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CO_2 fertilization of crops offsets yield losses due to future surface ozone damage and climate change

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Supplementary material for this article is available online

Abstract

Tropospheric ozone (O_3) is harmful to plant productivity and negatively impacts crop yields. O_3 concentrations are projected to decrease globally in the optimistic Representative Concentration Pathway of 2.6 W m^{-2} (RCP2.6) but increase globally following the high-emission scenario under the RCP8.5, with substantial implications for global food security. The damaging effect of O_3 on future crop yield is affected by CO_2 fertilization and climate change, and their interactions for RCP scenarios have yet to be quantified. In this study, we used the Joint UK Land Environment Simulator modified to include crops (JULES-crop) to quantify the impacts, and relative importance of present-day and future O_3, CO_2 concentration and meteorology on crop production at the regional scale until 2100 following RCP2.6 and RCP8.5 scenarios. We focus on eight major crop-producing regions that cover the production of wheat, soybean, maize, and rice. Our results show that CO_2 alone has the largest effect on regional yields, followed by climate and O_3. However, the CO_2 fertilization effect is offset by the negative impact of tropospheric O_3 in regions with high O_3 concentrations, such as South Asia and China. Simulated crop yields in 2050 were compared with Food and Agriculture Organisation (FAO) statistics to investigate the differences between a socioeconomic and a biophysical process-based approach. Results showed that FAO estimates are closer to our JULES-crop RCP8.5 scenario. This study demonstrates that air pollution could be the biggest threat to future food production and highlights an urgent policy need to mitigate the threat of climate change and O_3 pollution on food security.

1. Introduction

Ground-level ozone (O_3) is one of the leading air pollutants that substantially threatens human health and plant productivity (Tai *et al* 2014, Sadiq *et al* 2017, Leung *et al* 2020a). It is mainly produced photochemically from anthropogenic precursor gases, including carbon monoxide (CO), volatile organic compounds and nitrogen oxides (NO_x), which are mainly emitted from fossil fuel combustion. The phytotoxicity of O_3 has been shown to damage photosynthesis, reduce gas exchange, induce early leaf senescence, and inhibit growth in both natural vegetation and crops (Feng *et al* 2011, Sadiq *et al* 2017, Tai and Val Martin 2017, Hayes *et al* 2020, Seltzer *et al* 2020, Leung *et al* 2020b, Li *et al* 2022b). As plants play a vital role in regulating the ambient environment, ozone-induced damage in plants may further accelerate environmental degradation, with severe consequences for human and ecosystem health.

1.1. Ozone in a warming climate

Tropospheric O_3 concentrations are controlled by emissions and climate (Jacob and Winner 2009). First, global warming and climate change in response to increased greenhouse gas concentrations can enhance stratosphere-troposphere exchange of O_3 (Zeng *et al* 2008, Jacob and Winner 2009, Fiore *et al* 2012). Second, increased temperature also favors O_3 chemical production and peroxyacyl nitrate (PAN) decomposition, which can lead to higher tropospheric O_3 in certain regions (e.g. Zeng *et al* 2008, Jacob and Winner 2009). PAN is a secondary pollutant found in photochemical smog. It dissociates slowly in the atmosphere into NO_2 and peroxyacetyl radicals. If PAN is formed in or convectively lifted to the troposphere, it remains stable for long enough to be transported far away from urban sources. This process is vital for tropospheric O_3 production as it can indirectly transport NO_x to regions where it can more efficiently produce O_3. Third, enhanced convection from increased temperature transports O_3 precursors and lead to an increase in O_3 production. Lastly, lightning frequency increases with increased temperature and results in a 22% increase of lightning-produced NO_x (Zeng *et al* 2008). However, a warming climate could lead to higher water vapour in the atmosphere and a decreased in background O_3 concentration. In conclusion, the background O_3 and climate penalty-driven pollution have opposite sensitivities to climate change (Jacob and Winner 2009, Schauberger *et al* 2019).

1.2. Ozone impacts on agriculture

In the United States alone, crop losses due to tropospheric O_3 cost more than 5 billion USD annually (Ainsworth *et al* 2012, Betzelberger *et al* 2012). It is estimated that the cost in developing countries is much higher, where agricultural techniques are less advanced, and the productivity of staple crops are susceptible to the effects of climate change via more frequent occurrences of droughts, floods, pests and disease outbreaks (The Royal Society 2008). A recent study by Li *et al* (2022a) showed that O_3 damage causes 7%–19% relative yield losses in China from 2010 to 2017 for rice, wheat and soybean (Li *et al* 2022a). The estimated global average yield loss due to O_3 damage in 2000 is 5.4%–15.6% for soybean, 7.3%–12.3% for wheat, 2.8%–3.7% for rice, 2.4%–4.1% for maize (Van Dingenen *et al* 2009).

Several studies have investigated the global impact of O_3 on agricultural crop yields with future air quality scenarios (Van Dingenen *et al* 2009, Avnery *et al* 2011, Tai and Val Martin 2017) to the year 2030 or 2050. Van Dingenen *et al* (2009) provided the first estimate of global crop yield losses due to O_3 in the future, using the optimistic 'current legislation scenario' that assumes current air quality legislation is being fully implemented in 2030. Avnery *et al* (2011) commented that such scenario is overly optimistic as legislation enforcement often lags behind the announcement. Avnery *et al* (2011) examined the impact of O_3 exposure on future crop yields using the Intergovernmental Panel on Climate Change Special Report on Emissions Scenarios (IPCC SRES) year-2030 scenarios and found that O_3 causes 12.1% and 16.4% soybean yield loss in 2030 for the Representative Concentration Pathway (RCP)2.6 and RCP8.5 scenarios, respectively, which the RCP2.6 and RCP8.5 scenarios cover the minima and maxima of the O_3 projections However, neither Avnery *et al* (2011) nor Van Dingenen *et al* (2009) account for the effects of rising CO_2 concentration and climate change in future scenarios, which could not fully project future crop yield changes. A recent study by Tai *et al* (2021) summarized three approaches of modeling O_3 impact on crop yields: concentration-based metrics, flux-based metrics, and mechanistic modeling. They found that only mechanistic modeling (i.e. JULES-crop) could address the co-effects of CO_2 fertilization. JULES-crop model is thus selected to further perform factorial simulations with the combination of RCP2.6 climate and RCP8.5 CO_2, climate and O_3 scenarios to investigate the sensitivity of crops to these driving factors.

This study investigates future crop yield response climate change, O_3 and CO_2 and their interactions using JULES-crop over the period 2005–2100. Many existing studies (Fiore *et al* 2012, Schauberger *et al* 2019, Hayes *et al* 2020, Sampedro *et al* 2020) simulate crop response to climate projections spanning only a few years each due to computational limitations, while this study simulate long transient timeseries. This approach could help distinguish an actual anthropogenic-forced climate signal from internally generated climate variability (Nolte *et al* 2018). With rising CO_2 expected in the RCP8.5 scenario, the exposure-yield relationship derived from concentration-based metrics would be less applicable due to the effect of CO_2 fertilization (Tai *et al* 2021). JULES-crop, in this case, could provide insights on how CO_2 interacts with O_3 damage on yield.

2. Methodology

JULES-crop is a model that parameterize and simulate crop production (Osborne *et al* 2015). Osborne *et al* (2015) showed that JULES-crop could simulate yield variation successfully using historical climate data. More detail about JULES-crop is in supplementary materials (available online at stacks.iop.org/ERL/17/074007/mmedia). Furthermore, the effect of O_3 on crop is parameterized using Sitch *et al* (2007) and has been previously extensively evaluated for Soybean at a Free-air enrichment experiment by Leung *et al* (2020b). To test if JULES-crop could be used to realistically simulate future yield loss, we compared the results with the estimates from the Food and Agriculture Organisation (FAO) Working Paper

Table 1. Annual crop productions of the four major crop producing regions for each crop in million tonnes as of 2020 (FAO 2022).

Maize (million tonnes)		Wheat (million tonnes)		Soybean (million tonnes)		Rice (million tonnes)	
USA	360.25	China	134.25	Brazil	121.79	China	213.61
China	260.87	EU	126.66	USA	112.55	India	178.31
Brazil	103.96	India	107.59	Argentina	48.79	Bangladesh	54.91
Argentina	58.39	USA	49.69	China	19.61	Indonesia	54.65

Table 2. Summary of future transient runs with a combination of prescribed CO_2 and O_3, black: climate change only, red: climate change and CO_2 change, blue: climate change and O_3 change, purple: combined effect of climate change, CO_2 and O_3 change together.

Run ID	Climatology	CO_2	O_3
RCP2.6	RCP2.6	Const. 2005	Const. 2005
RCP2.6 + CO_2 + O_3	RCP2.6	RCP2.6	RCP2.6
RCP2.6 + CO_2	RCP2.6	RCP2.6	Const. 2005
RCP2.6 + O_3	RCP2.6	Const. 2005	RCP2.6
RCP8.5	RCP8.5	Const. 2005	Const. 2005
RCP8.5 + CO_2 + O_3	RCP8.5	RCP8.5	RCP8.5
RCP8.5 + CO_2	RCP8.5	RCP8.5	Const. 2005
RCP8.5 + O_3	RCP8.5	Const. 2005	RCP8.5

2050 projections. Rather than being a process-based approach like JULES-crop, which represents vegetation processes and is driven by climate forcing, FAO makes yield projections based on socio-economical data. The data includes arable land availability, yield growth potentials and ceilings for present-day crops, water availability, and irrigation potential. In principle, all these characteristics may be affected by climate change (Alexandratos and Bruinsma 2012). Since FAO uses a bottom-up approach to region-specific data, it has higher resolution and regional relevance, which could be more helpful in informing local policymakers and regional planning. The regions we selected are four of the highest yield production countries/regions for the four crops. There are eight in total: USA, China, Brazil, Argentina, EU, India, Bangladesh, Indonesia (table 1).

2.1. Simulation protocol

To evaluate the performance of JULES-crop simulation, JULES-Crop is applied over the historical period from 1961 to 2005 with climatology from CruNCEP, modelled ozone fields and observed CO_2 data to simulate crop yields for four major global crops: soybean, wheat, maize, and rice (see supplementary material). The order of O_3 damage for the four crops simulated by JULES for year 2000 is consistent with the estimation by Van Dingenen *et al* (2009), whereby soybean has the highest sensitivity and maize has the least (supplementary material).

For future simulations, JULES was forced over the 2005–2100 period with changing CO_2, O_3 and climate according to the RCP2.6 and RCP8.5 scenarios.

The simulations are initialized from the historical simulations from Osborne *et al* (2015). However, when a driving variable is fixed (i.e. O_3 or CO_2), it is fixed at the year-2005 value for the transient future period. The model is applied for the 2005–2100 transient simulation using a factorial design varying or fixing CO_2, O_3 and varying climate according to the RCP scenarios (table 2). Given that the historical simulations were driven with merged Climatic Research Unit and National Centre for Environmental Prediction data (CRUNCEP) and the future simulations with HadGEM2-ES climatology, and the fact that the model requires 1–2 years of spin-up for the fast fluxes (soil moisture, soil temperature and NPP), we spun up the model for 5 years using 2005 climatology before the actual simulation.

The future harvested areas for the four crops (i.e. wheat, soybean, maize, and rice) were kept constant at the year-2000 distribution as presented by Monfreda *et al* (2008) and Ramanutty et al (2008) since the yield changes are independent of changes in the cultivated areas. There were 13 global simulations, including eight factorial future transient simulations with combinations of the two RCP scenarios driving data prescribed with CO_2 and O_3 (table 2). RCP2.6 and RCP8.5 were selected as they represent the upper and lower boundary of future RCP and climate change scenarios. These runs were used to investigate the relative impacts of climate change, CO_2 and O_3 damage on crop yields. The relative contribution of a driving variable is calculated by subtracting the yield of the baseline RCP-2005 run from RCP (to estimate the climate change contribution), RCP + CO_2 (to estimate the CO_2 contribution) and subtracting the baseline yield from RCP + O_3 (to estimate the O_3 contribution).

3. Results and discussions

3.1. Impacts of different combinations of climate, CO_2 and O_3 changes on global crop yields

As shown in figure 1, JULES-crop simulates a higher yield for all crops in RCP8.5 than in RCP2.6 if the CO_2 fertilization effect is included. However, without

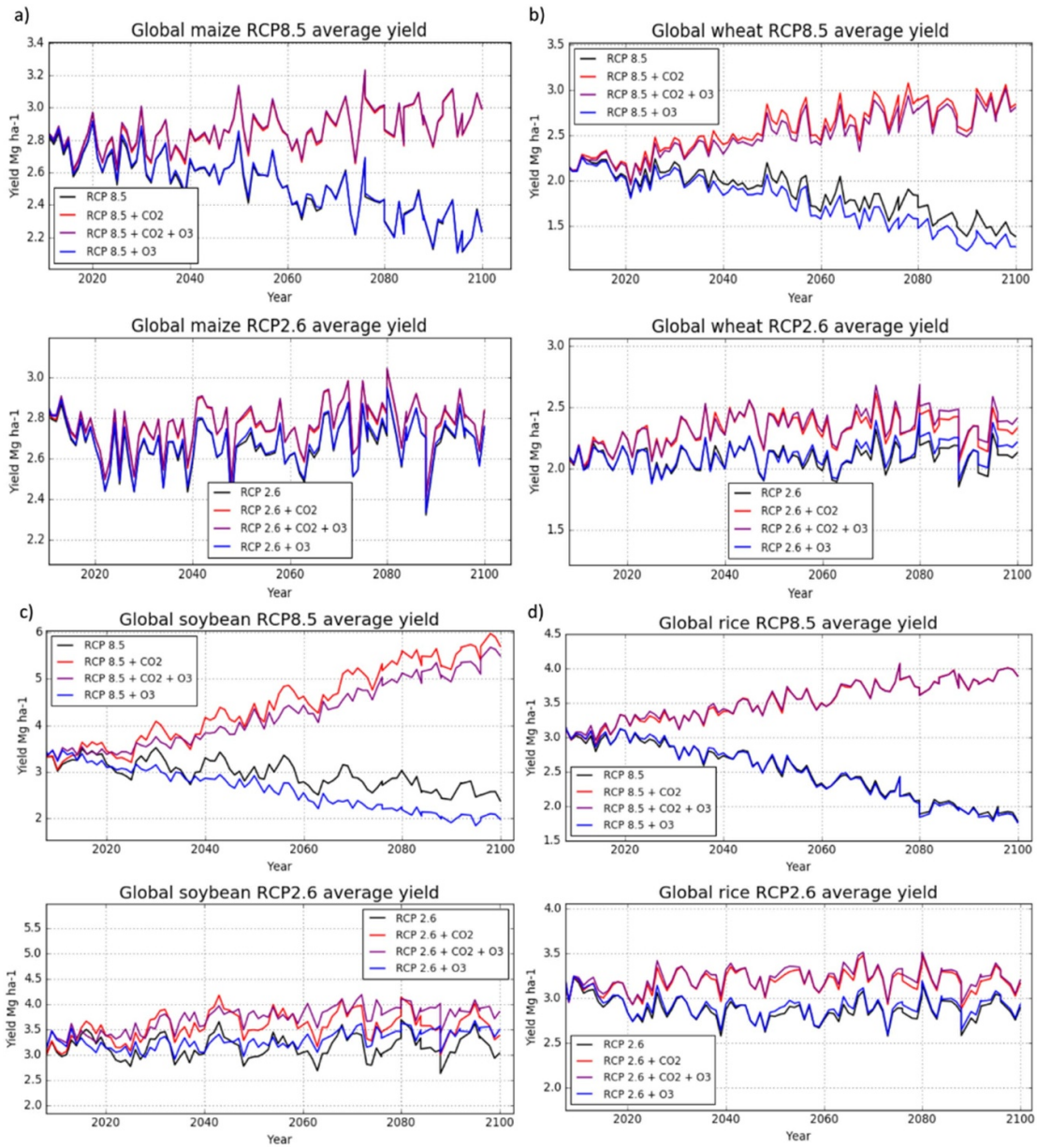

Figure 1. Global average crop yield from 2010 to 2100 for (a) maize, (b) wheat, (c) soybean and (d) rice simulated by calibrated JULES-crop in RCP2.6 and RCP8.5 scenarios with constant 2005 CO_2 and O_3 in black line, varying CO_2 and constant 2005 level O_3 in red, constant 2005 CO_2 and varying O_3 in blue and varying O_3 and CO_2 in purple.

CO_2 fertilization, RCP8.5 results in a lower yield than RCP2.6 due to O_3 damage and climate change alone (blue line in figure 1). The effect of O_3 damage is greatest for soybean and wheat; as C3 plants they are more sensitive to O_3 damage than C4 maize (Long *et al* 2005, Williams *et al* 2017).

In JULES-crop, the effect of CO_2 fertilization is higher than O_3 damage; the CO_2 increase in RCP8.5 more than compensates the O_3 damage, and in RCP2.6, the compensation cancels out the O_3 damage effect for soybean and wheat. CO_2 can also reduce the leaf stomatal conductance of vegetation and therefore reduce plant O_3 uptake and damage. Climate change alone in RCP8.5 has a significant negative effect on yields, causing around one-third of the yield loss from 2010 to 2100 for all four crops (see supplementary materials for more information). Global soybean experiences the highest yield loss from O_3 damage among the crops, losing around 1 tonne per hectare. The climate change impact on crop yields in RCP2.6 is significantly less than the impact in RCP8.5; the yield stays mainly constant from 2005 to 2100.

The O_3 impact is substantially higher in RCP8.5 than in RCP2.6 (figure 1). The impact of O_3 on crop yield is higher when CO_2 increases are not included in the simulation. This effect is the result of a higher CO_2 concentration causing stomatal closure and reducing the uptake of O_3 into the stomata, which leads to a lower plant O_3 impact. This means that CO_2 fertilization offsets yield loss due to O_3 damage. However, this mechanism does not apply to maize and rice in the RCP8.5 scenario (figure 1(a): maize and 1d:

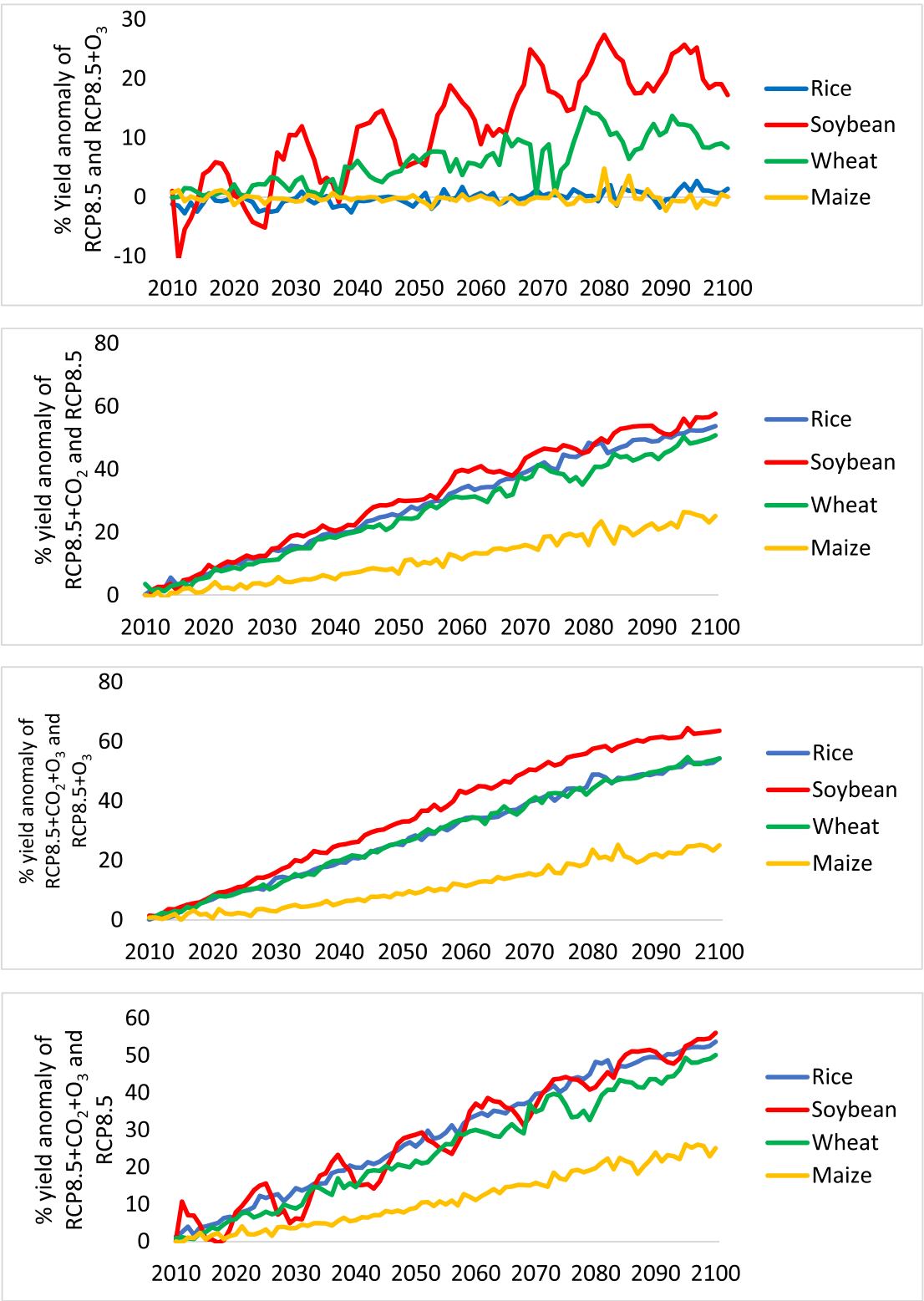

Figure 2. Percentage of yield anomaly of the four crops in the following combinations of scenarios (from top to bottom): RCP8.5 minus RCP8.5 + O_3, RCP8.5 + CO_2 minus RCP8.5, RCP8.5 + CO_2 + O_3 minus RCP8.5 + O_3 and RCP8.5 + CO_2 + O_3 minus RCP8.5.

rice), whereby including O_3 does not further reduce the yield compared to the standard scenario (without CO_2-O_3 interactions). The result suggests that climate change dominates the changes in maize and rice yields, which can be explained by the regional analysis in the next session.

Figure 2 shows that soybean is the most sensitive to O_3 damage, followed by wheat. Rice and maize have similar O_3 damage sensitivity. All three C3 plants (soybean, rice and wheat) show higher sensitivity to CO_2 rise than the only C4 plant (maize) among the staple crops. Under the combined effect of CO_2

fertilization and O_3 damage, soybean shows a slightly higher compensation effect than the other C3 crops when compared with simulations without enhanced CO_2 fertilization. All C3 crops show similar percentage yield change when RCP8.5 + CO_2 + O_3 are compared with the climate change-only scenario.

The general yield loss of the four crops due to O_3 damage simulated by JULES-crop are consistent with other studies. Together with results from previous studies, we show that the sensitivity of the four crops to O_3 are ranked in the order from high to low as soybean, wheat, rice, and maize, with soybean being the most sensitive and maize being the least (Van Dingenen *et al* 2009, Feng *et al* 2022). Maize is the least sensitive because as a C4 plant, maize has an efficient CO_2-concentrating mechanism, which essentially decouples stomatal conductance and the ensuing ozone damage from photosynthesis.

Climate change-only simulations show that temperature and precipitation change in RCP8.5 scenarios have a considerable negative impact on crop yield. Figures S4 and S5 shows that all crops are negatively impacted by climate change, with rice most impacted. This is because most rice-producing countries are concentrated in the tropical regions, where climate change would cause temperature rises above the optimal temperature threshold of rice (Erda *et al* 2005, Parry *et al* 2005, Auffhammer *et al* 2012).

In the RCP8.5 scenario, the simulated crop yield for all four crops decreased due to climate change alone (see supplementary materials for more detail). Yields for all four crops fall by more than 7%, according to table S4. These simulated reductions in yields resulting from climate change are mainly due to increasing temperature and frequency and intensity of extreme weather events such as storms (Villarini and Vecchi 2012) as reported by many other studies (Kang *et al* 2009, Asseng *et al* 2014, Porter *et al* 2014, Levis *et al* 2016, Mills *et al* 2018, Schauberger *et al* 2019). The reductions will be explained in the next section.

According to figures 1, S4 and table S4, on a global scale, RCP8.5 climate with RCP8.5 + CO_2 + O_3 scenarios simulate increases in yields for all crops. It increases the most for soybean (>60%), and then wheat and rice (20%–30%), and it increases the least for maize (<6%). The fact that maize has the smallest increase in yield of the four crops is due to the phenology of C4 plants. In RCP2.6 scenario, the CO_2 concentration increases to 440 ppm in 2050 and decreases back to 400 ppm in around 2075. Therefore, the overall CO_2 fertilization effect in RCP2.6 is small compared to the RCP8.5 scenario. When the CO_2 fertilization effect is not considered, O_3 damage is very noticeable; yields decrease for all crops in 2050 with the largest decline in soybean (22%) and wheat (16%); yield reductions in rice and maize are smaller in comparison (<8%). O_3 damage on soybean is higher than on other crops in general. According to UNEP (2018), the average O_3 induced soybean yield loss is around 23%, while other crops are less than 10%. Mills *et al* (2018), using multiple observations, also concluded that soybean is more sensitive to O_3 than other crops. Osborne *et al* (2016) showed that the O_3 sensitivity of soybean has increased overtime by one third between 1960–2000. It is possible that selective breeding strategies that target high yield and high stomatal conductance has inadvertently selected for soybean cultivars that have higher O_3 sensitivity overtime (Osborne *et al* 2016).

Figure 3 summarizes the factorial runs by plotting the global yield change from 2010 to 2100 according to the annual CO_2 and O_3 concentration combinations. The colour of the data points represent the yield change. The yield for all crop types decreases when CO_2 is below 430 ppm. When CO_2 is above 500 ppm, even with a high O_3 concentration, the yield still increases. For RCP8.5 + O_3 scenario, with increasing O_3 concentration alone (the horizontal straight line), yields decrease for soybean and wheat because they are both O_3 sensitive crops. Since O_3 damage is most significant during the crop growing period, the regional seasonal O_3 concentrations were plotted in figure S1.

At the global scale, O_3 damage impact on rice yield is not as large as expected (Pang *et al* 2009, Tang *et al* 2011) according to figures 1 and 3. Therefore, we look at the regional yield change to find which regions contribute to the reduction of yield in RCP8.5 when CO_2 and O_3 are not included in the model in the next section.

3.2. Impacts of O_3 and CO_2 alone on regional crop yield

Usually, crop growing seasons coincide with high-O_3 seasons. Figure 4 shows that higher O_3 concentrations during the growing season negatively correlate with yield for all regions. According to figure 4, using the RCP8.5 scenario, the higher the O_3 concentration during the growing season, the more crop yield will be affected by higher temperatures. This effect is also reported by Van Dingenen *et al* (2009) and Avnery *et al* (2011), who used a concentration-based approach to estimate yield loss.

In general, in RCP2.6, decreases in O_3 concentrations are not mainly due to an assumed clean air policy but rather due to a climate change mitigation policy, which reduces emissions of the greenhouse gases such as CH_4 and postulates a transition to more renewable energy production (Chalmers *et al* 2012, Wild *et al* 2012, Jones and Warner 2016). The reduction of O_3 is a co-benefit of the decline in O_3 precursors (CH_4, NO*x*, CO) from the transition to renewable energy. Therefore, this suggests that climate change mitigation is as important as clean air policy in improving food security. However,

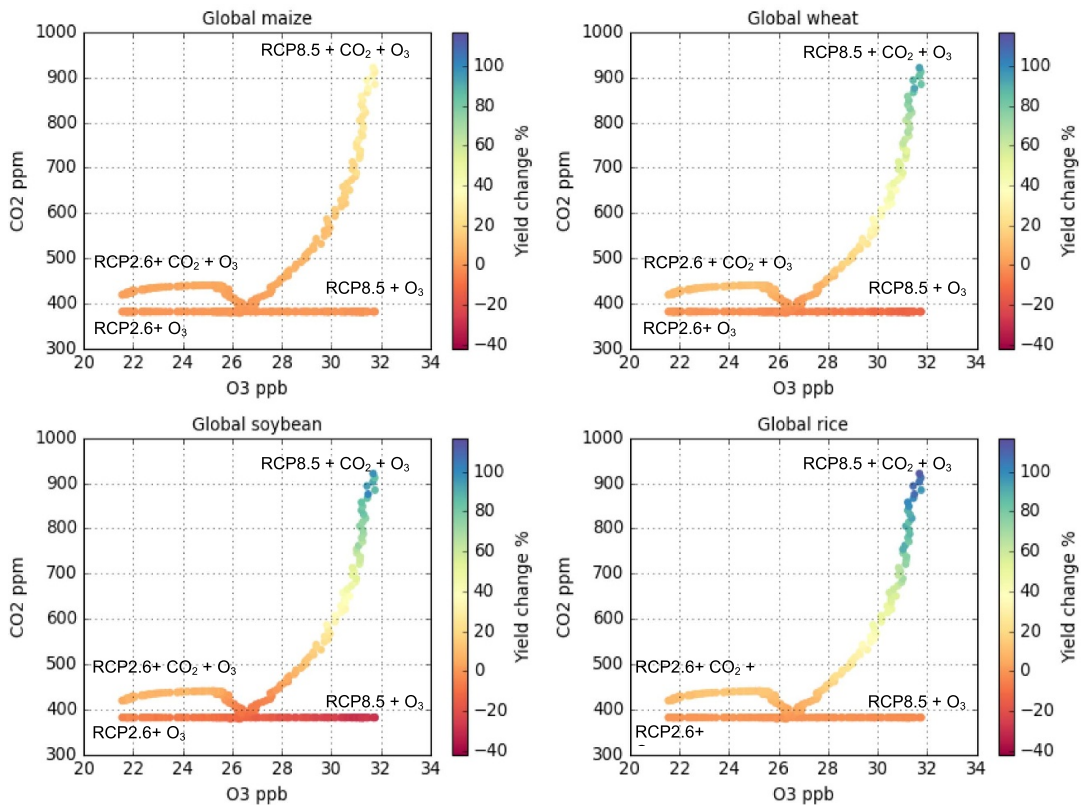

Figure 3. Global crop yield change from 2010 to 2100 relative to yield at 2005 according to CO_2 (*y* axis) and O_3 (*x* axis) concentration. Each point represents a year. The colour represents the yield change relative to the year 2005 yield.

regarding the yield improvement alone on a plant physiology perspective, a clean air policy will be more beneficial as CO_2 fertilization affords a substantial yield increase, and it can compensate for the O_3 damage on crop yield.

According to figures S6–S8 in RCP8.5, soybean, wheat, and rice experience a significant yield increase in all regions, although O_3 concentration increases because of the strong CO_2 fertilization that overshadows the damaging effect of O_3 (figure 5). Since maize is a C4 crop less sensitive to CO_2 and O_3 increases, it shows a slight increase in yield. RCP2.6 in figure S3 shows that O_3 concentration decreases in 2030, resulting in increased yield in all regions. The yield increase in RCP2.6 is around 10%–15%, while RCP8.5 could be up to 80%.

3.3. Impact of climate change alone on regional crop yield

Figure 6 implies that majority of the rice yield reduction is because of climate change. The climate change in Indonesia contributes to the largest decline of rice yield from 6.5 to 4.0 tons ha^{-1}, mainly due to increases in ambient air temperature with the annual average temperature over 30 °C from 2070 (figure 4).

In the RCP8.5 scenario, Asian countries experience a high frequency of extreme weather events with heatwaves of temperatures greater than 30 °C projected to increase by 131% (Lee *et al* 2014) compared to the current climate (figure 6). The frequency of heavy rainfall is expected to increase by 24% in RCP8.5 for some regions, as shown in figure S5. These extreme weather events would result in frequent floods and droughts (Lee *et al* 2014). In the RCP8.5 scenario, an intensified monsoon season over East Asia is projected. Since all the key rice-producing countries are in East Asia, this significantly impacts the yield. Advancements in agronomical technology would not be quick enough to adapt to the changing climate (Jagadish *et al* 2012, Scheben *et al* 2016).

Since heatwaves in East Asia usually coincide with the rice growing season, it has an enormous impact on yield. Nevertheless, high CO_2 concentrations in the RCP8.5 scenario offset the yield loss from climate change.

3.4. Comparison between JULES-crop and Food and Agriculture Organisation yield projections

In table 3, JULES-crop yield is compared against the FAO Working Paper 2050 projections. According to this data, the FAO projection is much more optimistic than JULES-crop using the RCP8.5 and 2.6 projections. All four crops show a higher yield growth in FAO data than JULES-crop RCP8.5 and 2.6 scenarios simulations. The difference is that because

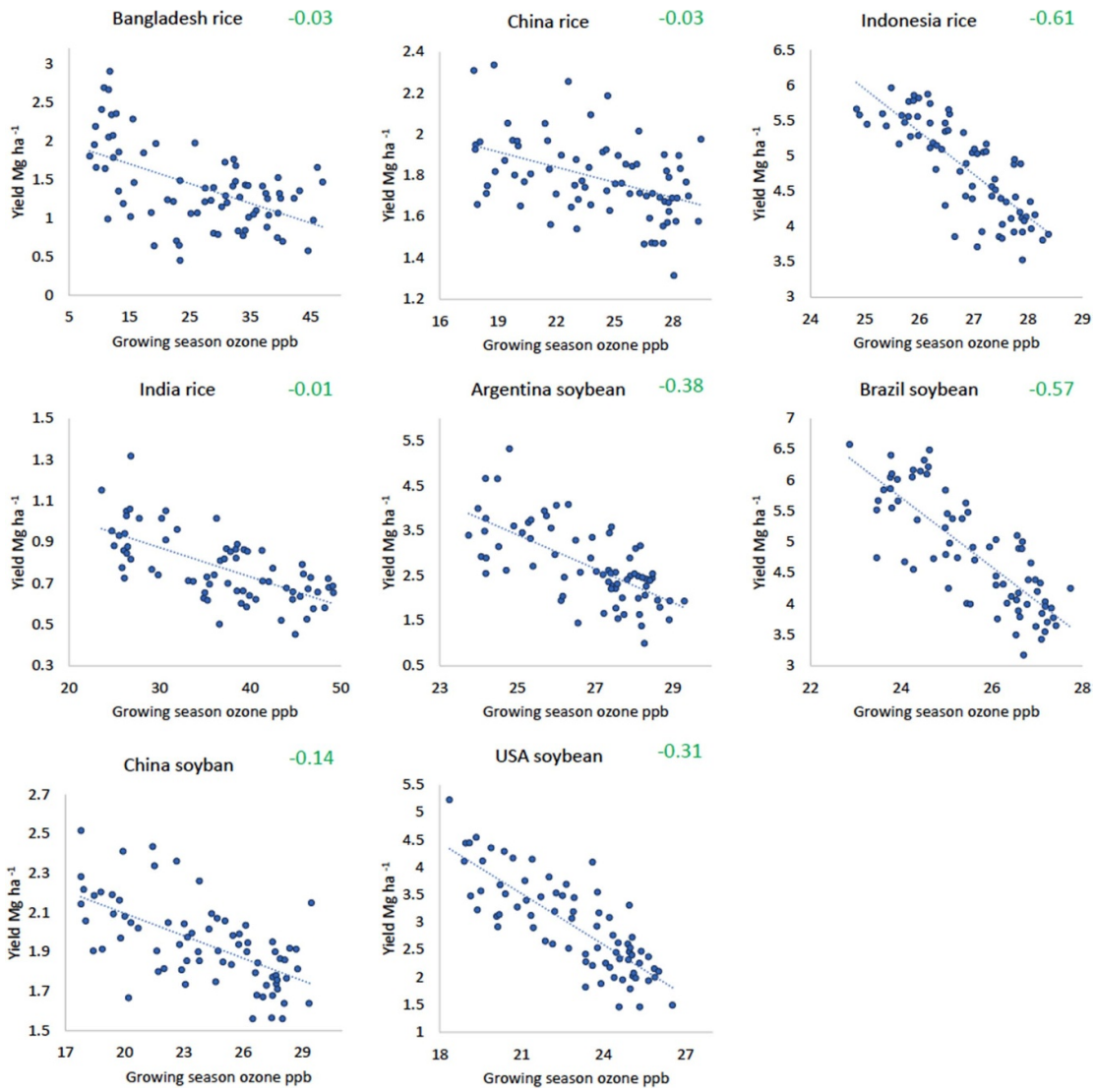

Figure 4. Scatter plots of modeled JULES crop yield and average modelled O_3 concentration in ppb during the growing season for rice and soybean. June–August are the growing season for the Northern hemisphere regions and tropical. December–February are the growing season for southern hemisphere regions. The numbers on the top right represent Pearson correlation.

FAO projections are based on socioeconomic factors, it is fundamentally different from the biophysical factors JULES-crop uses. Among the four crops, soybean yield growth for RCP8.5 is the closest to FAO projection, suggesting that soybean calibration improves the yield estimation (table 3).

JULES-crop future simulations allow a comparative study of human and climate influence on crop yields. In general, climate change, O_3 damage and CO_2 fertilization also result from human activities. We can divide the factors into active and passive human influences. Active human influences includes land use change, fertilizer application, irrigation, and other management methods, which follow primarily socioeconomic and technological development. Passive influences are the biophysical effects that JULES-crop currently represents, i.e. impacts of climate change, O_3 damage and CO_2 fertilization on yields. FAO statistics consider the active but not the passive influences. The crop production projection in the FAO report (Alexandratos *et al* 2015) was based on demand and trade projections. Demand and trade were based on demographic and socioeconomic projections for each country. Alexandratos *et al* (2015) argues that future yield growth is attained mainly by closing the yield gap in developing countries, whereas yield ceilings have already been reached in some developed countries. Mills *et al* (2018) also found that O_3 damage is one of the most important factors that contribute to yield gap, especially O_3 sensitive crops, soybean and wheat (Mills *et al* 2018). The FAO report does not account for extreme weather events or pest infestation outbreaks, and it also neglects CO_2 fertilization, leading to a considerable underestimation of productivity. Therefore, it tends to be overly optimistic (table 3). While JULES-crop does not have nitrogen limitation, for the RCP scenarios with CO_2 and O_3, it is thus also over-optimistic, assuming that the CO_2 effect would be fully translated into yield growth (Long *et al* 2004).

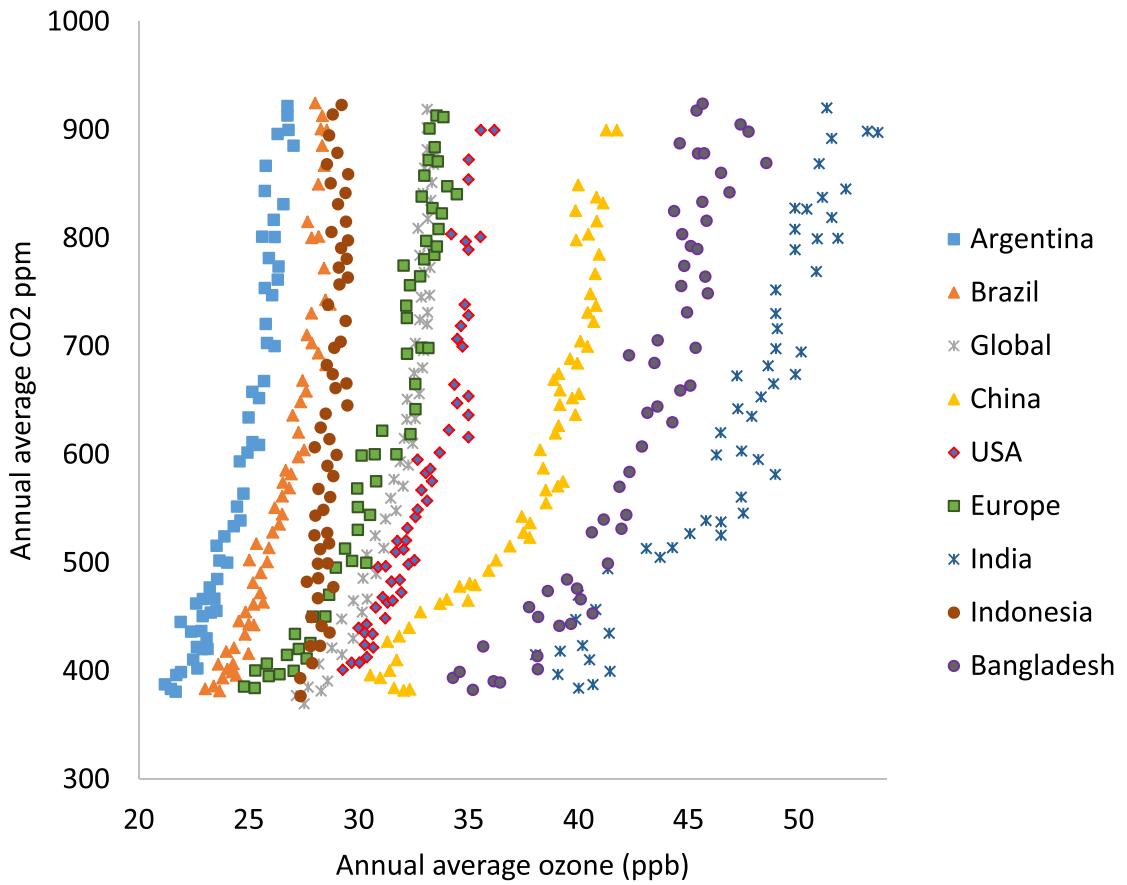

Figure 5. Regional CO_2 and O_3 concentration in RCP8.5 scenarios from HadGEM2. Each dot represents a year.

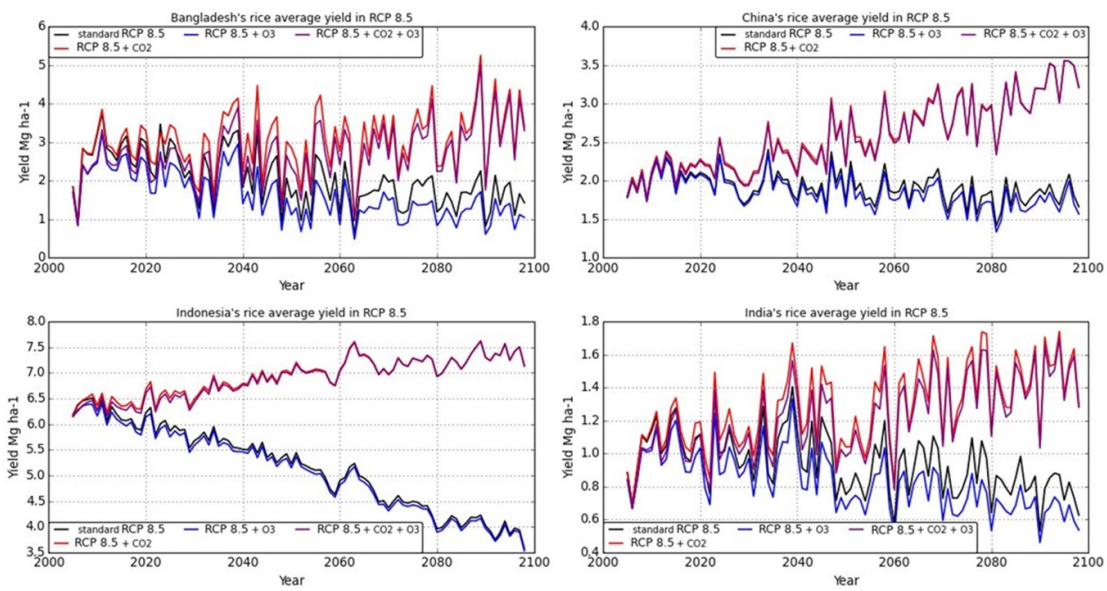

Figure 6. Rice yield in the four major rice-growing regions Bangladesh, China, Indonesia and India in RCP8.5 scenarios as simulated by JULES.

3.5. Impact of increasing CO_2 on human nutrition

Besides carbohydrates, a healthy diet should include nutrients such as protein, phosphate, and minerals. (Tulchinsky 2010). A phenomenon has been observed in non-legume C3 crops during high CO_2 conditions. The crops cannot assimilate sufficient nitrogen

Table 3. Comparison of crop yield (Mg ha^{-1} yr^{-1}) FAO projection and JULES-crop simulations of RCP8.5 and RCP2.6 scenarios in 2010 and 2050.

	FAO				RCP8.5 $CO_2 + O_3$ + climate				RCP2.6 $CO_2 + O_3$ + climate			
Crops	2010	2050	Difference		2010	2050	Difference		2010	2050	Difference	
Maize	4.74	6.06	+1.22	+26%	2.83	2.93	+0.09	+3.4%	2.75	2.77	+0.02	+1%
Wheat	2.77	3.82	+1.05	+38%	2.13	2.54	+0.41	+19%	2.06	2.38	+0.32	+15%
Soybean	2.3	3.2	+0.9	+39%	3.41	4.15	+0.75	+22%	3.31	3.84	+0.54	+16%
Rice	4.07	5.32	+1.25	+31%	3.04	3.68	+0.64	+21%	3.09	3.35	+0.25	+8%

from soils to maintain the usual C:N ratios in tissues (Bloom *et al* 2012, Myers *et al* 2014). This phenomenon has been known as 'carbohydrate dilution', in which CO_2 stimulated carbohydrate production by plants dilutes the rest of the grain components. Of all the elements, changes in nitrogen content at elevated CO_2 concentrations have been the most studied. This carbohydrate dilution effect has been observed consistently in most crops but less significant on leguminous crops. Research suggested high CO_2 concentration could stimulate greater nitrogen fixation to maintain tissue C:N ratios (Erda *et al* 2005, Myers *et al* 2014). As projections showed that atmospheric CO_2 would likely continue to increase in the future, programmes such as biofortification, supplementation and breeding crops cultivar for decreased sensitivity to CO_2 would help address the nutrient deficiency caused by CO_2 fertilization.

4. Conclusions

In conclusion, results from global JULES-crop simulations suggest that rising CO_2 has the greatest impact on global crops yield, climate change is the second most important, and O_3 pollution has a relatively smaller impact (except for soybean). This study shows that on a regional scale, the relative impact of climate, CO_2 and O_3 would be different from the global scale as O_3 air quality and climatic changes (e.g. in precipitation and temperature) varies considerably spatially.

This study demonstrates the co-benefits of climate mitigation and air quality improvement are the most powerful policies to develop. CO_2 fertilization may offset part of the adverse effects of climate change and air pollution. Still, such benefits of CO_2 fertilization would not be sustainable if the damaging effects of climate penalties and air pollution continues. CO_2 fertilization would also reduce the nutrient content of crops and may lead to potential malnutrition in food-insecure countries. In the long run, climate mitigation and clean air should combine with technology advancement of crop science. Continued development of cultivars that are heat tolerant, O_3 tolerant and supplemented with nutrients would help improve food security and human nutrition in the world of growing population.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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