



RESEARCH ARTICLE

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Key Points:

- Climate change, carbon dioxide concentrations, and ozone pollution affect crop yields, leading to impacts that depend upon emission type
- Impacts to date vary markedly across regions and crops, with large sensitivity of maize to methane and of tropical wheat to carbon dioxide
- Crop yields over coming decades will be strongly influenced by changes in non-CO₂ greenhouse gasses, ozone precursors, and aerosols

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Spatial Patterns of Crop Yield Change by Emitted Pollutant

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Abstract Field measurements and modeling have examined how temperature, precipitation, and exposure to carbon dioxide (CO₂) and ozone affect major staple crops around the world. Most prior studies, however, have incorporated only a subset of these influences. Here we examine how emissions of each individual pollutant driving changes in these four factors affect present-day yields of wheat, maize (corn), and rice worldwide. Our statistical modeling indicates that for the global mean, climate and composition changes have decreased wheat and maize yields substantially whereas rice yields have increased. Well-mixed greenhouse gasses drive most of the impacts, though aerosol-induced cooling can be important, particularly for more polluted area including India and China. Maize yield losses are most strongly attributable to methane emissions (via both temperature and ozone). In tropical areas, wheat yield losses are primarily driven by CO₂ (via temperature), whereas in temperate zones other well-mixed greenhouse gases dominate. Rice yields increase in tropical countries due to a larger impact from CO₂ fertilization plus aerosol-induced cooling than losses due to CO₂-induced warming and impacts of non-CO₂ gasses, whereas there are net losses in temperate zones driven largely by methane and other non-CO₂ gasses. Though further work is needed, particularly on the effects of aerosol changes and on nutritional impacts, these results suggest that crop yields over coming decades will be strongly influenced by changes in non-CO₂ greenhouse gasses, ozone precursors, and aerosols and that these should be taken into account in plant-level models and when examining linkages between climate change mitigation and sustainable development.

Plain Language Summary Changes in both climate and atmospheric composition are known to affect crop yields, but as both these factors are driven by a variety of emissions, it is not obvious what is the net effect of individual pollutant emissions on food supplies. Here we use a statistical crop model based on extensive field studies and modeling along with results from climate and composition response simulations to evaluate the net impact of individual emissions from human activities on three major staple crops: wheat, maize (corn), and rice. We find that although carbon dioxide dominates climate change to date, other pollutants play a large role in driving crop yield changes, sometimes dominating overall impacts. This suggests that efforts to mitigate climate change or improve air quality will have distinct effects on agriculture, depending on which pollutants are targeted; that local benefits might be maximized by targeting specific pollutants; and that projections of future climate should pay close attention to the role of non-CO₂ emissions including taking into account their effects of air quality.

1. Introduction

Many prior studies have investigated agricultural responses to climate change, as summarized, for example, in the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC; Porter et al., 2014). Though changes in the composition of the atmosphere in the case of CO₂ are typically included, changes in other aspects of atmospheric composition are generally omitted. Impacts of ozone, however, are relatively well understood, as acknowledged by the AR5 (Porter et al., 2014), and have been quantified in many studies (e.g., Avnery et al., 2011; Porter et al., 2014; Van Dingenen et al., 2009). Those studies, however, do not include climate change impacts. As such, extant research does not provide a clear indication of the impact of the individual emissions that drive, in many cases, both climate change and ozone concentrations. An initial study to quantify the effects of individual pollutants on agriculture was performed recently, examining global aggregate results only (Shindell, 2016). Here we build on that work, now examining the spatial

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distribution of the crop yield impacts of all major pollutants that occur via the physiological (CO₂ and ozone exposure) and climate-related (temperature and precipitation) impacts of emissions. We consider greenhouse gasses (GHGs), aerosols, and both aerosol and ozone precursors all as pollutants since all adversely affect the environment.

Changes in aerosol-related emissions and atmospheric aerosol concentrations are likely to have multiple effects on crops, including leading to changes in nutrient deposition (e.g., Mahowald, 2011), diffuse versus direct sunlight available for photosynthesis (Mercado et al., 2009), and total photosynthetically active radiation reaching plants due to atmospheric (Chameides et al., 1994) or deposited (Greenwald et al., 2006) aerosol. There are few field studies available to quantify the role of each of these effects, preventing us from applying the type of meta-analysis used to characterize other crop impacts in this study, and hence, impacts of aerosol composition change are not included here (impacts of aerosols on climate are included). Additional work on aerosol-related crop impacts would of course be useful.

2. Modeling

We have developed an empirical crop model based on statistical relationships for the impacts of temperature, precipitation, CO₂ concentrations, and ozone rather than plant level simulations. Crop responses to changes in meteorological variables and CO₂ concentrations are based on a meta-analysis of more than 1,000 modeling studies (Challinor et al., 2014), incorporating relationships observed in field studies. The availability of these three response factors from meta-analysis determines the scope of our analysis, which includes wheat, maize (corn), and rice and uses separate response coefficients for each of these according to temperate or tropical conditions.

Processes included in the modeling are summarized in Figure 1. We first use a model that calculates time-dependent composition in response to emissions of each agent involved in climate change. Residence times for all species are those given in the IPCC AR5 (Myhre et al., 2013), with the exception of CO₂, which is evaluated using a simple carbon cycle model incorporating four response times representing major terrestrial and oceanic carbon reservoirs (Joos et al., 2001; the version used in IPCC AR4). In the next step, radiative forcing values are calculated based on the radiative efficiency of each compound given in the IPCC AR5 (Myhre et al., 2013), supplemented by results from our prior modeling for the indirect effects of aerosols, as AR5 values are not available. For short-lived species, global mean forcing values per unit emission are used, as we only explore the response to worldwide changes in short-lived species. It is clear that radiative efficiency varies with the location of emissions (Myhre et al., 2013), and this could be addressed in future work. Global mean temperature responses are then calculated using an impulse-response function based on the climate sensitivity and response times of the Coupled Model Intercomparison Project Phase 5 (CMIP5) models (Geoffroy et al., 2013), which is consistent with estimates based on paleoclimate data and analysis of modern climate (Collins et al., 2013). This impulse-response function includes two exponential decays, one with a time constant of 8.2 years representing the relatively rapid response of the land and upper ocean and a second with a time constant of 290 years representing the comparatively slow response of the deeper ocean, and has a climate sensitivity to doubled CO₂ of 3.2 °C. Through this stage, the entire modeling follows that described previously (Shindell, 2016), except that the impulse-response function has been updated.

To extend beyond our prior work, we now incorporate the spatial pattern of both temperature and precipitation responses based on an analysis of nine global climate models that have performed idealized simulations examining the individual responses to CO₂, CH₄, SO₄, and BC (Myhre et al., 2017). Aerosols were increased globally by large factors (5× present day for sulfate and 10× for BC) to obtain statistically significant signals. Responses to localized aerosol perturbations might differ, and hence, here we present only responses to worldwide aerosol changes. All results are interpolated to 1° × 1° horizontal resolution, with the native resolution in the underlying climate models ranging from 2.8° × 2.8° to 1.4° × 1.4°. We assume that the temperature and precipitation responses per unit forcing to other well-mixed greenhouse gasses (WMOGHGs; N₂O and F-gasses) is similar to the responses to CO₂ (as is found to be the case for methane). Similarly, we assume the response to other scattering aerosols or aerosol precursors (OC, NH₃, and the portion of NO_x that leads to nitrate) is similar to the response to SO₂. Multimodel mean results for the temperature and precipitation impacts of CO and NO_x emissions via tropospheric ozone and methane are excluded, as these are not

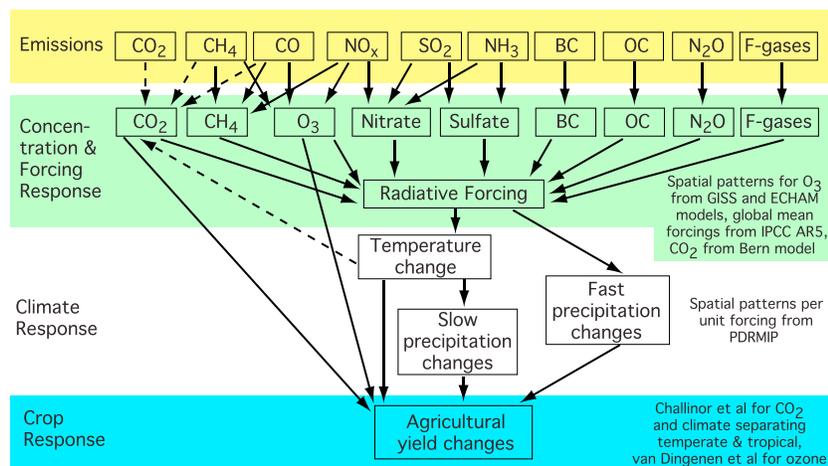


Figure 1. Diagram of processes included in the model. Dashed arrows indicate processes that are part of the carbon cycle (direct impacts, meaning via CO₂ emissions or oxidation to CO₂, are downward arrows whereas indirect impacts, meaning via the carbon cycle response to temperature, are represented by the upward arrow). Text at right provides overview of inputs to each step of the modeling, with further details given in the main text. The Bern carbon cycle model is that of Joos et al. (2001). Sulfate and nitrate represent ammonium sulfate and ammonium nitrate, respectively.

available. Based on the IPCC AR5, the net forcing from these two gasses (excluding nitrate-related impacts) is 0.1 W/m², a small value compared with forcing due to, for example, CO₂ of 1.7 W/m². Nevertheless, it would be useful to add the impacts of these gasses along with nonmethane volatile organic compounds for completeness. The multimodel mean temperature response patterns are uniformly scaled according to the amplitude of global mean temperature change calculated in the simple model as described in the previous paragraph. Precipitation patterns are also uniformly scaled following the relationship in the climate models between those patterns and global mean temperature for individual forcers.

Crop responses to temperature are regionally varying with values in units of percent yield per degree warming of (temperate regions and tropical regions): maize (−2.4, −3.4), wheat (−2.4, −13.8), and rice (−3.2, −2.0) based on the meta-analysis (Challinor et al., 2014). This compares with the uniform global mean value of −4.9% yield change per degree for all crops in Shindell (2016) based on this same meta-analysis. For consistency with the underlying meta-analysis, we define regions as follows: Tropical regions are those from 30°S to 30°N except for longitudes 20°W to 60°E (North Africa and the Middle East) where we use 20°S–20°N for all crops. Central and Eastern China, defined as 22–40°N, 100–122°E, is assigned to be temperate for wheat and maize, but tropical for rice (thus northeast China is temperate for all), as those were the classifications used in the meta-analysis from which the response functions are derived.

Turning now to composition, in addition to the response of CO₂ concentrations to CO₂ emissions, we include the very small “direct” oxidation of CH₄ and CO to CO₂. We also include the “indirect” CO₂ response to all other climate drivers via their impact on the carbon cycle (Gasser et al., 2017; see dashed arrows in Figure 1). Hence, all emissions affect the carbon cycle, though no others as greatly as direct emissions of CO₂.

Impacts of methane emissions on ozone are based on simulations with the GISS and ECHAM global composition-climate models (Shindell et al., 2012), whereas ozone responses to CO and NO_x are based on prior modeling with the GISS model only (Shindell et al., 2005). There are multiple ozone metrics associated with crop yields. We use M7 and M12 (the mean 7- or 12-hr exposure during the growing season, depending on the crop) rather than accumulated ozone over a threshold of 40 ppb (AOT40) since the latter is by definition highly nonlinear, as it uses a threshold, so not well suited to the linear framework used here. Metrics based on stomatal flux of ozone (e.g., Mills et al., 2011) are likely better than those based on surface concentrations, as they take into account variations in ozone uptake by plants under different meteorological conditions, but are not practical to implement in our framework with currently available model results. While direct human impacts on crops via land management (e.g., application of fertilizer and cultivar choice) obviously have large impacts on yields, these processes are not included in this

Table 1
Global Crop Production Changes (kt Annual in 2010) due to Historical Emissions Through 2010 by Pollutant and Process

Process → Pollutant ↓	Temperature	Precipitation	Fertilization	Ozone	Net	Relative yield (%)
Wheat						
CO ₂	-32,300	0	26,700	—	-5,600	
CH ₄	-16,200	0	200	-4,900	-20,900	
N ₂ O, F-gasses	-9,900	0	—	—	-9,900	
PIC	4,700	-250	—	-500	4,000	
SO ₂ , NO _x , NH ₃	15,300	-250	—	-9,600	5,400	
Total					-27,100 ± 7,600	-5.8 ± 1.6
Maize						
CO ₂	-23,300	10	29,700	—	6,400	
CH ₄	-11,200	10	300	-5,900	-16,800	
N ₂ O, F-gasses	-6,900	0	—	—	-6,900	
PIC	-2,900	-210	—	-600	-3,800	
SO ₂ , NO _x , NH ₃	10,800	-200	—	-11,600	-900	
Total					-22,500 ± 9,100	-4.4 ± 1.8
Rice						
CO ₂	-18,000	20	32,800	—	14,800	
CH ₄	-8,500	10	200	-2,000	-10,300	
N ₂ O, F-gasses	-5,300	10	—	—	-5,300	
PIC	2,500	-150	—	-200	2,100	
SO ₂ , NO _x , NH ₃	8,200	-170	—	-3,900	4,200	
Total					5,400 ± 2,200	1.0 ± 0.4

Note. All values rounded to the nearest 100 except precipitation, which is rounded to the nearest 10. PIC stands for products of incomplete combustion. Uncertainties based on Monte Carlo sampling of all variables and represent 95% confidence intervals. Note that 1 kt equals 1 Gg and production changes are due exclusively to yield changes as cultivated area is held constant.

study, which aims to isolate the indirect effects of worldwide pollutant emissions largely outside the control of local land managers.

Uncertainties are propagated through from all sources using a Monte Carlo evaluation with 20,000 samples randomly selected across the distributions of each components' uncertainty range. Relative uncertainties in RF are taken from the AR5, whereas uncertainties in crop yield responses are those reported in the meta-analysis (Challinor et al., 2014). Uncertainty in climate response comes from the multimodel CMIP5 analysis (Geoffroy et al., 2013). All are 5–95% confidence intervals, and the sampling assumes that all have a normal Gaussian distribution except for climate sensitivity (which is asymmetric, with a long tail at the high end). GHG and pollutant emissions are taken from the CMIP5 data set (Lamarque et al., 2011). Effects are calculated as the time-dependent response to historical emissions since 1850, and we show results for 2010 (which are hence based on all emissions through that year). Note that results for the impacts of short-lived aerosol and nonmethane ozone precursors represent the effect of worldwide emissions and the impact of emissions at any given location might differ. Crop distributions for 2010 are taken from the Food and Agricultural Organization data sets (FAO, 2010).

3. Results

3.1. Global Level Crop Responses

Annual production changes in 2010 due to all emissions through that year vary dramatically across crops at the global scale, with large losses in wheat and maize but a modest gain in rice production (Table 1; note that changes in production represent changes in yield, as cultivated area is kept fixed in this analysis). The primary processes driving crop yield changes are temperature change, CO₂ fertilization (in response to CO₂ emissions), and ozone changes (in response to CH₄ and NO_x emissions), and hereafter, we concentrate only on those. Other ozone and fertilization impacts are small, as are precipitation impacts. Note that precipitation, unlike temperature, shows substantial shifts in location rather than a more homogeneous increase, so that gains and losses driven by precipitation changes largely cancel in the global average. They can be more

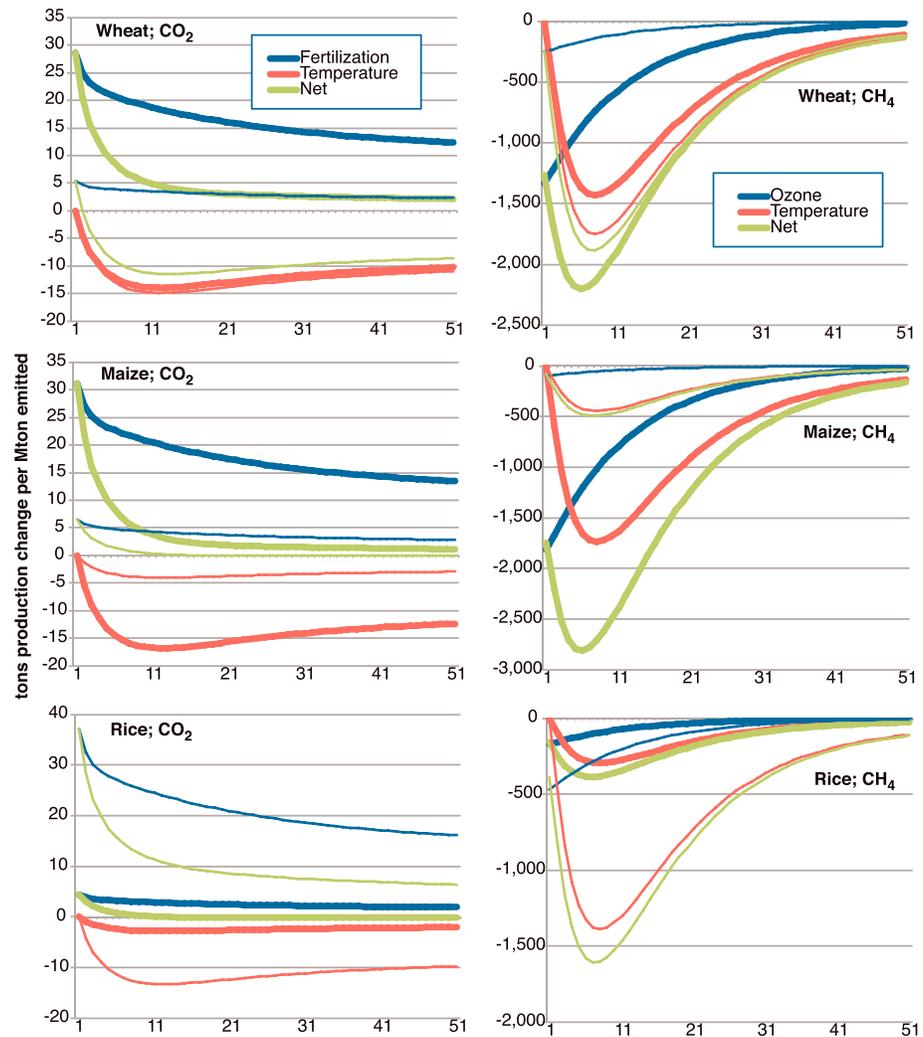


Figure 2. Tons of annual production change by year (relative to year of a single-year pulse emission) summed over temperate regions (thick lines) and tropical regions (thin lines) per Mt carbon dioxide (left) or methane (right) emission by process. Note the impacts of temperature changes induced by CO₂ on wheat are nearly identical for the temperate and tropical regions (so that the lines fall largely on top of one another). Values assume present-day cultivated areas.

important at national and local scales but are still generally small compared with other factors, so that excluding precipitation impacts in irrigation-controlled regions has little impact on our results.

The primary emission driving global crop yield losses for each crop is either methane or CO₂. Both these gasses cause large gross losses due to warming, whereas there are also large gross gains due to fertilization for CO₂ but not for methane (or other non-CO₂ GHGs). In the case of methane, losses due to temperature contribute ~2/3 to 3/4 of the total, with the remainder primarily due to ozone. N₂O, F-gasses, aerosols, and ozone precursors all have important impacts, though in many cases their opposing signs mean that they largely offset one another at the global scale. For example, crop yield gains from aerosol-induced cooling are in part mitigated by losses due to the increased ozone resulting from NO_x emissions.

Analysis of the response of temperate and tropical production to a single-year pulse of emissions helps explain the global totals and the differences across crops. We focus initially on the two primary emissions, CO₂ and CH₄. In temperate regions, CO₂ emissions cause a substantial short-term increase in production due to the instant response of concentrations to emissions, but the net effect decays within a decade or so to near-zero as the CO₂ fertilization is offset by the impacts of CO₂-induced climate change (Figure 2). In contrast, methane emissions lead to crop production reductions by means of both methane-induced

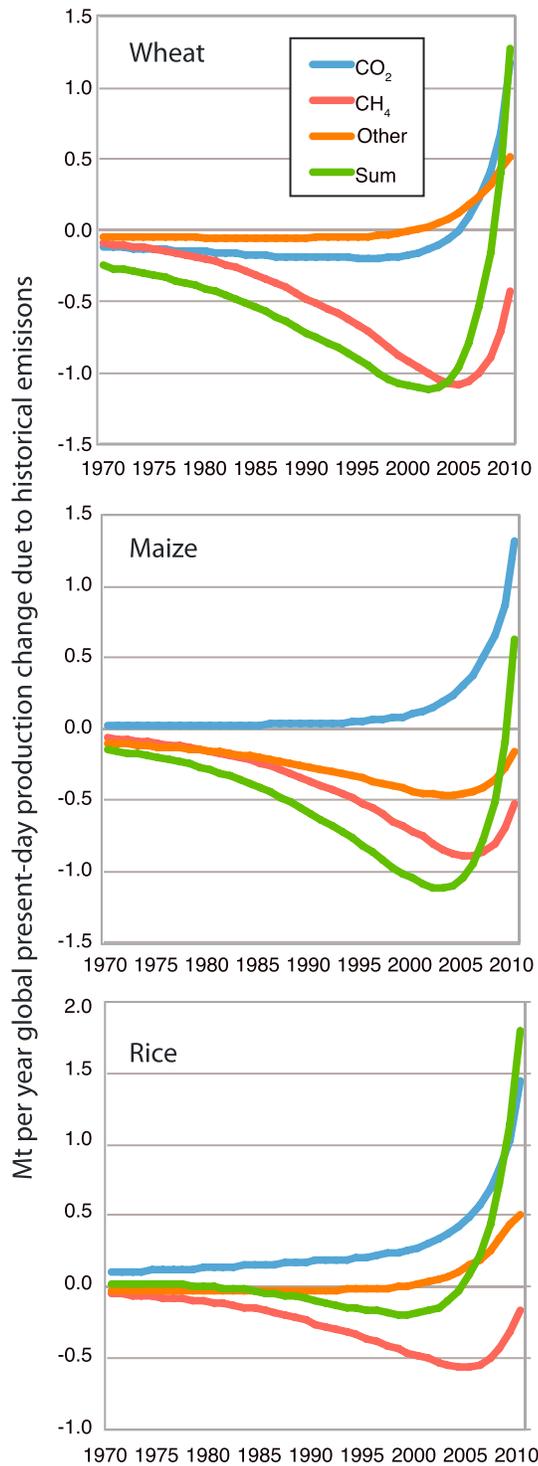


Figure 3. Mt per year global production change in 2010 for the indicated crops due to historical emissions by year from 1970 to 2010. Integrating the area under the curve (over all historical time) would yield the global totals in Table 1.

climate change and methane-induced surface ozone increase, causing large crop production losses over several decades. These two primary drivers of crop yield changes tend to drive yields down throughout the temperate zones.

The response to CO₂ is more complex in the tropics, as wheat is much more sensitive to temperature than to CO₂ fertilization, whereas tropical rice is more sensitive to fertilization than to temperature (Figure 2). This indicates that tropical wheat is damaged by both CO₂ and methane, whereas tropical rice production can increase when the positive impact of CO₂ outweighs the negative impact of methane. The results presented in Figure 1 are also influenced by where and in what volume these crops are currently grown, as these results are based on current crop distributions. For example, the responses of tropical and temperate maize to CO₂ and CH₄ are qualitatively similar, but the magnitude is larger for temperate regions, as more maize is grown there, whereas the situation is reversed for rice. They thus provide an indication of the present-day marginal impact of each additional ton of emission of these gasses.

Returning to the effects of all historical emissions, present-day production is primarily affected by the last decade's emissions for aerosols, CO, and NO_x, but longer-lived GHG emissions in the more distant past still influence today's production (Figure 3). Emissions of methane for most of the prior 20–25 years have large impacts, as do CO₂ emissions from about 5–40 or more years ago for rice and wheat. CO₂ emissions from the past several years have not yet greatly influenced climate, so their effect is largely via fertilization and hence can be opposite to the effect of CO₂ emissions from earlier years. For wheat and rice, impacts other than those from CO₂ and CH₄ are dominated by sulfur dioxide, and so recent emissions have led to increased production via cooling. In contrast, for maize impacts other than those from CO₂ and CH₄ are dominated by N₂O and F-gasses (as aerosol cooling influences are more closely offset by NO_x-induced ozone losses in maize-growing regions), so historical emissions from the past half century all have substantial impacts.

3.2. National Level Crop Responses

Turning to national level results, it is clear that many countries at Northern temperate latitudes experience large tonnage losses of all three crops (Figure 4). Many tropical countries show production gains for rice, but losses for wheat and maize. Australia and New Zealand also show wheat losses. Changes in maize production in the Southern Hemisphere temperate region differ from those in the Northern Hemisphere. The ozone response to methane is roughly half that in the North (as there is less NO_x available), and there is a noticeably weaker land warming, presumably since the Earth's surface is mostly ocean at Southern midlatitudes. These cause the losses due to CO₂-induced warming to be substantially smaller relative to gains from fertilization, so that CO₂ can have larger net positive effects than the negative effects of methane as those are substantially weaker than in the North. The result is small net gains rather than losses in a few countries, including Argentina, Uruguay, and New Zealand.

Focusing on the most affected nations (Table 2), we see that for maize, relative yield losses are comparable across many parts of the world with losses due to emissions to date ranging from ~5–6% across countries in North Africa, North America, Europe, and Asia. In tonnage lost, damages are concentrated on the United

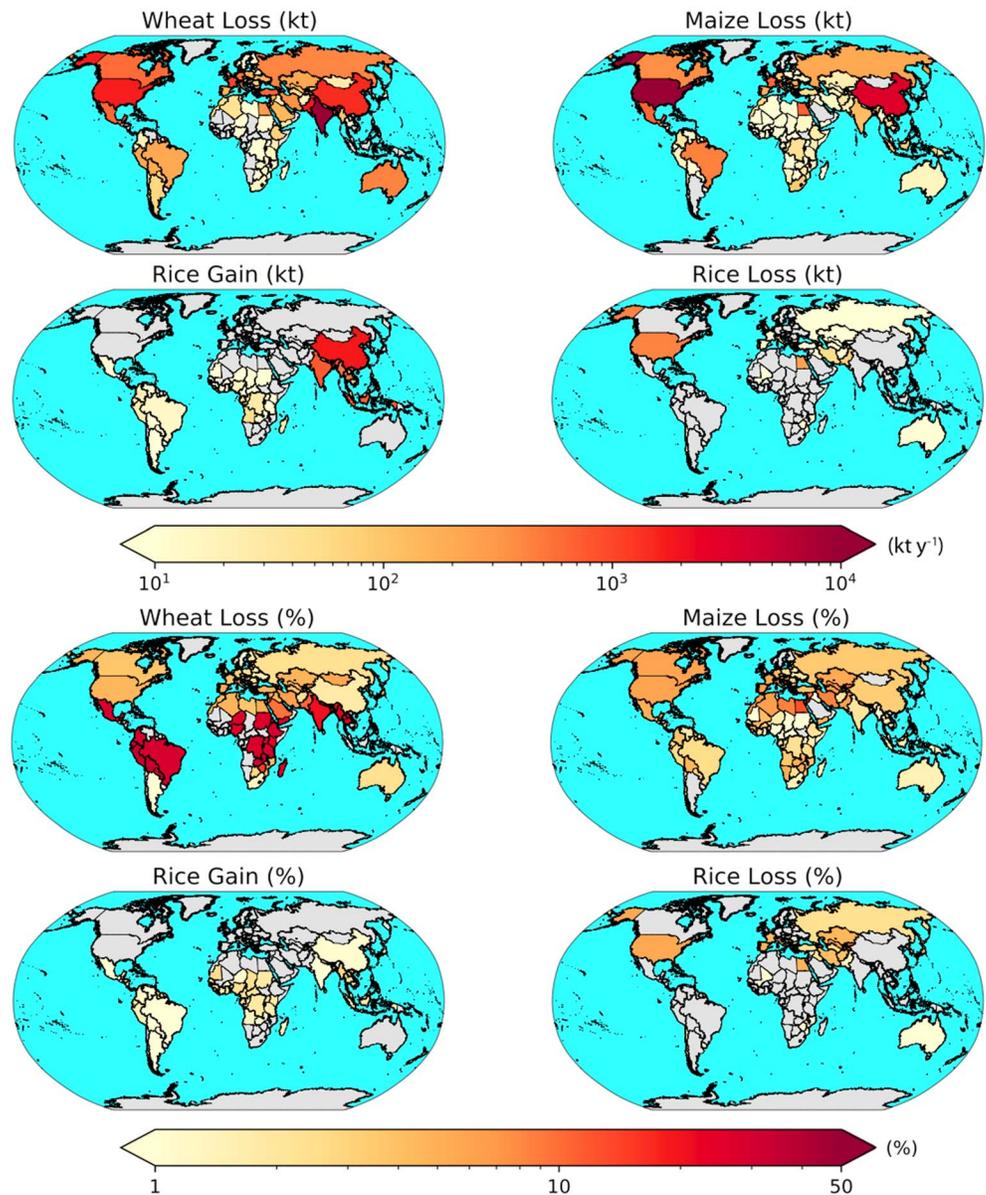


Figure 4. Annual production changes (kt/year, top; %, bottom) in 2010 due to historical emissions of all pollutants by country.

States (60% of world losses), and to a less extent China (14%), where total tonnage harvested is much greater than in other countries. All other countries experience 3% or less of the global tonnage loss.

For wheat, losses are especially large in tropical countries in both relative yield losses and in total tonnage due to the combination of damages from methane (via ozone and climate) and CO₂ (as temperature dominates over fertilization for tropical wheat). This leads to the largest relative yield losses among the three crops occurring for tropical wheat, with many nations in South Asia, Latin America, and Africa estimated to have experienced yield losses from 15% to 26%. Losses are especially high in India due to large total tonnage harvested combined with nearly 17% yield losses. In terms of total tonnage, India has nearly half (48%) of the world's losses, followed by Pakistan (7%), the United States (6%), China (6%), and France (4%). Large relative yield losses lead to low tonnage losses in parts of Africa where relatively little wheat is grown.

Rice production exhibits the most diverse pattern of responses to emissions to date, with losses generally seen in temperate countries and gains in tropical ones. As more rice is grown in tropical countries, this

Table 2
Largest National Level Production and Yield Changes

Country	By total production (kt/year; %)		Country	By relative yield (%; kt/year)	
Wheat (for countries with loss >50 kt/year)					
India	-12,971	-16.9	Bolivia	-26.0	-187
Pakistan	-1,768	-9.3	Paraguay	-24.8	-79
United States	-1,725	-4.3	Peru	-24.7	-221
China	-1,498	-1.7	Nepal	-23.4	-285
France	-1,091	-3.4	Brazil	-22.7	-202
Mexico	-630	-21.6	Ethiopia	-22.6	-70
Turkey	-624	-4.4	Mexico	-21.6	-630
Canada	-590	-3.6	Myanmar	-18.4	-93
Germany	-536	-2.9	India	-16.9	-12,971
Australia	-435	-2.3	Bangladesh	-16.5	-216
Russia	-405	-2.3	Pakistan	-9.3	-1,768
Iran	-345	-6.0	Saudi Arabia	-8.8	-137
Maize (for countries with loss >20 kt/year)					
United States	-13,341	-5.7	Egypt	-11.2	-706
China	-3,058	-3.2	Turkmenistan	-6.1	-20
Egypt	-706	-11.2	Spain	-6.0	-166
Mexico	-642	-4.7	Italy	-5.9	-562
France	-623	-5.0	Morocco	-5.8	-63
Italy	-562	-5.9	Switzerland	-5.7	-22
Brazil	-448	-2.5	United States	-5.7	-13,341
Canada	-367	-5.6	Pakistan	-5.6	-25
Russia	-212	-3.3	Canada	-5.6	-367
Hungary	-198	-3.9	Portugal	-5.4	-26
Romania	-181	-2.7	Khazakhstan	-5.1	-24
Spain	-166	-6.0	France	-5.0	-623
Rice (6 largest losses/gains for countries with change >50 kt/year)					
United States	-426	-5.3	United States	-5.3	-426
Japan	-378	-3.5	Egypt	-4.4	-252
Egypt	-252	-4.4	Iran	-3.8	-51
S. Korea	-243	-3.4	Japan	-3.5	-378
Pakistan	-71	-1.3	S. Korea	-3.4	-243
Iran	-51	-3.8	Pakistan	-1.3	-71
Myanmar	490	2.7	Thailand	2.2	479
Indonesia	697	1.7	Viet Nam	2.5	698
Viet Nam	698	2.5	Sri Lanka	2.6	59
India	750	0.6	Philippines	2.6	268
Bangladesh	908	2.9	Myanmar	2.7	490
China	1,823	1.1	Bangladesh	2.9	907

accounts for the overall increase in global level production despite relative yield losses in temperate countries that are larger than the relative yield gains in tropical ones (Table 1). Among the countries that experienced yield losses in rice, the largest portion occurs in the United States (27%), Japan (24%), Egypt (16%), and South Korea (16%; of total losses of 1.6 Mt). For the countries experienced yield gains for rice, the share is largest in China (27%), followed by Bangladesh (14%), India (11%), Vietnam (10%), and Indonesia (10%; of total gains of 6.7 Mt).

To examine the contribution of individual pollutants to the country-level results, we separate ozone and aerosol precursors into products of incomplete combustion (defined here as BC, OC, and CO, as these are generally emitted together from specific sources such as biomass burning or diesel fuel use) and the aerosol precursors SO₂, NO_x, and NH₃ (NO_x is also an ozone precursor; SO₂ and NO_x are often coemitted from sources such as power plants or vehicles; NH₃ is largely from agriculture and is included with the others simply for clarity of presentation, as its impacts are extremely small and could not be seen if shown as a separate set of bars).

We see that for wheat, the large sensitivity of tropical wheat to temperature leads to very large impacts from aerosol-induced cooling, so that the net effect is an offset between production increases due to aerosols and

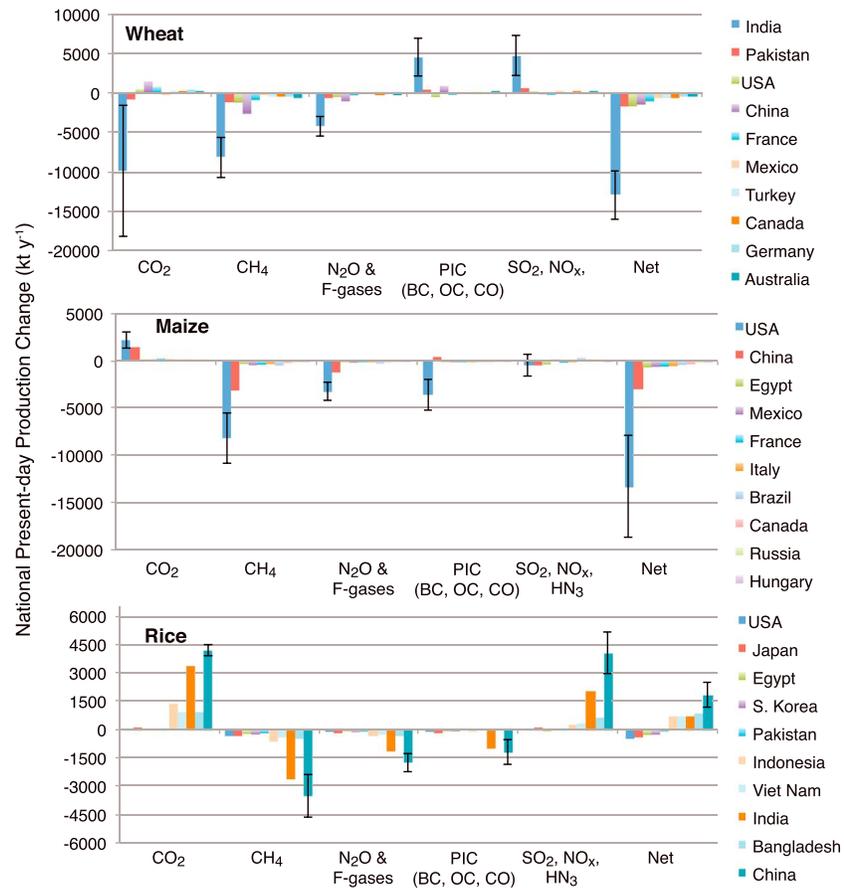


Figure 5. National level present-day crop production changes in response to historical emissions for the 10 countries with greatest net losses (maize and wheat) or the five greatest losses and five greatest gains (rice). PIC stands for products of incomplete combustion. Uncertainties are 95% confidence intervals and shown for the lead country only for clarity but are roughly proportional for other countries for each pollutant set.

damages from WMGHGs, with the latter winning out by approximately 2 to 1 (Figure 5). Countries in temperate zones, including China for wheat, see net production increases from CO₂ whereas tropical nations see losses (including India, which is mostly tropical). India and to a lesser extent China have particularly large impacts from aerosols and ozone precursors owing to large levels of local pollution. This also leads to a greater sensitivity to methane emissions, as their efficiency in producing ozone depends on the availability of NO_x and hence there are greater methane-driven wheat losses in China than in the United States (temperate wheat is especially sensitive to ozone; see Figure 2). Examining relative yields, tropical countries experience the largest losses due to the strong net negative impacts of CO₂ via temperature (Figure 6). Relative yield losses are quite large, 15–25%, in many tropical countries on all continents with tropical areas.

In the case of maize production, losses in total tons (Figure 5) are driven largely by methane, with marginally smaller damages associated with other gasses (the GHGs N₂O and F-gasses as well as products of incomplete combustion) offset in part by CO₂. The combined impact of methane via warming and ozone production makes it the dominant impact for all countries with major losses, however. Turning to relative yield losses (Figure 6), methane is again the largest driver except in the case of Egypt, which exhibits a high sensitivity of ozone to NO_x emissions. Prior studies have shown a maximum in the ozone response to pollution controls at Northern Hemisphere low latitudes due to the combination of highest pollutant loading in the Northern Hemisphere from the subtropics through midlatitudes and the greater availability of sunlight as one moves south through that region (e.g., Shindell et al., 2012).

For rice in total tons (Figure 5), fairly modest net production losses in temperate countries are largely attributable to methane, whereas production gains in tropical nations are predominantly driven by CO₂.

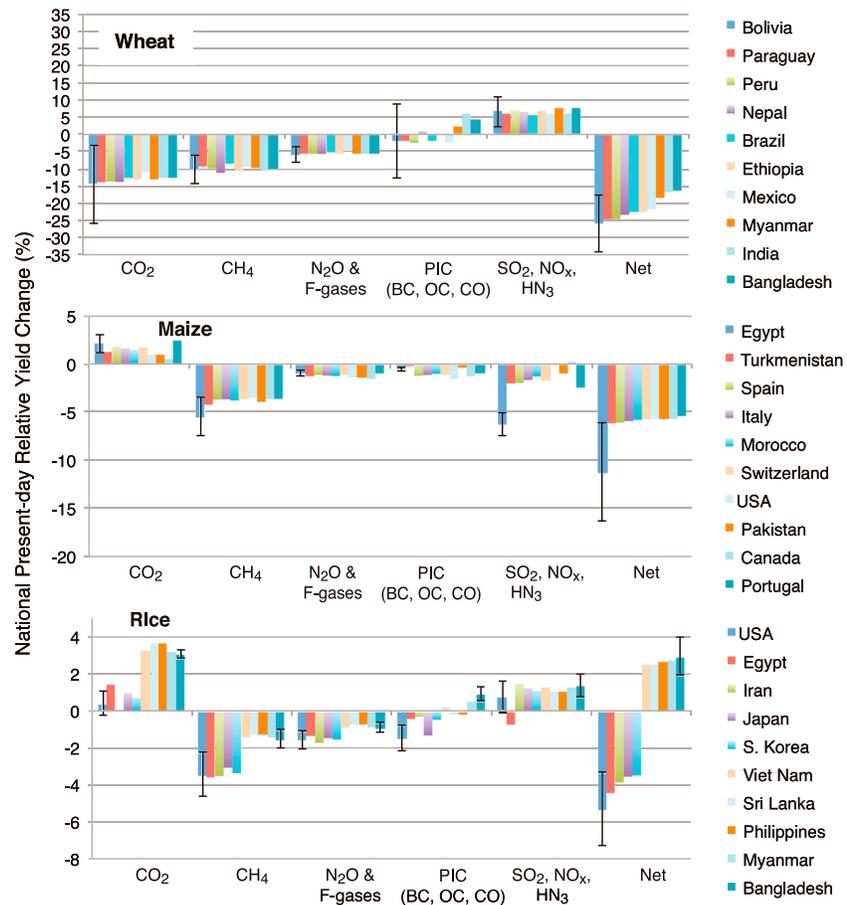


Figure 6. National level present-day crop yield changes in response to historical emissions as in Figure 5 but ranking by relative (rather than absolute) losses.

Aerosols also contribute to rice production gains in tropical countries with high pollution levels, including China, India, and Bangladesh, whereas non-CO₂ GHGs offset some of the gains from CO₂ and aerosols. In terms of relative yield changes (Figure 6), however, losses in temperate countries are larger in magnitude than gains in tropical nations. This is attributable to both (1) the large positive impact of CO₂ in the tropics compared with a net near-zero impact in the temperate zones due to the greater sensitivity of rice to fertilization relative to temperature in the tropics (Figure 2) and (2) the larger response of temperate ozone to methane relative to ozone in the tropical countries of Southeast Asia shown in Figure 6.

4. Discussion and Conclusions

It is interesting to consider the potential impacts of pollution controls in China and India. The effects of removing aerosols along with CO and NO_x would lead to production losses for wheat and rice (Figure 5). Such decreases in short-lived pollutants appear to be already taking place (Zheng et al., 2018). Conversely, methane reductions could greatly improve production of all three crops in all areas.

The losses experienced by a particular country are driven both by its location and the amount of crops grown there. The influence of the latter factor makes comparisons of historical “responsibility” to actual present-day losses complex. To simplify this comparison, we assume that maize losses are attributable to methane, whereas wheat losses are assumed to be due equally to CO₂ (owing to warming) and methane. Rice is substantially influenced by many pollutants, so is not included here as short-lived aerosol, and nonmethane ozone precursors are not considered since impacts of regional emissions may differ from the global mean. Though only a rough guide, it is nevertheless interesting to find that production losses are in some cases

far less than the national-level attributable share of time-weighted GHG emissions whereas in other cases they are much greater. For example, losses of maize in the United States are 6.2 times greater than the U.S. share of GHG emissions driving those losses, owing primarily to the very large share of worldwide maize produced in the United States, but losses of wheat are only 40% of the U.S. share of emissions driving wheat losses. In contrast, production losses for wheat in India are 8.8 times greater than the Indian share of GHG emissions driving those losses, due to India's position in the tropics (where wheat is very sensitive to warming and where methane increases lead to large ozone responses). India's losses of maize, however, are only 10% of their share of emissions, as India produced little maize. For China, production losses tend to be more similar to the Chinese share of historical GHG emissions (50% of share of wheat losses and 120% of share of maize losses).

The modeling performed here provides insight into the role of individual pollutant emissions, but further work is needed in several areas. For instance, production changes describe only a portion of the crop response to emissions, as factors such as nutritional content may also change (Myers et al., 2014). A full picture would also require consideration of the possible effect of the activity leading to emissions on production. For example, a large portion of N₂O emissions result from fertilizer application, the net impact of which is clearly still to increase production despite the effects shown here. Impacts of F-gases are similarly complex when these are used as refrigerants to prevent food spoilage. In the case of livestock, these results suggest that shifting to diets with lower consumption of cattle products (meat and dairy) could indirectly lead to substantial crop production benefits from decreased methane emissions, potentially including benefits for substitute sources of protein such as soybeans.

We also note that some limited-area studies show highly nonlinear yield changes with, for example, very steep declines at high daily temperatures for U.S. maize, soy, and cotton (Schlenker & Roberts, 2009). Data are unavailable for other crops or regions, so this cannot be incorporated here but indicates that the linearity of the meta-analysis (Challinor et al., 2014) may be oversimplified. It is possible, however, that a linear response to annual average temperatures may capture probabilistic increase in short-term extremes, as these may follow longer-term averages. Similarly, studies have suggested that responses to minimum and maximum daily temperatures are opposite for rice, and though the use of mean temperature in the meta-analysis presumably captures the average of these changes if daily extremes were to be substantially different from prior studies (e.g., under a future climate scenario), the relationship with mean temperature may no longer hold. Another factor that may be oversimplified is our use of a globally uniform (though crop-specific) CO₂ fertilization effect derived by the meta-analysis (Challinor et al., 2014). Some research has suggested regional differences but indicates that more research is necessary to adequately account for these in models (McGrath & Lobell, 2013). Additionally, as discussed in section 1, aerosols are likely to play an additional role through their effects on both direct and diffuse radiation and nutrient fertilization, so should be accounted for as these effects become better understood. Hence, there is ample room for improving our understanding of the crop response to individual pollutants. These results also highlight the prominent role of methane, suggesting that it would be useful to perform simulations with detailed, computationally expensive plant level and climate modeling driven by methane alone to compare with our statistical modeling approach.

The current results suggest that worldwide, we currently experience yield losses of wheat and maize of about 4–6%. Present-day (2010) losses due to historical emissions are greater than one million tons for maize in China and for wheat in Pakistan, the United States, China, and France, with losses exceeding 10 million tons for U.S. maize and Indian wheat. Relative yield losses are greater than 10% for several large producers, including wheat in India and Mexico and maize in Egypt. Yield losses are greater than 15% for wheat in several Latin American and South Asian countries, and Ethiopia owing to the large sensitivity of tropical wheat to warming. In contrast, South and East Asian countries have experienced yield increases in rice due to the combined influence of CO₂ fertilization and aerosol-induced cooling. Given the role of aerosols and that maize yield losses are largely attributable to methane, these results suggest that greater attention should be paid to the role of non-CO₂ emissions in affecting agriculture. In particular, there may be large agricultural benefits to targeting methane emission reductions, and such impacts are not well captured by the use of traditional metrics for comparison of GHGs that only reflect their climate impacts (Huntingford et al., 2011; Shindell et al., 2017).

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