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Ozone pollution threatens the production of major staple crops in East Asia

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East Asia is a hotspot of surface ozone (O_3) pollution, which hinders crop growth and reduces yields. Here, we assess the relative yield loss in rice, wheat and maize due to O_3 by combining O_3 elevation experiments across Asia and air monitoring at about 3,000 locations in China, Japan and Korea. China shows the highest relative yield loss at 33%, 23% and 9% for wheat, rice and maize, respectively. The relative yield loss is much greater in hybrid than inbred rice, being close to that for wheat. Total O_3-induced annual loss of crop production is estimated at US$63 billion. The large impact of O_3 on crop production urges us to take mitigation action for O_3 emission control and adaptive agronomic measures against the rising surface O_3 levels across East Asia.

Tropospheric ozone (O_3) is a secondary air pollutant produced by hydroxyl radical oxidation of carbon monoxide or hydrocarbons in the presence of nitrogen oxides (NO_x) and sunlight[1]. It is a greenhouse gas contributing directly to global warming[2] but also indirectly by reducing the carbon sink of terrestrial ecosystems[3,4]. Surface O_3 concentrations in the Northern Hemisphere have been increasing from 10 to 15 ppb in the pre-industrial period to ~50 ppb at present[5,6]. Despite the deceleration of the increase or even decrease in America and Europe in the last two decades[7], surface O_3 concentration is increasing in Asia and has outweighed trends in other regions[8].

Surface O_3 poses a threat to food security due to its deleterious effects on crop production[9–11]. Chronic O_3 concentrations of 31–50 ppb can reduce global annual yields of wheat, rice and maize by 7.1%, 4.4% and 6.1%, respectively[12], potentially leading to aggregated economic losses of multi-billion US$s per year[13]. Asia produces large portions of the world cereals: on average, 90% of rice, 32% of maize and 44% of wheat came from the region between 2014 and 2018[14].

For Asia, previous studies quantifying O_3-induced crop losses[12,15,16] are probably biased by the use of crop yield sensitivity that is inadequate to represent Asian crop genotypes and environmental conditions, the use of modelled surface O_3 levels and/or the omission of crop phenology from impact calculations. Here, we present a quantification of ambient O_3 impacts on Asian crops using data of accumulated O_3 exposure experiments and recently developed O_3 monitoring networks across East Asia. To do that, we have developed exposure–response relationships for three major cereals (rice, wheat and maize) on the basis of a set of experimental studies on Asian cultivars conducted in the major production regions. These relationships are combined with ground-based O_3 measurements from over 3,000 monitoring sites across East Asia (Fig. 1) to assess the yield losses induced by ambient O_3. Estimates of yield loss for Asia were then compared with the results of experiments with the application of ethylenediurea (EDU), which is an anti-ozonant widely applied in research to protect plants against O_3 damages[17,18]. The application of EDU to plants of wheat, rice and maize increases the crop yields via the protection against O_3 damages and the resultant yield increase is expected to provide an independent estimate of the yield losses by the present level of surface O_3.

Results

Current O_3 exposure levels. Among 3,072 sites in East Asia (Supplementary Table 1), 98.7% experienced a six-month accumulated daytime O_3 over a threshold of 40 ppb (AOT40) higher than 5 ppm h, which is the critical level for plant health protection (Fig. 1). The fractional exceedance over 5 ppm hours (ppm h) was highest at 99.4% of the sites in China, with a high AOT40 >50 ppm h located in North China Plain. The national average value was 30.9 ppm h for China, which is higher than the values of 17.5 ppm h in Japan and 21.2 ppm h in South Korea. When compared with other regions of the world on the basis of six-month AOT40 (April–September), China, South Korea and Japan had much higher values than did the United States (15.7 ppm h) and Europe (11.1 ppm h)[8]. Hence, East Asia, as a region, ranks first in terms of the threat of surface O_3 to plant health. The impact of surface O_3 on cereal production is of particular concern, since the AOT40 values are highest in the North China Plain and middle to lower reaches of Yangtze River Delta (Fig. 1), where major cereal production provinces of China are located.

Crop yield losses due to O_3 exposure in Asia. We estimated the relationships between the O_3 exposure dose and the relative yield (RY, the ratio of the grain yield under O_3 to the yield at the baseline O_3 dose) for rice, wheat and maize using data of O_3-enrichment

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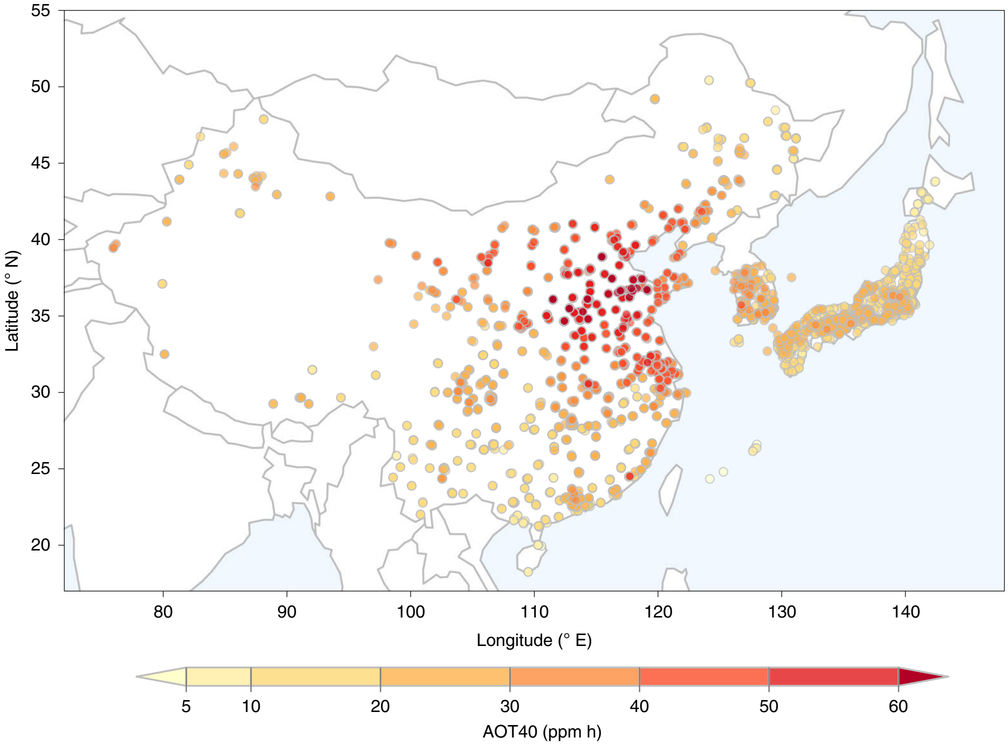

Fig. 1 | Current ozone pollution in East Asia as shown by the six-month (from 1 April to 30 September) AOT40. Daytime ozone level over an hourly threshold of 40 ppb (AOT40) was accumulated for the six months at individual monitoring sites and averaged across the latest three years (China, 2017–2019; Japan, 2015–2017; and South Korea, 2016–2018). The base maps are from spData package in R (https://cran.r-project.org/web/packages/spData/index.html).

experiments conducted in Asia. We collected more data from experiments with field-grown plants than previous studies (Supplementary Table 2). Instead of assuming a limited number of O_3 dose metrics a priori, we estimated both the O_3 dose metrics and the dose–response relationship simultaneously by fitting a model of RY on AOTx (accumulated daytime O_3 over a threshold of x ppb) to the results of O_3 exposure experiments. Since AOT0 can be regarded as a mathematical equivalent to M12 (mean daytime 12 h O_3 concentration), the AOTx for $0 \leq x \leq 40$ entails the two most-often used dose metrics (Methods). With x estimated at 19.4, 26.5 and 40.0 ppb for rice, wheat and maize, respectively (Supplementary Table 2 and Supplementary Fig. 1), the dose–response relationships describe well the results of the O_3-enrichment experiments (Fig. 2).

We hereafter define (1 – RY) as relative yield loss (RYL) and present the yield response to O_3 by RYL at AOT40 = 15 ppm h (Supplementary Table 2), which corresponds to around 80th, 90th and 95th percentiles of AOT40 values for maize, rice and wheat, respectively, at the crop production sites across the three countries. Wheat is the most sensitive, with the RYL being 38% and its 95% confidence interval (CI) at (34%, 42%), whereas maize is the least sensitive with RYL at 10% (8%, 12%). Rice is in between wheat and maize, with RYL at 19% (15%, 23%) in conventional inbred cultivars, whereas the high-yielding hybrid cultivars of rice showed much higher RYL at 42% (32%, 51%), being comparable to wheat.

These yield losses of rice and wheat based on O_3 elevation experiments in Asia are significantly greater than those derived from experiments in North America and Europe; however, they are comparable to those based on experiments in Asia (Supplementary Table 2).

We estimated the above yield loss by identifying interacting effects of other variables such as methodology of experiment and genetic variability of the crop species and removing their influences, when necessary. In rice and wheat, we found that the experiments with pot-grown plants showed smaller yield response to O_3 than the field-based experiments (Supplementary Table 3 and Supplementary Fig. 2). We omitted the pot experiments from the estimation of the yield loss, since we are concerned about the O_3 impacts on field-grown plants only. While we were also concerned about the confounding effect of experimental facility for O_3 elevation, it turned out to be non-significant (Supplementary Table 3). In rice, we detected greater yield loss in hybrid cultivars than in the inbred ones (Fig. 2a and Supplementary Table 2). We therefore estimated RYL in inbred and hybrid cultivars separately. For maize, we did not test the effect of the interacting variables because of the limited number of datasets.

O_3-induced yield losses estimated by EDU application. EDU is an anti-ozonant chemical that could increase crop yield under elevated O_3 concentrations in the ambient air due to its phytoprotective effects. The EDU application experiments in Asia revealed a decline of RY due to ambient O_3 and the yield loss as estimated with EDU experiments was mostly consistent with that found in O_3-enrichment experiments (Fig. 3). In wheat, many varieties exhibited lower yield losses when estimated on the basis of EDU application than when measured in O_3-enrichment experiments (Fig. 3b), a discrepancy which may be due to the insufficient yield protection by EDU application at higher levels of O_3 stress as discussed later (Discussion).

O_3-induced production losses in East Asia. Using the Asian-specific exposure–RY relationships (Fig. 2 and Supplementary Table 2) and the AOT40 values across the three countries (Supplementary Fig. 3), RYLs for different crops were calculated over East Asia (Fig. 4). Across East Asia, wheat is the most affected crop by the ambient

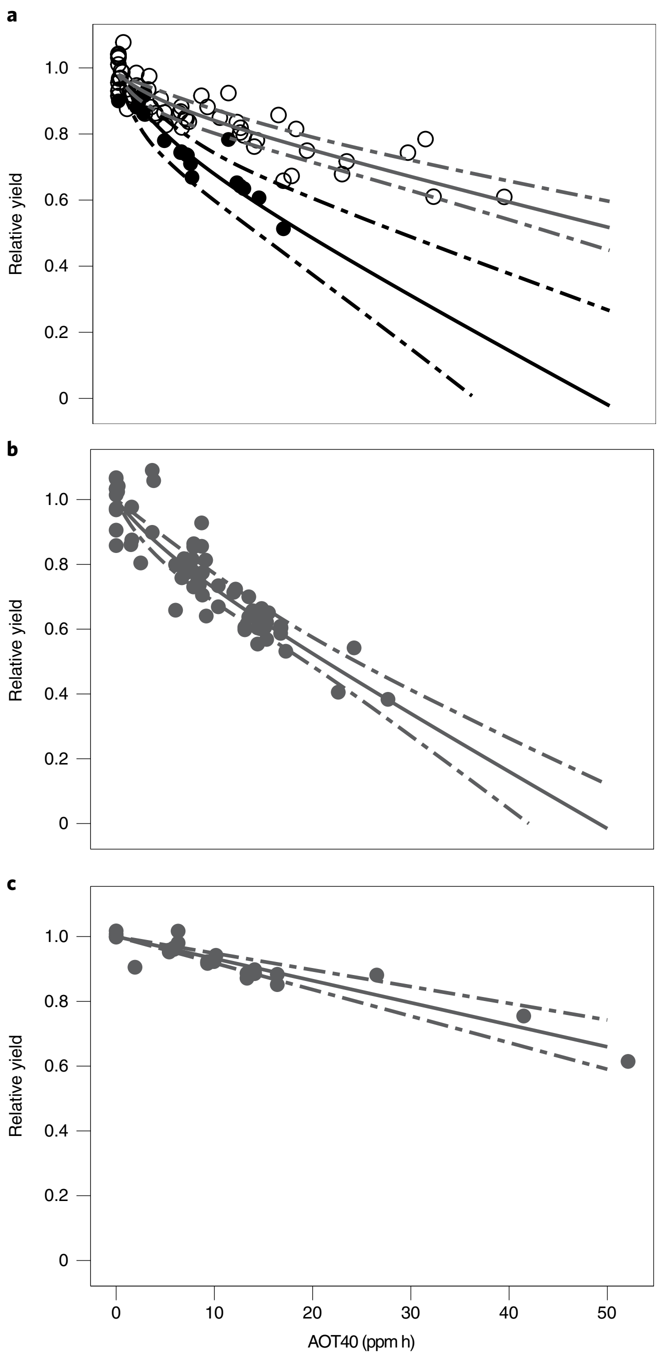

Fig. 2 | O_3-enrichment experiments for rice, wheat and maize conducted in Asia. **a**–**c**, Relationships between AOT40 for 90 d until maturity and RY of rice (**a**), wheat (**b**) and maize (**c**) in Asia. Each point represents the yield relative to that at zero AOT40 for each dataset. The solid lines represent the relationship between AOT40 and RY, whereas the dashed lines represent the 95% CI of the relationship (not the individual observations). In **a**, the filled circles represent hybrid cultivars, whereas unfilled circles represent inbred cultivars. Equations for the relationships are shown in Supplementary Table 2.

levels of O_3 (Fig. 4c), followed by hybrid and inbred rice (Fig. 4a,b), while maize is the least affected (Fig. 4d). The RYL of wheat exceeds 35% across the North China Plain (Fig. 4c), where the AOT40 reaches 15 ppm h (Supplementary Fig. 3c). With the major wheat-producing provinces (for example, Henan and Shandong) located in the North China Plain, national mean RYL of China reaches 33% (28%, 37%) (Table 1). The national mean RYL in South Korea is also high at 28% (23%, 32%) (Table 1), with AOT40 exceeding 10 ppm h at most of the wheat-growing areas. In Japan, in comparison, AOT40 is lower than 10 ppm h at about 85% of the wheat-growing areas, with the estimated national mean RYL at 16% (Table 1).

For China, rice RYL comes next to that of wheat, with the mean RYL at 23% (17%, 30%), RYL being much higher in hybrid rice, at 30% (23%, 39%), than that in inbred rice (12% (9%, 16%)) (Table 1). The spatial pattern of RYL in inbred rice showed maximum values in the North China Plain, from which RYL tends to decline toward northeast and southwest of China (Fig. 4a). Hybrid rice is grown only in the middle to the south of China and the RYL exceeds 35% in the northernmost part of the hybrid rice areas (Fig. 4b). In major hybrid rice areas at around 30° N and lower, rice is grown in double cropping and RYL ranges between 25 and 30% when early- and late-double crops are combined (Fig. 4b). However, RYL widely exceeds 30% for late-double rice (Supplementary Fig. 4d) due to the higher AOT40 values for late- than early-double crops in south China (Supplementary Fig. 3). On average, RYL in rice is less over South Korea and Japan than in China and spatially declines along the gradient from the west to the east and northeast (Fig. 4a).

RYL of maize for each country is lower than that of rice. The mean RYL in China is estimated at 9% (6%, 10%), followed by South Korea with RYL estimated at 5% (3%, 6%) (Table 1). The spatial distribution of RYL of maize is similar to that of wheat with a peak in the North China Plain and declines toward northeast and southwest (Fig. 4d).

Relative yield losses as converted to the crop production loss on mass basis were 62, 63 and 23 Mt in wheat, rice and maize, respectively (Table 2). The production losses converted to monetary losses were US$22 billion, US$33 billion and US$7.8 billion for wheat, rice and maize, respectively. The production loss on mass and monetary bases (Table 2) is thus largest in rice across East Asia as well as in each of the countries. As compared to the production loss in rice, that in wheat is at about the same magnitude as for China but is minor for Japan and about two orders less for South Korea (Table 2). Production loss of maize in China is less than that for wheat and rice and very small in South Korea (Table 2). In Japan, maize production per se is negligible at the national scale.

Production gains by mitigation of O_3 pollution in East Asia. Assuming a mitigation scenario of halving the AOT40, we estimated the production gains in the three cereals relative to their current amount of production and supply in the three countries. In wheat, the production gain relative to the current production amount is substantial, ranging between 20% in China and 8% in Japan (Supplementary Table 4). The production gain of wheat amounts to 21% of the domestic supply in China, whereas it is only 1 and 0.1% of the supply in Japan and South Korea, respectively. In the last two countries, the production is only a minor contributor to the supply of wheat. For rice, the production gain relative to the supply is 10% in China, 2% in Japan and 4% in South Korea (Supplementary Table 4). In China, the relative production gain of rice is less than that of wheat but the opposite holds true for Japan and South Korea. Supply of rice is dominated by the domestic production across the three countries (Supplementary Table 4). The production gain in maize is less than for the other cereals and negligible relative to the domestic supply in South Korea.

Discussion

We estimate that the RYL is particularly high for wheat in China, ranging between 28% and 37% (95% CI) (Table 1), which is higher than previous estimates (17–18%) based on O_3 data from the same monitoring network as in this study but for years 2015 and 2016[16]. This discrepancy is reconciled by a recent study[19], which reported

Table 1 | Relative yield loss of each crop in China, Japan and South Korea

Crop	Country		Yield loss (%)	95% confidence	
				Upper boundary (%)	Lower boundary (%)
Wheat	China		32.8	36.9	28.2
	Japan		15.8	19.5	12.2
	South Korea		27.8	32.2	23.3
Rice	China	All	23.0	30.3	17.4
		Inbred	12.2	15.9	9.2
		Hybrid	29.8	38.6	23.0
	Japan		5.1	8.1	3.2
	South Korea		10.7	14.9	7.7
Maize	China		8.6	10.4	6.4
	South Korea		4.7	5.6	3.5

The RYL (Fig. 4) was weight-averaged across each country by the production amount in each province (China and South Korea) or prefecture (Japan).

a large increase of wheat RYL, from 20% in 2015 to 33% in 2018, driven by the rapid increase of surface O_3 (ref. [20]). The wheat yield sensitivities to AOT40 are similar between the present study and the preceding studies because the previous studies are based on the Chinese experiments, which largely contribute to the datasets used in this study (Supplementary Table 5). For rice also, the current estimate of RYL between 16 and 30% (95% CI) across China (Table 1) is higher than the 6.4% estimated by the study[19] on the basis of a much smaller number of experiments with inbred cultivars only. The current estimate of 7–10% (95% CI) RYL for maize across China is also higher than the previous estimate of 5–6% (ref. [19]) due to the higher yield sensitivity in this study than the previous one, although the difference is small (2–3%).

The comparison between our estimated RYLs and those reported in previous studies at the same AOT40 level (Supplementary Table 2) suggests greater RYL response in Asian than European experiments, which is in line with the comparison between Asian and North American experiments with wheat and rice[21]. For wheat, the yield sensitivity in Asian experiments is higher than that in North American experiments but comparable to that in Europe[22]. A recent re-analysis[23] of the data of the Asian experiments, however, indicates a higher sensitivity compared to experiments in Europe, which is consistent with our study and other studies based on experiments in Asia (Supplementary Table 2). The higher sensitivity of wheat in experiments conducted in Asia than those conducted in the other regions could be related to the growing environment, where wheat is often grown in the lowland rice–wheat cropping system, as well as the physiological traits of the cultivars. However, little is known beyond these speculations.

For rice, the higher yield sensitivity estimated in our study is based on a considerably larger number of field-based experiments than the previous studies[12,24]. The entire or partial reliance on the pot-based experiments in the previous studies should be mostly responsible for the lower estimated sensitivity (Supplementary Fig. 2 and Supplementary Tables 2 and 3). The lower yield sensitivity rendered rice less sensitive than maize[12], which is at odds with this study and a previous report[24].

Our estimates of RYL due to O_3 across Asia have some uncertainties. First, the many O_3 monitoring sites (Fig. 1) are located in urban areas where the local O_3 level is lower than in rural and background areas[25–27]. Such biases in O_3 data would underestimate RYL in Asia. On the other hand, we think that the uncertainty due to the spatial estimation by Kriging is small. The other interpolation methods, inverse distance weighting and radial basis functions, produce similar estimates of production loss (Supplementary Table 6).

Second, despite the larger number of data points than the preceding studies, the RYL sensitivities are based on experiments conducted at very limited sites in each country: two sites each in China and India and only one site in Japan for rice and only one site each in India and China for maize. It is noteworthy that we have had no O_3 elevation experiments for wheat in the North China Plain, which is China's biggest wheat-producing region and world's hotspot of high O_3 levels nowadays. It is also noteworthy that no O_3-elevation experiments for rice have been conducted in the double-rice cropping region in the middle to south China. More experimental sites are needed to cover the O_3 impacts on a wider range of the crop genotypes under the diverse environment of Asia.

Third, the EDU application experiments reveal some wheat cultivars exhibiting lower estimated yield loss than that based on the dose–RY relationships (Fig. 3b). This may suggest our overestimation of RYL in the crops for some cultivars; however, it could be due to an inherent bias of the RYL estimation by EDU application. The difference between the cultivars in the EDU effect could be explained by different degrees of sensitivity to O_3 between cultivars or cultivar-specific efficacy of the phytoprotection by EDU. These two hypotheses can be tested separately only if the yield sensitivity to O_3 is quantified independently of the EDU treatment, which has

Table 2 | Production loss and economic loss due to ozone in China, Japan and South Korea

Crop	Country	Production loss (t)			Economic loss (US$)		
		Mean	95% confidence		Mean	95% confidence	
			Upper boundary	Lower boundary		Upper boundary	Lower boundary
Wheat	China	6.17×10^7	7.39×10^7	4.97×10^7	2.18×10^{10}	2.61×10^{10}	1.76×10^{10}
	Japan	1.54×10^5	1.98×10^5	1.14×10^5	4.65×10^7	6.00×10^7	3.45×10^7
	South Korea	1.31×10^4	1.61×10^4	1.03×10^4	1.16×10^7	1.43×10^7	0.91×10^7
Rice	China	6.15×10^7	8.95×10^7	4.36×10^7	3.08×10^{10}	4.48×10^{10}	2.18×10^{10}
	Japan	5.82×10^5	9.49×10^5	3.55×10^5	1.18×10^9	1.92×10^9	0.72×10^9
	South Korea	6.45×10^5	9.37×10^5	4.46×10^5	1.08×10^9	1.56×10^9	0.74×10^9
Maize	China	2.27×10^7	2.80×10^7	1.66×10^7	7.81×10^9	9.66×10^9	5.73×10^9
	South Korea	3.65×10^3	4.44×10^3	2.73×10^3	2.40×10^6	2.92×10^6	1.79×10^6

The production value in each country was averaged across three years (2016, 2017 and 2018) from FAO statistics[14].

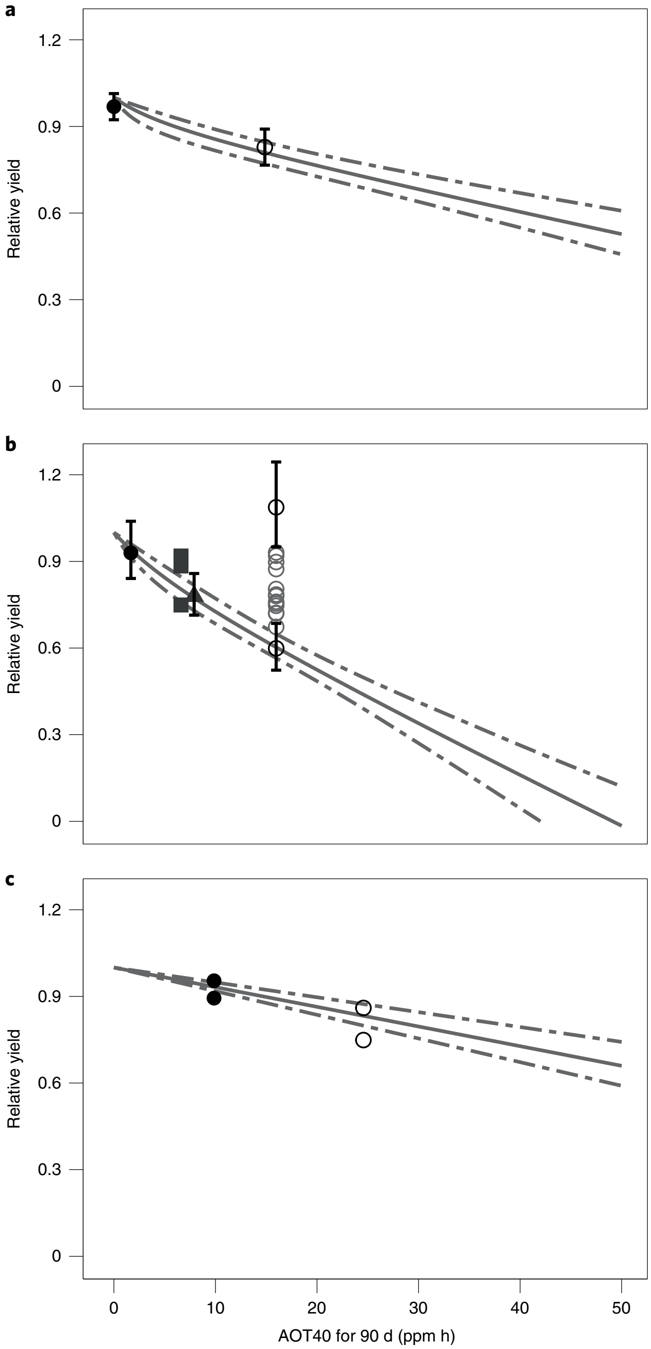

Fig. 3 | EDU experiments for rice, wheat and maize conducted in Asia. **a**–**c**, Relationships between AOT40 for 90 d until maturity and RY of rice (**a**), wheat (**b**) and maize (**c**) subjected to EDU applications in Asia. Each point represents the yield of a crop cultivar in the no-EDU plots relative to that in EDU-application plots. Solid and dashed lines in Fig. 2 are shown for comparison with the RYs as estimated with the EDU application. Different experiments are shown by different symbols: **a**, filled circles[53] and unfilled circle[28]; **b**, filled circles[53], squares[54], triangles[55] and unfilled circles[56]; **c**, filled circles[57]and unfilled circles also the same study[57] but under experimental O_3 increase. A 95% CI is shown where possible by a vertical bar attached to the mean. In **b**, vertical bars are shown only for the two extreme cultivars, while the CIs for the other cultivars are between those of the two extremes.

seldom been done[28]. It must also be noted that the efficacy of protection is 100% at best and that the efficacy could deteriorate as higher level of O_3 stress is imposed. EDU treatment thus inherently gives a conservative estimate or underestimate of the yield loss due to O_3 in the ambient air, particularly at elevated levels (more explanation in Methods).

Beyond these uncertainties, however, this study identifies the threat of elevated surface O_3 levels to crop production in East Asia, especially to wheat in China and rice across China, Japan and South Korea. For wheat, the very high RYL in the North China Plain (Fig. 4c) greatly exceeds the earlier prediction of wheat RYL in China of 2020[29]. This is a real threat to crop production because 60% of China's wheat harvest comes from the provinces in the North China Plain[30]. A glance at crop statistics in China (China Statistical Yearbook 2019 http://www.stats.gov.cn/tjsj/ndsj/2019/indexch.htm) does not indicate an evident decline in the crop yield in the provinces. However, detailed studies using a 'top-down' approach[10,31] could elucidate the influences of the rising surface O_3 levels on the crop production. In such studies, the O_3 impacts should be quantified along with the influences of the other temporal changes in air quality such as particulate matter[32].

For rice, the higher RYL sensitivity in hybrid cultivars than in the inbred ones has an implication to rice production in China, where >50% of rice paddies are planted to hybrid cultivars because of their high productivity[33]. Our coverage of hybrid rice is limited to only four cultivars, three in China and one in India, which is clearly disproportionate to the contribution of hybrid cultivars to rice production in China. Some studies have explored mechanisms of the greater impacts of O_3 on hybrid cultivars[34–36] but further studies are warranted to better quantify the O_3 impacts on hybrid rice cultivars.

The quantification of the O_3 impacts is a premise for any planned actions to protect Asian food production from the increasing threat of surface O_3. However, the real challenge would be to reduce the O_3 levels, which should be achieved by applying drastic cuts in the emissions from road transportation and the energy sector[11]. For the emission control, regional or national policies may not suffice in reducing O_3 concentrations to the required levels, because (1) reduced NO_x may decrease O_3 titration[37], (2) removal of $PM_{2.5}$ may release more HO_2 for O_3 formation[38] and (3) long-range transport may promote local O_3 level[39]. Therefore, stringent emission regulation with Pan-Asian coordination would be necessary to achieve higher reduction targets. Such pollution control would bring about considerable benefits from enhanced crop production (Table 2)[15,40,41] and improved grain quality[42].

In China, for example, halving of AOT40 levels would increase the supply of wheat, rice and maize by 20%, 9% and 4%, respectively (Supplementary Table 4). Economic benefits of the mitigation should be quantified considering the responses of the food system to the supply increase in the respective countries, which is beyond the scope of this study. The benefits are not limited to the economic ones, however. For example, the possible crop supply increases due to reduced O_3 impact would facilitate the efforts to secure the grain supply with reduced environmental costs in China[43]. Benefits from the mitigation of surface O_3 pollution should also include the protection of unmanaged vegetation and reduced damages to human health[15,20,44].

In Japan and South Korea also, the halving of AOT40 levels would increase the production of rice relative to the supply by 2% (Japan) and 4% (South Korea), which is arithmetically small but still important (Supplementary Table 4). The lower production gain in Japan and South Korea is partly because hybrid cultivars are not grown in the countries. For wheat and maize, contribution of the production gain to the supply looks negligible. Nevertheless, the reduced O_3 impacts should benefit the domestic production, particularly of wheat in Japan, by ameliorating the disadvantage of the yield loss by O_3 against the imports from other countries, such as the United States, Japan's largest wheat exporter[14]. While the AOT40 for wheat has been increasing in western and central Japan for the period from 1995 to 2014, it has been declining at most sites in the United States for the same period[45].

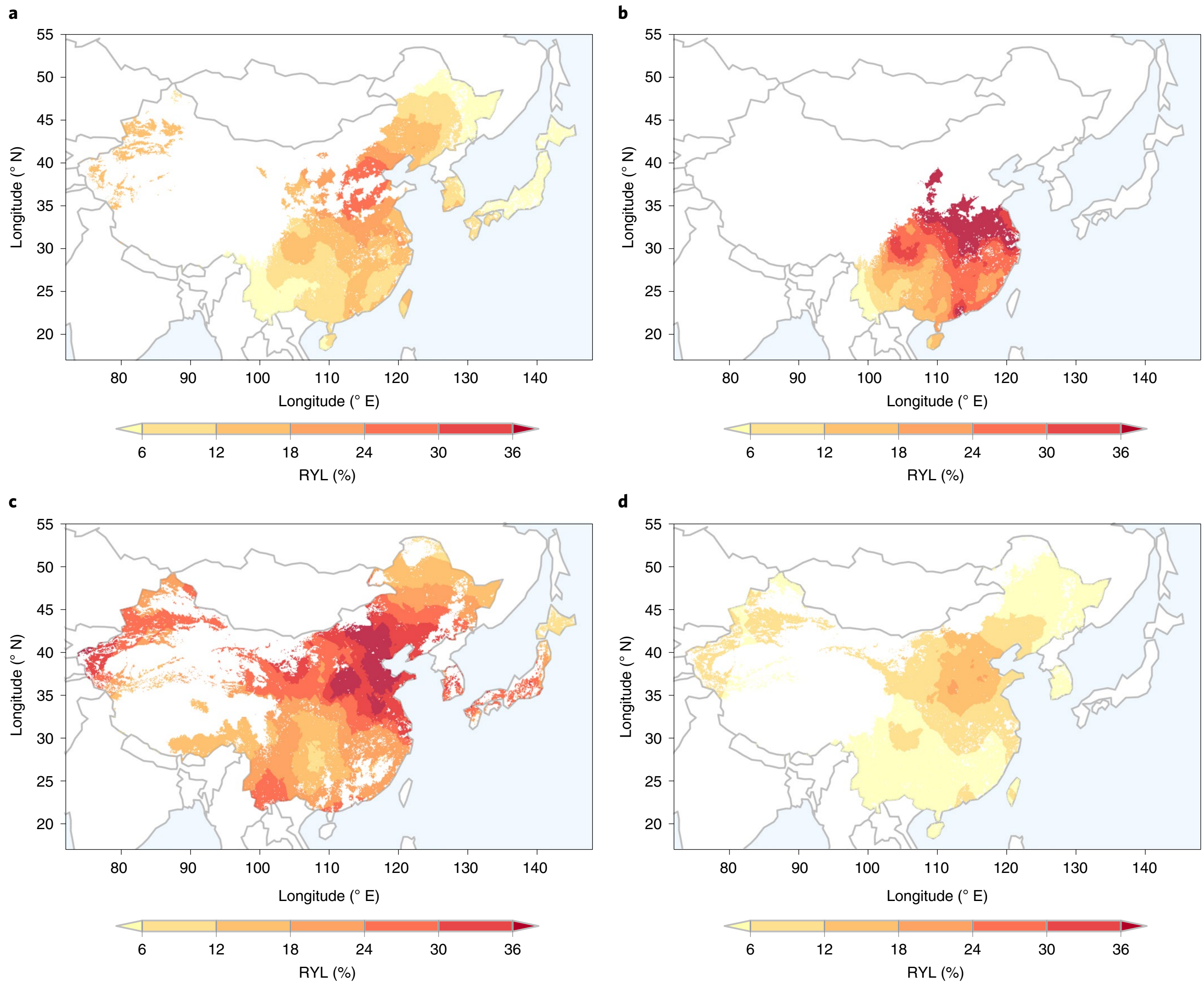

Fig. 4 | RYLs for different crops calculated from Asian-specific exposure–RY relationships and the AOT40 values across China, Japan and South Korea. **a**–**d**, RYL (%) of inbred rice (**a**), hybrid rice (**b**), wheat (**c**) and maize (**d**) in Asia. Results are derived from AOT40 averaged across the latest available three years (China, 2017–2019; Japan, 2015–2017; and South Korea, 2016–2018). For different crops, AOT40 is accumulated across a 90 d period until maturity. For double-crop rice in China, RYL was calculated separately for single or early-double crop and late-double crops and the resultant RYL was weight-averaged with the harvested amount in the respective province. The base maps are from spData package in R.

Like the three countries in East Asia, pollution control of surface O_3 will benefit the supply of rice across the countries in South and Southeast Asia, where the supply of rice comes predominantly from the domestic production. The supply of wheat in most countries in Southeast Asia depends on imports from other countries, whereas in many South Asian countries (for example, India and Pakistan), the domestic production suffices[14]. The pollution control of surface O_3 shall therefore benefit the supply of wheat and rice in South Asia. Against the prospect of persistent food shortage in South Asia for decades to come[46], the rising trend of lower tropospheric O_3 levels over India[47,48] urges us to quantify the crop production losses and possible benefits of air pollution control. By developing monitoring networks of surface O_3 throughout South Asia, we could demonstrate the risks of O_3 pollution more convincingly than earlier studies[12], using the Asia-specific exposure–RYL relationships presented herein. The quantification of the O_3 impacts on cereal supplies will motivate the efforts toward the region-wide emission control[44].

Besides the emission control to lower surface O_3 concentrations, O_3-induced crop yield losses could be reduced by a combination of agronomic practices such as adjustment of water supply, breeding and/or selection of more O_3-tolerant cultivars and hybrids and the application of anti-ozonants. Adjusting water supply could bring about cobenefits of water-saving and reduced O_3 impacts for irrigated farming, and development of O_3-tolerant cultivars and hybrids should efficiently mitigate the O_3-induced RYLs[12]. Incorporation of anti-ozonants such as EDU into the cultivation practices could also mitigate O_3-induced RYLs. Although EDU is currently used for research purposes (for example, to quantify the O_3 impacts), its application increases the yield of rice by up to 20% (Fig. 3a) and of wheat by up to 40% (Fig. 3b) in fields under high AOT40 at around 15 ppm h. Areas under even higher levels of AOT40 values are widely distributed in the North China Plain (Supplementary Fig. 3).

Adaptation of crop production to rising surface O_3 via either of the above pathways currently remains a possibility and we are yet to face many challenges of installing them in the agricultural practice. For EDU, for example, the lack of toxicity to animals[18] must be extended to humans and the economic cost is also critical for its adoption[17]. Above all, mechanisms of the plant-protective effects of the countermeasures must be resolved for their eventual adoption in the field.

Methods

Collection of ozone observation data. Hourly O_3 observations across China, Japan and South Korea were obtained from national air quality monitoring websites (Supplementary Table 1). We included a total of 3,072 monitoring sites that had over 1,647 hourly data during the daily time (8–20 h) from 1 April to 30 September (2,196 h in total) (Fig. 1). The site distribution was not spatially uniform, with a denser network in Japan, South Korea and eastern China and less stations in western China (Fig. 1). With extensive data quality controls, the unreliable records higher than 300 ppb were removed. To estimate ambient O_3 pollution level, we used the concentrations in the latest three years (Supplementary Table 1).

Calculation of O_3 exposure metrics. As an indicator of the O_3 pollution level across East Asia, we calculated *AOT40* values (ppm h) for 12 daytime hours (8–20 h local standard time) across the six-month period from 1 April to 30 September, as follows

$$AOT40 = \sum_{\mathrm{i}=1}^{183} \sum_{\mathrm{j}=1}^{12} \mathrm{Max}\left(C_{ij} - 40,\ 0\right), \tag{1}$$

where C_{ij} is hourly O_3 concentration (ppb) at the monitoring site.

For the crop loss estimation, we estimated the hourly O_3 concentrations at the crop canopy height multiplying those at the monitoring sites by a factor of 0.9 on the assumption that the canopy height was 1 m and the height of the air sampling at the monitoring sites was 5 m or higher above the ground level[49]. We then calculated *AOTx* values in the same way as *AOT40* but with the threshold of x at 0, 10, 20, 30 and 40 (ppb) and for the 90-d period until the maturity date of each crop, as follows

$$AOTx = \sum_{\mathrm{i}=1}^{90} \sum_{\mathrm{j}=1}^{12} \mathrm{Max}\left(C_{ij} - \mathrm{x}, 0\right). \tag{2}$$

The crop maturity dates in China were determined by using the crop calendar obtained from a satellite retrieval of plant phenology at the resolution of 1 km for the year 2015[50]. To fill gap of urban grids where phenology data are missing, we upscaled the 1-km grids to 30-km by assuming the same phenology within each of the coarser grids. For Japanese wheat calendar, we used the data in 2015 obtained from the crop statistics survey data of the Ministry of Agriculture, Forestry and Fisheries of the government of Japan. Rice phenology in Japan was shared by the National Agriculture and Food Research Organization, in which the harvest date in 2015 was used. The crop maturity dates at each monitoring site in South Korea were determined using a global crop phenology data product[51]. We used only the sites with >810 h of valid data during the total of 1,080 (12 × 90) h. For the missing hours, we scaled the value by 1,080 per actual hours. The maturity dates thus estimated are mapped in Supplementary Fig. 5.

For the crop loss estimation, we developed a scheme to cover two major O_3 exposure metrics: the daytime mean O_3 concentrations for 12 h (*M12*, ppb) and *AOT40*. In the same time window of daily 12 h for 90 d as for *AOT40* (equation (1)), the *M12* can be related to *AOT0*: *AOTx* at zero *x*, as follows:

$$AOT0 = \sum_{\mathrm{i}=1}^{90} \sum_{\mathrm{j}=1}^{12} C_{ij} = (1,080/1,000)\ M12. \tag{3}$$

AOTx with x ranging from 0 to 40 thus includes *M12* and *AOT40* as well as their intermediate O_3 doses, for example *AOT30*. Since the relationship between *AOTx* and *AOT0* depends on the temporal distribution of C_{ij}, which is a variable of the local pollution climate, *M12* and *AOTx* can be related to *AOT40* only empirically. For the empirical relationship between *AOT40* and the other O_3 doses, linear or quadratic function has been assumed before[45] but we fit a semi-empirical model of *AOTx* on *AOT40* with x as the threshold parameter ranging from 0 to 40 (ppb), as follows:

$$\begin{aligned} AOTx &= AOT40 + (40 - \mathrm{x})\ (1,080/1,000) \\ &-1/\left\{1/\left[(40 - \mathrm{p}_1)\ (1,080/1,000)\ \left(1 - (0.025\,\mathrm{x})^2\right)\right] + \mathrm{p}_2\ AOT40\right\}. \end{aligned} \tag{4}$$

Values of the empirical coefficients p_1 and p_2 were determined as 21.28 and 0.01023, respectively, by fitting equation (4) to the values of *AOTx* calculated with equation (2) using values of $x = 0$, 10, 20, 30 and 40 (ppb) and the observed hourly O_3 concentrations at the crop canopy height as noted earlier.

The model in equation (4) is empirical because the coefficients p_1 and p_2 are determined with the observations but it approaches the theoretical relationship as *AOT40* increases, as follows:

$$\lim_{AOT40 \to \infty} AOTx = AOT40 + (40 - \mathrm{x})(1,080/1,000)$$

which differentiates it from the purely empirical equations such as quadratic function. The semi-empirical model captures well the general tendency of *AOTx* as plotted against *AOT40* across the three crops in the three countries (Supplementary Fig. 6). It is noteworthy that the model would fit to the relationship between *AOT40* and *AOTx* for any x, for example 31, within the range from 0 to 40.

Collection and analysis of experimental data. Datasets were collected and summarized from peer-reviewed literature in the Web of Science (Thompson-ISI, http://apps.webofknowledge.com; last accessed end of January 2020) through keyword matching. Data from tables or text were extracted directly, while data from graphs were extracted using data extraction software (GetData Graph Digitizer v.2.26, http://getdata-graph-digitizer.com). The primary requirements of selected papers were: (1) the study area was in Asia; and (2) the studied plants were crops. Further criteria were applied for specific datasets as follows.

O_3 exposure–response relationships. We conducted the literature search using the keywords ('ozone' or 'O_3') and 'crop' or 'wheat' or 'maize' or 'rice' between years 1980 and 2020. Relevant papers were selected if all the following criteria were met:

(1) Crop plants were grown in two or more levels of O_3 concentrations, of which at least one level was higher than ambient,
(2) AOT40 values for an accumulation period of 45 d or longer are reported or calculable from the description of the experiment without using an empirical equation, and
(3) Grain yield values at maturity were reported.

In total, seven, 12 and four articles were selected for wheat, rice and maize, respectively, and the values of AOT40 and crop yield were extracted (Supplementary Table 5 and Supplementary Data). When an article reported more than one set of AOT40–crop yield values across varieties and/or years, each set of AOT40–crop yield constituted a dataset for the O_3-dose yield-loss relationships. When the experiments were done in combination with additional treatments (for example, drought and elevated CO_2), only those without the additional treatments were included. In total, 28, 58 and seven datasets were thus extracted for wheat, rice and maize, respectively (Supplementary Table 5 and Supplementary Data). Since the period of accumulation for AOT40 varied between 55 and 163 d across the datasets, the AOT40 values were standardized at 90 d for consistency with the estimation of the RYL on 90-d AOT40. The conversion to 90-d AOT40 was done as follows:

Case a. AOT40 values for a period (*L*) longer than 90 d were multiplied by 90/*L*.

Case b. AOT40 values for a period shorter than 90 d were used as they were.

The scaling for the case a is justified by consistency with the real-world situation, where a proportionality can be assumed between AOT40 for 90 d and AOT40 for a longer period of time (*L*). This approach was also recommended by the European air quality directive 2008/50/EC for gap filling. In most experiments where AOT40 values were given for less than 90 d (case b), the plants experienced ambient or subambient ozone levels for the period outside the accumulation period that should have contributed little to AOT40.

The crop yield response to O_3 was estimated modifying the method presented earlier[52], which allowed us to extract the datasets from the FACE (free-air controlled exposure) experiments with rice and wheat in China[52] and thereby estimate the sensitivity on a larger number of field-planted experiments than the previous studies[22,24] for Asia.

Crop yield (y) is a product of the yield at zero ozone impact (Y_0) and the *RY*, which is a linear function of the ozone dose on *AOTx*, as follows:

$$y = \mathrm{Y}_0\ (1 - S\,AOTx)\,, \tag{5}$$

where S is the sensitivity of the crop yield to the ozone dose, *AOTx* (ppm h) (equation (2)). Both sides of equation (5) were logarithmically transformed to yield an additive model, as follows:

$$\ln y = \ln \mathrm{Y}_0 + \ln\,(1 - \mathrm{S}\,AOTx)\,. \tag{6}$$

AOTx in equation (6) is replaced by equation (4) to describe it as a function of AOT40, as follows:

$$\ln y = \ln \mathrm{Y}_0 + \ln\,\{1 - \mathrm{S\,f}\,(\mathrm{AOT40}\,;\mathrm{x})\}\,,\ \text{and} \tag{7}$$

$$\begin{aligned} f\,(AOT40\,;\mathrm{x}) &= AOT40 + (40 - \mathrm{x})(1,080/1,000) - 1/ \\ &\left[1/\{(40 - 21.28)(1,080/1,000)\ \left(1 - (0.025\,\mathrm{x})^2\right)\} + 0.01023\,AOT40\right] \end{aligned} \tag{8}$$

The model in equation (7) was fit to the collated data of experiments for each crop species assuming an experimental error, as follows:

$$\ln y_{ij} = \ln \mathrm{Y}_{0\mathrm{i}} + \ln\left\{1 - \mathrm{S}\,f\left(AOT40_{ij}\,;\mathrm{x}\right)\right\} + \varepsilon_{ij}, \tag{9}$$

where y_{ij} is the yield at *j*th ozone level of the *i*th dataset, Y_{0i} is the yield at the zero ozone dose of the *i*th dataset, $AOT40_{ij}$ is the AOT40 value at *j*th ozone level of the *i*th dataset and ε_{ij} is the random error at *j*th ozone level of the *i*th dataset. The data on unrealistically high $AOT40_{ij}$ values (≥55 ppm h) were not included.

Values of the model parameters: x, Y_{0i} and S in equation (9) were estimated with the nonlinear regression in JMP-Pro v.16 (SAS Institute). In the regression, the parameter x was constrained within the range from 0 to 40 by replacing it with 39.999/ (1 + exp(−z)) and transforming the estimate $\hat{z}$ back to $\hat{x}$. Using the estimates of the parameters: $\hat{S}$ and $\hat{x}$, the crop yield relative to that at $AOT40 = 0$ is defined as *RY*, as follows:

$$RY = \left\{1 - \hat{S} f(AOT40\,;\hat{x})\right\} / \left\{1 - \hat{S} f(0\,;\hat{x})\right\}. \tag{10}$$

RY is thus expressed on *AOT40* and standardized at 1 for $AOT40 = 0$. We constructed CI of *RY* as well as those of $\hat{S}$ and $\hat{x}$ with bootstrap analysis using 25,000 times resampling in JMP-Pro v.16. The CI of *RY* represents the range of estimated *RY* at a specific O_3 dose considering the estimation errors of both $\hat{S}$ and $\hat{x}$ simultaneously, whereas use of only $\hat{S}$ to represent the yield response could be misleading due to its high correlation with $\hat{x}$ ($r > 0.9$). It is noteworthy that *RY* is a linear function of *AOTx* (equation (5)) but is nonlinear in relation to *AOT40* (equation (10)), which is evident for rice ($\hat{x} = 19.4$) and wheat ($\hat{x} = 26.5$) but not for maize ($\hat{x} = 40.0$) (Fig. 2 and Supplementary Table 2).

As we are concerned about the effects of rooting environment, pot-planted or field-planted, on the yield loss to O_3, we also fit the following model to the experimental data, as follows:

$$\ln y_{ij} = \ln Y_{0i} + \ln\left[1 - \left\{S_{pot}\,(1 - B_{root}) + S_{field} B_{root}\right\} f\left(AOT40_{ij};x\right)\right] + \varepsilon_{ij}, \tag{11}$$

where S_{pot} and S_{field} are the sensitivity of pot-grown and field-grown plants, respectively, and B_{root} is a binary variable that takes a value of zero for pot experiments and one for field-planted ones. We then estimated the *RY* with $\hat{S}_{pot}$ and $\hat{S}_{field}$ in place of $\hat{S}$ in equation (10) and constructed the CI of *RY* for potted and field-planted experiments, respectively, as noted above. Once we detected a significant difference in *RY* due to the root environment, we omitted the pot-based experiments from further analyses, since our concern is with the crops growing in the field only. In the same way as above, we estimated the sensitivity separately for the contrasts between:

(1) hybrid cultivars and inbred cultivars of rice
(2) experiments conducted in FACE and chambers including open-top chambers and greenhouses with rice and wheat, and
(3) experiments conducted in China, India and Japan.

In estimating the separate sensitivities in the above contrasts, we tried to avoid the confounding effects from the other determinants. For example, we limited the datasets for the above contrasts to those based on field-grown plants. In contrast (2) with rice, we further limited the datasets to inbred cultivars to avoid the confounding effect of hybrid cultivars, which constituted half of the 28 data points from the FACE experiments but only four of the 47 data points from the chamber experiments. We did not make the separate estimation of the sensitivity for maize due to the limited number of datasets.

EDU application to quantify the O_3 impacts on crop yield. Another database was built for the EDU effects on crop yield by surveying the peer-reviewed literature and cross-checking the list of cited references of review articles. Articles were included if: (1) the experiment was conducted under ambient O_3; (2) AOT40 values were reported or could be estimated; and (3) yield data indicating normal growth were reported. In total, seven articles were selected (Supplementary Table 7).

Under the AOT40 in ambient air (a) ($AOT40_a$), the yield without EDU application (y_{Cont}, where Cont is control) is described as

$$y_{Cont} = Y_0\left\{1 - S f(AOT40_a\,;x)\right\} \tag{12}$$

If we assume that EDU application protects the plants against O_3-induced toxicity and raises the yield (y_{EDU}) to the same level as that at zero *AOT40*, as follows:

$$y_{EDU} = Y_0\left\{1 - S f(0;x)\right\}, \tag{13}$$

the ratio y_{Cont} / y_{EDU} should represent the *RY* (equation (10)) at $AOT40_a$, as follows

$$y_{Cont}/y_{EDU} = \left\{1 - S f(AOT40_a;x)\right\} / \left\{1 - S f(0;x)\right\} = RY_a \tag{14}$$

If, instead, the protection of crop yield by EDU is insufficient, as follows:

$$y_{EDU} < Y_0\left\{1 - S f(0;x)\right\},$$

then the ratio y_{Cont} / y_{EDU} in equation (13) would be greater than RY_a, as follows:

$$y_{Cont}/y_{EDU} > RY_a \tag{15}$$

Since most EDU application experiments lack confirmation of the complete yield protection[28] (equation (13)), the ratio y_{Cont} / y_{EDU} should serve at best as a conservative indicator of the yield loss to ambient O_3.

The observed values of y_{Cont}, y_{EDU} and $AOT40_a$ were extracted from the selected articles (Supplementary Table 7) and, where possible, recalculated from the original measurements, and the RY (y_{Cont} / y_{EDU}) was calculated. The EDU application experiments often included more than one cultivar and reported cultivar differences in their response to EDU application. We therefore reported the RY for each cultivar and, where possible, its interval estimate. Where no cultivar difference was found in the RY response to EDU, the interval estimate of mean RY response across cultivars is calculated.

Regional and national crop loss estimation. We firstly calculated the crop-specific AOT40 for 90 d until crop maturity at each monitoring site and then applied Kriging for spatial estimation of the grid-based AOT40 (5-min resolution) for each crop across the whole region, which finally was masked by the crop distribution. The gridded AOT40 was used to estimate RYL using the AOT40–RY relationships obtained in this study (Supplementary Table 2).

The resultant crop yield losses on grid basis were averaged across each province (China and South Korea) or prefecture (Japan) to regional RYL (RYL_r), which was then weight-averaged to the national mean RYL (RYL_n). For the weight, we used the crop production amount collected from the crop statistics from Chinese Academy of Agricultural Sciences, Ministry of Agriculture Forestry and Fisheries, Government of Japan (https://www.e-stat.go.jp/) and Korean Statistical Information Service (https://kosis.kr/statisticsList/statisticsListIndex.do?vwcd=MT_ZTITLE&menuId=M_01_01). For rice in Chinese provinces where hybrid cultivars are widely grown, RYL_r was calculated separately for hybrid and inbred types and weight-averaged to RYL_n using the area for the respective types[33]. For Chinese provinces where double-cropping rice is prevalent, values of RYL_r for the early and late crops were weight-averaged using the production amount of the respective crops.

Using RYL_r, we estimated the regional crop production loss (PL_r) on mass basis, as follows:

$$PL_r = P_r\, RYL_r/\left(1 - RYL_r\right), \tag{16}$$

where P_r is the production amount on mass basis for the region. The PL_r was summed up to the national production loss (PL_n), which was then converted to the monetary loss using the value of agricultural production compiled at Food and Agriculture Organization of the United Nations (http://fenixservices.fao.org/faostat/static/documents/QV/QV_e.pdf).

In addition to the quantification of O_3-induced production loss at current level of AOT40, we estimated the increase of crop production under a mitigation scenario. As the target level of mitigation, we chose a 50% reduction of AOT40, which we think is possible in consideration of the quasi-doubling of AOT40 on average across China for the seven-year period from 2013 to 2019[20]. We calculated the production loss under the mitigation scenario as follows.

The RYL was calculated with the halved AOT40 at each grid and averaged across the province (China and South Korea) or prefecture (Japan) to the regional RYL under the mitigation scenario (RYL_{r_m}). The regional production loss (PL_{r_m}) is defined as:

$$PL_{r\_m} = P_{r\_m}\, RYL_{r\_m}/\left(1 - RYL_{r\_m}\right), \tag{17}$$

where P_{r_m} is the production amount under the mitigation scenario. By definition, the decrease of production loss due to the mitigation equals to the increase of production due to the mitigation, as follows:

$$PL_r - PL_{r\_m} = P_{r\_m} - P_r \tag{18}$$

Using equations (16) and (18), P_{r_m} in equation (17) is eliminated to yield

$$PL_{r\_m} = P_r\, RYL_{r\_m}/\left(1 - RYL_r\right) \tag{19}$$

The regional production loss under the mitigation scenario (PL_{r_m}) is summed up to the national production loss under mitigation (PL_{n_m}) and the reduction of the national production loss ($PL_n - PL_{n\_m}$) or the production gain due to mitigation is calculated. The production gain is expressed as a fraction of the production amount and that of the domestic supply as obtained from the FAO Food Balance[14].

Reporting Summary. Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability

The data supporting the findings of this study are available within the paper and its Supplementary Information and Supplementary Data. Source data are provided with this paper.

Code availability

The custom algorithm used for this study are available in the Methods.

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Author contributions

Z.F., E.P. and X.Y. initially designed the study. Z.F. had a leading role, served as the hub of communication among the authors and supervised the production of the manuscript. Y.X. checked the O_3 observation data and calculated AOT40. L.D. collected the O_3 dose and yield of crops and EDU studies. L.D. and K.K. estimated the O_3 dose–response functions and made Figs. 2 and 3. T.Z. estimated the regional yield loss and made Figs. 1 and 4. R.P. and Y.O. provided the O_3 data in South Korea. Z.F., E.A., V.C., X.Y. and K.K. drafted the paper. A.M., E.P. and all other coauthors reviewed the integrated manuscript, substantially contributed intellectual inputs and approved the final version for publication.

Competing interests

The authors declare no competing interests.

Additional information

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Our web collection on statistics for biologists contains articles on many of the points above.

Software and code

Policy information about availability of computer code

Data collection	The graphical data were converted to digital data by using GetData Graph Digitizer, version 2.26, http://getdata-graph-digitizer.com
Data analysis	JMP-Pro 16.0 (SAS Institute, Cary, USA).

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The data of experiments used to calculate the ozone dose- crop yield relationships are submitted as the Supplementary Data in Microsoft Excel format.

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All studies must disclose on these points even when the disclosure is negative.

Study description	This study is an estimation of crop yield loss due to surface ozone in 3 countries: China, Japan, and South Korea. The yield loss is estimated with the relationship between crop yield and ozone dose as derived from the experiments conducted in Asia and the current ozone monitoring data in the 3 countries.
Research sample	The Supplementary Data includes a collection of 93 sets of experimental data extracted from 22 articles. Each set of data contained 2 or more levels of ozone treatment dose and the corresponding crop yield.
Sampling strategy	Sampling was not involved. All the collected data were subjected to the data analysis after filtering anomalous data out.
Data collection	The data of experiments were extracted from the respective articles that were searched at the Web of Science. The ozone monitoring data were extracted directly at the data archival site in each country.
Timing and spatial scale	The ozone data were taken at c. 1570, 1180, 320 sites in China, Japan, and South Korea as routine air monitoring by the environmental agency in the respective country.
Data exclusions	From the ozone monitoring data, the hourly ozone concentrations higher than 300 ppb were excluded since they are very likely to be an anomaly. From the experimental data, data points with AO40 dose greater than 55 ppm h were excluded since they are too high to be relevant to the real world environment.
Reproducibility	Reproducibility of this research depends on that of the ozone dose-crop yield relationships. The ozone dose-crop yield relationships are reproducible on the assumption that the experimental data are reproducible because we used all the data to estimate the parameters of the dose-response relationships. All the experiment data are now submitted as the Supplementary Data.
Randomization	This does not directly apply to our study, but randomization was involved in the original experiments as reported in the articles from which we extracted the data. The ozone monitoring data are regarded as a realization of the ozone concentration field that is inherently random within the climate and air chemistry at each monitoring location.
Blinding	We took all the data as they are, and there is no room for blinding.

Did the study involve field work? ☐ Yes ☒ No

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Methods

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☒	☐	Flow cytometry
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