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Ozone impacts on crops in ODA countries: Evidence, risk and policy implications

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Executive Summary

Concentrations of ozone (O_3), an air pollutant at ground level, have increased since the 1900's and are predicted to continue to rise globally unless precursor emissions are substantially reduced. Major crop growing regions of the world such as North America, Europe, and South and Eastern Asia have high concentrations and key staple crops such as soybean, wheat, rice maize, and key subsistence crops such as beans are sensitive to O_3. O_3-induced damage can manifest itself as leaf injury (especially relevant for the market value of leafy crops) or reductions in crop yield, biomass or quality. In 2018, we reviewed the literature for field-based evidence of impacts of ambient O_3 levels on crops in countries receiving Overseas Development Assistance (ODA countries). Sources of data included assessments of visible leaf injury caused by O_3, improved yield quantity and quality reported in studies applying chemical protectants against O_3 and in studies reducing the O_3 concentration by filtration of ambient air. In addition, we assessed the risk of O_3 impacts on O_3-sensitive staple crops through modelling. The 2018 report entitled *"Evidence of ozone effects on crops in ODA countries: field data and modelling*" was submitted to Defra. Since then, we continued to collate field-based evidence of O_3 impacts on crops from observations of leaf damage, chemical protectant and air filtration studies.

As reported in 2018, most data continued to emerge from South and East Asia (China and India in particular), with a number of studies exploring the differences in sensitivity to O_3 of various crop and poplar varieties (a common agro-forestry crop). There remains a lack of data from Africa (although some evidence is presented here for Egypt), most of Central and South America and South Eastern and Eastern Europe, Caucasus and Central Asia. Since 2000, considerable evidence of O_3 impacts on crops has emerged from a limited number of locations in China, India and to some extent Pakistan. The reduction of crop yield losses due to O_3 in these countries is often in the range of 5 – 20%, with sometimes losses being reported in excess of 40%. The sensitivity to O_3 varies between crop species, with legumes such as bean and soybean being identified as very sensitive, wheat being sensitive and rice and maize being moderately sensitive to O_3. In addition, the O_3-sensitivity varies between varieties of crop species. Some recent Indian wheat cultivars have a higher O_3-sensitivity than previous varieties tested. As an important consideration for future food security, it should be noted that grain protein was also reduced for maize, wheat, mung bean, broad bean and peas. Data from China has shown that O_3 impacts on poplar vary across clones, ranging from no effect to reductions of up to 4% for total biomass. In Brazil, recent incidences of leaf injury have been found on both tobacco and guava crops, confirming their use as bio-indicator plants.

As reported in 2018, similar losses were estimated in a flux-based modelling study conducted for ODA countries for the staple crops wheat, rice, soybean and maize for the years 2010-2012. The mean modelled percentage yield losses for four major regions (South and Eastern Asia; Africa; Central and South America; South Eastern and Eastern Europe, Caucasus and Central Asia) ranged from 3.3-5.3%, 4.5-7.6%, 5.3-10.0% and 7.4-15.3% for rice, maize, wheat and soybean respectively. For rice, maize and wheat, the highest annual production losses were reported for South & Eastern Asia. For soybean, the highest production losses were seen in Central and South America. There is a particular need for field-scale trials to aid model evaluation and interpreting large-scale effects of O_3 on crops. There continues to be uncertainties in predictions due to the O_3 simulation method used (flux-based or concentration-

based) and the inclusion of sensitivity parameters for regional crop varieties. In the 2018 study, crop production losses might have been underestimated for South and Eastern Asian countries as the study was based on the O_3-sensitivity of European and North American varieties. Asian varieties of wheat and soybean might be more sensitive to O_3 than European and North American varieties. Indeed, recent inclusion of extra sensitivity in a process-based modelling study for Asian wheat varieties greatly increased yield loss estimates to about 35% in China and India.

Generally, calculation of O_3 damage based on intake via stomatal fluxes have resulted in lower yield loss estimates than concentration based metrics. For example, national yield losses for wheat in China were estimated as 10% using a flux method and 18% with a concentration based method. Although flux methods are considered more accurate, concentration based methods are still used if flux-effect relationships don't exist or to provide comparisons with previous work.

Considering the variation in O_3-sensitivity between varieties of crops species, there is scope for breeding more O_3-tolerant varieties to mitigate impacts of ground-level O_3 on crop production. There is a need to include assessment of O_3-sensitivity in crop breeding programmes and field trials to develop high-yielding O_3-tolerant varieties that are also more resilient to future climate stresses such as heat and drought. In addition, potential crop management options that could contribute to reducing the adverse impacts of O_3 on crops should be tested under field conditions, such as timing of irrigation and change and/or length of growing season by establishing faster developing varieties. Such approaches could contribute significantly to reducing the contribution of O_3 pollution to the current yield gap for crops.

Results from two detailed flux-based case studies focusing on the impacts of O_3 on crops in India and South Africa are presented. Across India, modelled O_3 flux varied in 2015, with the highest values in the eastern and central areas of the country. For wheat, the average estimated percentage yield loss for India was 11.3% and the total production loss was estimated at 11.8 million tonnes. Indian states with the highest wheat production, including Uttar Pradesh and Madhya Pradesh, were estimated to be at the highest risk of losses due to O_3. Results of modelled O_3 uptake by wheat and beans in South Africa for 2015 suggested that ground-level O_3 had a negative impact on crop production in South Africa. Average percentage yield loss due to O_3 across South Africa was 4.2% and 13.3% for wheat and beans, respectively. As wheat production in South Africa is currently higher than for beans (1.4 million tonnes vs. 35.4 thousand tonnes in 2015, respectively), the estimated production losses due to O_3 for wheat were higher than for beans, (61.7 thousand tonnes for wheat and 11.8 thousand tonnes for dry beans). The South African provinces with the highest estimated losses were the Northern and Western Cape (wheat) and the Free State and Mpumalanga (beans).

Globally, ground-level O_3 concentrations are predicted to remain stable or even rise in the future, depending on the implementation of current legislation. Stringent air pollution abatement policies are lacking in many developing countries. In some areas, climate change might further contribute to a rise in O_3 pollution. There is a need to take concerted action at the global scale to reduce ground-level O_3 pollution, particularly when it comes to reducing emissions of the precursor methane. Methane should be included in future air pollution monitoring programmes to assess future emission trends and its contribution to the production of ground-level O_3 in regions across the globe.

1 Introduction

Objective

Report on available evidence of impacts of ground-level ozone pollution on crops in ODA countries, assess risk of impacts and discuss policy implications.

1.1 Background

At ground level, (tropospheric) atmospheric ozone (O_3) is a secondary air pollutant and greenhouse gas. It is formed from solar radiation-driven chemical reactions between O_3 precursor gases, including carbon monoxide (CO), nitrogen oxides (NO_x), methane (CH_4) and non-methane volatile organic compounds (Royal Society, 2008; Simpson et al., 2014; Monks et al., 2015). There is annual and regional variation in concentrations depending on geographical location, proximity to sources of O_3 precursors (mainly from vehicle and industrial sources, biomass burning events) and meteorological conditions. O_3 concentrations are generally higher in rural areas compared to urban sites due to the movement of air-borne precursors downwind of the source and the titration of O_3 by nitrogen oxide (NO) in urban areas (Schultz et al., 2017; Mills et al., 2018a). A global database of O_3 observations now exists, established as part of the Tropospheric Ozone Assessment Report (TOAR; Schultz et al., 2017). However, very few data exist in Africa, Central and South America, Central Asia, South Asia and the Middle East. O_3 concentrations have increased since the 1900's and are predicted to continue to rise unless precursor emissions are reduced dramatically (Wild et al., 2012; Cooper et al., 2014; Lu et al., 2018a; Li et al., 2019; Yeung et al., 2019; Ronan et al., 2020). Especially in China and India, O_3 concentrations are rising (even in China, despite a decline in reported NO_x emissions since 2010; Pu Wang et al., pers. comm.) Trends for vegetation-relevant O_3 metrics between 1995 and 2014 at rural sites show that such metrics have been declining in North America, increasing in Japan, whilst no overall change was observed in Europe (Mills et al., 2018a). Continued growth is a key feature of economic policies in Asian countries such as China, India and Thailand, with other countries across the region striving to reach similar growth rates. As such, the pollution burden will continue to grow unless aggressive emission control policies are successfully implemented.

Major crop growing regions of the world (e.g. North America, Europe, and South and Eastern Asia) have high O_3 concentrations, often coinciding with growing seasons (Mills et al., 2001, 2018b; Wild et al., 2012; Cooper et al., 2014). O_3 is detrimental to human health, crops, and ecosystem productivity. Key crops such as wheat, rice, and soybean are affected via leaf damage and reductions in yield, although sensitivity varies between species and often between cultivars (Hayes et al., 2007; Hayes and Mills, 2011; Mills and Harmens, 2011). O_3 is taken up through leaf stomatal pores and reacts with a number of molecules inside the leaf forming reactive oxygen species. This triggers cellular response defence mechanisms that can cause early senescence and repression of growth and seed production through the diversion of resources (Ainsworth, 2017). The effects of O_3 and mechanisms of plant stress responses are still a subject for research.

1.2 Aim and structure of the report

The aim of this report is to review currently available evidence of impacts of ambient O_3 levels on crops in countries on the Official Development Assistance (ODA) list published by the Organisation for Economic Co-operation and Development (OECD; Figure 1).

http://www.oecd.org/dac/financing-sustainable-development/development-finance-standards/DAC-List-of-ODA-Recipients-for-reporting-2018-and-2019-flows.pdf

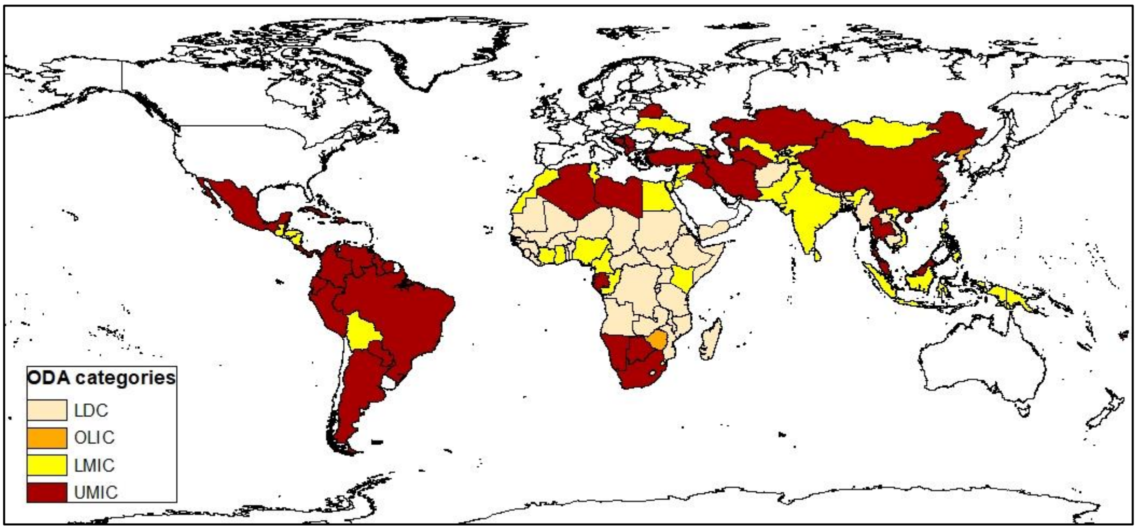


Figure 1. Map of countries on the Official Development Assistance (ODA) list published by the OECD for 2018-19. Countries are split into the following categories: LDC: Least Developed Countries; OLIC: Other Low Income Countries; LMIC: Lower Middle Income Countries; UMIC: Upper Middle Income Countries.

The report provides an update of the evidence first reviewed in 2018 (Harmens et al., 2018b). We continued to collate field-based evidence of O_3 impacts on crops (Chapter 2). Field-based evidence of O_3 impacts was reviewed by considering three sources of data:

- Observations of foliar damage on crops caused by O_3 in ambient air;
- Reports of foliar damage and crop yield losses by comparing O_3 impacts on crops grown in ambient air with those sprayed with a chemical protectant against O_3;
- Reports of crop yield losses by comparing the yield of crops grown in ambient air with the yield of the same crops grown in charcoal-filtered air in which the O_3 concentration was reduced (often to near pre-industrial levels).

Chapter 3 details recent estimates from modelled O_3 impacts on crops in ODA countries. In 2018, we focussed on flux-based modelling of O_3 impacts on the annual yield and production of four staple crop species (maize, rice, soybean, wheat) in 2010-2012 (Harmens et al., 2018b; Mills et al., 2018c).

2 Field-based evidence

The main sources of field-based evidence of O_3 impacts on crop yields continue to be from observations of leaf damage, chemical protectant and air filtration studies. In this chapter, we first provide an overview for the data presented in Harmens et al. (2018b), followed by any new data reported since (or not included in the original review). Most recent data has been reported for South and East Asia, especially China and India, and to some extent for Pakistan. Hence, new data is described separately for South and East Asia and for other ODA regions.

2.1 Visible foliar damage

Visible foliar damage normally takes the form of pin-head sized pale yellow, cream, or bronze coloured spots (also known as stipples) appearing between leaf veins (Figure 2). However, the spots can, in severe cases, join together covering larger portions of the leaf. The upper leaf is affected initially then damage spreads to both sides. Major crops (e.g. wheat, rice and beans) can be affected (Mills & Harmens, 2011), and instances can lead to reductions in the quality and quantity of crop yields (Mills et al., 2018c). Leaf injury remains an important parameter in determining O_3 tolerance (e.g. Bailey et al., 2019; Kaffer et al., 2019), but yields can be affected even without these visible signs (Marzuoli et al., 2017). Visible damage to leafy crops (e.g. lettuce, spinach, chicory) will reduce their market value. A number of studies have specifically documented leaf injury from ambient O_3 on a variety of crops (Harmens et al., 2018b; Table 1).

Figure 2. O_3-induced leaf injury in wheat (left), soybean (middle) and pearl millet (right).

Table 1. Documented incidences of foliar damage in ODA countries attributed to O_3 for the crop species listed (as reviewed in Harmens et al. (2018b) with additional and more recent references highlighted in blue). The range of mean (daytime) ambient O_3 levels during the growing seasons represented in the studies are shown in parts per billion (ppb).

Crop	China (46-181 ppb)	India (49-69 ppb)	Pakistan (25-125 ppb)	Egypt (39-80 ppb)	Brazil (8-46 ppb)
Common bean	✓				
Cotton			✓		
Courgette	✓				
Cowpea	✓			✓	
Grapevine	✓				
Guava					✓
Hops	✓				
Mung bean		✓	✓		
Okra	✓				
Onion			✓		
Peanut	✓				
Peas			✓		
Poplar	✓				
Potato		✓	✓	✓	
Radish				✓	
Rice		✓			
Soybean		✓		✓	
Sword bean	✓				
Tobacco		✓			✓
Turnip				✓	
Velvetleaf	✓				
Watermelon	✓				
Wheat		✓	✓		
Winter melon	✓				

References: China (Feng et al., 2014; Shang et al., 2020); India (Agrawal 2006; Sarkar and Agrawal, 2010a; Singh & Agrawal, 2011; Chaudhary et al., 2013; Kumari & Agrawal, 2014; Mishra & Agrawal, 2015; Gupta et al., 2018); Pakistan (Ahmad et al., 2013; Adrees et al., 2016); Egypt (Hasssan et al., 1995; Hassan et al., 2006; Ali & Abdel-Fattah, 2006; Tetteh et al., 2015); Brazil (Alves et al., 2016; Pina et al., 2017; Kaffer et al., 2019).

2.2 Chemical protectant studies

Chemical protectant studies utilize the antioxidant ethylenediurea (EDU, N-[2-(2-oxo-1-imidazolidinyl) ethyl]-N-phenylurea) as a method of determining sensitivity and impacts due to O_3 stress (Feng et al., 2010; Manning et al., 2011). Whilst EDU provides only partial protection, it continues to significantly reduces symptoms of O_3 injury (Agathokleous et al., 2015). The exact protection mechanism is still unknown, but it is currently thought that EDU works due to a combination of higher stimulation of anti-oxidative enzyme activity (therefore reducing resources for the anti-oxidative defence system and allowing more resources for growth) and scavenging of reactive oxygen species (ROS) generated by O_3 (Ashrafuzzaman et al., 2018; Feng et al., 2018; Fatima et al., 2019; Rathore & Chaudhary 2019). The chemical can be applied as a soil drench or foliar application in regular applications over the growing season. The use of EDU negates the need for chambers making it cost effective for screening plants in remote areas. Therefore, the method has been widely and successfully used in research, especially in Asia (Pandey et al., 2015). Previous crop trials utilizing EDU have resulted in positive yield/biomass responses in most species (Harmens et al., 2018b; Table 2). A meta-analysis showed that EDU significantly reduces O_3-induced visible leaf injury by 76%, stimulates photosynthesis by 8%, above-ground biomass by 7% and crop yield by 15% on average in comparison with non-EDU treated plants (Feng et al., 2010).

Table 2. Percentage increase in yield or biomass for different crop species and varieties grown in ODA countries with EDU treatment compared to those without (as reviewed in Harmens et al. (2018b) with additional and more recent references highlighted in blue). The range of mean (daytime) ambient O_3 levels during the growing seasons represented in the studies are shown in parts per billion (ppb).

Crop	China (40-71 ppb)	India (14-73 ppb)	Pakistan (40-91 ppb)	Egypt (39-98 ppb)
Broad bean				32-34
Common bean	46-55			
Carrot		23		
Castor bean		7-34		
Mung bean		49		
Mustard		7-59		
Palak		29		
Potato				12-47
Radish				18
Rice	0-4			
Sesame			33-43	
Soybean	10-45	30	47	31
Turnip				0-17
Wheat	13	2-36		

References: China (Wang et al., 2007; Yuan et al., 2015; Jian et al., 2018); India (Tiwari and Agrawal, 2009; Tiwari & Agrawal, 2010; Singh & Agrawal 2017; Fatima et al., 2019; Pandey et al., 2019; Rathore & Chaudhary 2019); Pakistan (Wahid et al., 2001; Wahid et al., 2012); Egypt (Hassan et al., 1995; Hassan et al., 2006; Ali & Abdel-Fattah, 2006; Ali 2016).

2.3 Air filtration studies

Air filtration studies compare the differences between crops grown in open top chambers with either charcoal filtered air (often representing pre-industrial O_3 levels), non-filtered air (representing ambient concentrations), or with the addition of targeted O_3 concentrations (used to investigate the impacts of enhanced O_3, for example in future scenarios). Whilst there are inevitable chamber effects to be considered, plants can be rooted into the ground (rather than grown in pots) providing closer representations of field conditions than smaller closed chambers (Feng et al., 2018). Evidence of reductions in yield for various crop species due to O_3 has previously been shown by comparing crops grown in charcoal filtered air compared to non-filtered ambient air (Harmens et al., 2018b; Table 3). These trials have also emphasized cultivar variation in O_3-sensitivity, for example, one rice cultivar showed no change in yield compared to another that showed an increase due to the charcoal filtered air treatment (Ishii et al., 2004).

Table 3. Percentage increase in yield or biomass for different crop species and varieties grown in ODA countries in charcoal filtered air compared to ambient unfiltered air (as reviewed in Harmens et al. (2018b) with additional and more recent references highlighted in blue. The range of mean (daytime) ambient O_3 levels during the growing seasons represented in the studies are shown in parts per billion (ppb).

Crop	China (17-65 ppb)	India (33-56 ppb)	Thailand (25 ppb)	Malaysia (32 ppb)	Egypt (25-56 ppb)
Broad bean					39-41
Cowpea					0-13
Maize	9	4-31			
Mustard		7-19			
Palak		27			
Poplar	4				
Rice	2	17-22	6-17	0-6	
Soybean	0-9	30	16-18		51
Wheat	2-25	13-26			61

References: China (Feng et al., 2007; Zheng et al., 2013; Zhang et al., 2014; Zhang et al., 2017; Feng et al., 2018; Feng et al., 2019b; Peng et al., 2020); India (Rai et al., 2007; Rai & Agrawal., 2008; Sarkar and Agrawal, 2010b; Bhatia et al., 2011; Singh and Agrawal, 2011; Sarkar & Agrawal, 2012; Kumari et al., 2013; Singh et al., 2013; Sarkar et al., 2015; Singh et al., 2019); Thailand (Ariyaphanphitak, 2004); Malaysia (Ishii et al., 2004); Egypt (Hassan et al., 2004; Ali & Abdel-Fattah, 2006; Tetteh et al., 2015; Ali 2016).

2.4 Recent data (2018-2020) South and East Asia

Data on different cultivars' relative susceptibility to O_3 pollution is useful in selecting the most tolerant varieties for breeding and growth in different regions, a factor reiterated by two recent studies conducted in northern **India** (Fatima et al., 2019; Pandey et al., 2019). The trials have identified and confirmed O_3 sensitivity in commonly used wheat (*Triticum aestivum*) cultivars and the use of EDU as screening method for O_3 tolerance. Both reported reductions in biomass and yield in mean growing season (December to March) ambient O_3 concentrations of ~50 ppb. The weight of grains plant^{-1} was significantly reduced in all cultivars without EDU treatment, but varied from 9-33% across the three cultivars tested at Varanasi (2015/2016 season, Fatima et al., 2019), 4-36% across the eleven cultivars tested at Lucknow and 2-20% for the same eleven cultivars at Banthra (2011/2012 season, Pandey et al., 2019).

Similarly, Rathore & Chaudhary (2019) have shown the potential to reduce yield losses by identifying more O_3 tolerant varieties of castor bean (*Ricinus communis* L.). In north-west **India** at Gandhinagar, where ambient O_3 levels were low at a mean for the study period of 14 ppb day^{-1} (maximum 43 ppb, 2016/2017 season), seed weight $plant^{-1}$ was decreased in plants without treatment of EDU by between 7-34% across four different cultivars.

Two varieties of maize (*Zea mays* L.), a normal and quality protein variety, showed reductions in yield (kernel weight m^{-2}) of 4% (normal) and 6% (quality) when grown in open top chambers (at Varanasi) with non-filtered air (ambient mean growing season concentration was 56 ppb, December 2012-April 2013) compared to those in charcoal filtered chambers (Singh et al., 2019). Thousand grain weight was also reduced by 14.9% (normal) and 7.9% (quality). Kernel quality was reduced for most parameters (e.g. decline of around 7% for starch, 4% for phosphorous and 2% for potassium). However, although protein content (%) was increased (by 5% and 8%, per cultivar), the total amount of grain protein yield per unit area was reduced, with subsequent implications for nutritional value (conform Broberg et al., 2015). This is because O_3 stressed plants can take up more nitrogen in proportion to the biomass accumulated (Wang & Frei 2011; Singh et al., 2019). In wheat, the reduced grain nitrogen yield per nitrogen applied per unit area resulted in a reduced nitrogen efficiency with respect to both protein and grain yield due to O_3 (Broberg et al., 2017).

Further evidence from **Pakistan** (Faisalabad, in the north-east Punjab region) has illustrated the impact of current O_3 pollution on common crops grown in the area: wheat (*T. aestivum* L.), mung bean (*Vigna radiate* L.) and peas (*P. sativum* L.) (Adrees et al., 2016). Visible leaf injury and reductions in biomass, photosynthetic rate, grain yield, and seed quality, were recorded with increasing ambient O_3 levels at three different locations (representing a natural gradient in O_3 with daytime mean hourly O_3 over the growing seasons, 2013-2014, of between 25-33ppb, 111-125 ppb and 292-350 ppb at each of the sites). A difference was recorded between the two cultivars of each species tested, but maximum losses were 48%, 56% and 52% for grain yield and 41%, 48% and 43% for grain protein (%) content for wheat, mung bean, and peas respectively.

Most of the data from **China** has come from open top chambers studies, and this method was again used at Tangjiapu (north-west of Beijing) to assess the impact of O_3 on a commonly grown maize cultivar (*Zea mays* L., Zhengdan 958; Peng et al., 2020). Total biomass and yield (hundred kernel weight) were reduced by 17% and 9% respectively in non-filtered chambers (September 2018 harvest; AOT40 (accumulated O_3 above a threshold of 40 ppb) of 11 ppm h^{-1}; POD_6 (accumulated stomatal flux of O_3 above a threshold of 6 nmol m^{-2} s^{-1}) of 1 mmol m^{-2} Projected Leaf Area) compared to charcoal filtered air. Water use efficiency, an important consideration for regions of Asia where agricultural water is limited, was not affected at non-filtered, ambient O_3 levels. However, it is worth noting that a significant decrease in water use efficiency was seen at the grain filling stage in elevated O_3 treatments (non-filtered air with the addition of a targeted 60 and 80 ppb O_3).

Recent research in **China** (Changping District, north-west of Beijing) has increased knowledge regarding the sensitivity of different wheat (*Triticum aestivum*) varieties, where ambient growing season mean O_3 concentrations of 57 ppb (daytime, October 2015 - June 2016) significantly reduced yields (g m^{-2}) by around 20% compared to EDU treated plants (Feng et al., 2018). For soybean, Zhang et al. (2017) reported a yield (seed plant^{-1}) reduction of 9% over two growing seasons in plants raised in non-filtered air (where daily mean O_3 concentrations ranged between 20 and 65 ppb, June-September 2013 and 2014, at Harbin) compared to those grown in charcoal filtered air. No recent data was found relating to the direct impact of O_3 on rice yields. However, ambient O_3 in non-filtered open top chambers (mean May-September 2015 of 38 ppb) was shown to induce lodging in the Japonica rice cultivar 'Koshihikari', commonly grown across **Asia** (Yamauchi et al., 2018).

Poplar (*Populus*) is a common agro-forestry crop in Asia (Fang 2008; Weisgerber & Han 2000). In a review of the exposure of poplar to O_3 in open top chambers, Feng et al. (2019b) found that compared with charcoal filtered treatments ambient O_3 levels (mean 40-50 ppb) reduced photosynthesis by 33%, leaf chlorophyll content by 13%, and stomatal conductance by 25%. Decreases were also recorded for total biomass (4%), leaf biomass (16%), plant height (5%), base diameter (18%) and root biomass (11%). Shang et al. (2020) has demonstrated a difference in sensitivity to O_3 in five clones commonly grown in **China**. At ambient O_3 (daily mean 53 ppb, May-September 2014, Changping District) one of the five clones showed visible foliar injury, however, in comparison to charcoal filtered controls, no significant reductions in total biomass were observed.

2.5 Recent data (2018-2020) other ODA regions

There remains a lack of information in other ODA regions. In **Africa**, further evidences was provided for the effect of ambient O_3 on broad bean (*Vicia faba* L. Baladey) yields in **Egypt** from an experiment using a mixture of charcoal filtered and non-filtered air, open-air ambient plots and application of EDU (Ali 2016). During the study in rural eastern **Egypt**, mean O_3 concentrations were between 39-56 ppb (December 2010-May 2011). In plants without application of EDU, O_3 significantly reduced the total biomass (by 8-11%), seed weight (by 39-41%) and seed protein content (mg g^{-1}, by 34%) in the non-filtered and ambient air treatments compared to the charcoal filtered chamber. The foliar EDU applications in the trial not only increased total biomass (by 3-4%) in the non-filtered and ambient air treatments compared to their non-EDU treated counterparts, but also the weight of seed per plant (by 32-34%). The overall nutritional quality of the seed (derived from a combination of sugars, proteins, potassium and calcium) was also improved. Interestingly, the increased biomass gained from application of EDU was more prominent in the shoot and leave than in the roots (although some improvement in root nodulation was also noted), which resulted in yield improvements due to the translocation of photosynthates to enhance flowering and seed. Although overall seed quality was improved with EDU, the treatment also increased the amount of non-nitrogen compounds, leading to a reduction in protein content. This is in contrast to the increase in seed protein found in soybeans treated with EDU (Ali & Abdel-Fattah, 2006).

In **South America,** further instances of foliar injury have been reported in southern **Brazil** affecting tobacco and guava, confirming their use as bio-indicator plants. Tobacco (*Nicotiana tabacum* 'Bel-W3′) plants, placed in a mixture of urban and industrial locations across the Rio Grande do Sul state and exposed to ambient air, showed leaf damage characteristic of O_3 stress (Kaffer et al., 2019). The leaf injury index ranged from 11-28% even though O_3 levels during the trial (mean concentrations of between 8 and 33 ppb during the periods October 2014 to

April 2015 and September to November 2015) were within standard limits set by Brazilian legislation (80 ppb). Precursors to visible leaf injury have also been identified in tobacco (*Nicotiana tabacum* ‘Bel-W3′) and guava (*P. guajava* ‘Paluma’) exposed to natural O_3 (mean concentrations between 25 and 46 ppb) in an urban area of Sao Paulo (Alves et al., 2016). Compared to control plants (kept in a greenhouse with filtered air) physiological alterations including cell wall thickening and wart-like protrusions along with accelerated cell senescence were observed.

3 Risk assessments: modelled O_3 impacts

3.1 Background

Assessing the risk of O_3 impacts on crops through modelling has so far been based on three broad approaches: exposure-response relationships between O_3 concentration and crop yield; flux-effect relationships between modelled stomatal O_3 fluxes and crop yield or quality, accounting for plant O_3 uptake rather than exposure; and process-based simulation of physiological effects of O_3 on plant processes. Generally, stomatal flux-based methods have provided a better fit to measured losses than concentration-based methods and allow for other factors to be considered that contribute to O_3 uptake (for example plant development, soil water status and climatic conditions). Therefore, they are considered to be more biologically relevant (Emberson et al 2018; Mills et al. 2018c; Fischer 2019; Ronan et al., 2020).

Global modelling using the flux based POD_3IAM metric (Phytotoxic Ozone Dose above a stomatal flux of 3 nmol m^{-2} s^{-1}, adapted for large-scale Integrated Assessment Modelling) has been used to identify crop growing areas most at risk from adverse O_3 impacts on the staple crops soybean, wheat, rice and maize (Mills et al., 2018c). Data extrapolated from that study for ODA countries were reported in detail in Harmens et al. (2018b). The mean modelled percentage yield losses for four major regions ranged from 3.3-5.3%, 4.5-7.6%, 5.3-10.0% and 7.4-15.3% for rice, maize, wheat and soybean respectively (Table 4). For rice, maize and wheat, the highest annual production losses were reported for South & Eastern Asia. For soybean, the highest production losses were seen in Central and South America. An earlier modelling study with wheat only indicated that global wheat yield losses calculated using the flux-based method are about 30% lower compared to using a concentration-based approach (Mills et al., 2018b). For China and India, flux-based wheat yield losses are about 50% lower compared to concentration-based yield losses.

Table 4. Yield (%) and production losses (million tonnes, MT; averaged over 2010-2012) for important crops in different global regions as modelled in Mills et al. (2018c).

	Soybean		Wheat		Maize		Rice	
Region	Yield	MT	Yield	MT	Yield	MT	Yield	MT
South & Eastern Asia	15.3	5.2	10.0	29.8	7.6	30.5	5.4	45.7
SEE/EECCA	12.9	0.4	6.9	5.5	6.0	2.4	4.5	0.1
Central & South America	9.5	13.6	6.3	1.7	4.9	7.1	3.5	1.1
Africa	7.4	0.2	5.3	3.1	4.5	3.3	3.3	0.9

Variation in losses across cropping seasons are likely to occur due to seasonal variations in O_3 concentrations. For example, results from flux based modelling (POD_{10}, accumulated stomatal flux of O_3 above a threshold of 10 nmol m^{-2} s^{-1}) showed that rice yield in Vietnam was reduced by 5.7% for the first crop (November to February), 0.51% for the second crop (March to June) and 3.8% for the third crop (July to October) (Danh et al., 2016).

3.2 Recent modelling data

Confirming the spatial variation in O_3 impacts reported by Mills et al. (2018c), lower crop yields in tropical regions were also estimated by Shindell et al. (2019). They used an empirical crop model with a statistical relationship approach (for impacts of temperature, precipitation, CO_2 (carbon dioxide) concentrations, and O_3) and M7 and M12 exposure indexes (seasonal mean daytime 7 h and 12 h surface O_3 concentrations). They noted that South and East Asia have large impacts from aerosols and O_3 precursors, leading to a greater sensitivity to methane emissions.

AOT40 exposure-based modelling is also still being used. The metric has been reported in a large number of studies, and can therefore be used as a method of comparison (Mills et al., 2018b; Pleijel et al., 2019). However, it should be noted that the spatial variation differ for concentration and flux-based modelling (Mills et al. 2018c). Modelled yield losses for wheat and rice in **India** were revisited by Sharma et al. (2019) using a different set up of a previously used O_3 simulation model (WRF-Chem simulated O_3, converted to AOT40). Yield loss estimates increased using the updated method: from 5% to 21% for wheat and from 2% to 6% for rice. For wheat, these results correspond with the AOT40-based yield losses of 22% calculated by Mills et al. (2018c) and with a recent review of yield losses in India reported from modelling studies. The review concludes a reduction of 30% compared to yields under 1970's solar radiation and O_3 below 40 ppb, with O_3 causing two thirds of the modelled losses (Fischer 2019). It is suggested that current losses are exacerbated by new varieties bred for increased yields and greater use of irrigation causing higher stomatal conductance.

In **China,** two new studies have estimated losses due to O_3 for wheat, rice, maize and soybean using this concentration-based approach. Lin et al. (2018) estimated national relative yield losses of 29% for wheat (similar to the 25% losses calculated by Mills et al., 2018b), 17% for early rice (May-July), 12% for single crop rice (August-October), 11% for late rice (September-November), and 5% for maize for the year 2014. Yi et al. (2018) estimated national losses of 2.3% for rice (season not specified), 8.9% for maize and extremely high losses of 64.5% for wheat, and 61.2% for soybean. Assumptions relating to O_3 concentration and dose-response functions may have caused the differences in results between the two studies. However, much lower yield reductions for wheat were estimated by Feng et al. (2019a) using measured O_3 concentrations and both AOT40 and POD_{12} (Phytotoxic Ozone Dose over a threshold of 12 nmol O_3 m^{-2} s^{-1}) metrics. National (**China**) wheat yield losses (mean 2015 and 2016) were calculated as 10% (POD_{12}) and 18% (AOT40). Uncertainties in climatic variables and the lack of corrections (in some studies) for vertical gradients of O_3 and wind near the crop canopy are suggested as possible reasons for the previous high estimates.

In a global study using a process based model (LPJmL) with simulated O_3-induced plant damage occurring via stomatal fluxes inside and outside the leaf (with O_3 data derived from a chemical transport model), Schauberger et al. (2019) provide estimated losses of soybean and wheat for the period 2008-2010 (Table 5). Different sensitivities (as reported in studies Emberson et al. (2009) and Feng et al. (2012)) between Asian and Western (European and North American) wheat were included.

Table 5. Percentage yield reductions due to O_3 for soybean and wheat in different global regions estimated using a process-based crop model (Schauberger et al., 2019).

	Yield loss (%)	
Region	Soybean	Wheat
Central & South America	3.8	1.4
China (East Asia)	6.2	34.2[a]
India (South Asia)	5.3	36.7[a]
Europe	10.7	14.2
Africa & Middle East	1.8	6.1

[a] *Increased O_3 sensitivity used for Asian wheat varieties.*

Results showed soybean losses to be less than in previous studies, but generally higher for wheat in Europe and especially Asia. However, the results for **China** and **India** may include an element of error due to issues arising from the growth period used of April to August (instead of the more realistic January to March) and the use of greater sensitivity for Asian varieties (Fischer 2019). Pleijel et al. (2019) tested differences in wheat sensitivity to O_3 for different global regions (using literature data from field grown plants, AOT40 metric, and dose response relationships), and while there was a significant difference between the sensitivity of North American wheat compared to European and Asian wheat (in grain yield) there was no difference between Asian and European wheat.

3.3 O_3 impact on wheat production in 2030

Emission data from the "Current Legislation Emissions" (CLE) scenario developed under the European Union's Seventh Framework Programme project ECLISPE (Evaluating the Climate and Air Quality Impacts of Short-Lived Pollutants; Stohl et al., 2015) were used to calculate O_3 fluxes to wheat for 2010 and 2030, using the metric POD_3IAM (LRTAP Convention, 2017). Subsequently, percentage wheat yield losses and production losses were calculated and mapped for ODA countries. The methodology is described in further details in supplement 2 of Harmens et al. (2019b). The spatial variation in percentage yield and production losses was similar for 2010 and 2030 (Harmens et al., 2019b); here we only include the maps for 2030 (Figure 3). The highest wheat yield and production losses are seen in China and India, with some locally high losses in Egypt too. Hence, the highest losses are predicted for South and Eastern Asia, followed by South and Eastern Europe, Caucasus and Central Asia (SEE/EECCA region; Table 6). For 2030, the total wheat production losses are estimated to be 17.9 and 19.6 million tonnes in 'Lower Middle Income Countries' and 'Upper Middle Income Countries' respectively, compared to and 19.4 million tonnes developed countries. Similar losses for 2010 and 2030 can be explained by the slight rise in global methane emissions and hardly any change in nitrogen oxides emissions between 2010 and 2030.

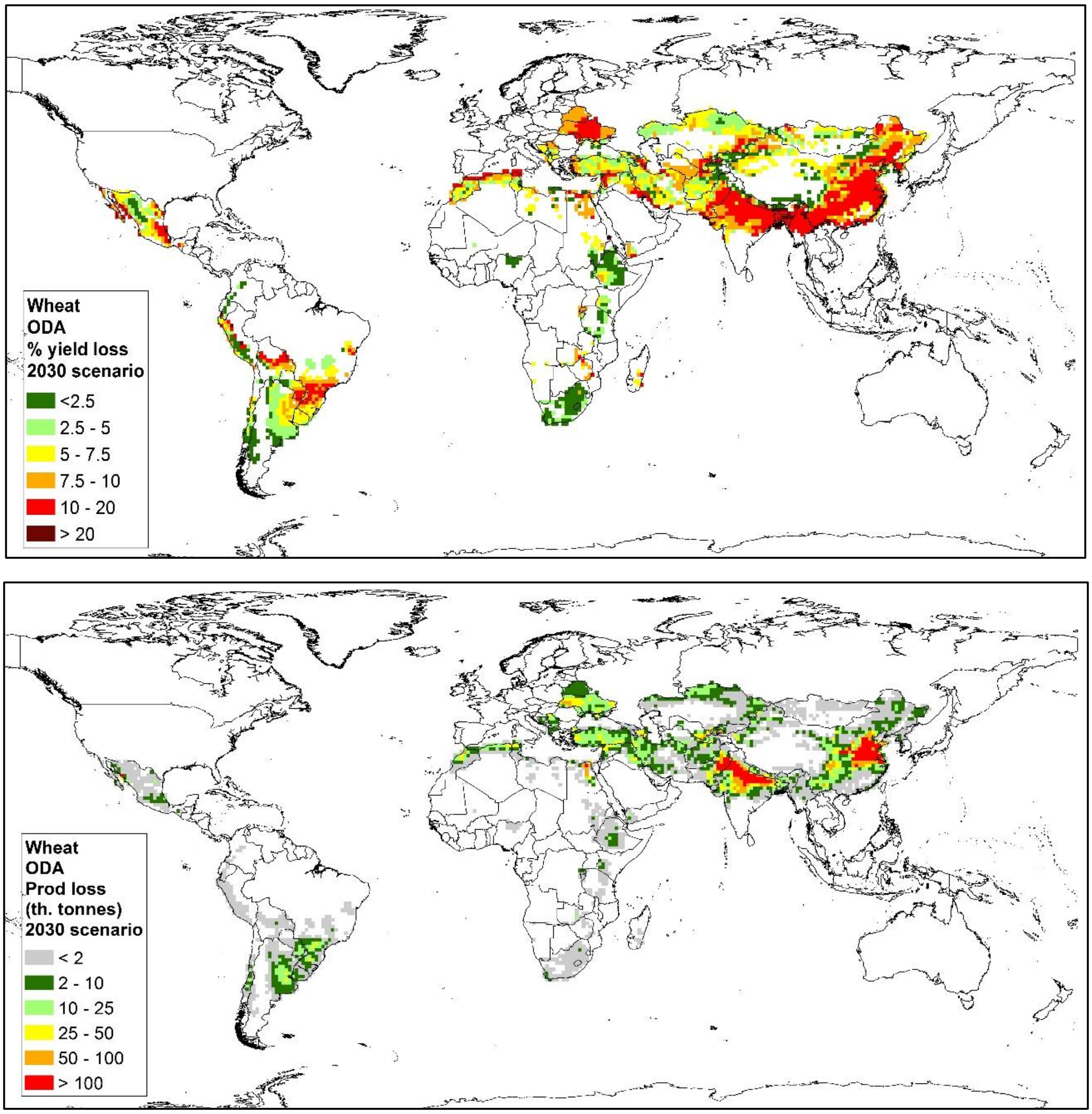


Figure 3. Average wheat yield (%) and production loss (thousand tonnes) per 1° by 1° degree grid cell for wheat growing in ODA countries in 2030, assuming full implementation of current legislation. Grid cells were included if the total crop production per cell was >500 tonnes.

Table 6. Average wheat yield (%) and production loss (million tonnes, MT) predicted for 2030, assuming full implementation of current legislation. Total annual production (million tonnes), average for the period 2010-2012, was used as reference for the production data.

Region	Yield loss (%)	Production (MT)	Production loss (MT)
Central & South America	6.26	25.84	1.74
South and Eastern Asia	9.26	236.45	28.28
SEE/EECCA	6.59	69.93	5.25
Africa	5.38	43.63	3.04

3.4 Case studies: India and South Africa

We provide some more in-depth analysis of O_3 impacts on major crops grown in India and South Africa. These countries were chosen as more detail on crop production and distribution data is available for these countries from collaborating scientists.

Each case study uses a flux-based approach, taking into account environmental factors affecting the stomatal uptake of O_3 (including light, temperature, soil moisture and relative humidity). The use of O_3 fluxes rather than O_3 concentrations should produce a more realistic assessment of yield losses due to O_3 and their spatial distribution.

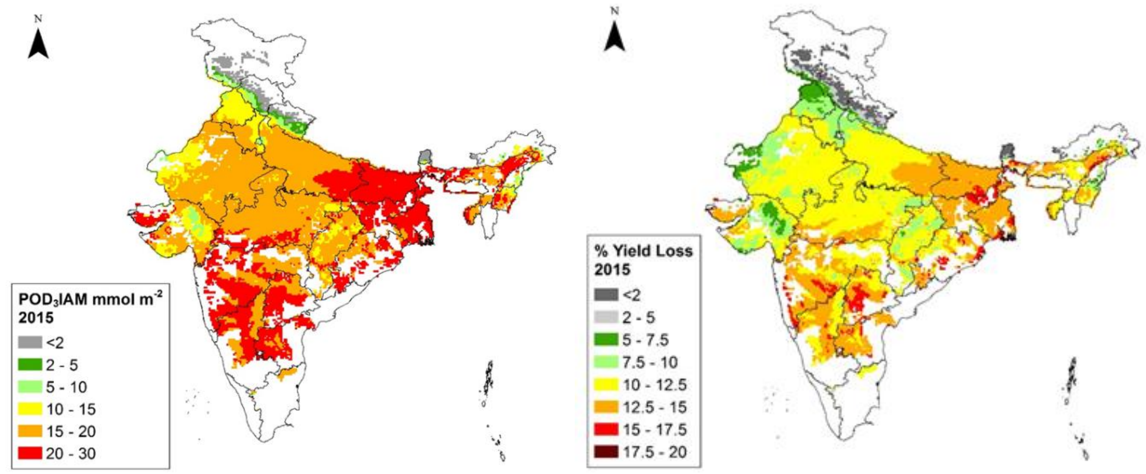
India

India is the second largest producer of wheat (FAOSTAT 2018). However, 70% of the land area under wheat cultivation shows stagnation in yield (across the period 1961 - 2008) due to a possible combination of many (location-specific) factors, including heat stress, depletion of soil fertility, soil erosion and pests/diseases (Ray et al., 2012).

Using global chemistry transport models with concentration based metrics of O_3, the extent of wheat yield loss due to O_3 has been calculated as between 13-28% (Van Dingenen et al., 2009) and between 8 – 27% (Avnery et al., 2011). A more recent global study using O_3 flux estimated wheat yield losses of between <2 and >20% across India (mean of 13%), varying with region (Mills et al., 2018c). There is also substantial empirical evidence that O_3 has a negative impact on the yield of Indian wheat. For example, a decrease in yield (weight of grains per plant) of between 10.7 and 31.3% was seen for 14 Indian wheat cultivars exposed to elevated O_3 (+30ppb above ambient) in open top chambers throughout the growing season (Singh et al., 2018).

This case study combined fine-scale O_3 flux data (0.11 x 0.11 degrees, from the EMEP-WRF South Asia model for 2015), spatial data on wheat production across India (using Spatial Production Allocation Model data for 2010) and Indian government data on wheat production per state with the aim of improving current estimates of the impact of O_3 on Indian wheat production. The EMEP-WRF model outputs both irrigated (calculated without soil moisture limitation) and non-irrigated (calculated using soil moisture limitation) POD_3IAM values per grid cell. The percentage of irrigated production per 0.11 x 0.11 degree grid cell (using SPAM data) was used to calculate the weighted POD_3IAM per cell.

Modelled O_3 flux (POD_3IAM) varied across India in 2015 (Figure 4a). Values were highest in the northeast of India (e.g. Bihar, eastern areas of Uttar Pradesh, West Bengal and Jharkhand) and in central states, including Maharastra, Telangana, Andrha Pradesh and Karnataka. The average POD_3IAM across India was 17.8 mmol m^{-2}. Yield loss due to O_3 followed a similar pattern to O_3 flux, with the highest values (15-20%) seen in eastern and central areas of India (Figure 4b). The state with the highest average yield loss was Bihar (14.2%), while the average yield loss across India was 11.3%. In the states with the highest wheat production in 2015, yield loss was 11.7% (Uttar Pradesh), 11.5% (Madyha Pradesh) and 8.1% (Punjab). The total wheat production loss due to O_3 was estimated at 11.8 million tonnes. Indian states with the highest wheat production, including Uttar Pradesh and Madhya Pradesh, were estimated to be at the highest risk of losses due to O_3 (Figure 5). Results per Indian state are summarised in Table 7.



4a) b)

Figure 4. a) Modelled O_3 flux (POD3IAM) for 2015 from the EMEP-WRF South Asia model (per 0.11 x 0.11 grid cell). Flux values are weighted by the percentage of irrigated wheat production per cell; b) Yield loss (%) due to O_3 for Indian wheat in 2015.

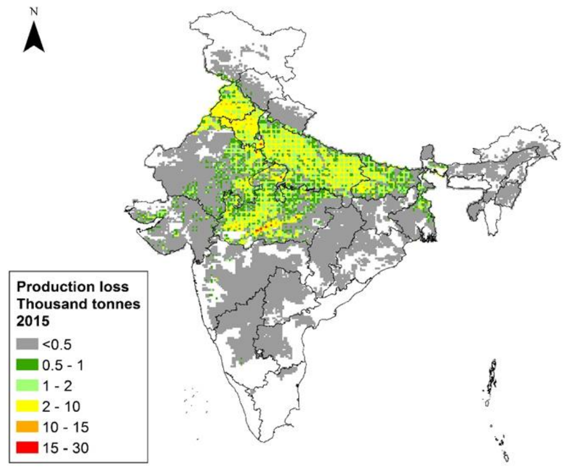


Figure 5. Wheat production loss (thousand tonnes per 0.11 x 0.11 grid cell) in India due to O_3 in 2015.

While the spatial patterns of O_3 flux and yield loss for India vary between this case study and a previous global study for the period 2010-12 (Mills et al., 2018c), the average annual yield (12.6% for India in global study) and production loss (12.6 million tonnes for India in global study) remain similar. The above-mentioned modelled wheat losses are based on O_3 flux-effect relationships developed for European varieties (LRTAP Convention, 2017). The results would be more robust if flux-effect relationships for Indian wheat cultivars most commonly grown were used. Although some past studies suggest that Asian wheat varieties are more sensitive to O_3 than European varieties (e.g. Emberson et al., 2009), a more recent study (Pleijel et al., 2019) suggests that this is not the case. It is also recommended to conduct a sensitivity analysis in the future to investigate how variations in growing seasons (for example due to late arrival of monsoon rains, irrigation practices or use of early maturing varieties adapted to heat resistance) might affect O_3 fluxes and subsequent impact on wheat yield and production.

Table 7. Summary statistics for wheat production per Indian state. Production data is from the SPAM 2010 model. Production totals for 2015 were estimated using a conversion factor value, calculated per state from Indian government production data for the years 2010 and 2015.

Indian state	Prod. 2010 (Th. tonnes)	Prod. 2015 (Th. tonnes)	Av. POD_3IAM	Av. % Yield Loss	Prod. loss (Th. tonnes)
UTTAR PRADESH	27814	24915	18.43	11.73	3325
MADHYA PRADESH	9911	22987	18.22	11.59	3056
PUNJAB	14326	13986	12.80	8.13	1284
RAJASTHAN	8166	11172	16.52	10.51	1392
HARYANA	10588	10335	15.46	9.83	1121
BIHAR	4488	5205	22.33	14.23	863
GUJARAT	3214	1986	16.03	10.20	230
WEST BENGAL	1033	1135	22.05	14.05	191
JAMMU & KASHMIR	659	735	2.64	1.62	40.94
UTTARAKHAND	739	640	6.14	3.87	64.29
MAHARASHTRA	1784	588	20.48	13.04	91.47
HIMACHAL PRADESH	448	557	4.14	2.58	27.57
JHARKHAND	92	159	21.79	13.88	25.81
KARNATAKA	254	158	20.16	12.84	23.60
DELHI	131	131	9.60	6.08	9.58
CHHATTISGARH	115	125	16.90	10.75	15.48
ASSAM	58.15	38.40	20.27	12.91	5.62
TELANGANA	13.38	13.38	21.53	13.72	2.07
MANIPUR	6.21	6.21	17.77	11.31	0.87
ARUNACHAL PRADESH	5.85	5.85	12.69	8.06	0.35
TRIPURA	4.81	4.81	19.10	12.16	0.70
SIKKIM	3.77	3.77	1.37	0.81	0.15
NAGALAND	3.11	3.11	12.40	7.87	0.25
MEGHALAYA	2.68	2.68	20.86	13.29	0.43
CHANDIGARH	2.61	2.61	12.20	7.74	0.22
ODISHA	5.63	0.77	20.53	13.08	0.11
ANDHRA PRADESH	0.57	0.57	21.35	13.60	0.09
DADAR & NAGAR HAVELI	0.14	0.14	17.62	11.21	0.02
TAMIL NADU	0.08	0.08	15.91	10.12	0.01
KERALA	0.0001	0.0001	21.02	13.39	0.00002
INDIA	83868	94894	17.76	11.30	11773

South Africa

While there is little measured data on O_3 concentrations for much of Africa, model simulations suggest that O_3 increased over the last four decades in central Africa (Ziemke et al., 2019). In South Africa, O_3 monitoring is carried out across a network of air quality monitoring stations (https://saaqis.environment.gov.za/). High O_3 concentrations are observed in many parts of South Africa, which exceed the limit of an 8h moving average of 61ppb (Laakso et al., 2013). Wheat is an important cereal crop in South Africa and is in the top five crops in terms of production (FAOSTAT 2018). In 2015, the total requirement for wheat was 2.7 million tonnes, which was higher than the total production (Department of Agriculture, Forestry and Fisheries, 2016). Dry beans (*Phaseolus vulgaris*) are also regarded as an important field crop in South Africa due to their high protein content and dietary benefits.

This case study combined fine-scale O_3 flux data (0.33 x 0.33 degrees, from the EMEP-WRF Africa model for 2015), spatial data on crop production across South Africa (using Spatial Production Allocation Model data for 2010), flux-effect relationships from experimental data and government data on crop production per province to estimate current impacts of O_3 on crops in South Africa. The EMEP-WRF Africa model was run using emissions data based on the IIASA ECLIPSE v6a (Evaluating the Climate and Air Quality Impacts of Short-Lived Pollutants) GAINS (Greenhouse gas – Air pollution Interactions and Synergies) model emissions scenarios for 2015, 2030 and 2050. The Current Legislation (CLE) scenario was used, which assumes full implementation of national legislations as of 2013. The model outputs both irrigated (calculated without soil moisture limitation) and non-irrigated (calculated using soil moisture limitation) POD_3IAM values per grid cell. Using information on percentage of irrigated production (SPAM 2010 spatial data) and growing seasons for irrigated and non-irrigated crops across South Africa, grid cells were classed as either irrigated or non-irrigated to assign an O_3 flux value per cell. For wheat, the flux-effect relationship used to calculate O_3 yield loss was from the LRTAP Convention (2017), as there was not enough experimental data from African wheat varieties to provide a robust relationship. For beans, experimental data from the UK CEH Bangor solardomes (for 7 varieties of *Phaseolus vulgaris*) were used to develop a flux-effect relationship.

Modelling O_3 uptake by wheat and beans in South Africa for 2015 suggests that ground-level O_3 has a negative impact on crop production in South Africa. O_3 flux (POD_3IAM) values for wheat were highest in the north of the country, in Limpopo province, with values >12 mmol m^{-2} (Figure 6a, Table 8). The highest average flux value was for the Free State (8.8 mmol m^{-2}), where 28% of South African wheat was produced in 2010. In the Western Cape, the province with the highest wheat production in 2010, O_3 flux values were low. The average flux for South Africa was 6.6 mmol m^{-2}. In 2015, O_3 flux (POD_3IAM) values for bean were highest in the north of the country, particularly in Limpopo and also parts of the North West, Gauteng and Mpumalanga provinces (Figure 6b). The highest average flux value was for Gauteng province (14.3 mmol m^{-2}; Table 9). Flux values were also relatively high in the Free State (up to 18mmol m^{-2}), which is where the majority of bean production in South Africa occurs. The average flux for South Africa for beans was 11.3 mmol m^{-2}.

a) b)

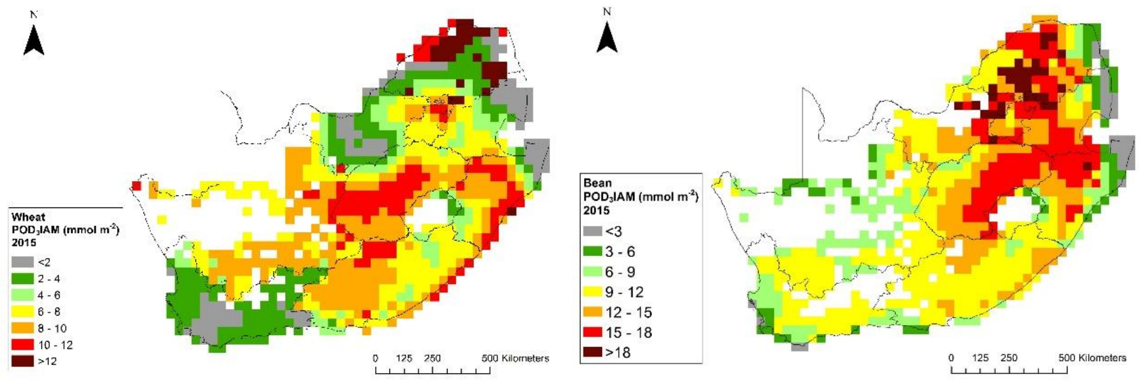
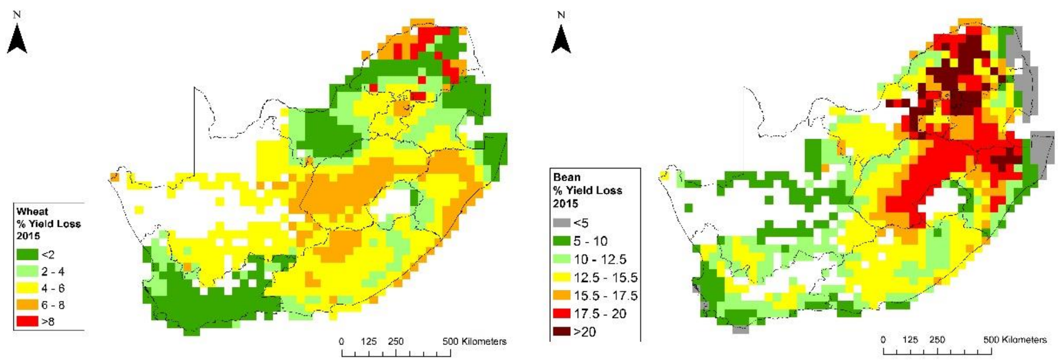


Figure 6. Modelled O_3 flux (POD_3IAM) for 2015 from the EMEP-WRF Africa model (per 0.33 x 0.33 degree grid cell) for a) wheat; b) beans.

Estimates of wheat yield loss due to O_3 varied between <2 and >8%, with grid cell values highest in the north of the country, in Limpopo province (Figure 7a). The highest average yield loss was seen in the Free State (5.6%). In the provinces with the greatest levels of wheat production, yield loss varied between primarily <2% for the Western Cape, areas of 6-8% loss for the Free State and primarily 4-6% yield loss for the Northern Cape. Across South Africa, the average yield loss for wheat was 4.2%.

Estimated yield loss for beans was considerably higher than for wheat, with maximum values >20% (Figure 7b). Losses were highest for grid cells in the northern part of South Africa, particularly in Limpopo and Gauteng. The highest average yield loss was see in Gauteng (16.8%). Areas of losses >20% were also seen in the North West, Mpumalanga and KwaZulu-Natal provinces. In the Free State, the province with the greatest bean production in South Africa (in 2010), estimated yield losses were relatively high, particularly in the eastern half of the province, with estimates of 17.5-20% yield losses. The average yield loss across South Africa for beans was 13.3%.

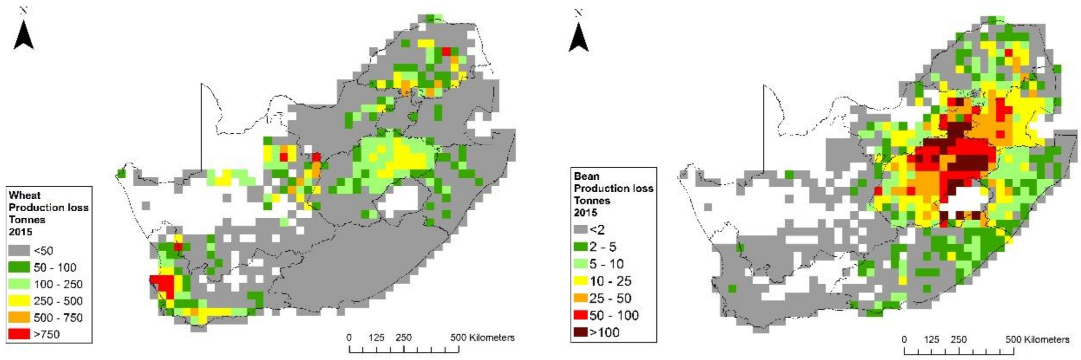


a) b)

Figure 7. Yield loss (%) due to O_3 for a) Wheat; b) Beans in South Africa, 2015, per 0.33 x 0.33 degree grid cell.

As South African wheat production is currently higher for wheat than beans (1.4 million tonnes vs. 35.4 thousand tonnes in 2015, respectively), the actual production losses for wheat were higher than for beans. Wheat production losses due to O_3 were highest in the Northern and Western Cape provinces of South Africa (Fig. 8a), with 15.7 and 14.0 thousand tonnes lost respectively. The Free State (13.7 thousand tonnes) and Limpopo (10.7 thousand tonnes) also showed relatively high losses. The total estimated wheat production loss due to O_3 for 2015 in South Africa was 61.7 thousand tonnes.

Bean production losses due to O_3 were lower than estimates for wheat. The highest losses were seen in the Free State (6,591 tonnes) and Mpumalanga (1,542 tonnes) (Figure 8b). The total estimated bean production loss due to O_3 for South Africa was 11.8 thousand tonnes. Results per South African province are summarised in Table 8 (wheat) and 9 (beans).



a) b)

Figure 8. Production loss due to O_3 for South Africa in 2015, for a) wheat; b) beans, in tonnes per 0.33 x 0.33 degree grid cell.

Irrigated wheat show higher O_3 uptake that rainfed wheat due to stimulation of opening of the leaf pores at higher plant available water in the soil and due to growing later in the season when O_3 concentrations are slightly higher. Applying deficit irrigation or alternate wetting and drying might reduce O_3 uptake by wheat and therefore mitigate O_3-induced yield and production losses. As beans are considered an important crop in South Africa due to their high protein content, it is predicted that efforts may be made to increase bean yield in the future, resulting in higher production losses in the coming years. Assuming full implementation of national legislation from 2013, we predicted no significant changes in O_3 fluxes and impacts on wheat and bean losses for 2030 and 2050 compared to 2015 (with losses lowest in 2030). Therefore, legislation currently in place will not lead to significant improvements. With estimated losses for beans at up to 20% in some areas of the country, further action is required to mitigate O_3 impacts on crops in South Africa in the future. There is also a need to compare measured surface O_3 data in South Africa with estimated modelled values from the EMEP-WRF model. Initial analyses indicate higher O_3 values towards the end of the year (spring-summer) for both observed and modelled data, however the modelled data also show high values at the start of the year in contrast to measured data.

Table 8. Summary statistics for South African wheat. Production data is from the SPAM 2010 model. Production was estimated for 2015 using a conversion factor value, calculated per province from South African government production data for the years 2010 and 2015.

Province	Total wheat prod. (2010) (Th. T)	% Irrigated production	Total wheat prod. (2015) (Th. T)	Av. POD_3IAM 2015	Av. % Yield loss 2015	Total Prod Loss 2015 (Th. T)
Western Cape	670	21.81	881	2.53	1.56	14.04
Northern Cape	272	55.56	279	8.24	5.21	15.68
Free State	520	4.97	242	8.84	5.60	13.65
Limpopo	109	40.33	240	7.00	4.42	10.69
North West	123	20.14	85.97	4.01	2.50	2.39
KwaZulu-Natal	39.88	32.97	54.50	7.24	4.57	2.94
Mpumalanga	38.65	19.18	32.21	4.66	2.92	1.21
Eastern Cape	22.99	56.63	19.16	7.83	4.95	0.97
Gauteng	11.27	15.57	2.25	7.88	4.98	0.12
South Africa	1806	23.63	1837	6.62	4.18	61.69

Table 9. Summary statistics for South African beans. Production data is from the SPAM 2010 model. Production was estimated for 2015 using a conversion factor value, calculated per province from South African government production data for the years 2010 and 2015.

Province	Total bean prod. (2010) (T)	% Irrigated production	Total bean prod. (2015) (T)	Av. POD_3IAM 2015	Av. % Yield loss 2015	Total Prod Loss 2015 (T)
Free State	20568	7.26	33300	13.74	16.15	6591
Mpumalanga	11789	10.42	8322	11.62	13.66	1542
Eastern Cape	1800	16.75	7201	10.92	12.83	1070
Gauteng	3288	13.10	4326	14.25	16.75	889
KwaZulu-Natal	6837	30.93	3703	10.20	11.99	522
Limpopo	7894	63.89	3107	13.53	15.90	650
North West	4957	29.58	2163	13.43	15.78	459
Northern Cape	1023	89.47	614	8.84	10.38	69.4
Western Cape	630	35.50	420	8.57	10.07	41.5
South Africa	58786	22.48	63156	11.29	13.26	11,833

4 Challenges, mitigation options and policy implications

4.1 Challenges

This review is an update from our report submitted in 2018 (Harmens et al., 2018b). The challenges and conclusions drawn in the 2018 report are still valid. For the majority of ODA countries, little to no field-based evidence is available for O_3 impacts on crops. Data is especially lacking for Africa (although some evidence is presented here for Egypt), most of Central and South America and South Eastern and Eastern Europe, Caucasus and Central Asia. In many of these regions, for example Central Africa, Brazil and Argentina, O_3 flux modelling indicates that O_3 fluxes may well be high enough to be causing visible injury and reducing crop yield. Thus, the lack of field evidence of effects should not be interpreted as there being no effects. The absence of evidence reflects a lack of experimental work or leaf injury assessments and likely a lack of knowledge on O_3 impacts on crops in these regions. What limited evidence that does exist, e.g. from isolated sites in North or South Africa and Brazil, is currently in the form of visible leaf injury. In contrast, in the last two decades, considerable evidence of O_3 impacts on crops has emerged from a limited number of locations in China, India and to some extent Pakistan, where experts on O_3 impacts on vegetation are active, with updated information since 2018 provided in this report. The sensitivity to O_3 varies between crop species, with legumes such as bean and soybean often reported as very sensitive, wheat being sensitive and rice and maize being less sensitive to O_3 (in agreement with Hayes and Mills, 2011). In addition, the sensitivity to O_3 varies between varieties of crop species.

Global modelling indicates that the highest production losses for wheat, rice and maize are in South and Eastern Asia, with China and India having the highest production and O_3-induced losses for these crops. For both wheat and rice, greater production losses were estimated for ODA countries compared to developed countries. Estimated annual production loss for wheat (mean of 2010-2012) in ODA countries was ca. 75% greater than for developed countries (Mills et al., 2018c). Around two-thirds of the demand for wheat is from developing regions of the world, and the total demand in developing countries has grown annually by twice that for developed countries (1.37% and 0.69% respectively, for the period 2001-09; Shiferaw et al., 2013). For wheat it was shown that the global yield and production losses are not expected to decline in the coming decade due to hardly any change predicted in ground-level O_3 concentrations and uptake in wheat under full implementation of current legislation. For rice, estimated production losses were largely in ODA countries rather than developed countries, in part due to the distribution of rice production in the world. Many countries in South and Eastern Asia rely heavily on rice, with consumption in India, China and Indonesia (countries showing high estimates of production losses due to O_3) providing ca. 27%, 29% and 52% of dietary energy consumption per capita per day respectively (FAOSTAT, 2013).

Other modelling-based studies to assess the extent and magnitude of O_3 risk to agriculture in Asia suggest that yield losses of 5–20% for important crops may be common in areas experiencing elevated O_3 concentrations (Emberson et al., 2009). As in our study, these assessments have relied on European and/or North American dose–response relationships and hence assumed an equivalent Asian crop response to O_3 for local cultivars, pollutant conditions and climate. A review conducted by Emberson et al. (2009) indicated that Asian grown wheat and rice cultivars are more sensitive to O_3 than North American dose–response relationships would suggest. Sinha et al. (2015) also reported higher O_3-sensitivity (by a factor two or more) for South Asian wheat, maize and rice cultivars compared to European and American varieties. When the higher sensitivity is taken into account, yield losses for wheat can rise to about 35% in China and India (Schauberger et al., 2019), however, some uncertainties are associated with this estimate arising from the application of a less realistic growth period for wheat in that study. In addition, Pleijel et al. (2019) found no difference in O_3-sensitivity between Asian and European wheat varieties, only a difference in O_3-sensitivity between American wheat varieties compared to European and Asian varieties. Recent field-based studies using a chemical protectant against O_3 suggest that current ambient O_3 levels reduce wheat yield by about 20% in a suburb of Beijing, China (Feng et al., 2018), with losses varying between varieties.

4.2 Options to mitigate O_3 impacts on crops

The preferred option to reduce adverse impacts of O_3 on crop production and quality would be to reduce emissions of O_3 precursors. To achieve this, more ambitious air pollutant abatement policies are required globally, i.e. policies that go beyond current legislation (Harmens et al., 2019b). For important staple crops, areas currently most at risk of adverse impacts of O_3 on food production include China, India, Europe and North America. However, in many parts of developing regions, other crops such as beans are important as a subsistence crop to local farmers; beans tend to be very sensitive to O_3.

Many studies have reported varietal difference in response to O_3. Hence, there is scope for breeding more O_3-tolerant varieties to mitigate impacts of ground-level O_3 on crop production. Recent experimental advances have improved understanding of the O_3 sensing, signalling and response mechanisms in plants (Ainsworth, 2017). This provides a fundamental background and justification for breeding and biotechnological approaches for improving O_3 tolerance in crops. Traits for O_3 tolerance have been identified in model and crop species, and although none has been cloned to date, experiments have identified candidate genes associated with the traits. Biotechnological strategies for improving O_3 tolerance are also being tested, although there is considerable research to be done before O_3-tolerant germplasm is available to growers for most crops. Strategies to improve O_3 tolerance in crops have been hampered by the lack of translation of laboratory experiments to the field and lack of awareness of crop breeders on impacts of O_3 on crop production. So far, impacts of O_3 on crop varieties has not been included in screening for high-yielding varieties. Mills et al. (2018c) discussed breeding new varieties with multiple stress tolerance for O_3 and typically co-occurring stresses such as heat, pests and diseases, aridity and nutrients. Breeding for O_3 tolerance traits may cause potential synergies or trade-offs that need to be considered in breeding programmes.

In addition, potential management options should be tested that might result in a reduction of O_3 impacts on crops. Such management options include:

- Reduced irrigation. O_3 impacts on crops could be reduced by partial leaf pore closure induced by reduced irrigation, which could also save water use for irrigated crop production. In rice-growing countries, in response to the increasing water demands by other sectors than agriculture, alternate wetting and drying irrigation has become popular in an attempt to reduce water usage and methane emissions (Bouman et al., 2007; Carrijo et al., 2017). Recently, Harmens et al. (2019a) showed that reduced irrigation stimulates individual grain weight and harvest index of an African wheat variety, which compensated for the O_3-induced reductions observed in well-watered plants. Hence, reduced irrigation could potentially be exploited to mitigate O_3 impacts on crops, however further study is required at the field scale.
- Fertilizer application to compensate for crop yield losses. Although crop yield losses from O_3 exposure could potentially be mitigated by increasing the fertilizer application rate, recent analysis has indicated that this mitigation approach may be associated with an aggravation of other environmental problems, such as nitrate leaching, conversion of fertilizer to N_2, emission of N_2O and even NO, which promotes further O_3 formation (Broberg et al., 2017). O_3 has shown to reduce fertilizer use efficiency in wheat and particularly soybean (Broberg et al., 2017, 2020). Since the absolute protein concentration is on average much higher in soybean than wheat (about three times higher) and rice (about four times higher), O_3 has a much larger negative effect on protein yield in soybean than cereals. This has serious consequences considering the important role of soybean as a protein source for food and feed globally. The application of additional fertilizer is also not very cost-effective considering the relatively high cost of fertilizer in many developing countries.
- Chemical protection against O_3 damage. The benefits of the application of EDU have been reviewed in this study, however, EDU has not been evaluated yet for application at the field scale and concerns have been raised about potential toxicity to aquatic plants (Agathokleous et al., 2015). Other potential chemical protectants include inhibitors of the crop stress hormone ethylene, anti-transpirants that reduce leaf pore opening or chemicals that mimic isoprene emissions from plants. However, none of them have been tested at the field scale yet.

4.3 Policy implications

The atmospheric chemistry of ground-level O_3, a secondary pollutant, is complex. Despite a decline in emissions of precursors such and nitrogen oxides (NO_x) and volatile organic compounds (VOCs) in developed regions such as Europe and North America in recent decades, O_3 concentrations are at best only declining in parts of those regions, but often not changing at all or still rising in some areas (Tørseth et al., 2012; Simpson et al., 2014; Mills et al., 2018a). Whilst reduced precursors emissions might have led to a decline in peak O_3 concentrations in some regions, background concentrations tend to rise at the same time, due to long-range transport from other regions. Both rising background and peak O_3 concentrations contribute to the adverse impacts of O_3 on sensitive crop species (Harmens et al., 2018a). Hence, global action is needed to reduce emissions of O_3 precursors. Ground-level O_3 concentrations are predicted to increase regionally by 1 to 8 ppbv in 2050 under various air pollution and climate change scenarios (Turnock et al., 2018). Under current legislation, there is a growing importance to control methane emissions to reduce ground-level O_3 concentrations. Currently, methane emissions are not monitored and reported systematically, which should be addressed in future air quality policy developments. Future policies aimed at reducing ground-level O_3 concentrations would benefit from global concerted actions considering O_3 and its precursors are transported across the globe and O_3 being a short-lived climate forcer too, contributing to global warming.

Whilst NO_x emissions have declined in the last decade in China (Pu Wang, pers. comm.), O_3 concentrations are still rising (Li et al., 2019). Part of this might be contributed to the little change in VOC emissions, with trends in methane emissions being unknown. However, a more important factor determining O_3 trends in the North China Plain might be the recent decrease in particulate matter ($PM_{2.5}$), slowing down the aerosol sink of hydroperoxy radicals and thus stimulation O_3 production (Li et al., 2019). O_3 concentrations are not systematically monitored in rural India and urban monitoring often lack quality assurance of the data (Pommier et al., 2018). Nevertheless, modelling studies report a significant increase between 1990 and 2010 (Lu et al., 2018b) and further increases in the future in line with rising precursor emissions, in some areas exacerbated by climate change (Pommier et al., 2018).

In many developing regions, stringent air pollution abatement policies are to be developed yet. Hence, high quality air pollution monitoring networks such as established in the UNECE region are non-existent. If present, they are often limited to urban areas and little is known about the level of air pollution in rural areas and impacts on food production. Whilst options to mitigate O_3 impacts on crops have been described above (e.g. breeding tolerant varieties and adapting irrigation management), in the long-term a reduction in O_3 precursor emissions is required.

5 Conclusions

This study provides field-based evidence of the adverse impacts of ground-level O_3 on sensitive crop species in ODA countries. However, the majority of the evidence is available only for a selected number of countries in South and Eastern Asia (such as China, India and Pakistan) and from a small number of sites. The reduction of crop yield losses due to O_3 is often in the range of 5 – 20%, with sometimes losses being reported in excess of 40%. Beans and soybean are very sensitive to O_3, followed by the other most-studied staple crop wheat, and with the staple crops maize and rice being moderately sensitive. There is a need to enhance monitoring of impacts of current ambient O_3 concentrations on crop yield and production in other ODA countries and at more sites in large countries to cover the different climatic regions, crops species and varieties grown for food production, especially in countries and regions were ambient O_3 concentrations are relatively high. Modelling studies are often based on knowledge available for varieties grown in developed countries. Such studies show that for rice, maize and wheat, the highest annual production losses in ODA countries are in South and Eastern Asia. For soybean, the highest production losses were calculated for Central and South America. Initial indications are that Asian crop varieties might be more sensitive to O_3 than those grown in Europe or North America. Hence, crop production losses might be higher when modelling is based on Asian crop varieties. Predictions indicate that O_3 pollution remains a problem of global concern in the future, with ground-level O_3 concentrations hardly changing or still rising in many developing regions up to 2050. Hence, food productions remains at risk from adverse impacts of O_3, not only regarding quantity but also quality. Like climate stresses such as heat and drought, O_3 is contributing to the yield gap in food production. Global action is needed to reduce ground-level O_3 pollution in the future, with a focus on reducing emissions of the precursor gas methane. In the absent of stringent air pollution abatement policies, inclusion of O_3-sensitivity assessments in crop breeding programmes and field trials to develop high-yielding O_3-tolerant varieties that are also more resilient to future climate stresses such as heat and drought stress, might contribute to a reduction in future impacts. In addition, potential crop irrigation management options that could contribute to reducing the adverse impacts of O_3 on crops should be tested under field conditions.

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