Evidence of ozone effects on crops in ODA countries: field data and modelling

Contract AQ0846, ICP Vegetation

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Client Defra

Client reference AQ0846

CEH reference NEC06012

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Signed

Date 29/03/2018

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Executive summary

Ground-level (ozone) O_3 concentrations are high in many crop-growing areas of the world, e.g. in North America, Europe, and South and Eastern Asia. Concentrations are increasing rapidly in developing countries and are predicted to continue to increase in coming decades unless suitably ambitious measures are taken to cut precursor emissions. O_3 pollution has adverse impacts on crop production of sensitive species such as beans, soybean, wheat, rice and maize, and therefore contributes to the yield-gap reported for these crops. In this study, we reviewed the literature for field-based evidence of impacts of ambient O_3 levels on crops in 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. The review has shown that for the majority of ODA countries, little to no field-based evidence has been collated 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 contrast, in the last 15 years, 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 often being identified as very sensitive, wheat being sensitive and rice and maize being less sensitive to O_3. In addition, the sensitivity to O_3 varies between varieties of crop species.

Similar losses were reported for a 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. Although rice is the least sensitive to O_3 of the four crops investigated, rice had the highest total production loss in ODA countries (47 MT (million tonnes), growing in 88 ODA countries), primarily due to high production in areas of the world with high O_3 fluxes. Maize (43 MT, growing in 105 ODA countries) and wheat (40 MT, growing in 67 ODA countries) showed similar estimates of production losses, but wheat is grown in fewer ODA countries than maize. Soybean had the lowest estimate of production loss, at 19 MT (growing in 43 ODA countries). However, if soybean production begins to increase further globally, particularly in South and Eastern Asia, there will be higher production losses for this very O_3-sensitive crop species. It should be noted that for wheat, soybean and maize the modelling study was based on dose-response relationships established mainly from European and/or North American data. However, the review provides some examples showing that Asian varieties of the crops studied might be more sensitive to O_3 than European and North American varieties. Therefore, crop production losses might be underestimated for South and Eastern Asian countries in the current modelling study.

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 stress. 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. These approaches will contribute significantly to reducing the current yield gap for crops.

1. Introduction

1.1 Background

Tropospheric or ground-level ozone (O_3) is a secondary pollutant formed in the atmosphere by 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 (nmVOCs; Monks et al., 2015; Royal Society, 2008; Simpson et al., 2014). Annual variation in O_3 concentrations depends on geographical location, proximity to sources of O_3 precursors and prevailing meteorological conditions. This variation in concentration is determined by both photochemical and physical processes, including photochemical production and destruction of O_3, hemispheric transport, and removal by deposition at the Earth’s surface (Monks et al., 2015). For example, in Pakistan, a strong correlation was found between fire events and the tropospheric O_3 column (Noreen et al., 2017) and spring time maxima of ground-level O_3 concentrations were observed in South-Africa, which was attributed to increased regional biomass burning in spring (Laban et al., 2018). Ground-level O_3 concentrations are high in many crop-growing areas of the world, e.g. in North America, Europe, and South and Eastern Asia (Cooper et al., 2014; Mills et al., submitted; Wild et al., 2012). Concentrations are increasing rapidly in developing countries and are predicted to continue to increase in coming decades unless suitably ambitious measures are taken to cut precursor emissions (Cooper et al., 2014; Wild et al., 2012).

Recently, a database of global O_3 observations was established as part of the Tropospheric Ozone Assessment Report (TOAR; Schultz et al., 2017). Data are included from stations which have at least 5 months of hourly measured O_3 data in any given year between 1970 and 2015. The majority of data are available from measurement stations in Europe, North America, Japan and South Korea, with about an equal number of sites being classified as urban or rural. The TOAR data confirmed that O_3 concentrations are generally higher at rural than urban sites due to the titration of O_3 by higher levels of NO_x at urban sites. Very few data exist in Africa, Central and South America, Central Asia, South Asia and the Middle East. Trends for vegetation-relevant O_3 metrics between 1995 and 2014 at rural sites show that such metrics have been declining on North America, increasing in Japan, and with no overall change being observed in Europe (Mills et al., submitted).

Recently, more data on O_3 concentrations in Asia have become available. Rapid industrialisation and economic growth across many parts of Asia have resulted in increased emissions of O_3 precursor pollutants and hence elevated O_3 concentrations. Asia is now the world's biggest emitter of NO_x, a major O_3 precursor, and its NO_x emissions are predicted to further increase over the coming decades (Royal Society, 2008). The largest emissions of NO_x are reported in China, followed by India (less than half the emissions of China), however, it should be noted that high uncertainties are associated with data provided by different global and regional emission inventories (Monks et al., 2015). Until 1990, O_3 concentrations in Chinese cities were low compared to the USA and Europe, but they have increased quite rapidly since then due to increased emissions from automobile traffic and the use of fossil fuels, particularly coal, in electricity generation and industry. The annual mean background O_3 over China shows a spatial gradient from 33.7 ppb in South China to 23.5 ppb in the Northeast/North China (Feng et al., 2015). Current O_3 concentrations are rising at a higher rate in China than in other countries, and the daily 24 hour mean often exceeds 50 ppb on average across the crop growing season in some regions (Tang et al. 2013; Zhao et al. 2009). In recent years, ambient O_3 concentrations have often reached 150 ppb in the afternoon from May to August in farmland near Beijing city. Based on current legislation and current implementation status, China's total NO_x emissions are estimated to increase by a factor of 1.5-2 over the next two decades. Asia is also projected to see a huge increase in the proportion of the population living in urban areas. 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 introduced and successfully implemented.

O_3 damages the leaves of sensitive crops such as wheat, rice and soybean and reduces their yield (Grünhage et al., 2012; Mills et al., 2007; Mills and Harmens, 2011), with species varying in their O_3-sensitivity (Hayes and Mills, 2011). O_3 enters the leaves through the stomatal pores and reacts with biomolecules inside the leaf to form reactive oxygen species, thereby triggering metabolically expensive defense mechanisms, promoting leaf senescence and diverting resources away from growth and seed production (Ainsworth, 2017).

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; Annex 1).

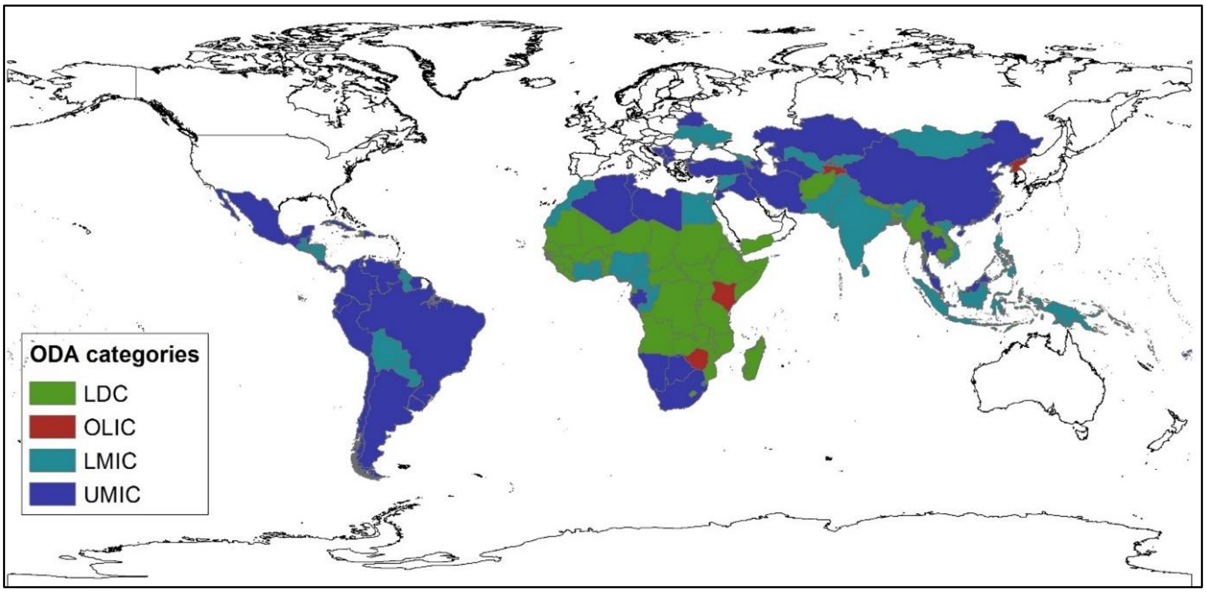


Figure 1. Map of countries on the Official Development Assistance (ODA) list published by the OECD (see Annex 1). Countries are split into the following categories: LDC: Least Developed Countries; OLIC: Other Low Income Countries; LMIC: Lower Middle Income Countries; UMIC: Upper Middle Income Countries.

For the purpose of this report, four major regions were considered:

- South and Eastern Asia;
- Africa;
- Central & South America;
- South Eastern and Eastern Europe, Caucasus, Central Asia (SEE/EECCA).

Both field-based evidence (Chapter 2) and modelled data (Chapter 3) on O_3 impacts on crops are included in this report.

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).

Global flux-based modelling of O_3 impacts on four staple crop species (maize, rice, soybean, wheat) was conducted and modelled impacts on their average annual yield and production in 2010-2012 were mapped for ODA countries where the crops were grown in excess of 500 tonnes per 1^o by 1^o degree grid cell. Modelled impacts on yield and production were also tabulated for the four major regions and ODA categories mentioned above and per ODA country (see Annex 2).

2. Field-based evidence of O_3 impacts on crops

2.1 Introduction

Field-based evidence of O_3 impacts on crops was reviewed by considering three sources of data:

1. *Leaf damage*

When O_3 is taken up by the leaf via the leaf pores (stomata), it is transformed into cell-damaging compounds causing localised cell death. This becomes visible on the leaf surface as small pale yellow, cream or bronze pin-head sized blotches (http://icpvegetation.ceh.ac.uk/publications/documents/CEHOzoneInjury_webmidres.pdf). In severe cases, these spots (known as stipples) can join together to cover large areas of the leaf surface (Figure 2). Spots on the leaves occur between leaf veins, appearing first on the upper leaf surface and then spreading to both sides as the damage worsens. Leaves towards the base of stems and branches (older leaves) are usually more affected than younger leaves as they have been exposed to O_3 for a longer period and O_3 impacts accumulate over time. Visible leaf injury has been recorded on various crop species in Europe (Hayes et al., 2007; Mills et al., 2011), which may lead to a reduction in yield quality and/or quantity. Yield can also be negatively affected by O_3 in the absence of visible leaf damage. Visible leaf damage to leafy crops (e.g. lettuce, spinach, chicory) will reduce their market value.

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

2. *Chemical protectant*

A common experimental chemical protectant against O_3 damage is the antioxidant EDU ((N-[2-(2-oxo-1-imidazolidinyl) ethyl]-N-phenylurea)), a chemical that provides (partial) protection against O_3 when applied in appropriate quantities (dependent upon species and cultivar) as a soil drench or foliar spray at frequent intervals over the crop growth period (Feng et al., 2010; Singh et al., 2014). However, there is still uncertainty as to the mechanism by which EDU confers protection to O_3 (Paoletti et al., 2009; Manning et al., 2011; Agathokleous et al., 2015) and potentially other oxidative stresses and heat stress. The latter might confound the demonstration of O_3 effects at ambient conditions. EDU is known to suppress acute and chronic O_3 injury on a variety of plant species, generally by enhancing activities of antioxidants and anti-oxidative enzymes. 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).

3. *Air filtration*

In open-top chambers, crops can be exposed to non-filtered ambient air and to charcoal-filtered air, where O_3 concentrations are reduced to levels in the same range as pre-industrial O_3 concentrations (Figure 3). The beneficial effect of air filtration on crop yield can be determined in these open-top chambers. For example, Pleijel et al. (2018) reported that ambient air had significant ($p < 0.05$) negative effects compared to charcoal-filtered air on grain yield (−8.4%) and grain quality (starch yield: −10.9%, protein yield: −6.2%). The reduction in grain yield was similar to the average reduction (-9.4%) reported by Mills et al. (in press) in a study modelling the impact of O_3 on wheat yield globally.

Figure 3. Exposure of wheat to O_3 in open-top chambers placed over the crop as it emerged. Source: H. Pleijel, University of Gothenburg, Sweden.

2.2 South and Eastern Asia

Food production in many countries of South and Eastern Asia is under threat due to the rapidly increasing population, industrialisation and economic growth. In Asia there are currently no air quality standards to protect agriculture from ground level O_3. Knowledge on the impacts of O_3 on crops in South Asia was reviewed by Emberson and Büker (2011) and recently updated by Emberson et al. (2014). The majority of studies conducted in South Asia report on the impacts on crop yield, although some studies also report on visible leaf injury. For India and Pakistan, the majority of studies assessing impacts of O_3 on crops were conducted at one site in India (Varanasi) and one site in Pakistan, close to Lahore (Emberson and Büker, 2011; Emberson et al., 2014). In the last 15 years, a wealth of studies have been conducted in China to highlight the impacts of O_3 on crops (e.g. Feng et al., 2010; 2014; 2015; 2017).

Leaf damage

In **China**, visible leaf injury has been observed at ambient O_3 concentrations near Beijing for the following crop species: okra plant, velvetleaf, peanut, winter melon, sword bean, watermelon, hops, courgette, common bean (Figure 4), cowpea and grapevine. Symptoms of visible leaf injury vary per crop species and are described in more detail in Feng et al. (2014). Areas where high leaf injury impacts were most prevalent were those mainly downwind from Beijing. Different types of beans showed distinctive and severe O_3-induced leaf injury symptoms at most of the sites studied. Hence, bean species are a good bio-indicator of O_3-induced visible leaf injury. This is in agreement with studies conducted in Europe and the USA, showing that bean species are the most sensitive to O_3 (Hayes and Mills, 2011). Yuan et al. (2015) observed a higher foliar injury index of up to 55% in O_3-sensitive compared tolerant varieties of common bean at a high ambient 8 h mean O_3 concentrations of ca. 70 ppb in Changping.

Figure 4. O_3-induced leaf injury on an American (left) and local variety (right) of common bean grown near Beijing.

In **India**, visible leaf injury on crops has mainly been reported in the vicinity of the city Varanasi, Uttar Pradesh on the Indo-Gangetic plain. Agrawal (2006) reported an increase in leaf injury from 8 to ca. 30% on tobacco along a rising O_3 gradient away from the urban area of Varanasi. Visible leaf injury was observed in rice grown in non-filtered air and open air plots (5-monthly mean O_3 concentration of 49 ppb), with the percentage of leaf area showing visible injury ranging from 10 – 15%, whereas no visible injury was observed in charcoal-filtered air (5-monthly mean of ca. 4 ppb). Much higher levels of visible leaf injury where observed when the mean ambient O_3 concentration was increased by 10 or 20 ppb, i.e. the percentage leaf area affected was ca. 37 and 60% respectively (Sakar and Agrawal, 2010b). Damaged leaves showed changes in the internal protein profile compared to healthy leaves. Mung bean varieties showed differential sensitivity to O_3 in ambient air. The percentage leaf area showing visible injury generally increased in time, with older leaves showing more damage than younger leaves. The percentage area affected ranged from 5 – 24% 20 days after germination, to 10 – 38% 60 days after germination (Chaudhary et al., 2013; Mishra & Agrawal, 2015). Foliar injury on potato was ca. 22% in ambient air, with no injury being observed when potatoes were grown in elevated CO_2 concentrations (Kumari & Agrawal, 2014). Singh and Agrawal (2011a) reported leaf injury between 20 – 25% for soybean, with injury being reduced by up to 50% when applying the chemical protectant EDU. Growth of two wheat varieties in a field near Lucknow at an average ambient O_3 concentration of 60 ppb (range: 15 – 100 ppb) resulted in visible injury, first on leaves of the most O_3-sensitive variety, whilst the injury was much less or even absent in EDU-treated plants (Gupta et al., 2018).

In **Pakistan**, Ahmad et al. (2013) reported 30-70% foliar injury on crop species (onion, potato, cotton) when mean monthly O_3 concentrations in ambient air exceeded 45 ppb at two rural sites close to Peshawar (north-west Pakistan).

Chemical protectant studies

EDU has been widely used across South and Eastern Asia to assess crop yield losses due to O_3 (Agathokleous et al., 2015; Emberson et al., 2014; Feng et al., 2010; Singh and Agrawal, 2017; Singh et al., 2015a). In **China**, EDU significantly alleviated O_3-induced foliar injury in O_3-sensitive varieties of common bean and increased their rate of photosynthesis, seed (by 46-55%) and pod weight (by 56%) compared to non-EDU treated plants (Yuan et al., 2015). Wang et al. (2007) reported that rice and wheat respond differently to ambient O_3 concentrations (generally 40 – 60 ppb) and EDU applications. In wheat, characteristics such as yield (12.7%), seed number per plant, seed set rate, and harvest index were increased significantly at 300 ppm EDU treatment. In contrast, these characteristics were not affected by EDU application in rice. The different response to EDU between wheat and rice could be attributed to the fact that the wheat cultivar used is more sensitive to O_3 than the rice cultivar and that the average O_3 concentration was lower during the rice growing than the wheat season. Soybean cultivars show a wide range of sensitivity to O_3 in ambient air (Jian et al., in press), with EDU enhancing average biomass by less than 10% in a very O_3-tolerant variety, and by more than 45% in a very O_3-sensitive variety. Whereas Jian et al. (in press) investigated impacts of ambient O_3 and EDU on biomass and plant biochemistry, impacts on yield were not reported. With O_3 concentrations predicted to rise in the future in South and Eastern Asia, higher yield reductions are to be expected. In addition to impacts on crop yield and quality, many of the above studies also report impacts of ambient O_3 on plant growth and metabolism, including photosynthesis, chlorophyll and antioxidant content, and the activity of anti-oxidative enzymes.

A comprehensive review of EDU application as a measure to mitigate O_3 impacts on crop yield in **India** was recently provided by Sing et al. (2014) and Singh and Agrawal (2017). Ambient O_3 levels at suburban sites in India (Varanasi) often induce crop yield losses, generally in the range of 10-20% (but sometimes even more than 40%) for important crops such as wheat, soybean, mung bean and palak, with yield losses varying per variety (Emberson and Büker, 2011, and references therein). In sub-urban Varanasi, O_3 concentrations varied between 34 to 54 ppb during the growing season of wheat from December 2006 to March 2007. Protein content per grain and grain yield per plant increased significantly in EDU-treated wheat with increments varying between 2 and 26%, depending on the variety (Singh et al., 2009; Singh and Agrawal, 2009). EDU treatment alleviated visible leaf injury in field-grown wheat near Lucknow (Gupta et al., 2018). However, 1000-grain weight was only significantly increased after EDU application in the most O_3-sensitive variety. The magnitude of wheat yield stimulation in EDU-treated plants does not only vary per variety but is also dependent on the applied dose of EDU (Tiwari et al., 2005; Singh and Agrawal, 2010).

In soybean grown in suburban Varanasi, EDU alleviated the negative effects of ambient O_3 concentrations (mean O_3 concentration of 42 ppb) by enhancing the first line of defense against reactive oxygen species, protecting nitrogen assimilation enzymes at flowering and maintaining adequate supply of photosynthates to developing pods during pod filling stage (Rai et al., 2015). EDU provided maximum protection between flowering to pod filling stage and EDU provided more protection when O_3 concentrations were high. The number and weight of pods per plant increased significantly by ca. 27% under EDU compared to non-EDU treatment. At a rural site in the eastern Gangetic plains, mung bean yield per plant was stimulated by 49% in EDU-treated plants when grown at an average daytime O_3 concentration of 53 – 65 ppb, with peak concentration often exceeding 80 ppb and sometimes 120 ppb (Singh et al., 2010a). In palak, EDU-treated plants had a higher yield of 29% compared to non-EDU-treated plants at a mean 8 hour O_3 concentration of 52 – 73 ppb (Tiwari and Agrawal, 2009).

EDU also alleviated the negative impact of O_3 in ambient air on yield and oil content in seeds. Seed weight per plant increased by 7-17% and 34-59% in two varieties of mustard respectively, with yield enhancement varying with applied EDU concentration; seed oil content increased by 4-5% (Pandey et al., 2014). EDU enhanced seed weight per plant in O_3-sensitive varieties of Indian black gram by 36-44% but did not affect the yield of a more O_3-resistant variety at an ambient mean O_3 concentration ranging from ca. 40 – 60 ppb (Singh et al., 2010b; Singh et al., 2011b). Starch, total sugar, amino acids and potassium contents increased in seeds of EDU-treated plants leading to improvement in the quality response index (QRI) of seeds (Singh et al., 2010b). In carrot, a significant increase of 23% was recorded for the yield of carrot in EDU compared to non-EDU treated plants at an 8 hour mean O_3 concentration of 36 ppb (Tiwari and Agrawal, 2010).

In the suburbs of Lahore, **Pakistan,** EDU enhanced seed yield by 33-43% in different sesame varieties (Wahid et al., 2012). Whereas a similar stimulation of seed yield per plant was observed at the same site for soybean (47%) in the post-monsoon season, and even higher stimulation (113%) was reported in the pre-monsoon season in EDU treated plants (Wahid et al., 2001).

Air filtration studies

In **China**, Feng et al. (2007) reported a stimulation of 1000-grain weight by 17% and of grain yield per plant by 34% for winter wheat exposed to an 8 hour mean of 10 ppb compared to non-filtered air with an 8 hour mean of 52 ppb O_3. However, this stimulation was not significant, most likely due to the low replication (n = 3) in the study. In contrast, elevated O_3 concentrations (ca. 110 ppb) significantly reduced 1000-grain weight and grain yield compared to charcoal-filtered air. Similarly, Zheng et al. (2013) did not find a significant stimulation (1.3 – 2.5%) in yield for winter wheat in charcoal-filtered compared with non-filtered air; the same was true for rice. In the latter study, mean O_3 concentrations were 7 – 20 ppb in charcoal-filtered air and 17 – 28 ppb in non-filtered ambient air, i.e. the differences in O_3 concentrations between non-filtered and filtered air were rather small and ambient concentrations were low at the site. Based on exposure concentration and stomatal O_3 flux-response relationships obtained from O_3-FACE experiments in China, Feng et al. (2015) estimated that throughout China current and future O_3 levels induce wheat yield losses between 6.4-14.9% and 14.8-23.0% respectively. Whilst elevated O_3 (ambient + 40 ppb) significantly reduced soybean yields by 40% on average (32-46% among cultivars) compared with charcoal-filtered air, ambient O_3 concentrations (mean daily concentrations of 19 ppb) did not affect yield compared to charcoal-filtered air (mean daily concentrations of ca. 10 ppb; Zhang et al., 2014). Again, the lack of significant effects of air filtration on soybean yield is likely due to the relatively low ambient O_3 concentrations during the experiment. Elevated O_3 had a larger negative effect during seed filling than flowering stage.

In contrast to air filtration studies mentioned above, elevated O_3 has been shown to affect various crops species in China, with effects being reported on growth, yield quantity and quality and soil processes (Feng et al., 2017). Negative impacts of elevated O_3 have been reported mainly for winter wheat and rice, but also for soybean, oil seed rape, maize and spinach. Winter wheat has been shown to be more sensitive to O_3 than rice when grown in the field (Wang et al., 2012). Chinese winter wheat cultivars may be more sensitive to O_3 than European cultivars (Feng et al., 2012). O_3 impacts on rice yield were estimated to double or triple across the majority of rice-producing areas in the middle and lower parts of the Yangtze River and Southern China between 2000 and 2020 (Tang et al., 2014). Although a wide range of estimated yield losses have been reported for winter wheat in China, depending on O_3 metrics applied (Feng et al., 2017), the reported increase in relative yield loss between 2000 and 2020 is more robust and is in the range of 8.1 – 9.4% (Tang et al., 2014).

In **India**, a significant stimulation of yield was often observed in crops exposed to charcoal-filtered compared to non-filtered ambient air (Figure 5). The beneficial effect of air filtration varied between 8 – 30% for the crop species wheat (Rai et al., 2007; Sarkar and Agrawal, 2010a), rice (Bhatia et al., 2011; Rai et al., 2008; Sarkar and Agrawal, 2012; Sarkar et al., 2015), soybean (Singh and Agrawal, 2011), palak (Kumari et al., 2013) and mustard (Singh et al., 2012; 2013). Grain yield per plant in wheat was significantly stimulated by 26% in charcoal-filtered (8 hour mean O_3 concentration of 4.1 ppb) compared to non-filtered air (8 hour mean O_3 concentrations of 40.1 ppb; Rai & Agrawal, 2007). Sakar & Agrawal (2010a) reported a significant stimulation of grain yield per plant by 13 or 24%, dependant on variety, in charcoal-filtered (7 hour mean O_3 concentration of 5 ppb) compared to non-filtered air (7 hour mean O_3 concentrations of 48.2 ppb). In wheat and durum wheat, grain yield (g m^{-2}) was stimulated by 16 – 20% in charcoal-filtered (7 hour mean O_3 concentration of ca. 7 ppb) compared to non-filtered air (7 hour mean O_3 concentration of ca. 33 ppb). In soybean, the number and weight of seeds and pods per plant were reduced in non-filtered compared to charcoal-filtered air by up to ca. 30% (Singh and Agrawal, 2011). In maize, the yield increased by 21 to 31% in charcoal-filtered compared to non-filtered air (Bhati et al., 2013). For rice, Sakar et al. (2015) reported an increase in the number of grains per plant between 7-12% and in the grain weight per plant between 11-13% for two varieties grown in charcoal-filtered compared to non-filtered air, whereas Bhati et al. (2011) observed an increase in grain yield (g m^{-2}) of 17-22% in charcoal-filtered compared to non-filtered air.

Two rice cultivars showed a differential response to ambient O_3 (Rai and Agrawal, 2008; Rai et al., 2010). The O_3 resistance was higher in one variety during the vegetative growth phase and higher in the other variety during the reproductive phase. At ambient O_3 concentration, the grain yield per hectare was reduced by ca. 9% in the slow growing variety and ca.13% in the fast growing and high yielding variety. Concentrations of starch, protein, P, N, Ca, Mg and K decreased, while reducing and total soluble sugar increased in grains of both the cultivars in ambient compared to charcoal-filtered air. For mustard, seed yield and quality were significantly reduced by 7 - 19% in plants grown in non-filtered (ca. 3 ppb 12-hourly mean O_3)

compared to charcoal-filtered air (ca. 45 ppb 12-hourly mean O_3). However, this reduction could be mitigated by enhancing the dose of fertilization (NPK) by 50% (Singh et al., 2012). The nitrogen uptake and uptake efficiency was higher in plants grown in filtered compared to non-filtered air. Differential responses of mustard varieties to O_3 regarding nitrogen utilization efficiency could potentially be used as a measure of sensitivity in breeding programmes for yield improvement in mustard in a future rising O_3-polluted air in India. Significant reductions were also observed in protein, Mg, K, Zn, N, Ca, and oil contents in seeds grown in non-filtered compared to filtered air at a normal fertilization rate but not at the 50%-enhanced fertilization rate. In contrast to mustard, the nitrogen uptake efficiency in wheat was reduced in filtered compared to non-filtered air (Singh et al., 2015b). Whereas the application of 1.5 times the recommended NPK fertilization rate alleviated the negative effects of ambient O_3 on the number and weight of grains per plant in one variety, the opposite was true for another wheat variety.

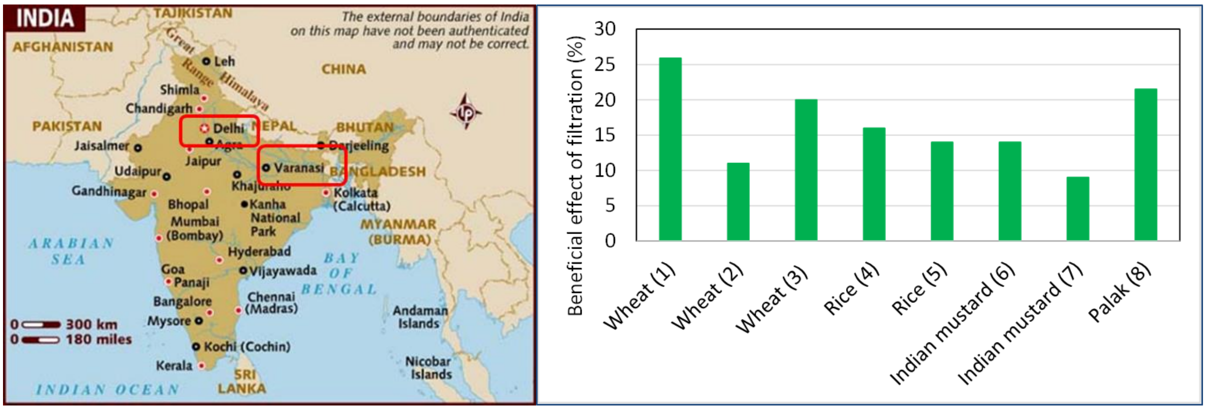


Figure 5. Examples of the beneficial effect of air filtration on crop yield at two sites in India (expressed as % decline in yield in ambient compared to charcoal-filtered air). The number in brackets refers to the experiment and publication as follows: (1) Rai et al., 2007, Varanasi; (2, 3, 5) Sarkar and Agrawal, 2010a, Varanasi; (4) Bhatia et al., 2011, New Delhi; (6) Singh et al., 2012, Varanasi; (7) Singh et al., 2013, New Delhi; (8) Kumari et al, 2013, Varanasi.

In **Thailand**, average O_3 concentration of 25 ppb as reported for Pathumthani reduced grain yield in Thai rice by 6-17% in rice compared to exposure to 0 ppb O_3, an unrealistic low O_3 level compared to pre-industrial O_3 of ca. 10 ppb. The reduction in soybean yield was 16-18% (Ariyaphanphitak, 2004). In Jasmine rice, the reduction in grain yield was due to the reduction in filled seeds per ear rather than a reduction in individual seed weight, with reductions being variety-dependant (Ariyaphanphitak et al., 2005). In Malaysia, a yield reduction of 6.3% was observed for one rice cultivar but not for another one when grown in non-filtered compared to charcoal-filtered air (Ishii et al., 2004).

Elevated O_3 exposure studies

To assess the potential impacts of rising O_3 concentrations in the future and develop dose-response relationship to estimate the impact of current ambient O_3 concentrations, crops are often exposed to elevated ambient O_3 concentrations in open top chambers or free air O_3 exposure systems. In such studies, O_3-sensitive and resistant varieties can be identified, which can help to breed O_3-resistant varieties in the future to secure food production in an enriched ground-level O_3 world (Ainsworth, 2017). Recently, Feng et al. (2017) reviewed the knowledge about the effects of elevated O_3 exposure on crops **in China**. Elevated O_3 exposure experiments have been conducted at five different sites in China with the agricultural crops winter wheat, rice, and oilseed rape by using open-top chamber (OTC) or free-air O_3 concentration enrichment (FACE-O_3) facilities. Significant yield losses were reported for wheat and rice at elevated O_3 exposure, with wheat being more sensitive to rising O_3 than rice. Compared with charcoal-filtered air, elevated accumulated O_3 concentrations above a threshold of 40 ppb (AOT40) in the range of 14 – 62 ppm.h reduced grain yield of winter wheat by 8.5 – 73% and AOT40 in the range of 14 – 83 ppm.h reduced grain yield of rice by 10 – 43%. The O_3-induced yield losses for winter wheat were attributed primarily to a reduction in 1,000-grain weight and harvest index, and the declines for rice were attributed primarily to a reduction in grain number per panicle and harvest index. In addition, elevated O_3 also significantly affected grain quality (Feng et al., 2017). A review of the effect of elevated O_3 on methane emissions in rice paddies concluded that increasing O_3 concentrations might mitigate the global warming potential of methane by reducing methane emissions. These findings indicate that the feedback mechanism between O_3 and its precursor emissions should be considered in the projection of future O_3 effects on terrestrial ecosystems (Feng et al., 2017).

Recently, Singh and Agrawal (2017) reviewed knowledge of O_3 impacts on crop yield and quality in **India**. The review included impacts of current ambient O_3 concentrations in comparison with charcoal-filtered air or EDU application and in comparison with elevated, potential future O_3 concentrations. The review highlighted the relatively high ambient O_3 concentrations in the Indo Gangetic Plain (IGP), the bread basket of India and the world. In recent decades, the highest trend of increase (3–5.6%) in O_3 concentration per decade has been observed over the densely populated IGP, while an increasing trend of 1.2–2% per decade has been observed for southern regions of India (Lal et al., 2012). Peak episodic O_3 concentrations occur during festival seasons (e.g. from fireworks) and during biomass burning of crop residues when emission of O_3 precursors are particularly high. Impacts of elevated O_3 levels have mainly been investigated for rice, the most important staple crop in India and South-East Asia, and wheat, the second most important staple crop of India. Yield losses up to ca. 45% have been reported for rice and wheat at elevated O_3 concentrations in India (Singh and Agrawal, 2017) and up to 48% for rice in Vietnam (Van et al., 2009). Reductions in yield of other important crops such as soybean, mung bean, mustard and linseed were also observed at elevated O_3 concentrations. In addition to impacts on crop yield, negative effects of O_3 on nutritional quality of grains and seeds have also been reported, such as a decrease in the content of starch, protein and nitrogen, with both increases and decreases in total soluble sugars being observed, dependent on crop species. When compared with rice grown in charcoal-filtered air, exposure to 62 ppb O_3 casued a 14% decrease in yield (Ainsworth, 2008). Many determinants of yield, including photosynthesis, biomass, leaf area index, grain number and grain mass, were also reduced by elevated O_3 concentrations.

2.3. Africa, Central and South America, South and Eastern Europe, Caucasus and Central Asia

Little field-based evidence is available for impacts of O_3 on crop yield in these regions. In **Africa**, some data is available for **Egypt**, primarily from chemical protectant studies. When applying EDU, Hassan et al. (1995) reported a reduction in the number of leaves with O_3 injury and the degree of injury by 80% or more, depending on the location. The same was true for turnip, although the reduction was less (33 – 63%) and not always significant. Both root and shoot dry weight of radish decreased in the absence of EDU by 24-30% and ca. 18% respectively at two sites studied. Root and shoot dry weight of turnip decreased significantly in the absence of EDU by 17 and 11% respectively at one site only. In potato, leaf injury symptoms were reduced greatly in plants treated with EDU and/or chlorothalonil (a fungicide), and the yield of treated plants was higher than that of the untreated ones, with the EDU providing a greater protection than chlorothalonil (Hassan et al., 2006). The combination of chemical protectant (EDU) and fungicide (chlorothalonil) was most effective in reducing the number of damaged leaves. Moreover, the percentage of protection was higher in a rural area (10 hour mean O_3 concentration ca. 48 ppb) than in a suburban area (10 hour mean O_3 concentration ca. 39 ppb) due to the higher levels of O_3 in the rural area.

At a rural site in eastern Egypt monthly concentrations of ambient O_3 reached ca. 44 ppb in August; in charcoal-filtered air in open top chambers, the O_3 concentration was reduced to ca. 8 ppb. Both charcoal-filtered air and EDU lengthened the growing season of soybean, i.e. time till flowering, pod appearing and filling, and time until harvest (Ali and Abdel-Fattah, 2006). This implies that ambient O_3 concentration induced early die-back in soybean. Both charcoal-filtered air and EDU reduced the number of injured leaves, and increased the plant nitrogen content, seed yield (g m^{-2}) and seed oil and protein content (%). With respect to seed yield, EDU was as effective as filtering ambient air when applied as a soil drench and as foliar spray (Ali and Abdel-Fattah, 2006). EDU provided protection against negative effects of O_3 up to 23% when applied as soil drench plus foliar spray. Filtered air (compared to 25 ppb O_3, 8 h average) improved wheat yield by 103 and 61% respectively for grain yield (g per plant) and 1000-grain weight respectively (Hassan, 2006). Interestingly, under saline conditions (50 mM NaCl), adverse impacts of O_3 on wheat yield were completely mitigated. In cotton, elevated O_3 exposure reduced the yield of cotton by 15 – 23% (Hassan & Tewfik, 2006). The yield of African cow pea varieties was reduced when exposed to elevated O_3 concentrations in Japan, but was not affected when comparing charcoal-filtered air with non-filtered air (Tetteh et al., 2015).

In **South America**, some data from **Brazil** indicate that relatively low ambient O_3 concentrations induce visible leaf injury in the common guava, an evergreen shrub or small tree grown for its fruit (Assis et al., 2015; Pina et al., 2017). In 2007 & 2008, the percentage of incidences of foliar injury in an urban tropical forest of São Paulo ranged from 17 – 100%, the severity ranged from 9 – 20% and the leaf injury index ranged from 2.8 – 8.7% (Pina et al., 2017). In 2004 & 2005, slightly lower incidences of foliar injury, severity and leaf injury index were observed; no foliar injury was observed in charcoal-filtered air (Pina et al., 2007). Hence, common guava can be used as an indicator species for the protection of urban tropical forests against adverse impacts of O_3.

3. Modelled O_3 impacts on yield of four staple crops (2010-2012)

Flux-based modelling of O_3 impacts on four staple crop species (soybean, wheat, maize and rice) was conducted in order to estimate yield and production losses due to O_3 on a global scale. Previous studies have used concentration-based methods to estimate the global effects of O_3 on crop yield (e.g. Avnery et al. 2011, Van Dingenen et al. 2009), with the greatest impacts predicted to be in areas with the highest O_3 concentration. By taking into account environmental factors affecting the stomatal uptake of O_3 (including light, temperature, soil moisture and relative humidity), the use of a flux-based approach should produce a more realistic assessment of global yield losses and their spatial distribution.

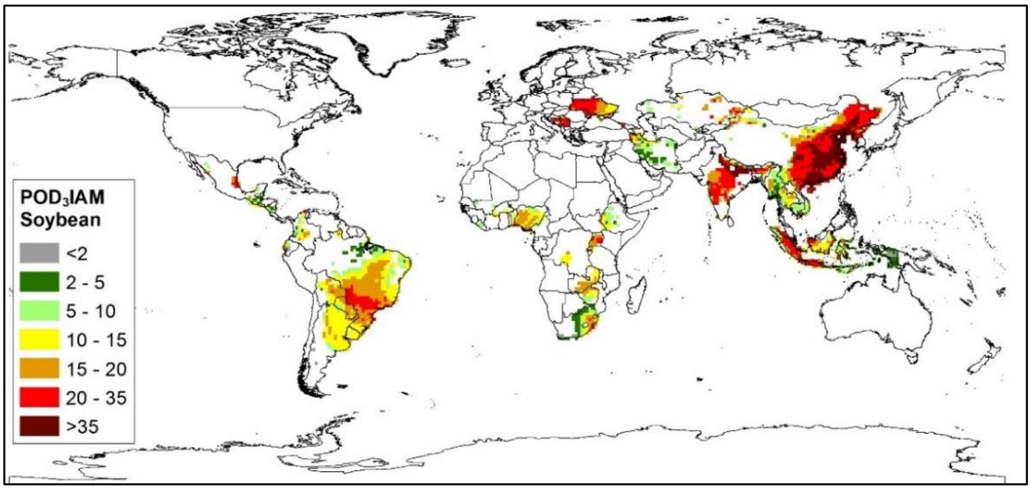
3.1 Modelled O_3 flux (POD_3IAM)

Global modelled O_3 flux (POD_3IAM (Phytotoxic Ozone Dose above 3 nmol m^{-2} s^{-1}; generic crop parameterisation; LRTAP Convention, 2017) values were calculated using the EMEP MSC-W (European Monitoring and Evaluation Programme, Meteorological Synthesising Centre – West) chemical transport model, version 4.16 (Simpson et al. 2012). Daily values (for the period 2010-12) were produced for each cell in a global 1° by 1° grid. Each cell was assigned to a climate zone, using global climatic zone data from the European Soil Data Centre (ESDAC) at the Joint Research Centre (JRC). For each year of data, the 90 day POD_3IAM was calculated per grid cell, with the accumulation period based on the crop growing season within the climate zone of each cell. An average 90 day POD_3IAM per cell was then calculated using the data from 2010-2012. As the model produces flux values for both irrigated and non-irrigated conditions, this process was repeated for both sets of values, for each of the four crop species of interest.

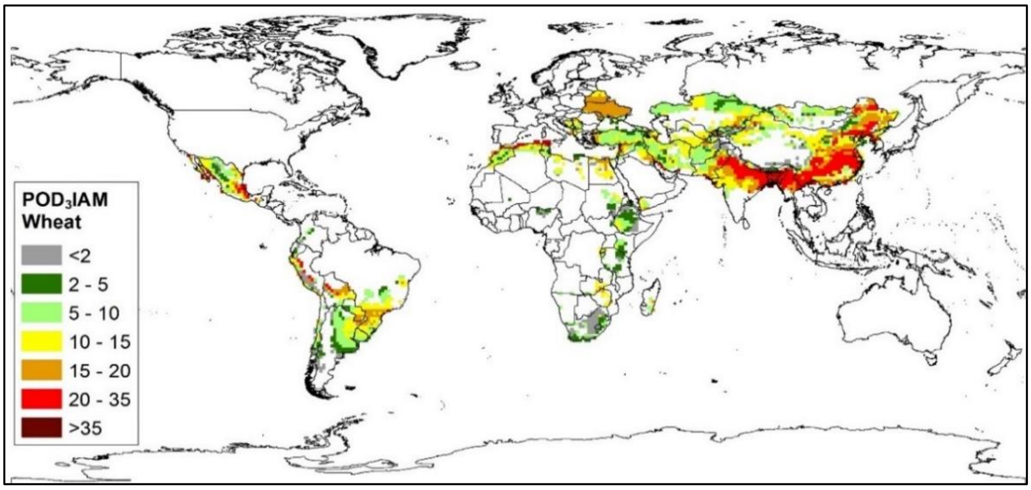
Modelled crop production data (year 2000) for each crop was downloaded from the GAEZ data portal (version 3; http://www.fao.org/nr/gaez/en/), and production summed per grid cell. To provide an estimate of production for the period 2010-12, a conversion factor per country was derived using national data from FAOSTAT. Data for both irrigated and non-irrigated production was used, with cells only included in further analysis if the total production was >500 tonnes per cell. Cells were classed as irrigated (>75% irrigated production per cell) or non-irrigated (<=75% irrigated production per cell) based on the percentage of irrigated production within each cell. For further detail on the methodology, see Mills et al. (in press).

POD_3IAM values were then mapped for all ODA countries, for grid cells containing soybean, wheat, maize and rice production (Figure 6).

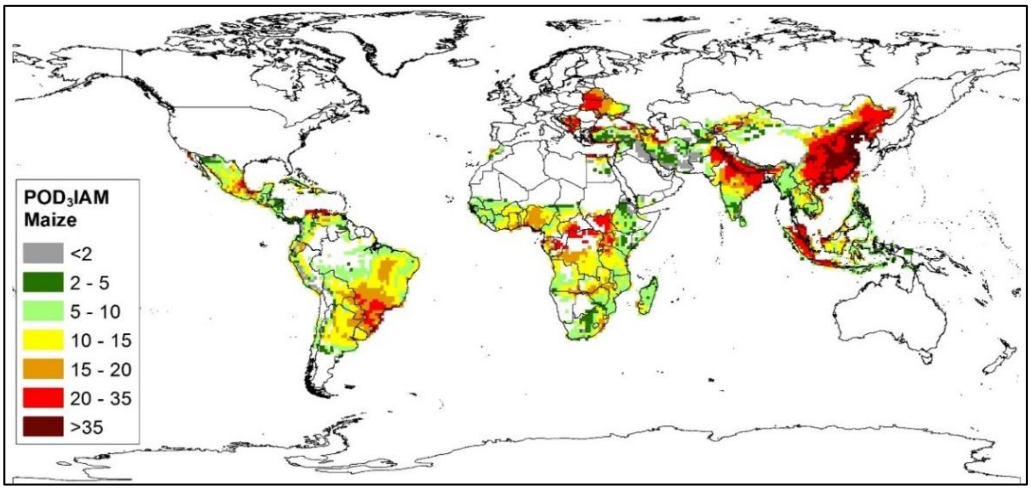
a)


POD3IAM
Soybean
<2
2 - 5
5 - 10
10 - 15
15 - 20
20 - 35
>35

b)


POD3IAM
Wheat
<2
2 - 5
5 - 10
10 - 15
15 - 20
20 - 35
>35

c)


POD3IAM
Maize
<2
2 - 5
5 - 10
10 - 15
15 - 20
20 - 35
>35

d)

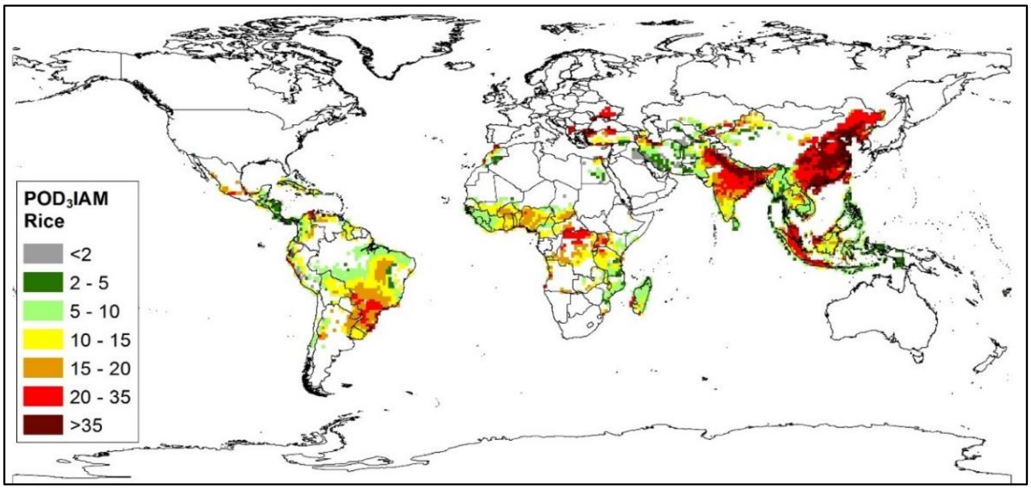


Figure 6. Modelled O_3 flux (POD_3IAM) for a) soybean, b) wheat, c) maize and d) rice growing in ODA countries, averaged for the period 2010-12. Grid cells (1° by 1° degree) are included if the total crop production per cell is >500 tonnes. For cells classed as irrigated (>75% irrigated production), irrigated POD_3IAM values were used, otherwise non-irrigated POD_3IAM values were used.

When comparing the POD_3IAM maps for each crop species, variations are seen due to differences in the areas of the world where the crops are produced and the crop growing seasons within each country. There are some common patterns for all crops however. There are high POD_3IAM values for all crops in South and Eastern Asia, particularly in China, India and Indonesia. In Central and South America, while POD_3IAM values in ODA countries vary with crop species, there are some high values in the south-west of Brazil for maize, rice and particularly soybean. In African ODA countries, there is little soybean and wheat grown while for rice and maize there are some high POD_3IAM values where the crops are growing in the centre of the continent, e.g. in the Democratic Republic of Congo (maize and rice) and South Sudan (maize). In SEE/EECCA countries, there are high POD_3IAM values for soybean and maize in western Ukraine.

3.2 Calculating percentage yield loss and production loss

Yield loss (%) (due to O_3) was calculated for wheat using the methodology adopted by the Convention on Long-Range Transboundary Air Pollution in 2017 (LRTAP Convention, 2017). The following equation was used:

$$\% \text{ Yield loss} = (POD_3IAM - 0.1) * 0.64 \qquad \text{(Equation 1)}$$

A reference POD_3IAM value of 0.1 to represent O_3 uptake at pre-industrial or natural O_3 levels was first subtracted. The slope of the relationship between POD_3IAM and percentage yield reduction is 0.64 (Mills et al., in press) and represents the percentage reduction per mmol m^{-2} POD_3IAM.

For soybean, maize and rice, % yield loss was calculated using Equation 1, and was then multiplied by a conversion factor representing the relative sensitivity of the crop compared to wheat. These values were derived by comparing the slopes of the 7 hour mean response function for each crop with that for wheat. The response function for soybean was taken from Osborne et al. (2016), while those for maize, rice and wheat were taken from Mills and Harmens (2011). The response functions for wheat and rice were updated after a literature search revealed new experimental data post 2011.

Production loss (due to O_3) was calculated using the following equation:

Production loss (tonnes) = Crop production * (% yield loss/100) (Equation 2)

Results per region and ODA category were tabulated for each crop (Tables 1 – 8) and yield and production loss were mapped (1° by 1° degree resolution) for each crop (Figures 7 – 10). Data per country for each crop is presented in Annex 2.

3.3 Modelling results for soybean, wheat, maize and rice

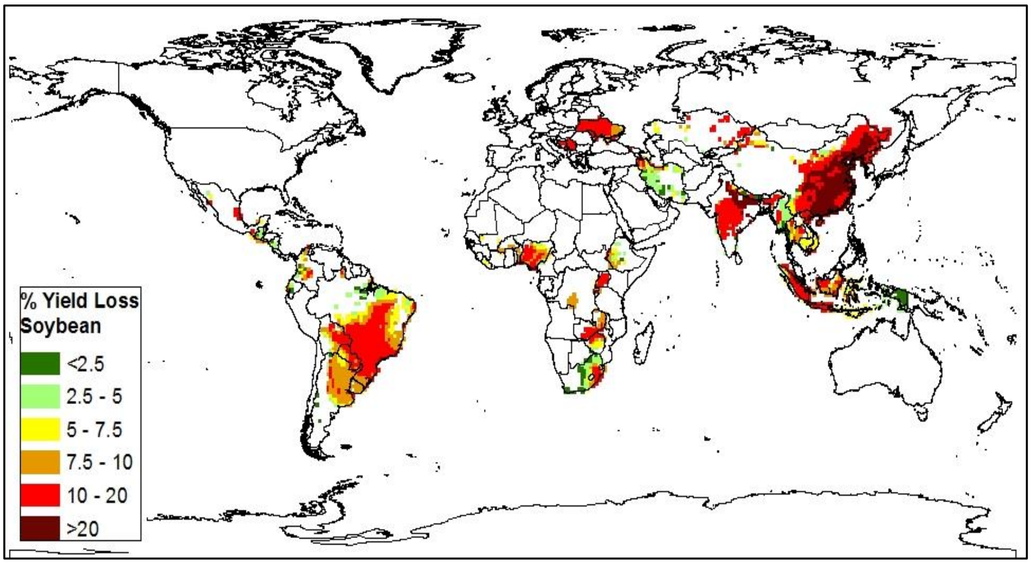
Soybean

For soybean, although high yield losses were estimated for South and Eastern Asia (Table 1, Figure 7a), production losses were lower than for Central and South America as actual production was lower in this region. There was also a lot of inter-grid cell variation in the soybean yield loss data for South and Eastern Asia (Table 1). Production loss was highest in Central and South America (Table 1, Figure 7b), particularly in Brazil and Argentina (see Annex 2). The highest production losses for South and Eastern Asia were in China and India. Due to lower soybean production in the SEE/EECCA countries and Africa, production losses due to O_3 were also lower (Table 1, Figure 7b). When % yield loss was split by ODA category, values were lowest for the Least Developed Countries (Table 2), which are primarily in Africa, and where soybean is grown in areas with mostly low POD_3IAM values (Figure 7a). Average % yield loss was similar for the other ODA categories and comparable to the value for Developed Countries (Table 2). Total production loss for ODA countries was highest for Upper Middle Income Countries at 15.9 MT, while soybean production loss for Developed Countries was 16.5 MT.

Table 1. Soybean average yield loss (%), total annual production (MT; Million tonnes) and total annual production loss (MT) per region, averaged for the period 2010-12. 'StdDev' is the standard deviation of the average % yield loss, which is a measure of the variation in the data for each region.

Region	% yield loss	StdDev	Production (MT)	Production loss (MT)
Central & South America	9.48	3.30	126.13	13.61
South and Eastern Asia	15.32	8.08	29.36	5.21
SEE/EECCA	12.86	3.60	2.69	0.37
Africa	7.38	3.70	2.05	0.17

7a)



7b)

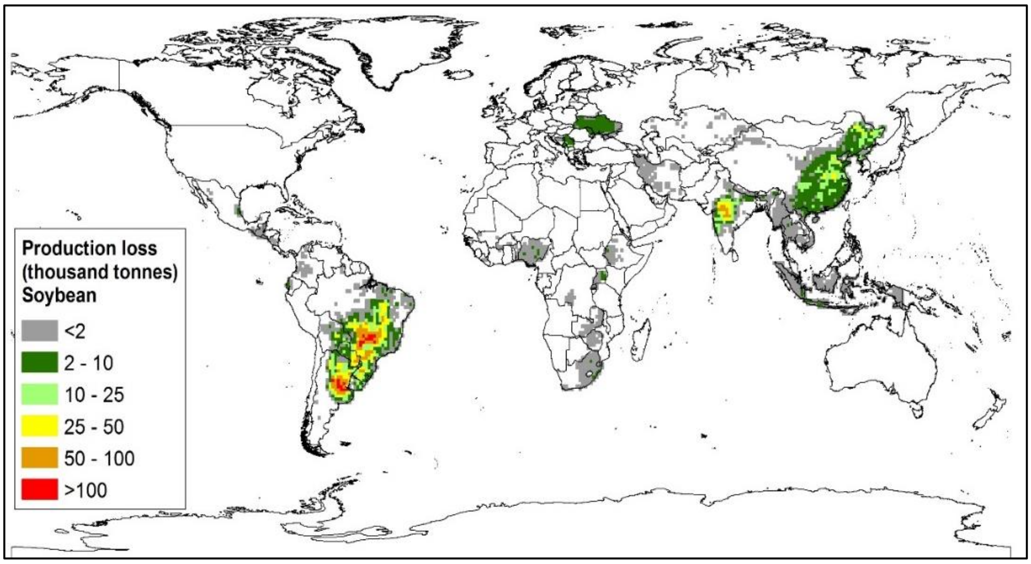


Figure 7. a) Average **y**ield loss (%) per 1° by 1° degree grid cell for soybean growing in ODA countries; b) Total annual production loss (thousand tonnes) per grid cell, for soybean growing in ODA countries. Grid cells were included if the total crop production per cell was >500 tonnes.

Table 2. Average yield loss (%) for soybean, total annual production (Million Tonnes; MT) and total production loss (MT) for each ODA category, LDC: Least Developed Countries; OLIC: Other Low Income Countries; LMIC: Lower Middle Income Countries; UMIC: Upper Middle Income Countries; DC: Developed Countries. Values have been averaged for the period 2010-12. ‘StdDev’ is the standard deviation of the average % yield loss, which is a measure of the variation in the data for each category.

ODA category	Yield loss (%)	StdDev	Production (MT)	Production loss (MT)
LDC	7.92	3.84	1.09	0.09
OLIC	12.43	6.41	0.38	0.07
LMIC	11.39	5.54	25.56	3.26
UMIC	12.78	7.45	133.19	15.92
DC	13.46	6.97	93.42	16.46

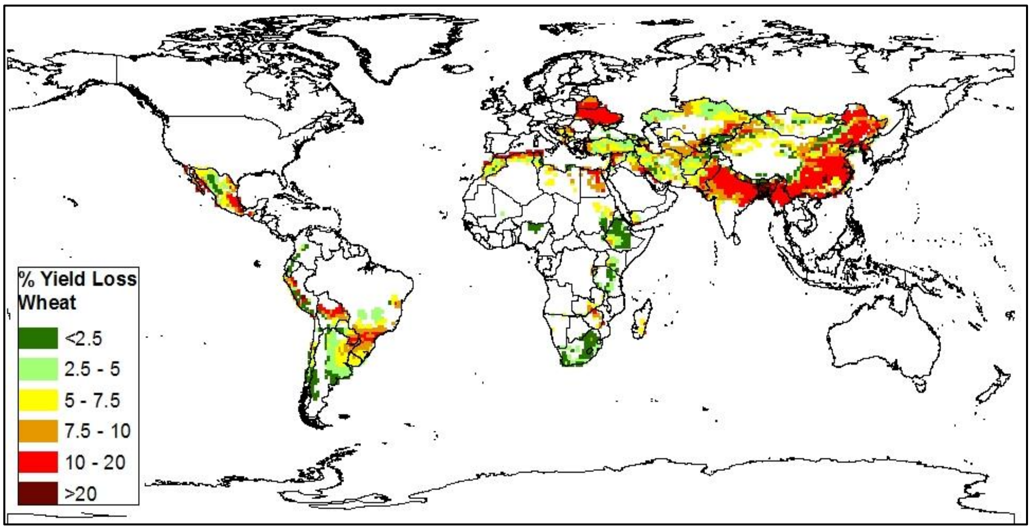
Wheat

For wheat, % yield loss was predicted to be highest in South and Eastern Asia (Table 3, Figure 8a). Production loss was also highest in this region, particularly in China and India (Figure 8b). Estimated % yield loss was similar for the other regions and the lowest production loss was for Central and South America, the region with the lowest actual wheat production (Table 3). Yield loss varied with ODA category, with Lower Middle Income Countries having the highest values (Table 4). Total production loss was high for Lower Middle Income Countries and Upper Middle Income Countries, the total for each being comparable to the losses predicted for developing countries (Table 4). Production loss summed for wheat in all of the ODA categories was ca. 75% greater than the total for Developed Countries.

Table 3. Wheat average yield loss (%), total annual production (MT; Million tonnes) and total annual production loss (MT) per region, averaged for the period 2010-12. ‘StdDev’ is the standard deviation of the average % yield loss, which is a measure of the variation in the data for each region.

Region	Yield loss (%)	StdDev	Production (MT)	Production loss (MT)
South and Eastern Asia	9.96	5.51	236.45	29.84
SEE/EECCA	6.87	3.09	69.93	5.45
Africa	5.32	3.63	43.63	3.07
Central & South America	6.29	4.14	25.84	1.69

8a)



8b)

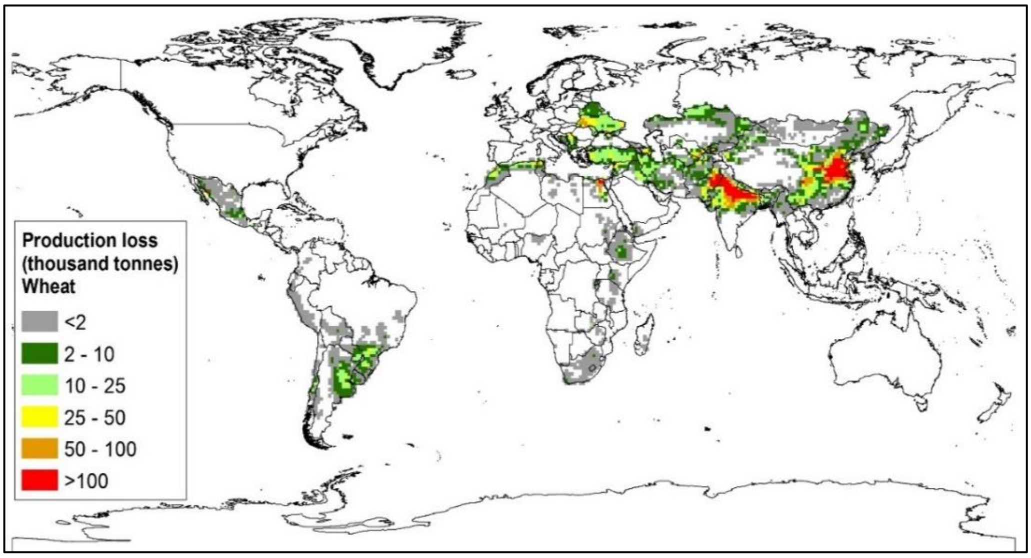


Figure 8. a) Average **y**ield loss (%) per 1° by 1° degree grid cell for wheat growing in ODA countries; b) Total annual production loss (thousand tonnes) per grid cell, for wheat growing in ODA countries. Grid cells were included if the total crop production per cell was >500 tonnes.

Table 4. Average yield loss (%) for wheat, total annual production (Million Tonnes; MT) and total production loss (MT) for each ODA category, LDC: Least Developed Countries; OLIC: Other Low Income Countries; LMIC: Lower Middle Income Countries; UMIC: Upper Middle Income Countries; DC: Developed Countries. Values have been averaged for the period 2010-12. 'StdDev' is the standard deviation of the average % yield loss, which is a measure of the variation in the data for each category.

ODA category	Yield loss (%)	StdDev	Production (MT)	Production loss (MT)
LDC	6.77	6.21	10.23	0.75
OLIC	6.63	4.07	1.22	0.08
LMIC	8.89	4.88	157.68	19.81
UMIC	7.36	4.60	206.72	19.42
DC	6.59	3.92	297.41	22.63

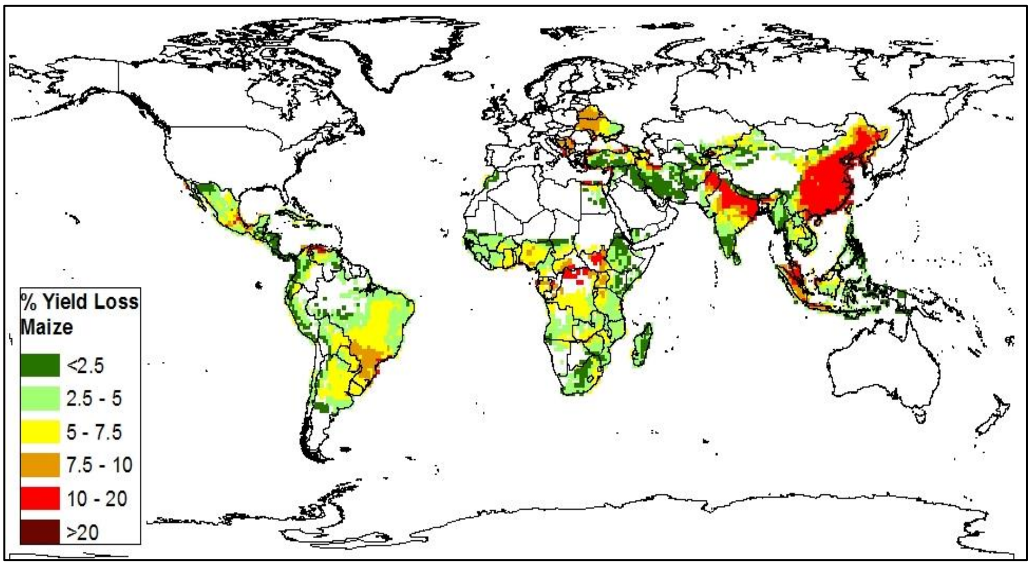
Maize

For maize, yield loss was predicted to be highest in South and Eastern Asia (Table 5, Figure 9a). Production loss was also highest for this region (Table 5, Figure 9b), with the majority of losses seen in China (Annex 2). Estimated % yield loss was similar for the other regions and the lowest production loss was for SEE/EECCA countries, the region with the lowest actual maize production (Table 5). Yield loss varied with ODA category, with the highest ODA losses estimated for Upper Middle Income Countries at 6.2%, and Developed Countries having a slightly higher value of 6.8% yield loss (Table 6). Total production loss was similar for Upper Middle Income Countries (33.8MT) and Developed Countries (35MT) and considerably lower for the other ODA categories (Table 6).

Table 5. Maize average yield loss (%), total annual production (MT; Million tonnes) and total annual production loss (MT) per region, averaged for the period 2010-12. 'StdDev' is the standard deviation of the average % yield loss, which is a measure of the variation in the data for each region.

Region	Yield loss (%)	StdDev	Production (MT)	Production loss (MT)
South and Eastern Asia	7.63	5.04	261.25	30.47
Central & South America	4.88	2.26	120.66	7.09
Africa	4.49	2.47	70.39	3.33
SEE/EECCA	5.95	3.16	34.02	2.44

9a)



9b)

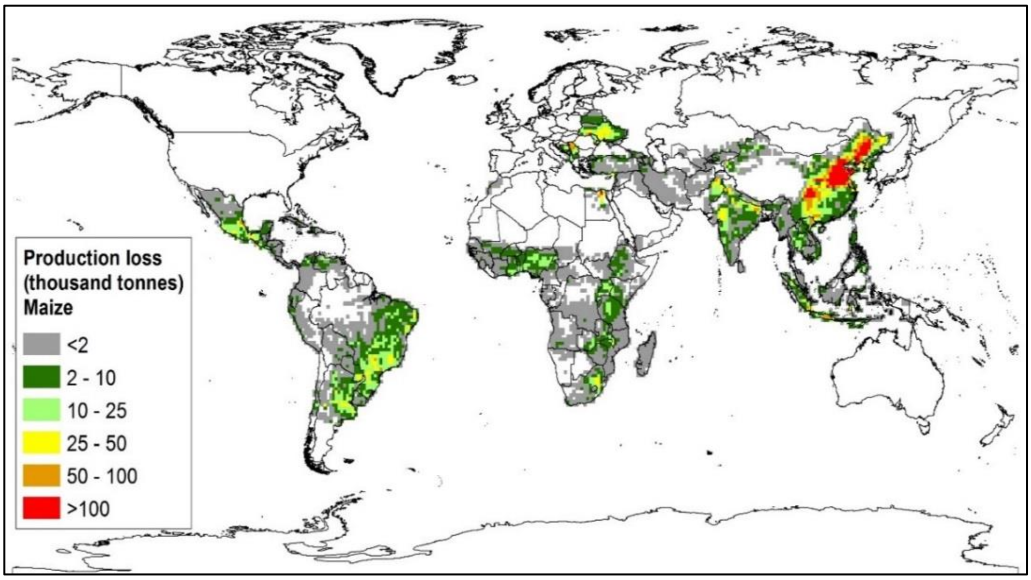


Figure 9. a) Average **y**ield loss (%) per 1° by 1° degree grid cell for maize growing in ODA countries; b) Total annual production loss (thousand tonnes) per grid cell, for maize growing in ODA countries. Grid cells were included if the total crop production per cell was >500 tonnes.

Table 6. Average yield loss (%) for maize, total annual production (Million Tonnes; MT) and total production loss (MT) for each ODA category, LDC: Least Developed Countries; OLIC: Other Low Income Countries; LMIC: Lower Middle Income Countries; UMIC: Upper Middle Income Countries; DC: Developed Countries. Values have been averaged for the period 2010-12. 'StdDev' is the standard deviation of the average % yield loss, which is a measure of the variation in the data for each category.

ODA category	Yield loss (%)	StdDev	Total production (MT)	Production loss (MT)
LDC	4.65	2.44	37.21	1.88
OLIC	5.42	3.43	6.85	0.46
LMIC	5.73	3.45	105.26	7.18
UMIC	6.23	4.31	337.00	33.81
DC	6.85	4.11	382.75	35.00

Rice results

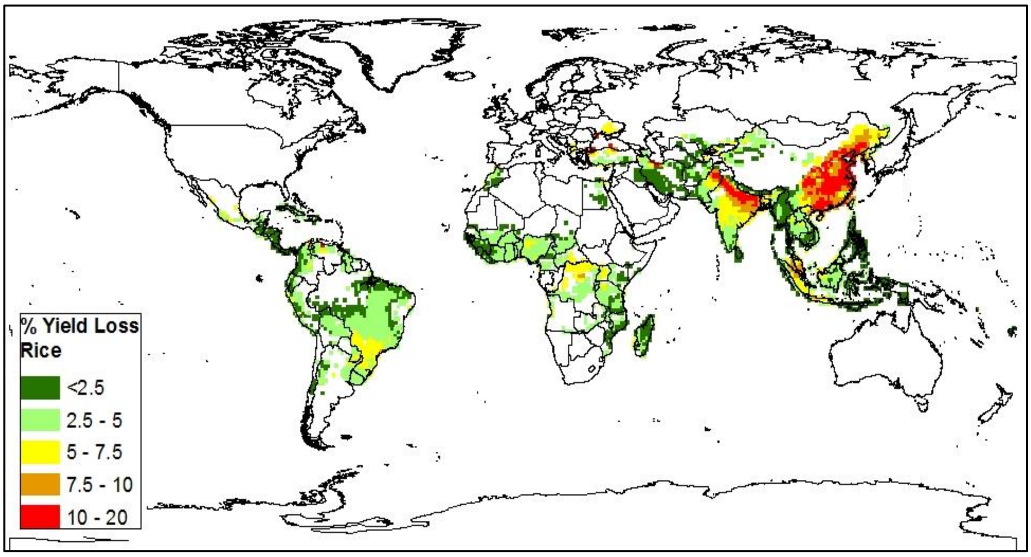
For rice, yield loss was predicted to be highest in South and Eastern Asia (Table 7, Figure 10a). Production loss was also considerably higher for this region (Table 7, Figure 10b), with the majority of losses seen in China and India (Annex 2). Estimated % yield loss was similar for the other regions and the lowest production loss was for SEE/EECCA countries, the region with the lowest actual rice production (Table 7). Average yield loss varied with ODA category, but the range of yield losses was only 3 – 5% (Table 8). The highest average yield loss was in Developed Countries at 5.47%. Total production loss was highest in Upper Middle Income Countries and Lower Middle Income Countries. Production loss summed for rice in all of the ODA categories was 48 MT, compared to 2 MT for Developed Countries.

Table 7. Rice average yield loss (%), total annual production (MT; Million tonnes) and total annual production loss (MT) per region, averaged for the period 2010-12. 'StdDev' is the standard deviation of the average % yield loss, which is a measure of the variation in the data for each region.

Region	% Yield loss	StdDev	Production (MT)	Production loss (MT)
South and Eastern Asia	5.44	3.53	628.77	45.66
Central & South America	3.47	1.57	26.99	1.06
Africa	3.30	1.68	28.98	0.93
SEE/EECCA	4.46	2.98	1.89	0.10

Note: There is also yield and production loss data for one country (Fiji) in Australasia, see Annex 2.

10a)



10b)

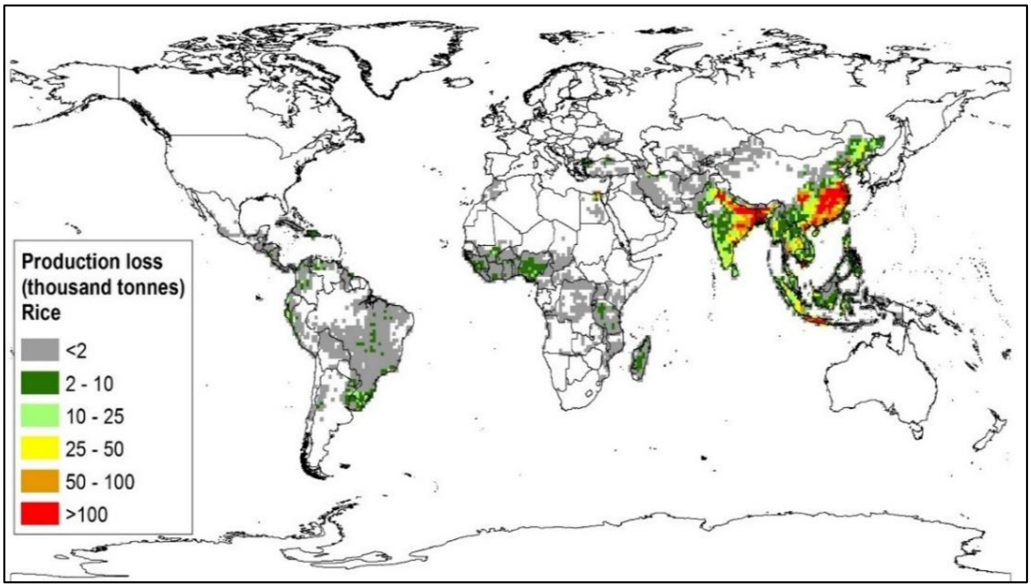


Figure 10. a) Average **y**ield loss (%) per 1° by 1° degree grid cell for rice growing in ODA countries; b) Total annual production loss (thousand tonnes) per grid cell, for rice growing in ODA countries. Grid cells were included if the total crop production per cell was >500 tonnes.

Table 8. Average yield loss (%) for rice, total annual production (Million Tonnes; MT) and total production loss (MT) for each ODA category, LDC: Least Developed Countries; OLIC: Other Low Income Countries; LMIC: Lower Middle Income Countries; UMIC: Upper Middle Income Countries; DC: Developed Countries. Values have been averaged for the period 2010-12. 'StdDev' is the standard deviation of the average % yield loss, which is a measure of the variation in the data for each category.

ODA category	% Yield loss	StdDev	Production (MT)	Production loss (MT)
LDC	3.26	1.70	109.37	4.89
OLIC	4.60	2.61	2.68	0.22
LMIC	4.10	2.54	305.42	18.50
UMIC	4.96	3.31	269.16	24.15
DC	5.47	2.77	30.25	2.09

4. Opportunities and challenges for the future

This review has shown that 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 injury assessment 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 15 years, 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 sensitivity to O_3 varies between crop species, with legumes such as bean and soybean often been 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.

The global impacts modelling (Chapter 3) indicated that the highest production losses for wheat, rice and maize are in South and Eastern Asia. With concentrations rapidly rising in this region, O_3 poses a huge threat to food production in a region characterised by high production of these staple crops. For both wheat and rice, greater production losses were estimated for ODA countries compared to developing countries. Estimated production loss for wheat in ODA countries was ca. 75% greater than for developed countries (Mills et al., in press). 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 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. However, 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. The data show that at ambient O_3 concentrations found at the Asian study sites (which vary between 35–75 ppb 4–8 h growing season mean), yield losses for wheat, rice and legumes range between 5–48, 3–47 and 10–65%, respectively. For legumes the scatter in the data makes it difficult to reach any equivalent conclusion on relative sensitivities. As such, existing modelling-based risk assessments may underestimate the scale of the problem in Asia through use of North American or European derived dose–response relationships. Feng et al. (2012) came to a similar conclusion based on a study with winter wheat.

Sinha et al. (2015) established crop-yield–exposure relationship for South Asian wheat, maize and rice cultivars grown in Pakistan and found that these relationships are a factor of two or more sensitive to O_3-induced yield losses compared to European and American varieties. Relative yield losses based on the AOT40 metrics ranged from 27 to 41% for wheat, 21 to 26% for rice, 3 to 5% for maize and 47 to 58% for cotton. The Indian National Food Security Ordinance entitles ca. 820 million of India's poor to purchase about 60 kg of rice or wheat per person annually at subsidized rates. The scheme requires 27.6 Mt of wheat and 33.6 Mt of rice per year. The mitigation of O_3-related crop production losses in Punjab and Haryana alone could provide > 50% of the wheat and ca. 10% of the rice required for the scheme. The upper limit for O_3-related crop yield losses in all of India amounts to 3.5–20% of India's GDP (Sinha et al., 2015). The mitigation of high surface O_3 would require relatively little investment in comparison to the economic losses incurred in India. Therefore, O_3 mitigation can yield massive benefits in terms of ensuring food security and boosting the economy. However, it should be noted that it is difficult to assess the impact of ambient O_3 on crop productivity for large countries such as India and China using a unified dose-response model, since the crop varieties and climates differ greatly by region, particularly in China. In China, past research on wheat and rice has been limited to the Yangtze River Delta, the Pearl River Delta, and the regions of Beijing, Tianjin, and Hebei. A more comprehensive study covering the major agricultural regions and staple food crops is crucial for estimating the surface O_3 impact on food production in China. A robust model of the relationship between crop productivity and O_3 exposure under different conditions should be established and validated against local field investigations (Feng et al., 2017). Currently there are no standards in China and India to protect crops from O_3. The co-benefits of O_3 mitigation should be clearly communicated, including a decrease in the O_3-related mortality and morbidity and a reduction of the O_3-induced warming in the lower troposphere.

Many studies included in this review 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. Some studies have shown that current-day varieties of wheat (Biswas et al., 2008; Pleijel et al., 2006), soybean (Osborne et al., 2016) and rice (Ismail et al., 2015) are more sensitive to O_3 than older varieties. High-yielding, modern varieties might inadvertently have been selected for higher O_3 sensitivity too. It might be that agronomic traits targeted by crop breeders are linked to traits associated with high O_3-sensitivity, such as low anti-oxidative capacity and high maximum leaf pore conductance, i.e. O_3 uptake (Biswas et al., 2008; Fiscus et al., 2005; Roche, 2015). Recently, Mills et al. (submitted) discussed breeding new varieties with multiple stress tolerance for O_3

and typically co-occurring stresses such as heat, pests and diseases and to a lesser extent aridity and nutrients. Breeding for O_3 tolerance traits may cause potential synergies or trade-offs that need to be considered in a developing a so-called ideotype for O_3 tolerance.

In addition, potential management options should be considered that lead to a reduction of O_3 impacts on crops. Such management options include (Mills et al., submitted):

- <u>Reduced irrigation</u>. 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). This approach could potentially be exploited to reduce O_3 impacts on rice or other crops, but requires further study at the field scale.

- <u>Fertilizer application to compensate for crop yield losses</u>. Although crop 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. This reduces fertilizer use efficiency, which is not very cost-effect considering the cost of fertilizer.

- <u>Chemical protection against O_3 damage.</u> 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., 2016). 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.

Conclusion

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 ODA 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. A modelling study showed that for rice, maize and wheat, the highest annual production losses in ODA countries in 2010-2012 were in South & Eastern Asia. For soybean, the highest production losses were calculated for Central and South America. 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 stress. 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. These approaches will contribute significantly to reducing the current yield gap for crops.

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Annex 1. DAC list of ODA recipients

DAC List of ODA Recipients
Effective for reporting on 2018, 2019 and 2020 flows

Least Developed Countries	Other Low Income Countries (per capita GNI <= $1 005 in 2016)	Lower Middle Income Countries and Territories (per capita GNI $1 006-$3 955 in 2016)	Upper Middle Income Countries and Territories (per capita GNI $3 956-$12 235 in 2016)
Afghanistan	Democratic People's Republic of Korea	Armenia	Albania
Angola[1]	Zimbabwe	Bolivia	Algeria
Bangladesh		Cabo Verde	Antigua and Barbuda[2]
Benin		Cameroon	Argentina
Bhutan		Congo	Azerbaijan
Burkina Faso		Côte d'Ivoire	Belarus
Burundi		Egypt	Belize
Cambodia		El Salvador	Bosnia and Herzegovina
Central African Republic		Georgia	Botswana
Chad		Ghana	Brazil
Comoros		Guatemala	China (People's Republic of)
Democratic Republic of the Congo		Honduras	Colombia
Djibouti		India	Cook Islands[3]
Eritrea		Indonesia	Costa Rica
Ethiopia		Jordan	Cuba
Gambia		Kenya	Dominica
Guinea		Kosovo	Dominican Republic
Guinea-Bissau		Kyrgyzstan	Ecuador
Haiti		Micronesia	Equatorial Guinea
Kiribati		Moldova	Fiji
Lao People's Democratic Republic		Mongolia	Former Yugoslav Republic of Macedonia
Lesotho		Morocco	Gabon
Liberia		Nicaragua	Grenada
Madagascar		Nigeria	Guyana
Malawi		Pakistan	Iran
Mali		Papua New Guinea	Iraq
Mauritania		Philippines	Jamaica
Mozambique		Sri Lanka	Kazakhstan
Myanmar		Swaziland	Lebanon
Nepal		Syrian Arab Republic	Libya
Niger		Tajikistan	Malaysia
Rwanda		Tokelau	Maldives
Sao Tome and Principe		Tunisia	Marshall Islands
Senegal		Ukraine	Mauritius
Sierra Leone		Uzbekistan	Mexico
Solomon Islands		Viet Nam	Montenegro
Somalia		West Bank and Gaza Strip	Montserrat
South Sudan			Namibia
Sudan			Nauru
Tanzania			Niue
Timor-Leste			Palau[2]
Togo			Panama
Tuvalu			Paraguay
Uganda			Peru
Vanuatu[1]			Saint Helena
Yemen			Saint Lucia
Zambia			Saint Vincent and the Grenadines
			Samoa
			Serbia
			South Africa
			Suriname
			Thailand
			Tonga
			Turkey
			Turkmenistan
			Venezuela
			Wallis and Futuna

(1) General Assembly resolution A/RES/70/253 adopted on 12 February 2016, decided that Angola will graduate five years after the adoption of the resolution, i.e. on 12 February 2021. General Assembly resolution A/RES/68/18 adopted on 4 December 2013, decided that Vanuatu will graduate four years after the adoption of the resolution on 4 December 2017. General Assembly resolution A/RES/70/78 adopted on 9 December 2015, decided to extend the preparatory period before graduation for Vanuatu by three years, until 4 December 2020, due to the unique disruption caused to the economic and social progress of Vanuatu by Cyclone Pam.

(2) Antigua and Barbuda exceeded the high-income threshold in 2015 and 2016, and Palau exceeded the high-income threshold in 2016. In accordance with the DAC rules for revision of this List, if they remain high income countries until 2019, they will be proposed for graduation from the List in the 2020 review.

(3) The DAC agreed to defer decision on graduation of Cook Islands until more accurate GNI estimations are available. A review of Cook Islands will take place in the first quarter of 2019.

Annex 2. Yield and production losses for crops due to O_3 tabulated per ODA country

Table A1. Soybean average yield loss (%) due to O_3, with standard deviation of the mean, total annual production and production loss (thousand tonnes) due to O_3 per ODA country, averaged for the period 2010-12. ODA categories are as follows: LDC: Least Developed Countries; OLIC: Other Low Income Countries; LMIC: Lower Middle Income Countries; UMIC: Upper Middle Income Countries.

Country	ODA region	ODA category	Yield loss (%)	StdDev	Prod. (th.T)	Prod. loss (th. Tonnes)
Brazil	Central & South America	UMIC	10.06	3.42	69,060.51	8,233.09
Argentina		UMIC	8.46	2.03	47,186.75	4,367.31
Paraguay		LMIC	9.52	1.95	6,748.79	691.43
Bolivia		LMIC	9.58	2.72	1,959.69	217.21
Uruguay		UMIC	8.29	0.68	781.14	63.89
Mexico		UMIC	10.65	4.92	208.51	24.86
Ecuador		UMIC	6.48	4.60	75.97	6.17
Colombia		UMIC	7.52	3.74	64.60	4.78
Guatemala		LMIC	5.30	2.90	33.27	1.53
El Salvador		LMIC	10.58	3.46	3.39	0.35
Nicaragua		LMIC	4.33	2.04	4.45	0.18
Guyana		LMIC	8.67	1.32	1.20	0.11
Belize		UMIC	4.67	NA	0.50	0.02
China	South & Eastern Asia	UMIC	19.38	7.31	14,214.27	3,076.14
India		LMIC	15.76	6.33	13,130.85	1,887.50
Indonesia		LMIC	9.35	5.32	845.75	96.00
North Korea		OLIC	18.47	4.70	326.65	70.39
Vietnam		LMIC	11.42	4.80	222.08	31.06
Thailand		UMIC	7.56	3.30	225.95	18.97
Myanmar		LDC	4.75	3.51	219.90	13.34
Cambodia		LDC	5.48	1.34	144.02	8.12

Nepal		LDC	11.65	8.11	19.44	2.98
Laos		LDC	6.40	1.17	8.97	0.56
Ukraine	SEE/EECCA	LMIC	13.36	3.27	2,021.51	271.37
Serbia		UMIC	14.66	2.60	420.68	62.90
Moldova		LMIC	15.45	1.20	91.37	14.13
Kazakhstan		UMIC	10.48	3.97	122.14	11.92
Montenegro		UMIC	15.72	NA	31.68	4.98
Bos. and Herz.		UMIC	13.56	0.43	2.68	0.36
Georgia		LMIC	13.92	NA	0.63	0.09
Nigeria	Africa	LMIC	9.51	2.73	501.02	50.18
South Africa		UMIC	5.55	3.96	638.86	39.59
Uganda		LDC	12.19	2.19	188.41	26.02
Ethiopia		LDC	6.94	3.03	234.71	14.94
Zambia		LDC	10.17	1.54	135.45	14.52
Iran		UMIC	5.02	3.21	157.03	8.76
Benin		LDC	8.94	0.86	55.52	5.01
Zimbabwe		OLIC	8.03	2.92	55.48	4.52
Rwanda		LDC	9.56	0.86	38.00	3.84
Congo DRC		LDC	9.06	0.71	15.33	1.35
Burkina Faso		LDC	7.71	2.08	22.93	1.30
Liberia		LDC	6.06	0.53	1.45	0.09
Mali		LDC	5.47	0.33	1.55	0.08

Table A2. Wheat average yield loss (%) due to O_3, with standard deviation of the mean, total annual production and production loss (thousand tonnes) due to O_3 per ODA country, averaged for the period 2010-12. ODA categories are as follows: LDC: Least Developed Countries; OLIC: Other Low Income Countries; LMIC: Lower Middle Income Countries; UMIC: Upper Middle Income Countries.

Country	ODA region	ODA category	Yield loss (%)	StdDev	Total Prod. (th. T)	Prod. loss (th. T)
China	South & Eastern Asia	UMIC	9.85	5.18	117,709.53	13,574.73
India		LMIC	12.59	5.36	86,638.51	12,622.97
Pakistan		LMIC	8.48	4.09	25,524.28	3,014.47
Afghanistan		LDC	5.25	2.71	3,983.24	263.28
Bangladesh		LDC	21.76	2.73	975.91	205.90
Nepal		LDC	7.50	7.42	951.45	98.82
Myanmar		LDC	15.05	3.17	176.44	26.89
Mongolia		LMIC	5.28	2.56	364.86	20.27
North Korea		OLIC	8.73	4.78	118.19	13.28
Bhutan		LDC	1.84	0.83	4.20	0.08
Ukraine	SEE/EECCA	LMIC	10.05	2.56	18,242.92	1,895.66
Turkey		UMIC	5.86	2.53	20,474.04	1,249.96
Kazakhstan		UMIC	5.87	2.30	14,079.92	816.26
Uzbekistan		LMIC	8.02	3.05	7,288.54	680.46
Belarus		UMIC	10.11	0.82	2,111.92	214.80
Serbia		UMIC	7.84	2.80	2,225.20	189.59
Turkmenistan		UMIC	8.05	1.00	1,411.70	117.13
Azerbaijan		UMIC	6.29	3.69	1,346.10	111.60
Moldova		LMIC	12.18	0.31	484.47	59.01
Tajikistan		OLIC	3.99	3.74	674.80	47.27
Kyrgyzstan		LMIC	2.25	2.56	677.51	18.89
Albania		UMIC	8.30	2.10	242.37	15.76
Macedonia		UMIC	6.10	1.76	230.11	14.99
Bos. and Herz.		UMIC	7.67	1.91	149.31	11.50

Armenia		LMIC	3.00	0.72	210.39	7.25
Georgia		LMIC	4.92	2.46	76.67	4.01
Montenegro		UMIC	5.33	NA	2.35	0.13
Iran	Africa	UMIC	6.57	2.58	13,544.50	872.95
Egypt		LMIC	7.96	3.49	8,126.01	730.63
Morocco		LMIC	7.06	2.97	4,922.42	333.41
Syria		LMIC	7.84	3.58	3,646.08	299.92
Algeria		UMIC	8.53	3.15	2,958.68	287.68
Iraq		UMIC	7.30	2.57	2,513.88	195.76
Tunisia		UMIC	7.68	4.69	1,261.45	144.05
Ethiopia		LDC	2.56	2.20	3,051.43	94.24
South Africa		UMIC	1.43	1.61	1,781.76	25.70
Zambia		LDC	7.49	1.85	220.01	19.79
Yemen		LDC	7.17	2.66	245.81	16.98
Kenya		OLIC	4.07	1.67	409.84	16.26
Sudan		LDC	4.79	4.28	338.84	10.90
Libya		UMIC	5.70	3.03	153.96	9.51
Rwanda		LDC	8.04	0.64	79.14	6.41
Tanzania		LDC	2.11	0.89	114.67	2.41
Nigeria		LMIC	0.94	0.79	122.83	1.54
Zimbabwe		OLIC	8.51	1.37	17.04	1.40
Lebanon		UMIC	7.38	NA	12.43	0.92
Madagascar		LDC	7.72	2.82	8.91	0.62
Eritrea		LDC	1.72	0.96	34.32	0.51
Palestine		LMIC	5.04	NA	9.63	0.49
Burundi		LDC	6.58	2.47	7.80	0.43
Namibia		UMIC	4.52	0.46	8.30	0.37
Mali		LDC	2.61	NA	10.60	0.28
Jordan		UMIC	4.85	NA	4.69	0.23
Lesotho		LDC	0.89	0.19	16.29	0.13

Niger		LDC	1.64	NA	5.10	0.08
Angola		LDC	5.37	NA	0.77	0.04
Somalia		LDC	0.79	NA	1.68	0.01
Argentina	Central & South America	UMIC	3.71	2.43	12,821.71	586.59
Brazil		UMIC	7.57	2.49	5,362.49	493.34
Mexico		UMIC	8.17	4.78	3,336.91	342.88
Paraguay		LMIC	7.07	3.23	1,143.11	107.55
Uruguay		UMIC	6.01	1.16	1,306.85	78.21
Chile		UMIC	3.25	2.98	1,435.79	54.66
Bolivia		LMIC	8.07	3.73	197.68	17.52
Peru		UMIC	7.00	6.35	216.97	12.72
Colombia		UMIC	2.88	1.98	9.67	0.26
Ecuador		UMIC	1.70	1.19	8.17	0.10

Table A3. Maize average yield loss (%) due to O_3, with standard deviation of the mean, total annual production and production loss (thousand tonnes) due to O_3 per ODA country, averaged for the period 2010-12. ODA categories are as follows: LDC: Least Developed Countries; OLIC: Other Low Income Countries; LMIC: Lower Middle Income Countries; UMIC: Upper Middle Income Countries.

Country	ODA Region	ODA category	Yield loss (%)	StdDev	Prod. (th. T)	Prod. loss (th. T)
China	South & Eastern Asia	UMIC	10.20	5.21	19,2561.08	25,523.98
India		LMIC	7.53	4.52	21,333.39	1,804.67
Indonesia		LMIC	5.18	3.05	18,499.16	1,241.57
Pakistan		LMIC	8.81	4.88	4,121.97	514.37
Vietnam		LMIC	6.37	2.18	4,575.13	362.84
Nepal		LDC	6.45	5.93	2,643.28	250.04
Thailand		UMIC	4.32	2.38	4,893.77	229.33
North Korea		OLIC	10.99	2.98	1,754.01	219.65
Philippines		LMIC	3.10	1.07	6,917.93	185.40

Myanmar		LDC	2.62	0.71	1,345.26	38.17
Laos		LDC	4.00	0.61	931.45	37.57
Cambodia		LDC	3.20	0.95	958.94	32.24
Bhutan		LDC	6.32	6.18	152.79	13.79
Malaysia		UMIC	9.30	3.74	58.47	5.60
Afghanistan		LDC	2.27	2.36	269.97	4.80
Sri Lanka		LMIC	2.81	0.65	166.81	4.42
Timor-Leste		LDC	2.99	1.47	55.87	1.88
Papua New Guinea		LMIC	1.74	0.24	9.24	0.16
Brazil	Central & South America	UMIC	5.47	2.06	60,602.33	3,753.86
Mexico		UMIC	4.88	2.45	21,046.13	1,272.03
Argentina		UMIC	4.80	1.63	22,409.23	1,216.38
Paraguay		LMIC	5.95	1.38	3,299.43	229.43
Venezuela		UMIC	5.37	3.69	1,879.83	132.28
Guatemala		LMIC	4.15	2.15	1,717.49	82.42
Colombia		UMIC	3.65	2.39	1,690.49	72.89
Peru		UMIC	3.18	2.08	1,575.75	63.27
Bolivia		LMIC	4.54	2.00	974.18	48.71
El Salvador		LMIC	5.40	2.69	798.14	46.05
Chile		UMIC	3.31	1.42	1,425.91	44.89
Ecuador		UMIC	4.10	2.54	1,090.47	43.24
Uruguay		UMIC	5.56	0.40	358.24	20.15
Haiti		LDC	5.25	1.00	306.78	17.15
Honduras		LMIC	2.53	1.20	498.77	15.90
Cuba		UMIC	4.39	0.84	345.31	14.61
Nicaragua		LMIC	2.43	0.92	453.62	12.07
Belize		UMIC	3.06	0.09	48.21	1.45
Panama		UMIC	1.76	1.38	91.57	1.44
Dominican Rep.		UMIC	4.21	1.19	32.44	1.37
Costa Rica		UMIC	2.02	0.53	16.59	0.37

Jamaica		UMIC	4.98	0.69	2.06	0.10
Guyana		LMIC	4.07	1.18	1.29	0.05
Nigeria	Africa	LMIC	5.78	1.80	8,655.55	541.07
South Africa		UMIC	3.22	1.91	11,811.08	443.48
Egypt		LMIC	4.85	4.62	7,629.09	341.35
Tanzania		LDC	4.95	1.28	4,995.52	248.93
Kenya		OLIC	4.06	2.13	3,831.28	178.48
Uganda		LDC	7.75	1.25	2,283.83	178.37
Malawi		LDC	4.62	0.98	3,729.15	173.33
Ethiopia		LDC	3.21	2.15	5,752.32	172.42
Zambia		LDC	5.40	1.13	2,798.54	170.47
Ghana		LMIC	6.09	0.93	1,748.76	111.02
Benin		LDC	6.23	2.34	1,161.92	72.99
Mozambique		LDC	4.01	1.34	1,525.17	69.62
Cameroon		LMIC	4.62	0.94	1,536.77	69.36
Congo DRC		LDC	6.70	2.20	1,122.18	68.68
Burkina Faso		LDC	4.81	0.94	1,292.95	64.64
Iran		UMIC	2.80	2.98	1,891.70	55.71
Zimbabwe		OLIC	4.34	1.86	1,075.99	55.17
Mali		LDC	3.43	0.95	1,467.25	54.62
Togo		LDC	6.39	0.76	623.53	41.60
Angola		LDC	4.51	1.26	942.06	40.85
Rwanda		LDC	6.33	0.98	583.82	36.23
Côte d'Ivoire		LMIC	4.44	0.95	647.07	27.77
Guinea		LDC	3.62	0.41	617.95	22.64
Madagascar		LDC	3.33	1.17	428.61	13.29
South Sudan		LDC	9.36	1.50	133.99	11.92
Chad		LDC	3.68	1.76	280.13	10.61
Central Afr. Rep.		LDC	7.02	1.75	156.89	10.10
Syria		LMIC	3.21	2.79	256.00	7.83

Morocco		LMIC	3.24	2.39	194.43	7.58
Burundi		LDC	4.85	1.38	127.80	5.90
Swaziland		LMIC	5.29	0.85	88.91	4.63
Senegal		LDC	3.45	1.12	135.85	4.42
Somalia		LDC	2.83	1.60	114.43	4.08
Gabon		UMIC	7.13	1.26	39.06	2.67
Yemen		LDC	3.03	1.56	76.16	2.41
Sierra Leone		LDC	3.97	0.40	48.08	1.87
Gambia		LDC	3.03	0.27	58.41	1.86
Lesotho		LDC	2.86	0.20	48.04	1.41
Namibia		UMIC	4.01	1.51	35.00	1.31
Botswana		UMIC	3.19	1.93	27.49	1.21
Congo		LMIC	8.43	1.67	9.31	0.76
Mauritania		LDC	2.63	0.34	16.44	0.47
Jordan		UMIC	2.93	1.27	8.25	0.27
Guinea-Bissau		LDC	2.59	0.26	9.34	0.24
Sudan		LDC	5.57	1.00	4.23	0.24
Eritrea		LDC	0.78	0.49	8.97	0.10
Iraq		UMIC	0.25	0.74	360.11	0.01
Ukraine	SEE/EECCA	LMIC	6.94	2.06	19,012.92	1,376.25
Serbia		UMIC	8.44	0.93	5,794.82	488.10
Turkey		UMIC	4.94	3.95	4,399.99	244.53
Moldova		LMIC	7.93	0.66	1,090.13	85.84
Belarus		UMIC	8.24	0.52	851.03	71.61
Bos. and Herz.		UMIC	8.48	1.71	529.58	42.02
Albania		UMIC	11.02	4.13	291.35	26.79
Kyrgyzstan		LMIC	4.97	2.94	437.02	24.99
Kazakhstan		UMIC	4.75	2.09	483.77	20.03
Georgia		LMIC	6.48	2.71	222.57	15.48
Uzbekistan		LMIC	3.49	2.10	358.69	14.48

Azerbaijan	UMIC	6.73	2.13	211.01	12.19
Tajikistan	OLIC	4.34	2.78	188.84	6.74
Macedonia	UMIC	7.85	0.13	83.10	6.50
Montenegro	UMIC	11.74	2.70	10.30	1.05
Armenia	LMIC	6.21	1.14	10.79	0.72
Turkmenistan	UMIC	0.26	0.30	43.66	0.14

Table A4. Rice average yield loss (%) due to O_3, with standard deviation of the mean, total annual production and production loss (thousand tonnes) due to O_3 per ODA country, averaged for the period 2010-12. ODA categories are as follows: LDC: Least Developed Countries; OLIC: Other Low Income Countries; LMIC: Lower Middle Income Countries; UMIC: Upper Middle Income Countries.

Country	ODA region	ODA category	Yield loss (%)	StdDev	Prod. (th. T)	Prod. loss (th. T)
China	South & Eastern Asia	UMIC	8.07	3.38	202,557.87	21,517.79
India		LMIC	6.22	2.97	154,332.47	11,359.70
Indonesia		LMIC	3.36	1.98	67,049.43	3,685.98
Bangladesh		LDC	6.21	1.39	50,560.12	3,431.27
Vietnam		LMIC	4.42	1.76	42,803.12	2,121.43
Thailand		UMIC	3.20	1.53	35,072.71	1,294.80
Myanmar		LDC	1.57	0.89	29,528.57	511.94
Pakistan		LMIC	4.73	3.13	6,148.99	402.22
Philippines		LMIC	1.92	0.62	16,830.34	325.19
Nepal		LDC	3.74	3.43	3,598.01	261.74
North Korea		OLIC	7.32	2.14	2,469.69	216.72
Malaysia		UMIC	5.68	2.36	2,589.98	170.26
Cambodia		LDC	2.09	0.61	7,212.83	163.50
Laos		LDC	2.96	0.70	3,304.65	108.87
Sri Lanka		LMIC	2.02	0.82	4,013.82	76.02
Afghanistan		LDC	2.49	2.17	548.37	12.52
Timor-Leste		LDC	2.21	0.94	104.78	2.53

Bhutan		LDC	0.66	0.46	37.82	0.31
Solomon Islands		LDC	0.17	0.09	2.54	0.004
Brazil	Central & South America	UMIC	3.72	1.48	119,14.85	509.80
Peru		UMIC	2.72	1.77	2,845.96	126.36
Argentina		UMIC	3.92	1.26	1,824.04	81.19
Colombia		UMIC	2.87	1.54	2,162.35	62.49
Ecuador		UMIC	2.90	1.91	1,573.09	56.41
Uruguay		UMIC	3.87	0.90	1,293.24	47.71
Venezuela		UMIC	4.71	2.37	911.34	42.30
Dominican Rep.		UMIC	3.18	0.88	861.25	28.27
Guyana		LMIC	2.92	0.68	564.16	20.09
Paraguay		LMIC	4.82	0.64	370.07	18.99
Cuba		UMIC	3.01	0.56	554.06	15.61
Bolivia		LMIC	3.17	0.92	407.48	13.90
Suriname		UMIC	3.23	0.05	289.62	9.39
Nicaragua		LMIC	1.65	0.74	422.19	8.27
Mexico		UMIC	4.46	1.61	184.90	7.75
Costa Rica		UMIC	0.96	0.44	274.48	3.22
Haiti		LDC	3.28	0.67	82.34	3.08
Panama		UMIC	1.21	0.90	234.79	2.60
Chile		UMIC	2.19	0.46	124.95	2.51
El Salvador		LMIC	3.74	1.48	30.95	1.23
Guatemala		LMIC	2.46	1.47	29.40	0.93
Honduras		LMIC	1.63	0.72	29.41	0.62
Belize		UMIC	2.07	0.13	9.54	0.20
Nigeria	Africa	LMIC	4.07	1.14	4,862.94	212.35
Egypt		LMIC	2.28	2.15	5,304.39	174.29
Madagascar		LDC	2.61	1.31	4,528.33	100.44
Iran		UMIC	2.13	2.26	2,244.34	91.85
Tanzania		LDC	3.11	1.21	1,961.38	66.84

Mali	LDC	3.04	0.80	1,983.43	60.81
Guinea	LDC	2.05	0.36	1,879.94	36.45
Côte d'Ivoire	LMIC	2.95	0.63	1,177.84	34.78
Ghana	LMIC	4.14	0.55	478.52	19.95
Sierra Leone	LDC	2.22	0.28	884.79	19.23
Congo DRC	LDC	5.05	1.32	291.60	14.97
Uganda	LDC	5.53	0.61	225.71	12.66
Burkina Faso	LDC	4.00	0.65	290.72	11.82
Senegal	LDC	2.12	0.56	568.74	11.10
Benin	LDC	3.97	0.43	216.14	9.43
Chad	LDC	3.66	1.18	184.84	7.05
Liberia	LDC	2.74	0.65	232.89	6.17
Mozambique	LDC	2.40	0.94	182.80	5.09
Togo	LDC	4.06	0.54	117.90	4.84
Rwanda	LDC	4.28	0.66	88.11	4.09
Malawi	LDC	2.76	0.81	116.05	3.84
Guinea-Bissau	LDC	1.77	0.35	195.66	3.62
Kenya	OLIC	3.11	1.11	104.68	3.32
Cameroon	LMIC	3.13	0.75	117.35	3.20
Burundi	LDC	3.32	0.97	92.81	2.65
Gambia	LDC	2.86	0.26	70.85	2.09
Mauritania	LDC	1.57	0.01	124.05	1.94
Central Afr. Rep.	LDC	4.81	1.22	36.24	1.76
Angola	LDC	4.39	1.19	43.24	1.75
Zambia	LDC	3.27	0.84	48.49	1.60
Morocco	LMIC	3.03	2.50	42.93	1.42
Iraq	UMIC	0.37	0.13	251.24	0.86
Niger	LDC	2.80	0.38	15.16	0.43
Ethiopia	LDC	1.42	NA	10.25	0.15
Somalia	LDC	2.77	0.70	4.81	0.13

Congo		LMIC	5.43	NA	0.69	0.04
Turkey	SEE/EECCA	UMIC	5.73	3.09	885.90	65.66
Ukraine		LMIC	6.90	1.09	157.89	10.22
Kazakhstan		UMIC	2.99	1.86	379.01	8.20
Uzbekistan		LMIC	3.18	2.36	231.05	6.77
Tajikistan		OLIC	3.12	2.14	104.80	2.20
Macedonia		UMIC	6.56	0.39	22.49	1.43
Kyrgyzstan		LMIC	3.54	2.03	12.24	0.36
Turkmenistan		UMIC	0.39	0.14	94.85	0.32
Azerbaijan		UMIC	3.51	0.67	2.10	0.07
Fiji	Australasia	UMIC	0.48	0.18	5.67	0.03

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