Commentary
Impacts of ozone on agricultural crops in southern Africa

Tracey L. Laban, Johan P. Beukes, Pieter G. van Zyl, Jacques M. Berner
Unit for Environmental Sciences and Management, North-West University, Potchefstroom

The potential for ozone (O_3) damage to agricultural crops, trees and native plants is well documented in literature. O_3 has been shown to cause a wide variety of effects to important agricultural crops including visible leaf injury, growth and yield reductions, as well as deteriorating nutritional quality in certain crops. O_3-induced damage is especially an issue of concern if it threatens food supply and the economies of countries that are based strongly on agricultural production. With the availability of global chemistry transport models, global and regional estimates of crop losses can be obtained (Van Dingenen, 2009; Avnery et al., 2011; Wang and Mauzerall, 2004). Present day global relative yield losses due to O_3 damage are estimated to range between 7% and 12% for wheat, 6% and 16% for soybean, 3% and 4% for rice and 3% and 5% for maize (Van Dingenen, 2009). In India it was calculated that O_3 damage to wheat and rice resulted in a nationally aggregated yield loss of 9.2%, that is sufficient to feed 94 million people living below the poverty line in that country (Ghude et al., 2014).

Agricultural crops contribute significantly to the economy in southern African countries. Staple crops in South Africa that meet the food needs for local consumption are maize and wheat, whilst economically important crops include sunflowers and sugarcane. These crops must be assessed for O_3-induced effects. The potential for elevated concentrations of O_3 is particularly high in many regions of South Africa because of the combination of intense and extended solar radiation, and the relatively high emission of precursor species, such as nitrogen oxides and volatile organic compounds, from human and natural sources. Rural and agricultural areas in southern Africa, subject to regional air pollution events could have even higher O_3 concentrations than industrialised areas (sources of O_3 precursors) if polluted air masses are transported to these areas.

An assessment of surface O_3 measurements over southern Africa indicated that maximum O_3 concentrations are between 40 and 60 ppb, but can reach more than 90 ppb during the springtime (Zunckel et al., 2004). Furthermore, modelled O_3 as part of the Cross Border Impact Assessment Project, indicated large areas on the sub-continent where surface O_3 concentrations exceed 40 ppb for up to 10 h per day (Zunckel et al., 2006). The implications are that at these levels of exposure southern African vegetation may be at risk to damage by O_3. Josipovic et al. (2010) did an assessment of critical level exceedance for O_3, utilising passive samplers and found O_3 levels below the critical levels. However, the methodology applied did not consider cumulative O_3 exposure over time, which really determines the long-term effects on crops. The seasonal pattern of O_3 in southern Africa reveals the highest concentrations during spring and winter, with lower concentrations during summer (Laakso et al., 2013). The diurnal cycle of O_3 is characterised by an increase from a minimum near sunrise to maximum values in the early afternoon, and decreasing to the early morning minimum (Zunckel et al., 2004). Therefore plant uptake of O_3 should be highest during midday and early afternoon when high rates of leaf gas-exchange coincide with rising O_3 concentrations.

O_3 enters the plant mainly through its open stomata (leaf pores) when plants take up carbon dioxide (CO_2) for photosynthesis. O_3 is a highly reactive molecule; inside the plant it produces several reactive oxygen species such as superoxides, peroxides and hydroxyl radicals. Among other negative effects, the oxidative action of O_3 destroys key enzymes and proteins, including the photosynthetic enzyme Rubisco, which will result in a much reduced photosynthetic efficiency. O_3 also causes damage to the stomatal apparatus resulting in the inability of the plant to control the opening and closing of the stomata. Reduced Rubisco and impaired stomatal function will cause less CO_2 being taken up by the plant leading to a reduced photosynthetic efficiency, and will ultimately lead to reduced growth rates and yield. At short periods of high concentrations of O_3, visible injury symptoms associated with O_3 damage include small flecks or stipples on leaf tissues. Visible injuries usually appears early in the growing season and continues to develop during the season. Continuous exposure over long periods to relatively low concentrations of O_3 may induce some of the same visible symptoms, including chlorosis (loss of chlorophyll), necrosis (premature death of cells and living tissue) and accelerated senescence (ageing) in leaves (De Temmerman et al., 2002). Injuries not visible to the naked eye result from pollutant impacts on plant physiological or biochemical processes. Some of these changes increase the resistance of the leaf to subsequent O_3 exposure whilst others decrease photosynthetic function.

O_3 damage to crops can be evaluated based on the AOT40, an index used in Europe that serves as the standard for protection of vegetation against O_3 pollution. AOT40 is defined as the accumulated O_3 exposure above a threshold concentration of 40 ppb during daylight hours of the growing season (UNECE, 2010). The AOT40 exposure index is cumulative, i.e. it integrates

$$AOT40\ (ppb\ h) = \sum_{i=1}^{n}([O_3]_i - 40), \qquad \text{for } O_3 \geq 40 \text{ ppb}$$

exposure over time in order to detect long-term effects. Experimental data has shown that the impacts of O_3 on plants are often better related to accumulated exposure above a threshold concentration rather than the mean concentration over the growing season. The European AOT40 critical level is 3000 ppb h for agricultural crops (over a growing season of 3 months) and 5000 ppb h for forests. However the AOT40 approach has limitations since it does not directly reflect the O_3 absorbed by plant surfaces, with damage being calculated solely on the basis of ambient O_3 concentrations. O_3 flux, which is the rate at which O_3 is absorbed by plant surfaces, is a better measure of biological response. The use of an impact assessment method approach based on the actual flux of O_3 through the plant stomata is recommended, but requires additional information such as O_3 flux data and dose-response relationships of different plant species.

Experiments to determine dose-response functions for plants have used controlled-environment greenhouses, field chambers and free-air systems (U.S. EPA, 2006). Research studies have derived relationships between "O_3 dose" or "O_3 exposure" and the yield of the major crop species through controlled O_3 fumigation experiments under near-field conditions using open-top chambers. An open-top chamber research facility exists at North-West University where O_3 assessments have been performed on maize, snap beans, garden peas and canola plants, and have demonstrated adverse physiological and growth effects due to elevated O_3 levels. Most recently, a sugarcane trial is underway on two local cultivars to determine the effects of elevated CO_2 concentrations, elevated O_3 concentrations, and also the combined effects of elevated CO_2 with elevated O_3 in the absence of drought stress. To our knowledge, there is no quantitative data on O_3 exposure-plant response (E-R functions) for sugarcane currently available.

Compared to the control plants (exposed to charcoal-filtered air), sugarcane plants exposed to concentrations of 80 ppb O_3 for 9 hours a day (photoperiod) showed chlorotic and necrotic lesions on their leaves, leaf senescence, as well as stunted growth. Evidence from visual changes also suggests that sugarcane crops are more sensitive to the elevated O_3 early in the growth season, while later showing signs of recovery to sustained O_3 stress. In this trial, seedlings of sugarcane were used in the open-top chambers and O_3 fumigation only commenced after a few weeks, once the plants had reached some level of maturity. Plant response to O_3 may vary with physiological age and young plants are considered more sensitive to O_3 exposure in the early stages of development (Reiling and Davison, 1994 and references therein). Developmental stage plays a major role in determining plant sensitivity to O_3.

It is important to note that O_3 stress does not act independently, but is one of many stresses that will affect growth and productivity of crops. O_3 can also cause altered sensitivity to biotic (e.g. pest and pathogen attack) and abiotic stresses (e.g. drought, floods). In some regions of southern Africa, drought stress is more common than O_3 stress and the combination of

(a)
Sugarcane leaves exhibiting visible injury from O_3 exposure: tiny, brown spots (stipples) and yellow patches early on – yellowing is a sign of chlorosis.

(b)
Sugarcane leaves exhibiting visible injury from O_3 exposure: reddish-brown lesions later on – a sign of necrosis.

O_3 stress and drought will often produce plant responses that are due primarily to the effect of drought (van Tienhoven, 2005). The more frequent occurrence of drought stress make plants in the southern African region more tolerant to O_3 stress compared to plants in Europe. Drought stress reduces the stomatal opening, and hence reduces O_3 uptake by the plant. There are also interactions between O_3 stress and other atmospheric gases that can modify the impact of O_3. For example, rising levels of atmospheric CO_2 are thought to ameliorate the influence of increasing ground-level O_3 concentrations i.e. plant stress caused by O_3 is offset by CO_2. O_3 stress on its own leads to foliar injury, suppressed growth and yield in plants, whereas elevated CO_2 generally enhances growth and yield; the combination of elevated O_3 and CO_2 can affect plant response differently compared to each stress occurring separately (Heagle et al., 1999). Also, the presence of other pollutants such as sulphur dioxide may act synergistically with O_3, increasing growth reductions (WHO, 2000).

There are two types of O_3 exposure, i.e. acute exposure where concentrations are high and range from 120 – 500 ppb for hours (as is the case at polluted sites), or chronic exposure where there is an elevated background concentration with daily peak concentrations of 40 – 120 ppb over several days in the growing season (Long and Naidu, 2002). But what is more damaging to plants, short-term exposure to very high O_3 concentrations or long-term exposure to moderate O_3 concentrations? In South Africa, chronic exposure in the range that can affect plants interspersed with short duration pollution episodes of peak concentrations often occurs. It has been stated that intermediate concentrations of O_3 may have the largest impact on crop yields (Krupa et al., 1995). On the other hand, Köllner and Krause (2000) pointed out that O_3 peaks are more important for yield losses than constant elevated O_3 exposure. Opinions therefore differ as to the extent of yield reductions resulting from periodic exposure to high concentrations (well above any supposed threshold) or chronic exposure to concentrations near the threshold. Nevertheless, more studies link chronic exposure to consequences of reduced growth and yield, adding that the severity varies for different crop species and also for different cultivars within a crop species.

Southern African impact studies to date have adopted the European AOT40 for assessing O_3 damage to crops (Avnery et al., 2011; van Tienhoven et al., 2006). However, despite the AOT40 for the southern African environment exceeding the European AOT40 level for crop damages (3000 ppb h), no vegetation damages have been reported. Van Tienhoven et al. (2005) explained that the reasons for this could be either that there is a lack of knowledge to distinguish between actual O_3-induced effects and effects from other stresses, or that the local vegetation may have had hundreds of years to adapt to elevated O_3 levels, as some Mediterranean species. The adaption aspect was also discussed by Scholes and Scholes (1998), who argued that local indigenous species, especially on the savannah, may be less sensitive to O_3 exposure compared to planted alien species such as pine and eucalyptus. The applicability of the AOT40 to tolerant southern African crops should be revisited. Note that while a value of 40 ppb (AOT40) has been employed in impact assessment research in Europe, a higher value of 60 ppb (AOT60) has been used in the U.S. The open-top chamber trials at North-West University have historically used 80 ppb O_3 treatments on maize, snap beans and canola, and found adverse physiological and biochemical effects on these species. Therefore these effects might be better related to the use of a higher threshold concentration than 40 ppb. However, the suitability of a higher threshold for South African species must still be established.

Most of the actions taken to control ground-level O_3 pollution are aimed at reducing human exposure to this pollutant. Given the concentration thresholds for effects, these measures may therefore be expected to have the greatest beneficial impact in terms of health, with somewhat less of an impact in relation to plants. The South African National Ambient Air Quality Standard for O_3 (8-h running average of 61 ppb) is based on World Health Organisation (WHO) guidelines that are primarily concerned with the protection of human health. Air quality guidelines based on the United Nations Economic Commission for Europe (UNECE) critical levels (UNECE, 1998) provide the best available scientific basis for the protection of natural ecosystems against O_3. However, country-specific research on exposure-response relationships is needed to provide sufficient data on the critical levels for South African vegetation (WHO, 2000). Information on critical levels is a means to update the existing air quality standards for ground-level O_3 which take into account not just the adverse effect on human health, but also on vegetative health, in order to protect the ecosystem as a whole.

O_3 impact studies focusing on local crop variants should be advanced using either the concentration-based AOT40 approach (good identification tool for crop damage, but not accounting for interacting stresses) or the flux-based approach (good yield loss assessment tool, but large data requirements). For the AOT40 approach, continuous ambient O_3 measurements are needed. For the flux-based approach, measurements of local environmental variables such as humidity and soil moisture (lower during droughts), temperature, radiation, vapour pressure deficit and wind speed are important parameters influencing O_3 uptake. Both these approaches will require exposure-response functions (concentration-response or dose-response) for local cultivars. The application of European crop exposure-response functions add to uncertainties in agricultural impact assessments. Therefore, local exposure-response relationships under ambient conditions, and in a changing climate, should be derived through routes such as open-top chamber experiments.

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