PNAS RESEARCH ARTICLE | ENVIRONMENTAL SCIENCES

Assessing the costs of ozone pollution in India for wheat producers, consumers, and government food welfare policies

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Edited by Erika von Schneidemesser, Forschungsinstitut fur Nachhaltigkeit–Helmholtz-Zentrum Potsdam, Potsdam, Germany; received April 29, 2022; accepted June 17, 2023 by Editorial Board Member Akkihebbal R. Ravishankara

We assess wheat yield losses occurring due to ozone pollution in India and its economic burden on producers, consumers, and the government. Applying an ozone flux–based risk assessment, we show that ambient ozone levels caused a mean 14.18% reduction in wheat yields during 2008 to 2012. Furthermore, irrigated wheat was particularly sensitive to ozone-induced yield losses, indicating that ozone pollution could undermine climate-change adaptation efforts through irrigation expansion. Applying an economic model, we examine the effects of a counterfactual, "pollution-free" scenario on yield losses, wheat prices, consumer and producer welfare, and government costs. We explore three policy scenarios in which the government support farmers at observed levels of either procurement prices (fixed-price), procurement quantities (fixed-procurement), or procurement expenditure (fixed-expenditure). In pollution-free conditions, the fixed-price scenario absorbs the fall in prices, thus increasing producer welfare by USD 2.7 billion, but total welfare decreases by USD 0.24 billion as government costs increase (USD 2.9 billion). In the fixed-procurement and fixed-expenditure scenarios, ozone mitigation allows wheat prices to fall by 38.19 to 42.96%. The producers lose by USD 5.10 to 6.01 billion, but the gains to consumers and governments (USD 8.7 to 10.2 billion) outweigh these losses. These findings show that the government and consumers primarily bear the costs of ozone pollution. For pollution mitigation to optimally benefit wheat production and maximize social welfare, new approaches to support producers other than fixed-price grain procurement may be required. We also emphasize the need to consider air pollution in programs to improve agricultural resilience to climate change.

ozone-flux | wheat production | wheat prices | food security | air pollution

Significance

We assess the economic burden of air pollution on India's wheat production, quantifying the cost of ozone pollution for producers, consumers, and the government in three policy scenarios. Previous studies overlooked the economic dynamics of supply changes and food security policies that are crucial in India's regulated grain markets. Ozone mitigation would cause a net loss of USD 0.24 to a gain of 4.2 billion in total social welfare. The minimum support price policy protects the farmers' welfare, but increases government costs, causing a net welfare loss. Both alternative policies allow prices to fall, resulting in overall increases in net social welfare but causing losses to producers. Therefore, farmer support policies need reexamination to maximize the social welfare of pollution mitigation for all stakeholders.

Over the past half-century, the success of the Green Revolution has seen India's wheat cultivation develop to levels capable of providing food security for the 1.2 billion population that depends primarily on food produced within the country. Wheat cultivation also provides an important livelihood for many of the 118 million Indian farmers, with about 30 million hectares or 17% of all the cultivated land in India under wheat cultivation (1), leading to the production of approximately 100 million tonnes (where 1 tonne = 1 Mg) of wheat grain annually. The Indo-Gangetic Plain (IGP) is South Asia's bread basket where the majority of India's wheat (2, 3) is cultivated. Wheat is one of the cheapest food grains and provides 20% of protein and 19% of calorie intake for the Indian population (4). For these reasons, the government extensively procures and distributes wheat to much of the population to provide food and nutrition security.

However, past decades, particularly since 2008, have seen a decline in the growth of wheat yields, even as inputs and resources to increase productivity have increased (5). These declines have largely been attributed to changes in climate, particularly heat and drought stress, and changes in the frequency and magnitude of rainfall events. These declines resulted in substantial investments in programs to improve crop management, in particular through investment in irrigation. Incidences and severity of wheat diseases such as stem rust and spot blotch have also increased in the IGP, which are attributed to an increase in relative humidity and rising night-time temperatures (6). An additional abiotic stress that has been identified as a potential factor in these stagnating yields is air pollution. Evidence suggests that ground-level ozone represents a serious and growing threat to cereal production across India resulting from ozone precursor emissions [namely nitrogen oxides (NOx) and volatile organic compounds] which have been increasing across the region since the 1980s. NOx emissions in particular have tripled across Asia since 1990, causing modeled concentrations of surface ozone to increase by 1.5 to 2.5 ppb/yr over the period 1988 to 2014 (7). The IGP region frequently experiences ozone episodes of 40 to 60 ppb likely to cause substantial damage to cereal

Author contributions: D.P., K.S., D.S., B.R., R.C., C.J., P.B., and L.D.E. designed research; D.P., K.S., D.S., B.R., R.C., and L.D.E. performed research; B.R. and R.C. designed the economic model; D.P., K.S., D.S., B.R., R.C., N.B., and L.D.E. analyzed data; V.S. and B.S. provided ozone monitoring data; and D.P., K.S., D.S., B.R., R.C., N.B., C.J., P.B., V.S., B.S., and L.D.E. wrote the paper.

The authors declare no competing interest.

This article is a PNAS Direct Submission. E.v.S. is a guest editor invited by the Editorial Board.

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This article contains supporting information online at https://www.pnas.org/lookup/suppl/doi:10.1073/pnas.2207081120/-/DCSupplemental.

Published July 31, 2023.

productivity (8). Studies suggest that ozone pollution across India causes anywhere between 5 to 40% yield loss in wheat, with the highest losses occurring in the IGP (8–11). These yield losses translate into national scale production losses of between 3.5 to 30 million metric tonnes (8, 10, 12–16), and subsequent economic losses of approximately USD 500 to 5,000 million per year (8, 10, 12, 13). As such, India currently faces one of the highest air pollution burdens of any global agricultural region; this situation looks set to continue well into the 2050s if no mitigation action is taken (17, 18).

These ozone impacts on wheat yield will affect wheat production and hence supply. Changes in supply will have effects on the wheat market price which will in turn have consequences for the various stakeholders relying on wheat as a commodity. Farmers or producers will be affected as price changes will alter earnings on the sale of wheat grain at the market; consumers will be affected as price changes will determine access to wheat commodities and remaining disposable income after spending on food. Additionally, price changes will also affect the cost-effectiveness of government food welfare schemes (2, 3). These welfare schemes are designed to support both producers and consumers.

The small asset base of most producers contributes to precarious agricultural incomes. The mean farm size is about one hectare, 86% of 118 million cultivators operate on less than two hectares, and 144 million are landless agricultural workers (1). To protect these vulnerable farmers from additional threats of price fluctuation, the Indian government fixes a Minimum Support Price (MSP) for wheat, ensuring procurement in case the open market price falls below the MSP (19). Indian consumers also rely heavily on wheat products which provide one-fifth of household calories and half of all calories obtained from cereals (20). Wheat price fluctuation would challenge consumers given that nearly 30% of the rural population lives below the poverty line on a monthly income of less than USD 20 (21), a situation that results in ∼15% of the total population being undernourished (22). Most of those in poverty spend more than 50% of their earnings on food (22). This situation occurs despite India's public distribution system (PDS), which guarantees the provision of subsidized grain to over 60% of the population (23) and supplies 5 to 7 kg of grain per capita per month to eligible households determined by income (24). Since mean wheat consumption is ∼9 to 11 kg of grain per capita per month, this still leaves even the poorest households vulnerable to price fluctuations. Finally, the Indian government makes substantial investments in food welfare with food subsidies close to 1% of GDP or nearly 16 billion USD (23); these subsidies support government procurement of a quantity of grain from producers at a MSP and the distribution of grain, at subsidized prices, to low-income consumers.

Here, we seek to understand the economic consequences of ozone-induced supply side losses on wheat price and subsequent costs for producers, consumers, and government food welfare schemes. To achieve this we estimate spatially differentiated ozone-induced wheat yield losses across India by applying a flux-based risk assessment approach which incorporates environmental factors that modify wheat sensitivity to ozone (15, 25). We assess the uncertainty of these predictions based on the 95% confidence interval (CI) of the flux–response relationship and translate this uncertainty in yield loss both as a national mean and spatially across India (*Methods*). We quantify the effect of these yield losses on wheat price and societal welfare using a supply and demand economic model (26) and apply three government policy scenarios that correspond to observed levels of price support interventions. Together, this allows us to explore the potential impact of ozone pollution on India's wheat market.

Account of Findings

Ozone Impact on Wheat Supply in India. We applied an ozone flux-based risk assessment approach, which provides a biologically meaningful estimate of pollution-induced yield losses by considering the modifying effects of crop physiology, environmental variables, and irrigated and nonirrigated conditions. Unless stated otherwise, we present all results as mean values over the 2008 to 2012 period with lower and upper estimates for the 95% CI. Over this period, the mean annual wheat production in India was 91Tg under ambient levels of ozone, which increased to 106 Tg in the counterfactual ozone-free conditions. Therefore, the ozone levels reduced annual wheat yields by 14.18 (11.6 to 17.21)% across the country when compared to ozone-free conditions. This equated to a mean annual production loss of 15.03 (11.42 to 18.91) Tg over 2008 to 2012. The largest production losses occurred in the agriculturally important IGP region (Fig. 1). The major wheat-producing states of Uttar Pradesh, Punjab, Rajasthan, Madhya Pradesh, Haryana, and Bihar together suffered a mean annual loss of 14.07 (10.75 to 17.65) Tg or 93.7% of the total production loss (Fig. 2). These findings compare favorably with a study by Mills et al. (15) that also used ozone flux but national, rather than state-level production data and excluded some low-production wheat growing areas from the analysis. Mills et al. (15) found around 12.5 to 17.5% wheat yield losses for large areas in northern India where ozone levels, climatic conditions, and irrigation promoted ozone uptake. These flux-based results contrast with earlier concentration-based estimates that were unable to capture the spatial heterogeneity in yield losses and often predicted higher relative yield losses (12).

We find that yield losses caused by ozone were higher under irrigated compared to rainfed conditions. This is because irrigation reduces the need for the plant to limit transpirational water loss and consequently increases stomatal ozone uptake. Fig. 3 *A* and *B* present yield losses due to ozone relative to the wheat yields in ozone-free conditions under fully irrigated, fully rainfed, and the actual levels of irrigation. Moving to fully irrigated wheat cultivation across India would cause an additional mean 0.35 (0.33 to 0.38) percentage point loss to the ozone-induced yield reduction that occurs under the existing mix of rainfed and irrigated wheat cultivation. However, the states of Karnataka, Gujarat, and Telangana, that receive low rainfall, would experience additional mean percentage point yield losses of 1.3 to 3.2 due to ozone if the wheat cultivation shifted from the existing mix of rainfed and irrigated to fully irrigated. The additional yield losses that occur due to ozone under irrigated conditions compared to the existing mix of rainfed and irrigation vary spatially (Fig. 3*C*). Nearly 20% of the wheat-cultivated area in Gujarat experiences additional percentage point losses of between 9.2 and 11.8; while in Telangana, 44% of the wheat cultivated area suffers an additional mean 4.44 percentage point loss under fully irrigated conditions compared to their current mix of irrigated and rainfed conditions. In the case of Rajasthan, 60% of the wheat-cultivated area experiences more than five additional point percent losses under fully irrigated conditions compared to the fully rainfed conditions.

The enhanced yield losses due to ozone on irrigated wheat are significant given that expansion of irrigation across India over the past 40 years has allowed wheat to become a major crop. Increased irrigation is responsible for wheat yields being 13% higher in the 2000s than in the 1970s (27). Irrigation is also considered crucial in adaptation to climate change and associated heat stress with irrigated wheat exhibiting approximately one-quarter of the heat sensitivity of wheat under fully rainfed conditions (27). Our results suggest that air pollution is potentially compromising the

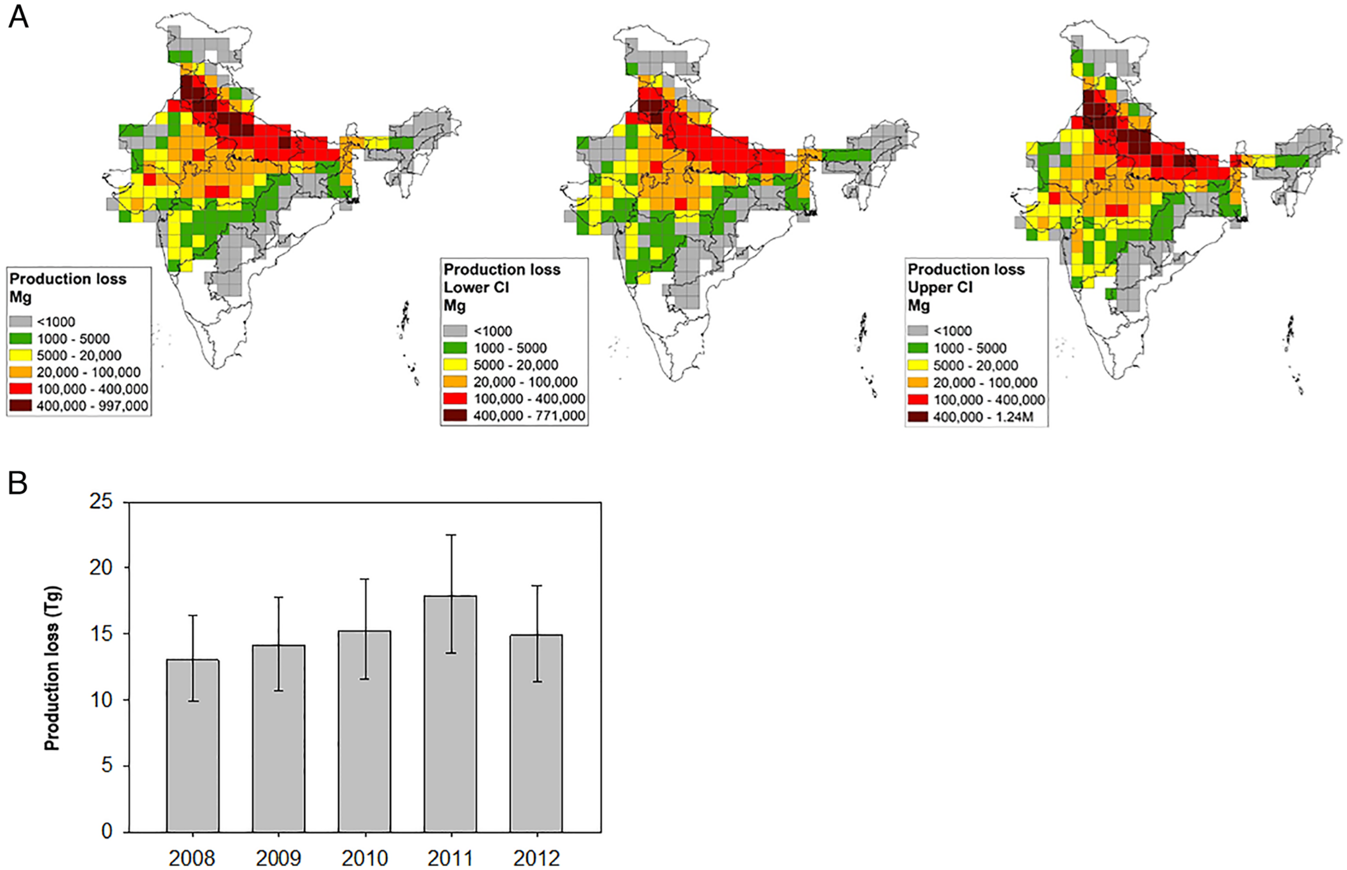

Fig. 1. Wheat production loss due to ozone in India. (*A*) Mean production loss (in Mg) across India over 2008 to 2012. Lower CI and upper CI represent 95% CI. Wheat production does not occur in white cells. (*B*) Total production loss in India (in Tg). Error bars represent lower and upper estimates for 95% CI.

benefits of irrigation and its expansion. Operation of irrigation infrastructure is highly subsidized in India and has poor revenue collection (28). Therefore, in those instances where irrigation is not achieving its full potential benefits, ozone pollution may create an additional economic cost to the government and a higher environmental burden to the country (29).

Ozone-Mediated Supply Effects on Price. Applying an economic model of supply and demand to project the impacts of yield changes on price (c.f. refs. 26 and 30), we explored the effects of ozone-induced changes on wheat supply and subsequent price changes. The wheat market clearing price during 2008 to 2012 under ambient ozone pollution conditions ranged from USD 159 to 202 per Mg of wheat. Here, we compare these 2008 to 2012 outcomes under ambient ozone pollution with outcomes that would be obtained in a counterfactual “pollution-free” environment.

We assume that in the pollution-free environment, government interventions that would also influence the wheat market price remain unchanged. This leads to three policy scenarios. The “fixed-price” scenario represents the current policy where the government procures wheat at a MSP (procurement price) directly from farmers. It assumes that the government extends this policy to the pollution-free environment and maintains the procurement price at current levels. As supply is greater in the pollution-free environment, wheat prices would decline in the absence of procurement. To protect farmers from economic loss, the government procures wheat until the market prices attain the current level of procurement prices. Hence, there is no change in wheat prices. Government expenditure rises because of additional procurement.

In the “fixed-procurement” scenario, it is assumed that government support to farmers is fixed in terms of quantity, i.e., it procures the same quantity of wheat grain as in 2008 to 2012. As supply is greater in the pollution-free environment, the government can procure the same quantity with a lower procurement price. As a result, government expenditures on grain purchase are lower under no-ozone conditions. Due to ozone mitigation, wheat prices decline by mean value of 43.0 (32.6 to 54.1)% over 2008 to 2012 resulting in a mean reduction of USD 2.32 billion (USD 1.76 to 2.92 billion over 2008 to 2012) in government cost.

In the “fixed-expenditure” scenario, the government support to farmers is fixed in monetary terms, i.e., it spends the same amount on farmer support as during 2008 to 2012. Because supply expands when ozone is mitigated, the government can meet its expenditure target with a combination of lower procurement prices and greater procurement than the observed levels in 2008 to 2012. Our results show that removal of ozone pollution will cause a mean decrease of 38.19% in the price of wheat allowing the government to procure extra grains compared to ambient ozone pollution conditions.

Ozone-Mediated Supply Effects on Welfare. In the “fixed-price” scenario, wheat supply increases when ozone is mitigated compared to the ambient ozone levels, but the prices do not fall. Consequently, ozone mitigation leads producers to gain by mean USD 2.7 billion annually (USD 2.05 to 3.39 billion) compared to the ambient ozone levels. As prices are fixed, consumers do not benefit from supply increases, while government costs increase by mean USD 2.491 billion (USD 2.24 to 3.70 billion) on account of

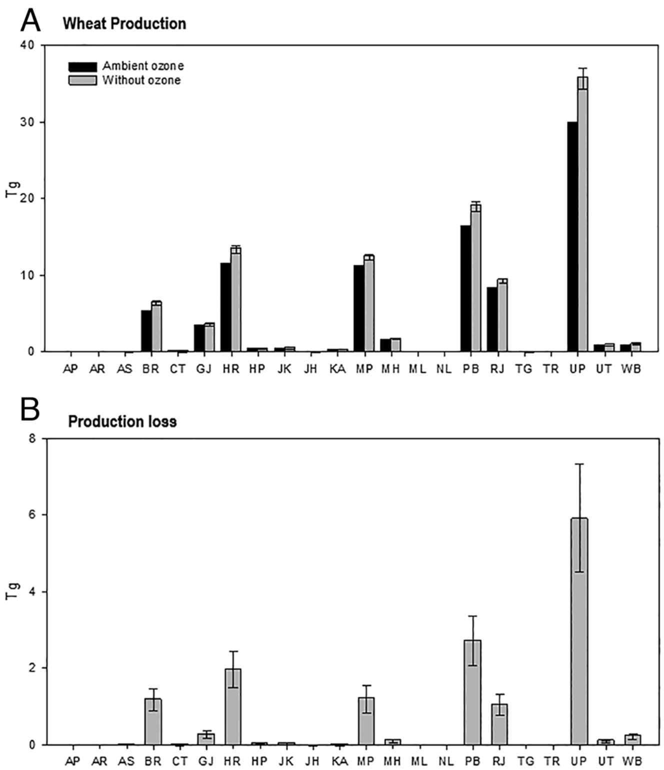

Fig. 2. The wheat production and production loss due to ozone pollution in different states of India under the actual level of irrigation. (*A*) Production under ambient levels of ozone pollution and without ozone pollution. (*B*) Total production loss due to ozone pollution. Bars represent mean values over 2008 to 2012; error bars represent 95% CI. AP: Andhra Pradesh, AR: Arunachal Pradesh, AS: Assam, BR: Bihar, CT: Chhattisgarh, GJ: Gujarat, HR: Haryana, HP: Himachal Pradesh, MH: Maharashtra, ML: Meghalaya, NL: Nagaland, PB: Punjab, RJ: Rajasthan, TG: Telangana, TR: Tripura, UP: Uttar Pradesh, UT: Uttarakhand, WB: West Bengal.

higher procurement (Fig. 4) due to ozone mitigation compared to the ambient ozone levels. Thus, in this scenario, ozone mitigation results in a decline of aggregate economic welfare by mean USD 0.24 billion (USD 0.18 to 0.31 billion) annually compared to ambient ozone levels.

By contrast, ozone mitigation will increase aggregate economic welfare in the other two scenarios compared to those observed under ambient levels of ozone pollution. In the "fixed-procurement" scenario, the removal of ozone pollution sees the economic welfare of producers decline by mean USD 6.01 billion (USD 4.38 to 7.88 billion) annually because of the fall in wheat prices compared to those in ambient ozone levels. For the same reason, consumer surplus increases by mean USD 7.88 billion annually (USD 5.86 to 10.19 billion). In addition, government costs decline by mean USD 2.32 billion annually (USD 1.76 to 2.92 billion). This decline happens for two reasons. First, the per unit subsidy to consumers declines because of the fall in market price when ozone pollution is mitigated. As a result, the government food subsidy costs fall. Second, the cost of farm support also declines. In the "fixed-expenditure" scenario, an ozone-free environment would see producers lose mean USD 5.10 billion annually (USD 3.70 to 6.71 billion) and consumers gain by mean USD 6.99 billion annually (USD 5.22 to 9.01 billion) compared to the ambient ozone levels (Fig. 4). Here, the expenditures on farm support are held constant, meaning that no savings are made in this regard, but as prices are lower, per unit subsidy is again lower after ozone mitigation, which leads to lower food subsidies.

Discussion

Our findings highlight several important issues related to ozone pollution, its physical effects on one of India's most important staple crops, and its economic and food security consequences. First, the substantial yield reductions, coupled with the relatively rapid increase in ozone concentrations since the 1990s, suggest that ozone could be an additional though often overlooked factor in the observed stagnation of wheat yields that have occurred in India since the mid-1990s (5). This stagnation is commonly attributed to temperature rises (26), but high temperatures and ozone concentrations tend to co-occur leading to confounding effects and to ozone damage often being inferred as temperature effects (31). It is worth noting that current ozone levels in India were found to impose a constraint on wheat yield similar to aridity and nutrient stress (16), which are abiotic stresses widely acknowledged to be of considerable concern in India (32). It is also useful to consider ozone-induced yield losses in relation to the effects caused by climate change since climate change is a recognized threat to crop productivity in India. Climate change-related shocks are predicted to affect wheat yields by between −10% and +4% in India between 2000 and 2030 (33). By contrast, we show that ambient ozone levels during 2008 to 2012 affected Indian wheat yields by −14.18% resulting in a market price approximately 40% higher than that under a pollution-free scenario. For context, it is useful to show that the total wheat loss that occurred due to ozone during 2008 to 2012 period was equivalent to ~56% (39 to 67%) of the annual total quantity of wheat procured by the government, ~82% (68 to 103%) of the total quantity of wheat distributed under the PDS, and ~68% (49 to 87%) of the total domestic sales of wheat under all welfare programs. As such, avoiding these losses by mitigating ozone precursors would alone see increases in wheat production that could supply a substantial fraction of the wheat required for food-based welfare programs.

The economic implications of supply changes resulting from pollution mitigation are heavily dependent on policy scenarios. Pollution mitigation is beneficial to farmers in the fixed-price scenario, but that is achieved at a cost to both consumers and the government. The cost is greater than the gains to farmers. The advantages of productivity increase are therefore lost in the fixed-price scenario. These perverse outcomes are avoided in the other two alternate scenarios. They lead to net economic gains in pollution-free conditions. Consumers and the government are better off (also see *SI Appendix*, Fig. S5*E*). The productivity increase stemming from ozone mitigation lowers wheat prices and subsidy expenditures. The fixed-expenditure and the fixed-procurement scenarios (relative to the baseline ambient ozone scenario) indicate that it is the consumers and the government who bear the cost of pollution as pollution shrinks supply, elevates prices and increases subsidy expenditures.

In the two "fixed-procurement" and "fixed-expenditure" scenarios, the downside is that producers face losses. However, since aggregate welfare gains are positive, governments can put in place compensation payments to producers and still retain the gains to consumers. The government will also need to redesign producer support to maintain producer incomes rather than prices. This will allow the benefits of greater supply to flow to consumers and the government. Furthermore, yield gains may permit an open trade policy and farmers could gain from greater exports as global markets are threatened by reduced supply from major wheat-producing regions due to the Russia–Ukraine war. To this end, foreign consumers and world food security would also gain from pollution abatement in India.

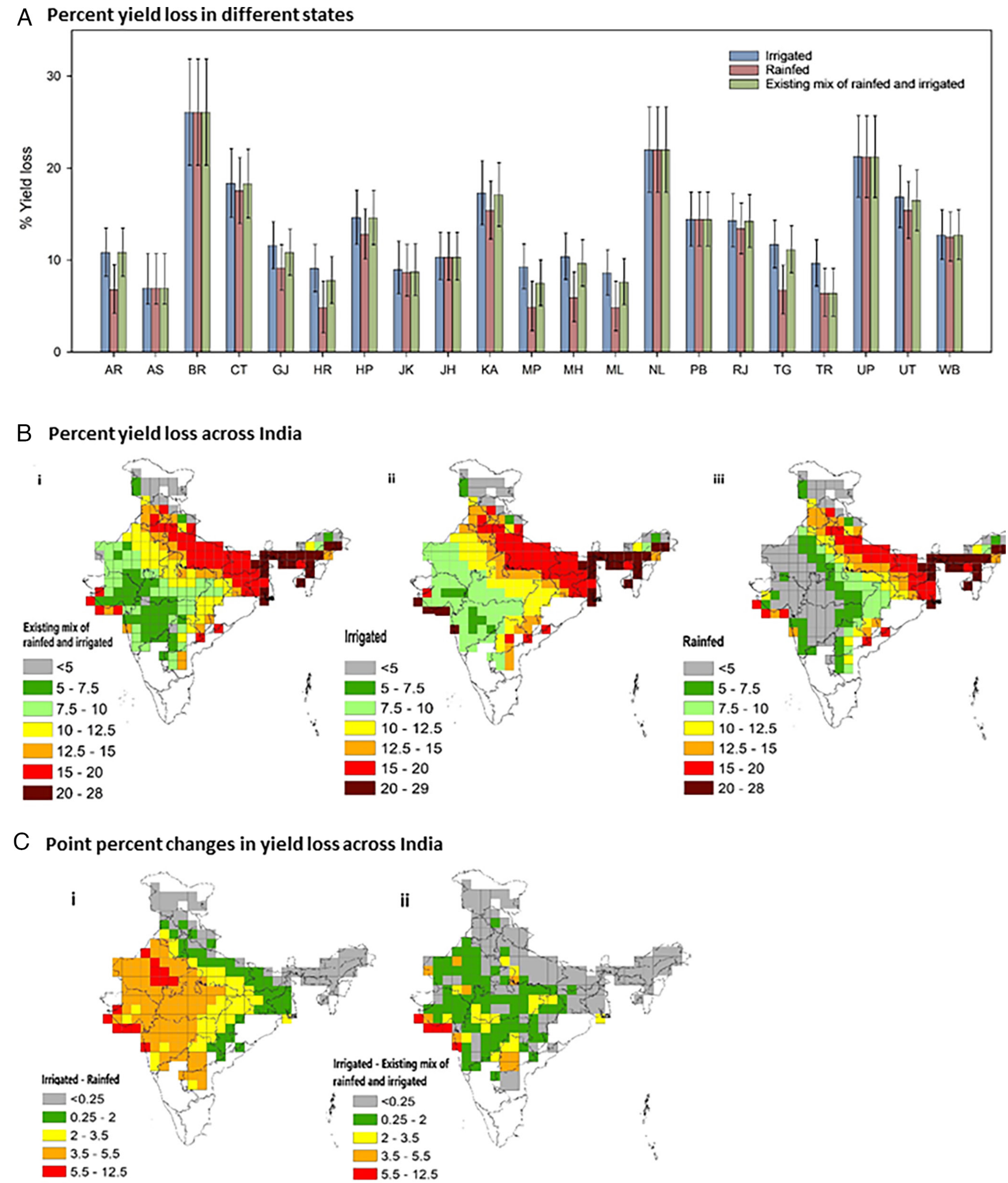

Fig. 3. Effect of irrigation on percent yield losses. (*A*) Percent yield loss in each state due to ambient ozone under fully irrigated, fully rainfed, and the existing mix of irrigation and rainfed conditions. Bars represent mean values ± lower and upper estimates for 95% CI over 2008 to 2012. AP: Andhra Pradesh, AR: Arunachal Pradesh, AS: Assam, BR: Bihar, CT: Chhattisgarh, GJ: Gujarat, HR: Haryana, HP: Himachal Pradesh, MH: Maharashtra, ML: Meghalaya, NL: Nagaland, PB: Punjab, RJ: Rajasthan, TG: Telangana, TR: Tripura, UP: Uttar Pradesh, UT: Uttarakhand, WB: West Bengal. (*B*) Percent yield loss (mean over 2008 to 2012) across India due to ambient ozone under (*i*) the existing mix of rainfed and irrigated, (*ii*) fully irrigated, and (*iii*) fully rainfed conditions. (*C*) Point percent changes in yield loss (mean over 2008 to 2012) when wheat cultivation shifts from (*i*) rainfed to fully irrigated and (*ii*) existing mix of rainfed and irrigated to fully irrigated conditions.

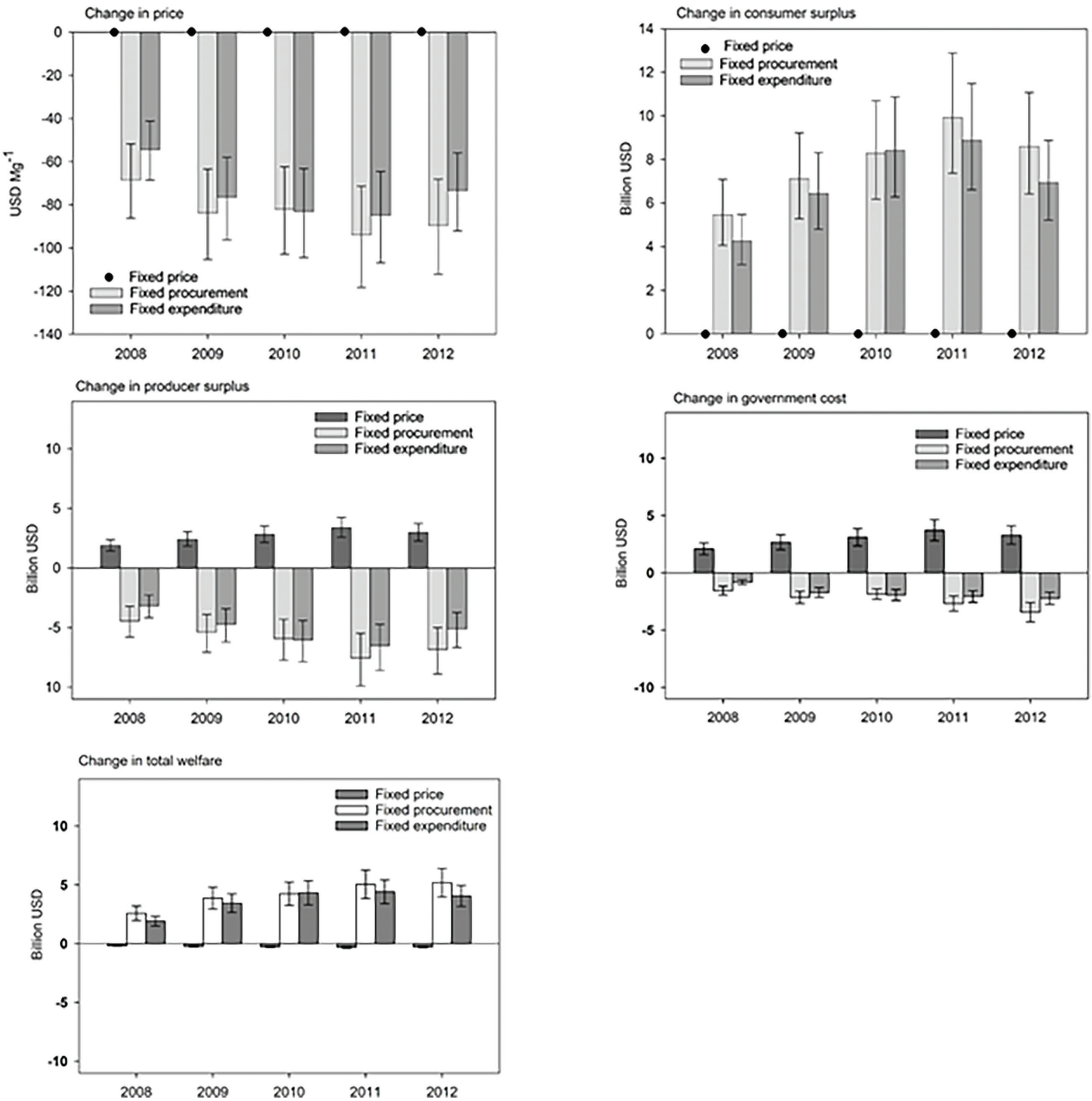

Fig. 4. Changes in the market price of wheat, consumer surplus, producer surplus, government costs, and total welfare in the three policy scenarios resulting from the ozone mitigation with respect to the baseline (ambient ozone pollution). Bars represent the annual mean over 2008 to 2012. Error bars represent lower and upper estimates for the 95% CI. There is no change in market price and consumer surplus in the "fixed-price" scenario due to ozone mitigation.

The cost of mitigating ozone pollution in India has not been estimated and is outside the scope of this study. However, several comparable studies indicate that the benefits of cleaner air through reduced health impacts alone will outweigh the mitigation costs for air pollution. For India, mitigating ozone and PM2.5 precursors will lead to health benefits that will outweigh the costs and allow India to achieve the Paris Climate agreement (34). We show that the additional economic benefits that will result via reduced damages to agriculture are significant and increase the economic benefits of pollution mitigation. Our findings on the economic impacts of reducing ozone pollution are also qualitatively similar to the economic impacts of cost-reducing technologies in agriculture that increase production (35). As such, policymakers may find it more persuasive to view ozone mitigation as a technological advancement since few agricultural technologies provide comparable yield increases—with little to no need of change in producer behavior.

This evidence suggests that policymakers should consider limits to wheat productivity arising from ozone pollution, which is itself an important GHG, and focus additional effort on mitigation of ozone precursors. Currently, the air quality standard (AQS) for ozone in India is based on an 8-h and 1-h time-weighted mean value of 100 and 180 $\mu g/m^{-3}$, respectively (equivalent to 50 and 90 ppb) (36). These standards are unable to account for cumulative ozone impacts known to affect vegetation and are likely to be less stringent than those recommended for vegetation by WHO and the UNECE's Convention on Long-range Transboundary Air Pollution (CLRTAP) (37). Furthermore, most real-time air quality monitoring sites in India are located in urban areas, omitting agricultural areas where ozone levels tend to be higher, so monitoring of AQSs may not accurately represent the ozone pollution burden to arable agriculture in India. The National Clean Air Program (2019), which is the most significant attempt to reduce air pollution in India to date, aims to consolidate the scientific, legal, and institutional requirements for air pollution mitigation under one umbrella. With an investment of US$ 630 million, it focuses exclusively on particulate matter (PM10 and PM2.5) and 122 cities, therefore excluding ozone and agricultural areas. Together, this suggests that policy is unlikely to prioritize reducing ozone concentrations to levels that would protect crop productivity.

Adaptation to ozone stress is also not considered within standard agricultural management practices in India. Adaptation options to limit ozone sensitivity include using early sown and/or early maturing varieties whose growing seasons tend to avoid high ozone episodes that occur during the particularly sensitive grain filling period (38) as well as limiting irrigation to reduce ozone uptake during high pollution episodes (39, 40). Since irrigation has been a crucial part of wheat yield increases in the past few decades (27), preventing ozone pollution will enable India to maximize the benefits of its costly irrigation programs. Further, a better understanding of the interaction between environmental stresses (e.g., pollution, heat, and drought) is urgently needed to ensure that adaptation to multiple stresses leads to synergies rather than trade-offs in crop productivity (16, 37, 41, 42).

A decrease in wheat prices will also reduce the cost of living, which could allow consumers to afford a more nutritious diet by adjusting their consumption bundles to new price patterns or afford nonfood items that can reduce poverty-related deprivations (43). Wheat price reductions, however, will disadvantage households that rely primarily on wheat cultivation for income, especially smallholder farmers. Conversely, households with little to no dependency on agricultural income will benefit from the decline in the relative price of agricultural commodities (33). Together, these factors would determine how ozone-induced changes in wheat prices influence poverty and the government response required to appropriately support both producers and consumers.

Methods

Our methodology has two key components. In the first, we estimated the ozone-induced crop yield losses for India using the Phytotoxic Ozone Dose above a threshold of 3 nmol O_3 per unit leaf area (PLA) $m^{-2}s^{-1}$ as recommended for large-scale integrated assessment modeling (POD_3IAM) in CLRTAP 2017 (44). In the second, we used an economic model of the wheat market to estimate how changes in yield and production will influence wheat commodity price under two scenarios of government intervention. Once changes in price caused by the ozone-induced yield losses are estimated with demand and supply functions, we then assess the effect of these price changes on the economic status of producers and consumers and government welfare schemes. Application of these methods requires various physical and economic data, i.e., meteorological, ozone concentration, irrigation, crop distribution, crop production statistics, demand and supply elasticities, and wheat procurement price data. The methodological coupling of these key components and datasets is described in *SI Appendix*, Fig. S4.

Calculation of Ozone Fluxes. The EMEP MSC-W (European Monitoring and Evaluation Programme, Meteorological Synthesizing Centre West) model is used to calculate ozone concentrations and ozone uptake to vegetation on a global scale. The EMEP model (45, 46) is a 3D chemical transport model whose results underpin the integrated assessment work of CLRTAP (47). For this study, version 4.16 of the model was used, which features a gas-phase chemical scheme of 137 reactions, and 20 vertical layers extending from the ground to the tropopause. The setup was as given in ref. 16, and provided ozone concentrations and vegetation uptake (see below) over India at a grid cell resolution of 1° × 1° for the years 2008 to 2012. The meteorological data required for the model were obtained from the ECMWF-IFS (European Centre for Medium Range Weather Forecasting Integrated Forecasting System) model.

Ozone causes damage to crops only after it has been taken up via the stomata. Methods to assess flux-based metrics and associated dose–response relationships to estimate damage have been developed over many years within the CLRTAP (15, 16, 25, 48–51), with the latest recommendations given in the Modelling and Mapping Manual of the CLRTAP (44). Stomatal ozone flux is estimated within the EMEP model and depends on the leaf-level stomatal conductance as well as a calculation of the vertical profiles of ozone down to the top of the vegetation canopy. This stomatal uptake of ozone when accumulated over the duration of the 90-d wheat growing season (during daylight hours) provides the POD_3IAM metric used within the CLRTAP (44). This metric is estimated within the EMEP model using EMEP-DO_3SE (45, 46, 48–50, 52) applied for both irrigated and rainfed conditions. The EMEP-DO_3SE model uses a multiplicative algorithm (Eq. **1**) to estimate stomatal conductance to ozone (g_{sto}).

$$g_{sto} = g_{max} \times f_{phen} \times f_{light} \times \max\{f_{min}, (f_{temp} \times f_{VPD} \times f_{SMI})\} \qquad [1]$$

where g_{max} (mmol O_3 m^2 PLA s^{-1}) is a species-specific maximum stomatal conductance which is modified according to species-specific functions that determine g_{sto} response to plant phenology (f_{phen}) and environmental variables irradiance (f_{light}), temperature (f_{temp}), vapor pressure deficit (f_{VPD}), and soil water content (f_{SMI}). The species-specific parameterizations used are for the flag leaf of wheat and are those recommended for large-scale integrated assessment modeling as described in the CLRTAP (44). The effects of rainfed conditions on stomatal ozone flux (F_{st} in nmol O_3 $m^{-2}s^{-1}$) were estimated via inclusion of the soil moisture index (SMI) whose estimation depends on the soil water content over the soil depth 0.28 to 1 m, field capacity, and permanent wilting point (see ref. 45). For irrigated conditions, it was assumed that soil moisture was not limiting g_{sto}. Stomatal ozone flux (f_{st}) at the top of the canopy of height h was then estimated from g_{sto} and the ozone concentration at the same height ($c(h)$) as described in refs. 45 and 50.

The POD_3IAM metric was estimated within the EMEP-DO_3SE model according to Eq. **2**.

$$POD_3IAM = \sum_{i=1}^{n} \max(f_{st,i} - y, 0)\,\Delta t, \qquad [2]$$

where $f_{st,\,i}$ is stomatal ozone flux (in nmol O_3 $m^{-2}s^{-1}$) at height h calculated at time-step i, n is the number of timesteps within the IAM accumulation period of 90 d, and Δt is model's time-step (1200s in global EMEP runs). y is the threshold of 3 nmol O_3 PLA $m^{-2}s^{-1}$ as recommended for large-scale integrated assessment modeling (POD_3IAM) by CLRTAP (44). The 90-d ozone accumulation period for each grid cell was derived by overlaying data describing wheat harvest dates obtained from the USDA Major World Crop Areas and Climate Profiles and the Indian crop calendar with climatic zones using the global "Climatic Zone" GIS data layer produced by the European Soil Data Centre at the Joint Research Centre following the methodology used by Mills et al. (15). Indian wheat is predominantly cultivated in Rabi (October to March), and 90-d accumulation periods back-projected from 2 wk before harvest fell primarily between January and March depending on location within India. For further information on Indian climate zones and the accumulation periods used, see *SI Appendix*, Table S3.

The POD_3IAM value for each EMEP grid cell was estimated according to the POD_3IAM values for rainfed and irrigated conditions and area weighted according to the proportion of rainfed and irrigated wheat production in the state.

Following Mills et al. (15), a reference POD_3IAM value of 0.1 mmol m^{-2} representing ozone uptake at preindustrial or natural ozone levels was subtracted from the POD_3IAM value for each grid cell. Percentage yield loss ($\Delta Y\%$) was then calculated following the dose–response relationship between POD_3IAM and percentage reduction in wheat yield provided in the CLRTAP Mapping Manual (44). The full data plot with equation and CI is given there.

$$\Delta Y\% = (POD_3IAM - 0.1) \times 0.64. \qquad [3]$$

Finally, for each grid cell, the wheat production that would have occurred in the absence of ozone pollution is estimated from the percent yield loss for that grid cell. We assume that ozone causes an additional crop loss, which is expressed by Eq. **3** and that ozone will have the same relative impact on yield irrespective of absolute yield. Since we apply this flux–response relationship on the observed crop yields, effects of other factors such as soil fertility, heat stress, and soil moisture are implicit in the wheat production for the grid cell occurring under the ambient conditions of climate and ozone levels.

Crop and Irrigation Data. State-level data describing Indian wheat production and harvested area under irrigated and rainfed conditions for the year 2005 were acquired at 5 arc minute (0.0833°) spatial resolution from the Spatial Production Allocation Model (SPAM) (53, 54) (*SI Appendix*, Fig. S1). District-level (i.e., the administrative division within a state) crop production and area data for 2008 to 2012 were obtained from the Ministry of Agriculture and Farmers Welfare (55). See *SI Appendix* for further details of these datasets. These district data were summed to give state-level data for each of the years from 2008 to 2012 and then coupled with the 2005 data—the only source of the area of wheat under rainfed and irrigated conditions. We assume that the proportion of irrigated and rainfed wheat in a state remains constant from 2005 to 2008 to 2012.

To match this coupled wheat distribution and production dataset with the POD_3IAM grid cell values, ArcGIS v. 10.1 (Environmental Systems Research Institute, Redlands, CA, USA) was used to create a 1° × 1° grid over India (*SI Appendix*, Fig. S2). The grid was overlaid on a map layer of Indian states to determine the contribution of the cells to different states. If a cell fell into two or more states, it was allocated to the state that contained the largest area of the cell. The cells where wheat production was nonzero were referred to as wheat-producing cells (WPCs). We assume that the irrigated fraction at the state level is equivalent to the irrigated fraction within each of the WPCs within that particular state and used 2005 SPAM data to estimate the rainfed vs irrigated fraction of wheat area and production for each WPC. We then use the 2008 to 2012 state data to convert these WPC fractions of rainfed and irrigated wheat into absolute values of wheat harvested area and production data under rainfed and irrigated conditions for each WPC. Again, this assumes that the contribution of the WPCs to total wheat production and area in a state did not change over the period 2005 to 2012.

Supply-Demand Economic Model. To model how the market price of wheat would change in response to a pollution-free environment and hence increased wheat supply, we apply a supply-demand model that uses the price elasticities of demand and supply for wheat. Such models have been widely used to estimate the economic benefits of agricultural research (30). All economic values are presented in terms of 2012 USD.

The demand and supply model is modified to take account of the Indian government intervention in the wheat market. To describe the model, let $D_0(P,Y)$ denote the demand as a function of price and income. Similarly, let $S_0(P,Z)$ denote the supply as a function of price and other factors summarized in Z (including ozone pollution). Government intervention in grain markets (rice and wheat) consists of the government purchasing a substantial part of market supplies and then distributing it to households at a subsidized price. As a result, government procurement, government sales and the market price satisfy the following equation:

$$D(P_0, Y + W) - G = S(P_0, Z) - R, \qquad [\mathbf{4}]$$

where P_0 is the market price in the presence of government intervention, G is government distribution, R is government procurement, and W is the cash equivalent of the subsidy on grain sales. Eq. **4** says that market supplies are reduced by the extent of government procurement while market demand is affected in two contrasting ways. First, it is reduced by the extent of government sales. Second, the subsidy adds to household incomes and that increases the demand for all goods including grain. Empirically, however, the income effect on grains is known to be very low and close to zero (56). Therefore, the income effect on wheat demand can be ignored. Also, since market demand is reduced by the same amount as government sales, equation Eq. **4** can be rewritten as

$$D(P_0) + E = S\left(P_0, Z\right), \qquad [\mathbf{5}]$$

where $E = (R - G)$ is the excess of procurement over subsidized distribution.

The policy mechanism is that the government buys wheat from farmers at an announced price called the procurement price. Because the procurement is open-ended, it results in the procurement price becoming the market price (57). As a result, the supply-demand Eq. **5** determines the excess procurement. From Eq. **5**, it is clear that if the government targets a particular price, then it can achieve it either by directly announcing that price and letting excess procurement be determined by the supply-demand equilibrium or by setting excess procurement E such that the targeted price emerges from the supply-demand equilibrium. While both are equivalent, it is the latter that is more analytically convenient. Since 1989, excess procurement in wheat has been mostly positive, and in those years, it has lifted demand and price above the levels that would have been without government intervention (58, 59).

The detailed description of the model to estimate the changes in market price, producer surplus (PS), and consumer surplus (CS) as a result of removal of ozone pollution is described in detail in *SI Appendix*. The equilibrium price P_0 is determined by the equality of the existing supply and demand functions. In the absence of ozone pollution, the supply curve shifts and the price falls to P_1. As a result, the CS increases. The change in PS is theoretically indeterminate because while producers gain from greater volumes, they also lose because of fall in prices. The net effect depends on supply and demand elasticities. All of these changes can be derived algebraically from Eq. **5**. The sum of the changes in consumer and producer welfare is, however, always positive after pollution is mitigated.

While it is hard to predict how government behavior adapts to reduction in ozone pollution, we consider the following policy scenarios.

1. Fixed price: In this scenario, we assume that the government intervention remains invariant to the pollution related supply changes in terms of the procurement price. The price P_0 is held constant at the historically observed levels and does not change when ozone pollution is removed.

2. Fixed procurement: In this scenario, we assume that the government intervention remains invariant to the pollution related supply changes in quantity terms. E is held constant at the historically observed levels and does not change when ozone pollution is removed. Supply expands, and the price (consistent with fixed procurement) falls in the absence of pollution. Consumers gain and government expenditures on procurement fall.

3. Fixed expenditure: In this scenario, we assume that the government intervention remains invariant to the pollution related supply changes in quantity terms. The government cost of procurement remains constant. Wheat supply expands in the absence of pollution. The procurement price falls, but when that happens, procurement increases to keep the expenditure on procurement constant. Hence, the fall in prices (relative to scenario 2) is balanced by the increase in procurement.

Our algebraic model departs from the graphical model by allowing for nonlinear supply and demand curves. The algebraic expressions describing the quantitative analysis of these scenarios and estimation of changes in producer and consumer surpluses, distribution costs, and government cost are provided in *SI Appendix*. The data and economic parameters used in our economic analysis are presented in *SI Appendix*, Table S4.

Uncertainty Analysis. The performance of the EMEP model has been evaluated across a range of global sites in previous studies (15, 60). Results for India have also been presented in Pommier et al. (61), who achieved a mean bias of 5.5 ppb across 7 rural stations and rms error of 6.6 ppb. However, Pommier et al. (61) used different emissions and meteorology to that used in this study and some measurement data from older years. The Mills et al. study (15) used EMEP rv4.10 with a similar setup as this study (though different emissions, see *SI Appendix*), and compared observed vs. observed modeled ozone for all sites in the Global Atmospheric Watch (GAW) program. They demonstrated very good agreement ($R = 0.96$, slope of 0.95) for the mean of daily maximum ozone (D_{max}) and also for the 7-h daytime (M7) metric. Stadtler et al. (60) also used a similar model setup to compare with the GAW network, and presented a time series of daily maximum ozone. Biases range from ca. 3% at Mace Head in Ireland to 19% at one Japanese site.

For this study, we used EMEP version rv4.16 (46). In *SI Appendix*, we compare this updated model's results with the GAW data, and also include comparisons for three Indian sites (Mohali, Anantapur, Gadanki).

We found a good overall performance of EMEP rv4.16 for most global sites from the GAW network (*SI Appendix*). However, there are no rural sites from India in the GAW network, and a severe lack of quality data from rural sites in India prohibits thorough evaluation of EMEP, as well as other chemical transport models, in this region (12, 61–64). A good-quality dataset for model evaluation was available for one semiurban site, Mohali (northern India). The model was found to generally overpredict the daily mean (D_{mean}) ozone levels (ca. 58% over January to March, the POD_3IAM accumulation period for most sites). However, daytime ozone (M7 and the 12-h daytime metric M12) was captured better than night-time concentrations (with the overestimation reduced to ca. 40% over the

January-March period). This implies greater certainty of modeled daytime ozone concentrations which are used to derive the POD_3IAM, but the lack of rural monitoring data means that we cannot quantify the uncertainty in any meaningful way. Thus, we accept the ozone and POD3IAM calculations as is, and concentrate the uncertainty analysis on the yield loss.

Uncertainty in yield loss estimations due to ozone was assessed by calculating a 95% CI of the dose–response relationship (Eq. **3**) using a symmetrical t distribution with 32 degrees of freedom (see *SI Appendix* for details). Applying these CIs provided percent yield loss due to ozone and, in turn, wheat production losses along with lower and upper estimates within the 95% CI for each grid. Uncertainty in yield and production loss estimates on a state and national level was then estimated by calculating yields and production for each grid and calculating the sum of grids in each state or all grids for the entire nation. The lower and upper estimates were calculated by the sum of the lower and upper estimates of yield and production for each grid.

The economic analysis uses the mean values over 2008 to 2012 and associated upper and lower bound of national yield and production loss estimates to estimate the 95% CI for the mean of the change in prices, producer and consumer surplus, and the change in government costs.

We focus on the uncertainty of the flux–response relationship since this determines the effect of ozone concentrations on yield.

Data, Materials, and Software Availability. District-wise, season-wise crop production statistics (55) are available at the Open Government Data Platform India at: https://data.gov.in/resource/district-wise-season-wise-crop-production-statistics-1997. The SPAM 2005 v3.2 Global Data (54) can be downloaded from https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/DHXBJX. The calculations of phytotoxic ozone dose (POD3IAM) from EMEP MSC-W model can be downloaded from zenodo (doi: 10.5281/zenodo.5512422). The link is provided from https://zenodo.org/record/5512442. The EMEP MSC-W model is available as public source code, with the latest version (rv4.45) and previous versions stored at https://github.com/metno/emep-ctm.

ACKNOWLEDGMENTS. D.P., L.D.E., and P.B. acknowledge the Norwegian Research Council–funded CiXPAG project (grant no. 244551) and the Stockholm Environment Institute (SEI) for financial support to this study under its Gender and Social Equity program. D.P. also acknowledges the Alexander von Humboldt foundation for the postdoctoral fellowship that supported her continuing working on the manuscript at ZALF after she moved from SEI. D.S. was supported by EMEP under UNECE. Computer time for EMEP model runs was provided by the Research Council of Norway through the NOTUR project NN2890K. Additional funding for work done by K.S. was from the UK Natural Environment Research Council, as part of the SUNRISE program, a National Capability Long-Term Science–Official Development Assistance project, NEC06476. V.S. and B.S. thank the IISER Mohali Atmospheric Chemistry Facility for data and the Ministry of Education, India, and IISER Mohali for funding the facility. The funders did not interfere with the study design, analysis, and preparation of manuscript or decision to publish.

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1. Ministry of Agriculture & Farmers Welfare, Government of India, Agricultural Statistics at a Glance 2018 (2019).
2. M. C. Broberg, Z. Feng, Y. Xin, H. Pleijel, Ozone effects on wheat grain quality–A summary. *Environ. Pollut.* **197**, 203–213 (2015), 10.1016/J.ENVPOL.2014.12.009.
3. Department of Agriculture & Cooperation and Farmers Welfare, Government of India. Farmers' Portal (2021). https://farmer.gov.in/M_cropstaticswheat.aspx.
4. S. Ramadas, T. M. K. Kumar, G. P. Singh, Wheat production in india: Trends and prospects. *Recent Adv. Grain. Crop. Res.*, 10.5772/INTECHOPEN.86341 (2019).
5. A. Madhukar, V. Kumar, K. Dashora, Spatial and temporal trends in the yields of three major crops: Wheat, rice and maize in india. *Int. J. Plant Prod.* **14**, 187–207 (2020), 10.1007/S42106-019-00078-0/TABLES/2.
6. D. P. Hodson, Shifting boundaries: Challenges for rust monitoring. *Euphytica* **179**, 93–104 (2011), 10.1007/S10681-010-0335-4/FIGURES/6.
7. M. Lin *et al.*, US surface ozone trends and extremes from 1980 to 2014: Quantifying the roles of rising Asian emissions, domestic controls, wildfires, and climate. *Atmos. Chem. Phys.* **17**, 2943–2970 (2017), 10.5194/ACP-17-2943-2017.
8. A. Sharma, Revisiting the crop yield loss in India attributable to ozone. *Atmos. Environ.* **1**, 100008 (2019). 10.1016/j.aeaoa.2019.100008.
9. L. D. Emberson *et al.*, A comparison of North American and Asian exposure-response data for ozone effects on crop yields. *Atmos. Environ.* **43**, 1945–1953 (2009).
10. S. D. Ghude *et al.*, Reductions in India's crop yield due to ozone. *Geophys. Res. Lett.* **41**, 5685–5691 (2014), 10.1002/2014GL060930.
11. B. Sinha *et al.*, Assessment of crop yield losses in Punjab and Haryana using 2 years of continuous in situ ozone measurements. *Atmos. Chem. Phys.* **15**, 9555–9576 (2015), 10.5194/acp-15-9555-2015.
12. R. Van Dingenen *et al.*, The global impact of ozone on agricultural crop yields under current and future air quality legislation. *Atmos. Environ.* **43**, 604–618 (2009), 10.1016/J.ATMOSENV.2008.10.033.
13. S. Avnery, D. L. Mauzerall, J. Liu, L. W. Horowitz, Global crop yield reductions due to surface ozone exposure: 2. Year 2030 potential crop production losses and economic damage under two scenarios of O3 pollution. *Atmos. Environ.* **45**, 2297–2309 (2011), 10.1016/j.atmosenv.2011.01.002.
14. S. Lal *et al.*, Loss of crop yields in India due to surface ozone: An estimation based on a network of observations. *Environ. Sci. Pollut. Res. Int.* **24**, 20972–20981 (2017), 10.1007/s11356-017-9729-3.
15. G. Mills *et al.*, Ozone pollution will compromise efforts to increase global wheat production. *Glob Chang. Biol.* **24**, 3560–3574 (2018), 10.1111/gcb.14157.
16. G. Mills *et al.*, Closing the global ozone yield gap: Quantification and cobenefits for multistress tolerance. *Glob. Chang. Biol.* **24**, 4869–4893 (2018), 10.1111/GCB.14381.
17. J. Sampedro *et al.*, Future impacts of ozone driven damages on agricultural systems. *Atmos. Environ.* **231**, 117538 (2020), 10.1016/j.atmosenv.2020.117538.
18. D. Fowler *et al.*, Ground-level ozone in the 21st century: future trends, impacts and policy implications. (Science policy report, The Royal Society, 2008).
19. D. S. Negi, P. S. Birthal, D. Roy, M. T. Khan, Farmers' choice of market channels and producer prices in India: Role of transportation and communication networks. *Food Policy* **81**, 106–121 (2018), 10.1016/J.FOODPOL.2018.10.008.
20. B. Shiferaw *et al.*, Crops that feed the world 10. Past successes and future challenges to the role played by wheat in global food security. *Food Secur.* **5**, 291–317 (2013), 10.1007/S12571-013-0263-Y/TABLES/9.
21. C. Rangarajan, Rangarajan report on poverty (2014). https://pib.gov.in/newsite/printrelease.aspx?relid=108291. Accessed 1 November 2022.
22. World Health Organization, The State of Food Security and Nutrition in the World: Safeguarding against economic slowdowns and downturns (Food and Agriculture Organization of the United Nations, 2019).
23. R. Puri, H. Alderman, S. Bhattacharya, U. Gentilini, Schemes To Systems | The Public Distribution System: Anatomy of India's Food Subsidy Reforms (2019). https://www.worldbank.org/en/news/feature/2019/02/21/schemes-to-systems-public-distribution-system.
24. J. Dreze, P. Gupta, R. Khera, I. Pimenta, Casting the net. *Econ. Polit. Wkly.* **54**, 7–8 (2015).
25. L. D. Emberson *et al.*, Modelling and mapping ozone deposition in Europe. *Water Air Soil. Pollut.* **130**, 577–582 (2001), 10.1023/A:1013851116524.
26. D. B. Lobell, W. Schlenker, J. Costa-Roberts, Climate trends and global crop production since 1980. *Science* **333**, 616–620 (2011), 10.1126/SCIENCE.1204531.
27. E. Zaveri, D. B. Lobell, The role of irrigation in changing wheat yields and heat sensitivity in India. *Nat. Commun.* **10**, 4144 (2019), 10.1038/s41467-019-12183-9.
28. F. Parween, P. Kumari, A. Singh, Irrigation water pricing policies and water resources management. *Water Policy* **23**, 130–141 (2021), 10.2166/wp.2020.147.
29. K. Damerau *et al.*, India has natural resource capacity to achieve nutrition security, reduce health risks and improve environmental sustainability. *Nat. Food* **1**, 631–639 (2020), 10.1038/s43016-020-00157-w.
30. J. M. Alston, G. W. Norton, P. G. Pardey, *Science Under Scarcity: Principles and Practice for Agricultural Research Evaluation and Priority Setting* (Cornell University Press for the International Service for National Agricultural Research (ISNAR), 1995).
31. A. P. K. Tai, M. Val Martin, Impacts of ozone air pollution and temperature extremes on crop yields: Spatial variability, adaptation and implications for future food security. *Atmos. Environ.* **169**, 11–21 (2017), 10.1016/J.ATMOSENV.2017.09.002.
32. C. S. Rao, Potential and challenges of rainfed farming in India in *Advances in Agronomy*, Sparks D. L., Ed. (Academic Press, 2015), pp. 113–181.
33. T. W. Hertel, M. B. Burke, D. B. Lobell, The poverty implications of climate-induced crop yield changes by 2030. *Glob. Environ. Chang.* **20**, 577–585 (2010), 10.1016/j.gloenvcha.2010.07.001.
34. A. Markandya *et al.*, Health co-benefits from air pollution and mitigation costs of the Paris Agreement: A modelling study. *Lancet Planet. Heal.* **2**, e126–e133 (2018), 10.1016/S2542-5196(18)30029-9.
35. J. M. Alston, Reflections on agricultural R&D, productivity, and the data constraint: Unfinished business, unsettled issues. *Am. J. Agric. Econ.* **100**, 392–413 (2018), 10.1093/AJAE/AAX094.
36. Central Pollution Control Board, National ambient air quality standards (2009). https://cpcb.nic.in/displaypdf.php?id=aG9tZS9haXItcG9sbHV0aW9uL1JlY3ZlZC1OYXRpb25hbC5wZGY=. Accessed 1 November 2022.
37. L. D. Emberson, Effects of ozone on agriculture, forests and grasslands. *Philos. Trans. R Soc. A Math. Phys. Eng. Sci.* **378**, 20190327 (2020), 10.1098/rsta.2019.0327.

38. C. Jamir, "Assessing ozone impacts on arable crops in South Asia: Identification of suitable risk assessment methods to improve crop biotechnology Ph.D. thesis, (University of York, York, UK,2011).
39. E. Teixeira *et al.*, Limited potential of crop management for mitigating surface ozone impacts on global food supply. *Atmos. Environ.* **45**, 2569–2576 (2011), 10.1016/j.atmosenv.2011.02.002.
40. H. Harmens *et al.*, Can reduced irrigation mitigate ozone impacts on an ozone-sensitive African wheat variety? *Plants* **8**, 220 (2019), 10.3390/plants8070220.
41. J. Sillmann *et al.*, Combined impacts of climate and air pollution on human health and agricultural productivity. *Environ. Res. Lett.* **16**, 093004 (2021), 10.1088/1748-9326/ac1df8.
42. D. K. Biswas *et al.*, Genotypic differences in leaf biochemical, physiological and growth responses to ozone in 20 winter wheat cultivars released over the past 60 years. *Glob. Chang. Biol.* **14**, 46–59 (2008), 10.1111/j.1365-2486.2007.01477.x.
43. N. Kaushal, F. M. Muchomba, How consumer price subsidies affect nutrition. *World Dev.* **74**, 25–42 (2015), 10.1016/J.WORLDDEV.2015.04.006.
44. CLRTAP (2017). "Mapping critical levels for vegetation". LRTAP convention modelling and mapping manual. http://icpvegetation.ceh.ac.uk/. Accessed 1 November 2022.
45. D. Simpson *et al.*, The EMEP MSC-W chemical transport model– Technical description. *Atmos. Chem. Phys.* **12**, 7825–7865 (2012), 10.5194/acp-12-7825-2012.
46. D. Simpson, "Updates to the EMEP/MSC-W model, 2017–2018" in Transboundary particulate matter, photo-oxidants, acidifying and eutrophying components. EMEP Status Report (2018).
47. M. Amann *et al.*, Cost-effective emission reductions to improve air quality in Europe in 2020: Analysis of policy options for the EU for the revision of the Gothenburg Protocol. (Final Report submitted to the European Commission, DG Environment, Laxenburg 2011).
48. L. D. Emberson *et al.*, Modelling stomatal ozone flux across Europe. *Environ. Pollut.* **109**, 403–413 (2000), 10.1016/S0269-7491(00)00043-9.
49. D. Simpson, M. R. Ashmore, L. Emberson, J. P. Tuovinen, A comparison of two different approaches for mapping potential ozone damage to vegetation. A model study. *Environ. Pollut.* **146**, 715–725 (2007), 10.1016/j.envpol.2006.04.013.
50. J.-P. Tuovinen, L. Emberson, D. Simpson, Modelling ozone fluxes to forests for risk assessment: Status and prospects. *Ann. For Sci.* **66**, 401 (2009), 10.1051/forest/2009024.
51. H. Pleijel *et al.*, Ozone risk assessment for agricultural crops in Europe: Further development of stomatal flux and flux–response relationships for European wheat and potato. *Atmos. Environ.* **41**, 3022–3040 (2007), 10.1016/J.ATMOSENV.2006.12.002.
52. P. Büker *et al.*, DO3SE modelling of soil moisture to determine ozone flux to forest trees. *Atmos. Chem. Phys.* **12**, 5537–5562 (2012), 10.5194/acp-12-5537-2012.
53. L. You, S. Wood, U. Wood-Sichra, W. Wu, Generating global crop distribution maps: From census to grid. *Agric. Syst.* **127**, 53–60 (2014), 10.1016/J.AGSY.2014.01.002.
54. International Food Policy Research Institute (IFPRI) International Institute for Applied Systems Analysis (IIASA), Global spatially-disaggregated crop production statistics data for 2005 Version 3.2 (2016), 10.7910/DVN/DHXBJX. Accessed 14 November 2021.
55. Ministry of Agriculture and Farmers Welfare, Government of India, District-wise, season-wise crop production statistics | Open Government Data (OGD) Platform India (2021), https://data.gov.in/resource/district-wise-season-wise-crop-production-statistics-1997.
56. P. Kumar, A. Kumar, S. Parappurathu, S. S. Raju, "Developing a decision support system for agricultural commodity market outlook" (NAIP-subproject at NCAP) estimation of demand elasticity for food commodities in India §. *Agric. Econ. Res. Rev.* **24**, 1–14 (2011).
57. P. Balakrishnan, B. Ramaswami, Public intervention and private speculation: The case of wheat procurement. *J. Quant. Econ.* **11**, 59–83 (1995).
58. B. Ramaswami, M. Murugkar, Incremental reforms in food policy: What are the possibilities? (Development in India: Micro and Macro Perspectives, New Delhi, Springer India, 2016) pp. 125–153. 10.1007/978-81-322-2541-6_8.
59. B. Ramaswami, Efficiency and equity of food market interventions. *Econ. Polit. Wkly.* **37**, 1129–1135 (2002).
60. S. Stadtler *et al.*, Ozone impacts of gas–aerosol uptake in global chemistry transport models. *Atmos Chem. Phys.* **18**, 3147–3171 (2018), 10.5194/acp-18-3147-2018.
61. M. Pommier *et al.*, Impact of regional climate change and future emission scenarios on surface O3 and PM2.5 over India. *Atmos. Chem. Phys.* **18**, 103–127 (2018), 10.5194/acp-18-103-2018.
62. M. Engardt, Modelling of near-surface ozone over South Asia. *J. Atmos. Chem.* **59**, 61–80 (2008), 10.1007/s10874-008-9096-z.
63. S. D. Ghude *et al.*, Satellite constraints of nitrogen oxide (NOx) emissions from India based on OMI observations and WRFChem simulations. *Geophys. Res. Lett.* **40**, 423–428 (2013), 10.1002/grl.50065.
64. D. E. Surendran *et al.*, Air quality simulation over South Asia using Hemispheric Transport of Air Pollution version-2 (HTAP-v2) emission inventory and Model for Ozone and Related chemical Tracers (MOZART-4). *Atmos Environ.* **122**, 357–372 (2015), 10.1016/j.atmosenv.2015.08.023.