oxygen to form ozone, specifically in the troposphere

Rapid desiccation caused by oxidative reactive oxygen species.

Heat damage is a common sight.

where all life occurs, the higher the risk of ozone affecting plant growth and development.

Reactive oxygen species

Ozone enters plants through the stomata, which are specialised epidermal cells. These cells regulate gas exchange between the inner leaf spaces and the outside air.

Stomata facilitate the uptake of carbon dioxide as building blocks for carbohydrate production in the photosynthesis process and release oxygen to the atmosphere as a by-product of photosynthesis. These cells also regulate plants' water balance by enabling the release of water vapour into the air around the plant. This creates a gradient along which water and nutrients that are dissolved in it, move from the roots to the leaves through the plant's vascular system.

Once absorbed in the plant's system, ozone is degraded to reactive oxygen species (ROS) that cause the oxidative degradation (breakdown) of metabolites and cell components such as membranes responsible for maintaining the integrity and normal functioning of cells and tissue.

The three best known ROS types are, respectively, the hydroperoxyl radical ($HO_2^{\bullet}$), which is better known as its ionised form, the superoxide radical ($O_2^{\bullet -}$), hydrogen peroxide (H_2O_2) and the hydroxyl radical ($^{\bullet}OH$). These chemical compounds are called ROS because they are highly reactive with many biologically significant molecules. Their order of increasing reactivity (phytotoxicity) is $H_2O_2 < O_2^{\bullet -} < {}^{\bullet}OH$.

Plant stressors and defence

Drought, heat and UV light stress often act together as stressors. Cold stress damage done to plants is also linked to the formation of ROS in stressed plants. When stressors such as these prevail, the energy of electrons that are split by sunlight (photons) from water molecules in the photosynthesis process, is no longer used to make sugars. Instead, it is used in reactions that produce ROS.

Oxidative reactions of ROS cause damage to plant cells and tissue, which manifests as wilting. In the case of progression to permanent wilting, the end-result is necrosis (die-off) of plant parts or entire plants. Damage caused by desiccation or cold/frost, occurs through the same mechanism – the formation and action of ROS.

Other stressors such as certain herbicides and pathogens have detrimental effects on plants that are linked to ROS production in response to such factors. Triazine (atrazine, terbuthylazine), uracil (bromacil), nitrile (bromoxynil) and bipyridilium (paraquat) herbicides kill susceptible plants through the production and phytotoxicity of ROS.

The mechanism of action of these herbicide groups is the inhibition of electron transport in the photosynthesis process, thus paving the way for free electrons to react with oxygen to form ROS as described above.

Plants defend themselves against stressors. Pathogens and wounds elicit plant responses that involve the production of the ROS hydrogen peroxide (H_2O_2) in plant cells and tissue. In this way, the so-called 'oxidative burst' is linked to the arsenal of plant defence mechanisms for protection against unwanted microbial intrusion, as well as physical wounding. Cauterisation is an effective medical treatment for wounds in humans, and it appears that it is also the case for plants.

Photoprotection and antioxidants

The production of ROS has been reported in unstressed plants, and relatively low ROS concentrations are maintained in tissue under these circumstances. This phenomenon is logical considering that stress can set in rapidly, hence the need for rapid-response ROS.

Antioxidants such as glutathione, ascorbic acid and phenolic compounds regulate (quench) ROS concentrations to levels below phytotoxic levels in unstressed plants. Antioxidation as a means of rendering crop species tolerant to stressors such as drought, heat or cold is regarded as a form of photoprotection that, in biological terms, is as crucial as the photosynthesis process itself [B.A. Logan in: N. Smirnoff (ed), 2005].

Such knowledge will no doubt be useful for genetic engineering to create stress-tolerant crop varieties. Still, the challenge is that antioxidation is multi-faceted and unlikely to lend itself to 'improvement' using single-gene transgenic upregulation.

Prof Charlie Reinhardt is a professor in the Agricultural Sciences programme at North-West University, and research leader in the SAHRI at University of Pretoria. For more information, phone Prof Reinhardt on 083 442 3427 or send an email to dr.charlie.reinhardt@gmail.com.