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Review

A comparison of North American and Asian exposure–response data for ozone effects on crop yields

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ABSTRACT

Modelling-based studies to assess the extent and magnitude of ozone (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. These assessments have relied on European and North American dose–response relationships and hence assumed an equivalent Asian crop response to O_3 for local cultivars, pollutant conditions and climate. To test this assumption we collated comparable dose–response data derived from fumigation, filtration and EDU experiments conducted in Asia on wheat, rice and leguminous crop species. These data are pooled and compared with equivalent North American dose–response relationships. The Asian data show that at ambient O_3 concentrations found at the 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. The results indicate that Asian grown wheat and rice cultivars are more sensitive to O_3 than the North American dose–response relationships would suggest. For legumes the scatter in the data makes it difficult to reach any equivalent conclusion in relative sensitivities. As such, existing modelling-based risk assessments may have substantially underestimated the scale of the problem in Asia through use of North American derived dose–response relationships.

1. Introduction

Ground level ozone (O_3) is the atmospheric pollutant that is most likely to threaten food production across the globe due to its phytotoxicity and prevalence over important agricultural regions of North America, Europe and Asia (e.g. Fuhrer and Booker, 2003, Royal Society, 2008). Over recent decades peak O_3 concentrations have declined in North America and Europe (Ashmore, 2005) due to reductions in precursor emissions. In contrast, over the same period, anthropogenic emissions of O_3 precursors across Asia have increased (Ohara et al., 2007). Limited monitoring of sub urban and rural O_3 concentrations conducted in Asia indicates that monthly mean O_3 concentrations now commonly reach 50 ppb during important agricultural growing seasons (EANET, 2006). Global photochemical models (e.g. Dentener et al., 2006) project that under current legislation emission scenarios, parts of Asia will experience further significant increases in O_3 concentrations by 2030. The potential impact of elevated O_3 on agricultural productivity is particularly relevant for the Asian region which is home to approximately 60% of the global total of undernourished people (MEA, 2005), and will see further large increases in population by 2030 (FAO, 2002).

As such, there is an urgent need to be able to assess the current and future risks from O_3 exposure to crops in Asia. Dose–response relationships are central to such risk assessments (Emberson et al., 2003) since they provide the link between a pollutant dose and a plant response of concern. Ideally, such relationships would be derived from co-ordinated standardised experimental campaigns assessing crop response to a range of pollutant concentrations

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(Unsworth and Geissler, 1992). To date the geographical distribution of such crop effect studies has been closely linked to observations of damage. In North America, effects on crops led to the National Crop Loss Assessment (NCLAN) Programme, a co-ordinated experimental programme using standardised protocols applied at six study sites across the region during the early 1980s (Heck et al., 1988). This was followed by the European Open Top Chamber (EOTC) Programme in the late 1980s and early 1990s (Jäger et al., 1992) as O_3 effects became evident in Europe (Fuhrer and Booker, 2003). These programmes resulted in the derivation of robust dose–response relationships for a number of key agricultural crops.

The resulting dose–response relationships have been used to estimate risk, either by mapping critical levels exceedance (where the critical level represents the pollutant exposure below which adverse effects would not be expected to occur) (Simpson et al., 2007) or by quantifying yield losses for economic crop loss estimates (Adams et al., 1989). Applications of the latter method in Asia (Aunan et al., 2000; Wang and Mauzerall, 2004) have estimated current day yield losses of up to 13% and 23%, rising to 16% and 35% for cereals and soybean, respectively, during 2020 assuming emission scenarios substantially lower than a "worst case" scenario. Wang and Mauzerall (2004) translated the current day yield loss estimates into economic losses of approximately US$ 5 billion for wheat, rice, maize and soybean grown in China, Japan and South Korea.

However, these studies rely on dose–response relationships based on North American or European experimental data. Although analyses of such relationships for wheat, potato and barley found no significant differences between these regions (Mills et al., 2007), a similar analysis of transferability has not been conducted for Asia. Factors such as climate, crop phenology, agricultural management practices and pollutant exposure patterns will alter plant response to O_3 (Fuhrer and Booker, 2003) making it important to assess whether the modelling-based studies performed for Asia are credible and have sent the correct signals to policy makers in the region.

A significant number of experimental studies conducted in countries such as China, India, Japan and Pakistan have investigated a wide range of crop species and cultivars using a variety of experimental methods and design (e.g. Emberson et al., 2001, 2003; Mauzerall and Wang, 2001). This paper collates and pools data to test the hypothesis that dose–response relationships based on North American data provide an accurate prediction of crop responses to O_3 in Asia. This hypothesis test is limited to the North American studies since their method of characterising O_3 exposure (i.e. as a 7 h (M7) or 12 h (M12) growing season mean O_3 concentration, Mauzerall and Wang, 2001) is comparable with that used in the majority of the Asian studies. In contrast, the AOT40 index developed in Europe, (accumulated O_3 concentration above a threshold of 40 ppb; Fuhrer et al., 1997), can only be derived from hourly O_3 concentration data unavailable from the Asian studies. This exercise is limited to wheat and rice, due to their importance as staple crops across the Asian region, and legumes since they provide an important source of protein in many Asian diets. These crops also represent the most extensive datasets describing local crop yield responses to O_3.

2. Methods

Data were collected from the literature and through direct contact with colleagues in Asia for two crops, wheat (*Triticum aestivum* L.) and rice (*Oryza sativa* L.), and one group of crop species (legumes: soybean (*Glycine max* L.) and mung bean (*Vigna radiata* (L.) R. Wilczek)). Three different experimental methods (fumigation, filtration and chemical protectant studies) were targeted for data collection since they are well established for pollutant effects research (Bell and Marshall, 2000), provide evidence of plant response to pollutants under near field conditions and have been used across Asia. All the fumigation studies used open-top chambers (OTCs) and not free-air release systems. Completely enclosed chamber studies were excluded due to concerns over the introduction of experimental artefacts (e.g. modified temperature and humidity profiles).

Each experimental investigation had to meet a set of strict criteria to ensure data comparability. Studies were only included in which the pollutant treatment lasted for at least 60% of the total crop growth period, and with O_3 exposure described as a minimum of 4 h (M4) to a maximum of 8 h (M8) means during the daylight period over the growing season. This latter criterion enhances comparability with the exposure characteristics used during the NCLAN campaign. NCLAN experiments applied standard agronomic practices at all sites, with particular attention paid to the specification that experiments should be conducted under well-watered conditions (Heck et al., 1988). Similarly, data from Asian studies were only included where the plants were maintained under well-watered conditions with adequate nutrient supply and free from pests and diseases. For fumigation studies, the control treatment was either charcoal filtered air (CF) or non-filtered air (NF), with the latter required to have mean O_3 concentrations lower than 10 ppb. For other treatments, O_3 was added at defined concentrations to either CF or NF as appropriate, concentrations of other pollutants at the filtration study sites (i.e. NO_2 and SO_2) were also recorded to aid data interpretation. Filtration studies had, by definition, an NF and CF treatment. The potential chamber effect on yield was assessed by extracting, where available, results from ambient air (AA) treatments and comparing with NF (data not shown).

The anti-oxidant EDU (N-[2-(2-oxo-1-imidazolidinyl)ethyl]-N-phenylurea) is a common chemical protectant experimental tool that provides protection to crops from O_3 (Carnahan et al., 1978). In these studies, yield was compared between plants protected from O_3 effects by foliage- or soil-application of EDU and non-protected plants, both exposed to AA. Data were only extracted from these studies if they used an appropriate application of EDU which had previously been tested to ensure close to 100% protection.

All data were expressed as yield per plant relative to the respective control treatment. Each derived data point was plotted as dose *vs* response for each crop. Fig. 1 provides an overview of how data derived from different treatments (i.e. CF, NF, EDU, NF+

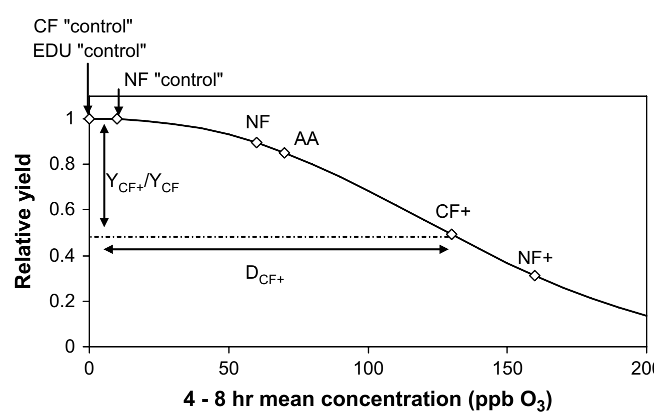

Fig. 1. An overview of the control and O_3 treatments in relation to each other in terms of exposure response. CF "control", EDU "control" and NF "control" indicate the control treatments; the exposure treatments are represented by NF for filtration, AA for EDU and CF+ or NF+ for fumigation. A data retrieval example is shown for the fumigation "CF+" treatment where yield loss (Y) is estimated by $Y_{CF+}/Y_{CF\ \text{"control"}}$ and the corresponding pollutant dose (D_{CF+}).

and CF+) might be expected to relate in terms of the relative O_3 dose (and subsequent response).

3. Results

The data collected within this study come from a total of 23 experimental datasets from 6 different countries as summarised in Tables 1–3. Of these experimental datasets, 10 provided data for wheat, 7 data for rice and 6 data for legumes. Figs. 2–4 plot the exposure and response data for the three species, alongside the Weibull exposure–response function derived from studies conducted in North America (Adams et al., 1989; Lesser et al., 1990). The figures also indicate the experimental method used for the derivation of each data point.

3.1. Wheat (T. aestivum L.)

The wheat data (Table 1) were derived from 10 experimental studies providing 22 data points: 3 from fumigation studies (providing 8 data points), 6 from filtration studies (12 data points) and 1 from an EDU experiment (2 data points). Of these studies 6 were conducted in pots and 4 in the field. Studies were conducted in India (4 studies), Pakistan (5 studies) and China (1 study). Most of the studies used winter wheat (8 studies) compared to only 2 spring wheat studies. A total of 13 different cultivars were investigated. In terms of O_3 concentration averaging periods, 5 of the studies (providing 10 of the data points) use M7 or M8, the remainder using M4 or 6 h (M6) growing season means. Equivalent filtration study growing season mean concentrations for SO_2 (recorded in 2 of the 6 studies) and NO_2 (recorded in 4 of the 6 studies) ranged from ~8–16 ppb and 23–40 ppb, respectively.

The data suggest that the effects on wheat are strongly influenced by the experimental method (Fig. 2). Filtration and EDU experiments gave high yield losses of up to 50% and 40% respectively at ambient O_3 concentrations (between 36 and 72 ppb M4–M8). In contrast the majority of fumigation experiments showed a much lower yield loss at equivalent O_3 concentrations; only after exposure to very high O_3 concentrations (in the region of 90–200 ppb M4–M8) did relative yields decrease to 20%. All but one of the filtration studies were derived from experiments conducted in Pakistan making it difficult to discern any influence of local conditions or local cultivars in determining O_3 sensitivity. However, the scatter of EDU data points (from Indian studies) across the sensitivity range recorded for Pakistani filtration experiments at equivalent O_3 concentrations suggests that the influence of particular local conditions was not a strong determinant of sensitivity.

The limited data do not suggest any obvious differences between the sensitivities of Asian winter and spring wheat varieties (Fig. 2) in contrast to the North American data that show a greater sensitivity for winter wheat (Lesser et al., 1990). However, the Asian data are by no means conclusive, since only 5 spring wheat cultivars have been investigated compared to 8 winter wheat varieties. The variation in O_3 sensitivity determined by cultivar is apparent in 7 experiments where multiple cultivars were used (see Table 1). At equivalent O_3 exposures, the relative yield of 2 different cultivars varied by as much as 24% in the study conducted by Wahid (2006) with average differences of almost 10% when 2–3 different cultivars were used in other experimental investigations.

Comparison with the North American dose–response relationships show that all data collected for Asian spring wheat cultivars under local conditions have a greater sensitivity to O_3 compared to the North American spring wheat dose–response relationship (Adams et al., 1989). In comparison, 4 winter wheat data points from a single Asian study showed greater resistance to O_3 whilst the remaining 12 data points (from 7 studies) all showed greater sensitivity compared to the North American NCLAN relationship, based on 4 different varieties (Heck et al., 1988).

3.2. Rice (O. sativa L.)

Table 2 gives details of the rice data that were derived from 7 studies providing 30 data points: 3 of the experimental datasets are from fumigation studies (providing 22 data points) and 4 from

Table 1
Summary of collated Asian data describing the yield response of wheat to ozone (O_3). Notation relates to fumigation (*Fu*), filtration (*Fi*) and EDU (*EDU*).

Reference	Study site	Experimental type (growth period) – field/pot – O_3 monitoring method	Cultivar (No. of data points)	SO_2 & NO_2 concs. (ppb)	O_3 concs. (ppb) averaging period	Yield response (parameter, rel. yield %)
Agrawal (2005)	India, Varanasi	*Fu* (Dec–March) – field – wet chemistry	Winter wheat: Malviya 234 (2), HP1209 (2)	–	70, 100; 4 h mean	Yield plant^{-1}, 95–83%
Ambasht and Agrawal (2003a)	India, Varanasi	*Fu* (Nov–April) – field – wet chemistry	Winter wheat: Malviya 234 (1)	–	70; 4 h mean	Yield plant^{-1}, 91%
Feng et al. (2003)	China, Dingxing County, Hebei Province	*Fu* (April–June) – pot – wet chemistry	Winter wheat: Jingdong-6 (3)	–	50, 100, 200; 7 h mean	Yield plant^{-1}, 90–20%
Maggs et al. (1995)	Pakistan, Lahore	*Fi* (Nov–May) – pot – wet chemistry	Winter wheat: Pak-81 (1), Chakwal-86 (1)	SO_2 no data NO_2 24	52; 6 h mean of 3 days week^{-1}	Yield plant^{-1}, 67–57%
Nasim et al. (1995)	Pakistan, Lahore	*Fi* (Nov–April) – pot – wet chemistry	Winter wheat: Pb-87 (1), Inqlab-95 (1)	no data	65; 6 h mean of 3 days week^{-1}	Yield plant^{-1}, 69–60%
Rai et al. (2007)	India, Varanasi	*Fi* (Dec–March) – field – UV absorption	Winter wheat: Malviya 234 (1)	SO_2 8.4; NO_2 39.9	40; 8 h mean	Yield plant^{-1}, 79%
Tiwari et al. (2005)	India, Varanasi	*EDU* (300 ppm) (Dec–March) – field – UV absorption	Winter wheat: Malviya 533 (1), Malviya 234 (1)	–	41; 8 h mean	Yield plant^{-1}, 87–81%
Wahid (2006)	Pakistan, Lahore	*Fi* (Nov–Feb) – pot – UV absorption	Spring wheat: Inqlab-91 (1), Punjab-96 (1), Pasban-90 (1)	SO_2 16; NO_2 30	72; 8 h mean	Yield plant^{-1}, 82–57%
Wahid and Maggs (1999)	Pakistan, Lahore	*Fi* (Nov–April) – pot – wet chemistry	Spring wheat: Rawal-87 (1), Punjab-85 (1)	no data	70; 8 h mean	Yield plant^{-1}, 64–52%
Wahid et al. (1995a)	Pakistan, Lahore	*Fi* (Dec–April) – pot – wet chemistry	Winter wheat: Pak-81 (1), Chakwal-86 (1)	SO_2 no data; NO_2 23.3	36; 6 h mean of 3 days week^{-1}	Yield plant^{-1}, 65–53%
Summary	**Countries**	**Experimental type**	**No. of data points**		**Range of ambient O_3 conc. (ppb)**	**Range and median of rel. yield under ambient conditions**
	China, India, Pakistan	3 *Fu*, 6 *Fi*, 1 *EDU*	22		36–72 4–8 h mean	52–95%, 68.0%

Table 2
Summary of collated Asian data describing the yield response of rice to ozone (O_3). Notation relates to fumigation (*Fu*) and filtration (*Fi*).

Reference	Study site	Experimental type (growth period) – field/pot – O_3 monitoring method	Cultivar (No. of data points)	"Control" treatment	O_3 concs. (ppb) averaging period	Yield response (parameter, rel. yield %)
Feng et al. (2003)	China, Dingxing County, Hebei Province	*Fu* (July–Oct) – pot – wet chemistry	Zhongzuo 9321 (3)	–	50, 100 and 200; 7 h mean	Yield plant^{-1}, 92–51%
Ishii et al. (2004)	Malaysia, Klang Valley	*Fi* (Oct–Jan) – pot – UV absorption	MR84 (1), MMR 185 (1)	SO_2 11.9; NO_2 9.5	33; 8 h mean	Yield plant^{-1}, 97–94%
Kobayashi et al. (1995)	Japan, Tsukuba	*Fu* (April/May–Aug/Sept) – field – UV absorption	Koshi-hikari (10), Nippon-bare (5)	–	17–97; 7 h mean	Yield plant^{-1}, 69–100%
Maggs et al. (1995)	Pakistan, Lahore	*Fi* (May/June to Oct/Nov) – pot – wet chemistry	Basmati 385 (1), IRRI 6 (1)	SO_2 no data; NO_2 22.5	60; 6 h mean of 3 days week^{-1}	Yield plant^{-1}, 63–53%
Van et al. (2008)	Vietnam, Gia Lam District, Hanoi	*Fu* (NF+) (Aug–Nov) – field – wet chemistry	R18 (4)	–	32–113; 7 h mean of 5 days week^{-1}	Yield cluster^{-1}, 90–52%
Wahid et al. (1995b)	Pakistan, Lahore	*Fi* (July–Nov) – pot – wet chemistry	Basmati 385 (1), IRRI 6 (1)	SO_2 no data; NO_2 12.6	36; 6 h mean of 3 days week^{-1}	Yield plant^{-1}, 63–58%
Wahid et al. (1997)	Pakistan, Lahore	*Fi* (July–Nov) – pot – wet chemistry	Basmati 370 (1), Basmati Pak (1)	no data	57; 8 h mean	Yield plant^{-1}, 71–55%
Summary	**Countries**	**Experimental type**	**No. of data points**		**Range of ambient O_3 conc. (ppb)**	**Range and median of rel. yield under ambient conditions**
	China, Malaysia, Japan, Pakistan, Vietnam	3 *Fu*, 4 *Fi*	30		33–60 4–8 h mean	53–97%, 85.2%

filtration studies (providing 8 data points). Of these studies, 5 were conducted in pots and 2 in the field. A total of 10 different cultivars were investigated across experiments conducted in 5 different countries. M7 or M8 indices were used in 5 of the studies providing 26 of the data points, the remaining data coming from studies using M6. Equivalent growing season mean concentrations of SO_2 were recorded for only 1 of the 4 filtration studies with a value of ~12 ppb, and for NO_2 for 3 of the 4 filtration studies with a range of ~10–23 ppb.

Fig. 3 shows a tendency for filtration studies to indicate a higher sensitivity (down to 50% relative yield) compared to fumigation studies (down to 80% relative yield) at ambient O_3 concentrations of between 33 and 60 ppb M4–M8. In the 5 studies that used multiple cultivars (see Table 2), it was evident that variability in yield loss was at least partly dependant upon cultivar type; for example, at equivalent O_3 exposures the relative yield varied by up to 16% in the study conducted by Wahid et al. (1997). An average variation in yield of approximately 9% was found when 2 different cultivars were used at equivalent O_3 exposures in the investigations.

Comparison with the North American dose–response relationship for rice (Adams et al., 1989) showed all but 1 of the Asian rice data points to have a greater sensitivity to O_3. The single data point was from a Chinese fumigation study at a very high O_3 concentration of 200 ppb, i.e. well outside the ambient range of O_3 concentrations experienced across Asia.

3.3. Legumes (G. max L. and V. radiata (L.) R. Wilczek)

Legume species used in the experimental studies (see Table 3) were either soybean (*G. max* L.) or mung bean (*V. radiata* (L.) R. Wilczek). 3 soybean studies provided 9 data points for 4 different cultivars and 3 mung bean studies provided 3 data points for 3 different cultivars. The experimental data are derived from 2 fumigation studies (5 data points), 3 EDU studies (6 data points) and 1 filtration study (1 data point). These studies were all conducted either in India (4 studies) or Pakistan (2 studies). M7 or M8 indices were used in 3 of the studies (providing a data point each) with the remaining data being derived from studies using M4 or M6. Equivalent growing season mean concentrations of other pollutants (i.e. SO_2 and NO_2) were not recorded in the only legume filtration study.

Data for soybean and mung bean are presented together in Fig. 4 to allow a comparison between species within the legume family;

Table 3
Summary of collated Asian data describing the yield response of various legumes to ozone (O_3). Notation relates to fumigation (*Fu*), filtration (*Fi*) and EDU (*EDU*).

Reference	Study site	Experimental type (growth period) – field/pot – O_3 monitoring method	Species and cultivar (no. of data points)	"Control" treatment	O_3 concs. (ppb) averaging period	Yield response (parameter, rel. yield %)
Agrawal (2005)	India, Varanasi	*Fu* (July–Oct) – field – wet chemistry	Soybean: PK472 (2), Bragg (2)	–	70, 100; 4 h mean	Yield plant^{-1}, 90–66%
Agrawal et al. (2005)	India, Allahabad	*EDU* (500 ppm) (July–Sep) – field – wet chemistry	Mung bean: Malviya Jyoti (1)	–	33; 8 h mean, 1 day week^{-1}	Yield plant^{-1}, 70%
Ambasht and Agrawal (2003b)	India, Varanasi	*Fu* (Nov–March) – field – wet chemistry	Soybean: Punjab 1 (1)	–	70; 4 h mean	Yield plant^{-1}, 89%;
Bajwa et al. (1997)	Pakistan, Lahore	*Fi* (March–June) – pot – wet chemistry	Mung bean: M-28 (1)	no data	61; 8 h mean	Yield plant^{-1}, 50%
Singh et al. (in press)	India, Varanasi	*EDU* (400 ppm) (March–June) – pot – UV absorption	Mung bean: Malviya Janpriya (1)	–	67; 8 h mean	Yield plant^{-1}, 67%
Wahid et al. (2001)	Pakistan, Lahore	*EDU* (400 ppm) (Aug–Oct and Feb–May) – pot – wet chemistry	Soybean: NARC-1 (4)	–	40–75; 6 h mean	Yield plant^{-1}, 68–35%
Summary	**Countries**	**Experimental type**	**No. of data points**		**Range of ambient O_3 conc. (ppb)**	**Range and median of rel. yield under ambient conditions**
	India, Pakistan	2 *Fu*, 1 *Fi*, 3 *EDU*	12		33–75 4–8 h mean	35–90%, 67.6%

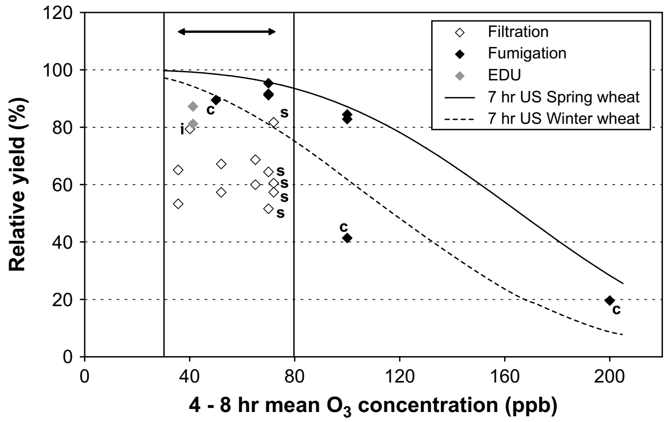

Fig. 2. Asian wheat yield loss data against 4–8 h growing season mean O_3 exposure. Dose–response relationships from North America (winter wheat: NCLAN, Lesser et al., 1990; spring wheat: Adams et al., 1989) based on 7 h growing season mean O_3 exposures are also shown. The Asian data are identified according to experimental type. "s" denotes spring wheat cultivars. "c" denotes Chinese studies, and "i" denotes the only Indian filtration study (all other filtration studies were performed in Pakistan). The local ambient pollutant concentration range defined by the experimental investigations is also indicated (arrowed vertical lines).

the data show no obvious difference in sensitivity between these species when either filtration or EDU experiments are used. However, soybean data derived from the fumigation studies have a far reduced sensitivity (with yield losses in the range of 10–15%) compared to those from the EDU studies (where yield losses varied between 30–65%) at equivalent ambient O_3 concentrations. In interpreting these results it is important to note that all soybean EDU data points are from 1 study conducted in Pakistan, whilst the soybean fumigation data points are from 2 studies conducted in India.

Interpretation of the sensitivity of these Asian legume data in relation to the North American dose–response relationship (Lesser et al., 1990) is not as straightforward as with wheat and rice. The Indian fumigation studies suggest that Asian soybean varieties grown under Indian conditions are less sensitive to O_3 as compared to North American soybean varieties. By comparison, all but one EDU and all filtration studies suggest that both Asian mung bean

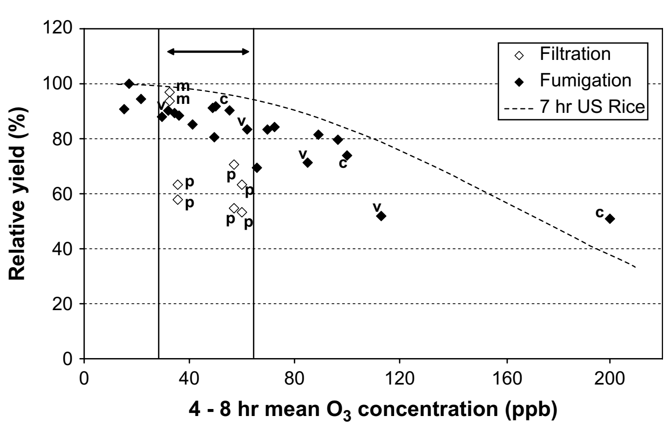

Fig. 3. Asian rice yield loss data against 4–8 h growing season mean O_3 exposure. A dose–response relationship for rice from the US (Adams et al., 1989) based on 7 h growing season mean O_3 is also shown. The Asian data are identified according to experimental type. "c", "m", "p" and "v" indicate studies conducted in China, Malaysia, Pakistan and Vietnam, respectively. All remaining studies were performed in Japan. The local ambient pollutant concentration range defined by the filtration experimental investigations is also indicated (arrowed vertical lines).

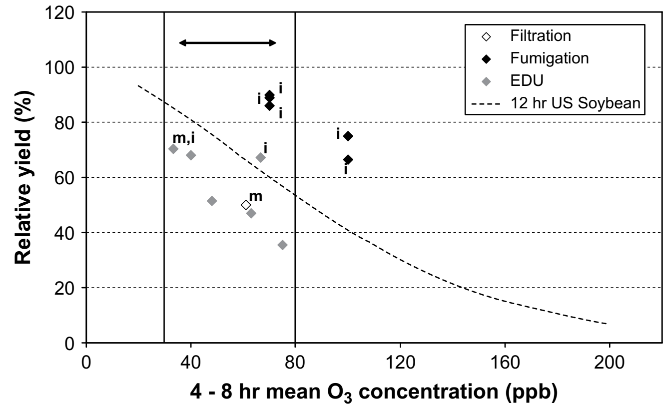

Fig. 4. Asian legume species yield loss data against 4–8 h growing season mean O_3 exposure. Dose–response relationships from North America (NCLAN, Lesser et al., 1990) based on 12 h growing season mean O_3 exposures for soybean are also shown. The Asian data are identified according to experimental type. 'm' denotes data for mung bean; all other data are for soybean. 'i' denotes data from India; all other data are from Pakistan. The local ambient pollutant concentration range defined by the filtration experimental investigations is also indicated (arrowed vertical lines).

and soybean varieties are more sensitive under local conditions than the soybean cultivars used in North America.

4. Discussion

The results strongly suggest that wheat and rice used in experimental studies performed in Asia predominantly show a greater sensitivity to O_3 than would have been predicted from the North American dose–response relationships. In the case of legumes, the results are not so conclusive, with fumigation experiments showing a lower sensitivity, and filtration and EDU experiments showing a higher sensitivity, compared to the North American soybean relationship, with no apparent difference in sensitivity between mung bean and soybean.

The data also show that under current day O_3 concentrations (determined according to filtration and EDU study site conditions) of between ~35–75 ppb M4–M8 for wheat and legumes, and ~35–60 ppb M4–M8 for rice, yield losses ranged between 5–48%, 3 and 47% and 10 and 65% for wheat, rice and legumes respectively. The respective median yield losses associated with these ranges were 32.0% ($n = 18$), 14.8% ($n = 17$) and 32.4% ($n = 10$), where n gives the number of data points used to derive the median values.

As such, these Asian data might suggest a ranking of increasing crop sensitivity to O_3 in the order of rice < wheat < legumes, consistent with other studies (Heck et al., 1988; Mills et al., 2007). However, the data show a large scatter both between and within individual studies. This can be ascribed to a number of different factors of which the most important are: i) the variety of experimental methods; ii) uncertainty associated with the characterisation of O_3 concentrations; iii) variability in environmental conditions and iv) use of a range of different cultivars. Here, we consider each of these in turn.

For all three species, the experimental method clearly affected the inferred sensitivity of crop response, with fumigation methods providing more conservative response estimates. For wheat and legumes, filtration and EDU studies suggest a similar sensitivity to O_3; there was insufficient data for rice to make this comparison. Fumigation and filtration studies would be expected to provide similar results since both used OTCs and, with the exception of a single study, used a CF treatment as the control. The data show that CF treatments provided M4–M8 values always less than 20 ppb; for comparison an M7 value of only 6 ppb was recorded in the single NF control treatment. Since the O_3 concentrations in the CF treatment were so low, it is assumed here that these O_3 concentrations were insufficient to affect yield and that CF treatments were comparable across sites.

However, differences between fumigation and filtration treatments may well be attributed to effects of other pollutants prevalent in the ambient air. In the fumigation studies, the use of CF+ would preclude effects since the fumigations would only include O_3. In contrast, filtration studies, which compare CF to NF, may contain harmful levels of other pollutants such as SO_2 and NO_2 which may have additive, synergistic or antagonistic effects (Bender and Weigel, 1994). For example, filtration studies conducted in Europe investigating impacts of SO_2 on *Lolium*, found that SO_2 effects were enhanced due to synergy with NO_2 (Bell, 1985).

Similar uncertainties may concern the EDU studies under NO_2 concentrations high enough to affect yield since it is possible (NO_2 being an oxidant) that EDU may also afford some protection to NO_2. However, to our knowledge there is no scientific evidence of EDU providing such protection. The concentrations of SO_2 and NO_2 recorded in the filtration studies can be compared with their respective critical levels of 11 and 16 ppb (Mills, 2004). Only 3 and 7 studies, out of a total of 11 studies, recorded values for concentrations of SO_2 (8–16 ppb) and NO_2 (10–40 ppb), respectively (see Tables 1–3). Of these studies, 2 and 5 exceeded the critical level for SO_2 and NO_2 respectively, with NO_2 exceedances being greater in magnitude. It is worth noting that the NO_2 critical level is established to protect all vegetation types. Crops, which benefit from applications of nitrogenous fertiliser, are less sensitive to elevated NO_2 levels than other species. However, the rather high levels of NO_2 recorded in these filtration studies (all 5 exceedances were above 20 ppb) would suggest that yield losses may have been affected; for example, a study by Bender and Weigel (1993) found that crop responses to O_3 were affected by the presence of SO_2 and NO_2 concentrations in the range of 20 ppb and 30–40 ppb, respectively. This may explain why larger yield losses were experienced at equivalent O_3 concentrations in many of the filtration studies.

Comparability of the EDU studies is reliant on the assumption that the EDU application provides close to 100% protection and hence can be considered equivalent to the control treatments of fumigation and filtration studies (as described in Fig. 1). The only study that to our knowledge has directly compared filtration and EDU methods (Fumagalli et al., 1997) attributed an $\sim$10% higher relative yield reduction in white clover grown in filtered air to the use of a relatively low EDU concentration which was unlikely to have afforded full protection. Since EDU is a nitrogen-containing compound, it has also been considered to function as a fertiliser which may affect yield (e.g. Ainsworth et al., 1996). However, Kuehler and Flagler (1999) and Paoletti et al. (in press) could not verify this suggestion in their respective studies on pine seedlings and ash trees.

For OTC studies, the chamber effect is a well-known factor that alters plant micro-climate and can enhance plant development (Mills et al., 2007). This chamber effect was in part quantified by comparing the yield effects of crops exposed to CF, NF and AA in 7 of the Asian filtration studies that provided the necessary data for the comparison. The relative difference between the yields of NF compared to AA, which indicate the chamber effect, ranged from 1.9–8.9% and 3.3–5.7% for wheat and rice, respectively. For legumes, only 1 mung bean study included an AA treatment and showed a difference of 12% between NF and AA. These percentages are substantially lower than the 23% chamber effect reported in a review of 73 NCLAN experiments (Krupa et al., 1994). Hence, the Asian conditions would not appear to have unduly influenced the magnitude of the chamber effect in comparison to the North American studies.

The use of both pot- and field-grown crops in the derivation of the Asian data may also have influenced yield loss assessments since the artificially limited environment of potted plants affects plant physiology and growth due to root growth restrictions and water uptake limitations (Samuelson and Kelly, 2001). Unfortunately the Asian data do not allow quantification of this effect as comparisons between pot- and field-grown plants were not performed. As such, the comparisons made in this paper necessitate the assumption that the relative yield loss would be the same for either pot- or field-grown plants even if the absolute yields may differ, this is important to recognise given the fact that the North American studies were all performed using field-grown plants.

This leads us to the second major source of variation, the appropriate characterisation of the O_3 exposure. In the Asian fumigation studies, the daily averaging period for O_3 characterisation was the only period when the plants received an O_3 dose, since O_3 was only added to the CF treatment; this is in contrast to the North American studies that added O_3 to the NF treatment. Many of the fumigation studies performed in India only applied pollutant additions for 4 h per day; outside these fumigation periods the plants experienced pollutant free conditions. By comparison, filtration and EDU studies continuously exposed plants to ambient pollution levels determined according to the prevailing diurnal pollution profile, similar to the North American studies which fumigated for the majority of the daylight period during which elevated O_3 concentrations would have been expected. This may explain why the fumigation data tend to show a smaller yield loss for equivalent M4–M8 values, since an equivalent O_3 concentration expressed as an M4 may miss yield influencing O_3 exposures outside the 4 h period that plants in filtration and EDU studies may experience. Modelling of diurnal O_3 profiles at selected sites across India by Mittal et al. (2007) indicates that elevated O_3 frequently occurs for up to 12 h per day; as such the 4 h averaging period may well be too short to truly characterise O_3 pollution. This situation could be overcome by extending the fumigation period, for example, the NCLAN Programme addressed this issue by extending the exposure window from 7 to 12 h in an attempt to capture more of the daily O_3 exposure (Lefohn and Foley, 1992).

The occurrence of data derived using averaging periods that vary between 4 and 12 h also raises issues in relation to data comparability. Assuming a standard diurnal profile with higher O_3 concentrations occurring around midday, mean O_3 concentrations would be highest when expressed as M4 $>$ M7 $>$ M12 indices. This means that equivalent yield losses would result from a higher O_3 concentration when expressed as M4 compared to M12. This situation is especially important when interpreting the data provided in Fig. 4 for legumes since the North American soybean dose–response relationship was derived using M12. It would be expected that equivalent yield losses would be found at higher M7 or M8 values, compared to M12 values, such that an M7 North American dose–response relationship may have sat closer to the Asian data points.

An additional factor is the use of the growing season mean indices that give equal weight to all hourly O_3 concentrations. The use of exposure metrics that emphasise, and accumulate, peak concentrations over time (e.g. the AOT40 index) are now recognised as providing more biologically relevant concentration-based indices (Fuhrer et al., 1997) and would have avoided issues related to the daily exposure window. Unfortunately their use was not possible in this analysis since the hourly O_3 data necessary to calculate the AOT40 index were not available.

Finally, the accuracy with which the O_3 indices are measured is dependent upon both the measurement method and frequency of O_3 concentration monitoring. Two methods were used to monitor Asian O_3 concentrations: firstly, wet chemistry methods which tended to monitor only infrequently (e.g. for only a few days per week during limited diurnal periods). The second method, continuous UV absorption, was only used in 5 of the 24 Asian studies. Wet chemical methods tend to be less precise than UV absorption methods and some can suffer from interferences from other pollutants such as NO_2 and SO_2 (Becker et al., 1985). This, coupled with the reduced frequency of the wet chemistry monitoring, introduces a level of uncertainty in the mean concentrations recorded and hence in the quantification of the O_3 index.

The third major source of variation is related to environmental conditions: a limitation of the NCLAN Programme was identified as the inadequate sampling of prevailing environmental conditions which are important due to their influence on crop sensitivity to O_3 (Rawlings et al., 1987). In general, the Asian data suggest no obvious trend by climate with the exception of data collected in Pakistan which tend to show consistently high sensitivities to relatively low O_3 exposures for wheat, rice and legumes. This may be due to the use of sensitive cultivars, local environmental conditions or particular diurnal O_3 profiles that pre-dispose the plants to damage. There is insufficient power in our data collation to test the effects of differences in climatic conditions.

The importance of the final factor, differential cultivar sensitivity, has been clearly identified within this data collation, with yield losses recorded from those studies which used two or more cultivars under equivalent O_3 exposures varying by as much as 24% and 16% for wheat and rice, respectively. Evidence of differential cultivar sensitivity to O_3 has been found previously for wheat (e.g. Barnes et al., 1990; Heagle et al., 2000; Quarrie et al., 2007; Biswas et al., 2008a,b) and rice (Ariyaphanphitak et al., 2005). The closed chamber study by Ariyaphanphitak et al. (2005) found a variation of the sensitivity of different Thai rice cultivars to equivalent O_3 exposures of up to 56%. Perhaps the most comprehensive cultivar sensitivity study was conducted for wheat by Quarrie et al. (2007). They investigated the genetic control of traits governing O_3 effects and found cultivar sensitivity to cause variations in average grain yield from 0 to 56% (with a mean of 18%) in 95 wheat doubled haploid lines.

There is also mounting evidence from studies using both European (Barnes et al., 1990; Velissariou et al., 1992; Pleijel et al., 2006) and Chinese varieties (Biswas et al., 2008a,b) that more recently bred cultivars of spring wheat are more sensitive to O_3, in spite of rising background O_3 concentrations. This increased sensitivity in modern cultivars has been attributed to physiological traits including higher stomatal conductances leading to higher O_3 fluxes and reductions in anti-oxidative capacity. The fact that O_3 tolerance is inherited (Fiscus et al., 2005) makes an understanding of the O_3 sensitivity of modern wheat genomes crucial for future breeding programmes to ensure O_3 sensitivity is not inadvertently bred into new varieties (Biswas et al., 2008b). It would be interesting to consider how the introduction of climate-specific plant physiological traits (e.g. enhanced water use efficiency in regions prone to drought) may influence sensitivity to O_3, especially given the broad geographic variability of this pollutant.

Finally, it is useful to place the site-specific studies analysed here within a regional context. Fig. 5 shows the location of the experimental sites from which South Asian filtration and EDU data were collected for wheat and rice in relation to modelled M7 for the year 2000 (Engardt, 2008). The 92-day modelled growing season was defined for wheat as a function of latitude (where end of growth period = max(55, 3.5077 × latitude − 1.7419)), and for rice as fixed from 1 Aug to 31 Oct (http://dacnet.nic.in/). For wheat, the modelling suggests that the study sites at Varanasi and Lahore are representative of south Asian locations experiencing mid- to high-range O_3 concentrations, with the model predicting M7 of 40–50 ppb, which compares with M4–M8 values between 36–72 ppb recorded at the sites. The modelling also suggests that large parts of south Asia (e.g. northern, mid and south India, north east Pakistan and most of Bangladesh) experience equivalent, if not higher (up to 50–90 ppb M7) O_3 concentrations compared to the study locations. The situation is similar for rice although here the study site is

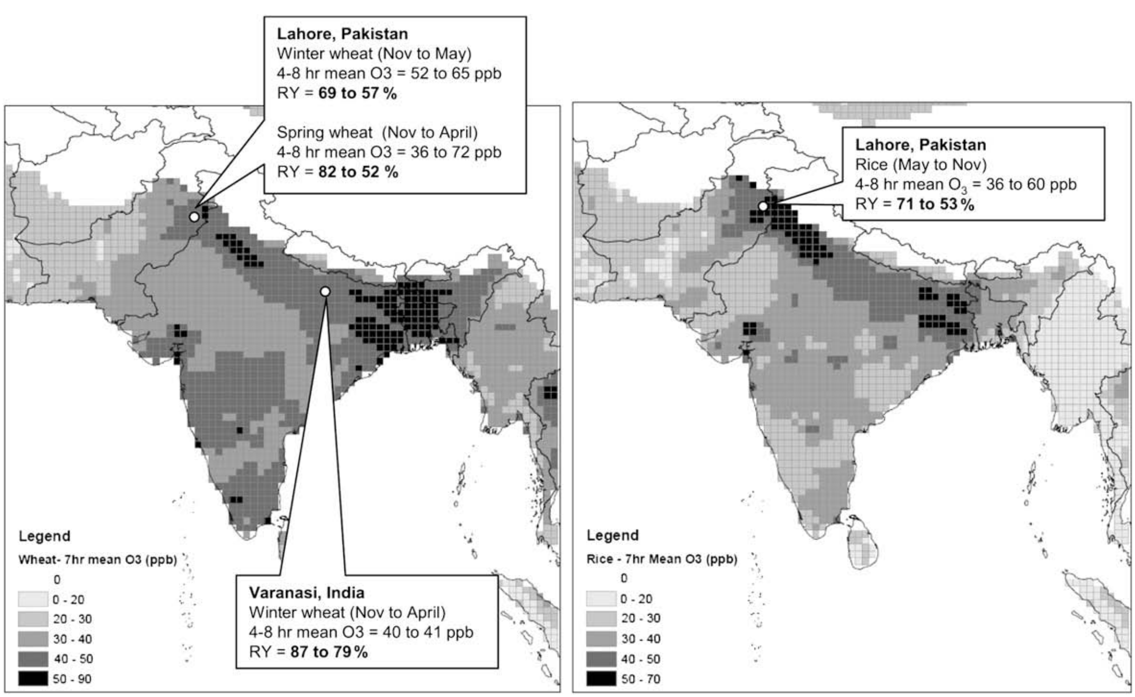

Fig. 5. Location of the South Asian study sites and associated experimental period O_3 concentration and yield losses presented in relation to modelled 7 h growing season mean O_3 concentrations (M7) for wheat (Dec/Jan–Mar/April) and rice (Aug–Oct).

located in regions predicted to have the highest modelled O_3 concentrations (50–70 ppb M7), which compares to the monitored study site M4–M8 of 36–60 ppb. However, in comparison to wheat, the modelled spatial extent of these high O_3 concentrations is reduced, with mid- and south-India and Bangladesh only experiencing M7 values in the range of 30–40 ppb. This is likely to reflect the effect of the prevailing meteorological conditions, namely the south west monsoon, in altering the seasonal O_3 profile.

Importantly, the broad geographical distribution of elevated O_3 concentrations suggests that the yield losses experienced at the study sites may well be indicative of similar losses found across substantial parts of the south Asian region with serious implications for crop productivity, especially in the agriculturally important Indo-Gangetic plain region (Timsina and Connor, 2001). This comparison also serves to emphasise the need for further co-ordinated research given the potential geographical extent of harmful O_3 concentrations and the extremely limited number of experimental study sites used across a region as large as South Asia; similar inequalities of scale are also a feature of both south east and east Asia.

5. Conclusions

In summary, we view the data collated within this paper as providing strong evidence that ambient O_3 pollution may be substantially reducing yields of important crops and crop varieties across Asia. The indication of enhanced O_3 sensitivity, compared to North America studies, of some of these Asian grown crop varieties strongly suggests that risk assessments previously conducted for the region (e.g. Wang and Mauzerall, 2004; Aunan et al., 2000) may have substantially underestimated the threat posed by O_3 to agricultural productivity.

To date, much attention has been placed on understanding the future impacts of climate change on agricultural productivity, with the IPCC forecasting yield losses in agricultural productivity of up to 25% by the 2050s for Asia (Hesselbjerg Christensen and Hewitson, 2007). In contrast, the data collected in this study suggest that O_3 may be causing a more immediate problem with substantial yield losses already occurring under current day pollution loads. In stark contrast to the crop productivity gains afforded by the Green Revolution, more recent evidence suggests a deceleration in the growth patterns of crop output (MEA, 2005). This stagnation in productivity has been attributed to a range of factors such as declining soil fertility and climate change. We argue that the work presented here suggests that elevated ground level O_3 may also be a significant contributing factor to this stagnation in the growth of crop yields.

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