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Fertile grounds: Navigating the environmental impact of fertilizer consumption

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Abstract

This article takes advantage of the economic geography of fertilizer production to show that a 10 per cent increase in the use of fertilizers is associated with a 3.09 per cent increase in agricultural nitrous oxide emissions over a 15-year long period from 2006 to 2020, and a 15.28 per cent increase in water withdrawals for agricultural purposes. Findings further indicate that the effects of fertilizer consumption on crop water footprints and agricultural methane emissions are not statistically distinguishable from zero. A back-of-the-envelope calculation reveals that these fertilizer-induced environmental externalities lead to approximately 15,450 annual deaths worldwide through nitrous oxide emissions.

Keywords: agriculture; fertilizers; yields; nitrous oxide; water footprints.

JEL classification: Q10, Q15, Q50

1. Introduction

Nitrogen (N) is at the core of several Sustainable Development Goals, ranging from enhanced food security to improved environmental outcomes (Schulte-Uebbing et al., 2022). Over the last 65 years, there has been an eight-fold increase in global nitrogen fertilizer use, causing croplands to expand in the USA and western Europe in the 1960s to eastern Asia in the early 21st century (Lu and Tian, 2017). Fertilizer consumption is widely acknowledged to enhance economic gains through an increase in agricultural yields (Marenya and Barrett, 2009; McArthur and McCord, 2017). Yet it is also associated with water contamination and eutrophication, and air pollution through emissions of nitrous oxides (Zhang et al., 2015; Pozzer et al., 2017). Although

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researchers acknowledge that nitrogen pollution from global fertilizer consumption has exceeded planetary boundaries and resulted in large economic damages[1] (Rockström et al., 2009; Steffen et al., 2015), there exists a lack of comprehensive knowledge about changes in environmental outcomes that can be directly attributed to the use of fertilizers. This is important because environmental externalities from fertilizer use have focused largely on water contamination, eutrophication and toxic algal blooms (Paudel and Crago, 2021; Schulte-Uebbing et al., 2022).

This article investigates the linkage between fertilizer consumption, economic development and environmental changes across the globe in two ways. First, it makes use of cross-country panel data over a 60-year long period from 1961 to 2020 to estimate the economic impact of fertilizer use on three key indicators: cereal yields, Gross Domestic Product (GDP) per capita and agricultural value added per worker. Second, it evaluates the environmental consequences of fertilizer use through changes in agricultural methane emissions, agricultural nitrous oxide emissions, freshwater withdrawals for agricultural purposes and crop water footprints (WFs). Each econometric model employs a rich panel of countries constructed from several years of data (60 years for economic variables and 31 years for environmental factors), allowing me to apply country and year fixed effects to identify the impact of fertilizer use on outcomes of interest. Consistent with prior literature, I include weather controls, and account for key economic characteristics (including the share of agricultural land, life expectancy at birth, fertility rate and agricultural machinery) in the empirical model. The two econometric steps involving the causal impact of fertilizers on economic and environmental indicators rely on an instrumental variable (IV) for a country's fertilizer use: global fertilizer price shocks interacted with the inverse of each country's cost-distance to the nearest fertilizer production site.

My identification strategy builds on the insights from McArthur and McCord (2017), in which the authors argue that the distance fertilizers travel from production facilities to agricultural sites of each country offers a valid source of exogenous cross-sectional variation in trade volumes and fertilizer consumption. Because "countries closer to fertilizer plants are more sensitive to the commodity's price variation relative to the transport costs that farmers incur" (McArthur and McCord, 2017), a unique economic geography of fertilizer production in conjunction with transport costs helps address the endogeneity of fertilizer consumption. The instrument also exploits temporal variation in fluctuations of global fertilizer price shocks exogenous to country's local conditions. The ratio between time-varying global indices of fertilizer prices and natural gas prices captures the magnitude of global fertilizer price shocks. The interaction term provides both temporal and spatial variation to account for the endogeneity of agricultural fertilizer use.

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[1] One estimate claims that global fertilizer runoff leads to 200–800 billion dollars worth of damage to the ocean every year (Economist 2018).

I provide three sets of results. First, my first-stage estimates illustrate that a 10 per cent decrease in global price shocks interacted with the inverse of the agriculture-weighted average cost-distance to N fertilizer production site results in a 6.9 per cent increase in the consumption of fertilizers. To illustrate the magnitude of this impact, a 10 per cent negative price shock to global fertilizer prices would increase fertilizer use by 1.45 kg/ha (for a country one standard deviation above the cost-distance measure, say, Malawi) and 8.24 kg/ha (for a country one standard deviation below the cost-distance measure, say, Bangladesh), respectively. Second, the IV results illustrate that a 10 per cent increase in the use of fertilizers led to a 3.3 per cent increase in cereal yields (approximately 79.86 kg/ha increase), with clear patterns of heterogeneity across continents, decades and income levels. This estimated impact corresponds to an increase in cereal yields of approximately 42.62 kg/ha in Malawi and 91.07 kg/ha in Bangladesh, respectively. Positive gains in cereal yields from fertilizer consumption are prominent in countries from Africa and Europe, although the estimated elasticity in high-income countries (0.66) is much larger compared to low-income countries (0.28). This is in line with the notion that poorer farmers are likely to cultivate soils deficient in soil organic matter, causing fertilizer interventions to exacerbate income inequality (Marenya and Barrett, 2009). Regression estimates further show that a 1 per cent increase in fertilizer consumption led to a 9.76 per cent increase in GDP per capita, and a 4.51 per cent increase in agricultural value per worker, implying that fertilizer use resulted in economic development around the world.

Finally, I note three specific observations from the IV estimates on the environmental impact of fertilizer consumption. First, a 10 per cent increase in the use of fertilizers led to a 3.09 per cent increase in agricultural nitrous oxide emissions over a 15-year long period from 2006 to 2020, and a 15.28 per cent increase in water withdrawals for agricultural purposes over the entire sample period. Second, this increase in nitrous oxide emissions from fertilizers is the largest in Asia (with an elasticity of 1.64), while the estimated impact of fertilizers on freshwater withdrawals is driven by countries in Africa (with an elasticity of 2.58) South and North America (with an elasticity of 2.12). I, however, do not find a statistically significant relationship between fertilizer use and agricultural methane emissions. Third, the effects of fertilizer consumption on four different indicators of crop WFs, which assess agricultural water consumption and productivity, are not statistically distinguishable from zero. These indicators include green unit WF, blue unit WF from capillary rise, blue unit WF from irrigation and the sum of these three WFs.

These results provide substantial evidence to conclude that while fertilizers enhance economic gains through increased yields and GDP per capita, they create environmental damages through a rise in nitrous oxide emissions and freshwater withdrawals. Applying my estimates with statistics based on global chemistry-climate models (Pozzer et al., 2017), I find that a 10 per cent increase in fertilizer consumption causes an increase in mortality attributable to air pollution of approximately 15,450 annual deaths worldwide through increased agricultural nitrous oxide emissions. My focus on point emissions from agricultural fertilizer use contributes to conducting benefit-cost analyses useful for assessing environmental policies aimed at mitigating climate change.

To the best of my knowledge, this is the first study to provide global estimates on the effects of fertilizer consumption on a range of environmental outcomes. The majority of studies employ *ex ante* simulation models to investigate environmental pollution in the agricultural sector (Thorp et al., 2007; Gowda et al., 2008; Nangia et al., 2008; Burkart and Jha, 2012; Iho and Laukkanen, 2012; Hendricks et al., 2014; Bostian et al., 2015; Pozzer et al., 2017; Schulte-Uebbing et al., 2022). My approach to studying the environmental consequences of agricultural fertilizer use is broadly related to Paudel and Crago (2021) and McArthur and McCord (2017). For example, Paudel and Crago (2021) employ an empirical model to directly estimate the relationship between fertilizer application and nutrient pollution in US water sites. Contrary to Paudel and Crago (2021), I focus on point emissions associated with agricultural fertilizer use. While McArthur and McCord (2017) evaluate the relationship between fertilizers and yields over a shorter 35-year long period (using data in 5-year intervals), I estimate the environmental impact of fertilizer consumption.

This study contributes to a rich literature that attempts to identify the relationship between the use of fertilizers and greenhouse gas (GHG) emissions (Williams and Shumway, 2000; Snyder et al., 2009; Chataut et al., 2023). For example, agronomic researchers study how the source of nitrogen in fields (including the rate, timing and placement) from different cropping and tillage systems affects primary GHG emissions (Snyder et al., 2009). In a different study, Zhang et al. (2013) illustrate that the use of advanced technologies could cut N fertilizer-related emissions by 20–63 per cent, highlighting different opportunities for climate change mitigation. Relatedly, the replacement of chemical fertilizers with organic ones has been linked with a decrease in nitrous dioxide emissions, although there exist uncertainties on the predictions of GHG emissions from fertilizer consumption (Walling and Vaneeckhaute, 2020; He et al., 2023). This article is broadly related to an influx of studies that combine both reduced-form and structural approaches to evaluate the environmental impact of fertilizer applications (Smith et al., 1997; Alexander et al., 2007; Preston et al., 2009). Contrary to simulation-based structural models used in understanding water quality implications of fertilizers (Rabotyagov et al., 2014; Kling et al., 2017), the reduced-form approach employed here models the cross-country relationship between fertilizer consumption, economic development and environmental outcomes in a more transparent manner.

My study is also related to the literature evaluating the effects of agro-environmental policies on a variety of environmental outcomes (Smith and Wolloh 2012; Keiser and Shapiro, 2018). Emerging research illustrates that agricultural policies without explicit environmental goals can indirectly affect the natural environment through its effect on agricultural input use behavior (Paudel and Crago, 2017; Lu et al., 2023; Kim and Paudel, 2025).

More recently, Weng et al. (2024) integrate an economic model of farmer decision-making with a model of terrestrial nitrogen cycling for the watershed in Wisconsin to quantify the co-benefits from a decrease in agricultural nitrate leaching. Finally, I believe that my findings are relevant to the broader literature on regulating nonpoint source pollution from agriculture (Shortle and Horan, 2001; Xepapadeas, 2011; Ribaudo and Shortle, 2019; Paudel and Rejesus, 2025).

The remainder of the article is divided into five sections. The next section presents a conceptual framework on the relationship between fertilizer consumption and environmental outcomes, describes the data used in the study and provides details on the empirical strategy. The following section presents the main results followed by a discussion on policy implications of the study. The final section concludes.

2. Theoretical motivation, data and methods

2.1 Conceptual framework

This section presents a conceptual framework involving the relationship between agricultural fertilizer use and environmental pollution. I adapt the theoretical model in Shortle and Horan (2013) at the country level. Consider country c, with a share of arable land where agricultural inputs are applied to grow a variety of crops. Within each country c, point sources and nonpoint sources result in emissions and runoff, respectively. While Shortle and Horan (2013) focus on watersheds and consider point and nonpoint sources to be industrial firms and farms, my country-level analysis does not make such distinctions. Following Shortle and Horan (2013), I model the production of polluting runoff r for the ith point source in country c by the following relation:

$$r_{ic} = r_{ic}(f_{ic}, p_{ic}, \alpha_{ic}, \nu_{ic}), \tag{1}$$

where f represents agricultural production inputs such as fertilizer, p represents pollution control inputs, α represents agricultural characteristics such as soil type, topography and arable acreage and ν represents stochastic environmental variables affecting runoff. This helps define the amount of pollutant a released in country c, as follows:

$$a_c = a_c(r_{1c}, ..., r_{nc}, e_{1c}, ..., e_{kc}, a_{c-1}, \zeta_c, \psi_c, \phi_c, \delta_c), \tag{2}$$

where r represents runoff in country c for nonpoint sources 1 to n, e represents point emissions in country c from sources 1 to k, a_{c-1} represents prior ambient pollution released in country c, ζ represents stochastic elements of the pollutant that account for events such as forest fires and dust storms in country c, ψ represents unique time-invariant characteristics of a country c such as geography and elevation, ϕ represents physical and chemical properties of atmosphere and δ represents stochastic environmental factors such as temperature, precipitation and humidity in country c. The validity of the theoretical model hinges on the assumption that the partial derivatives of the released pollutant with respect to runoff, emissions, fertilizers and lagged pollutant are greater than or equal to zero. Mathematically, the change in released pollutant from the change in fertilizer use is given by

$$\frac{\xi a_c}{\xi f_{ic}} = \frac{\partial a_c}{\partial r_{ic}} \frac{\partial r_{ic}}{\partial f_{ic}} \geq 0 \; \forall i, c. \tag{3}$$

Using the conceptual framework above, I construct an empirical model to estimate environmental outcome as a function of agricultural fertilizer use at the country level. The environmental outcomes include agricultural nitrous oxide emissions, agricultural methane emissions, freshwater withdrawals for agricultural purposes and four different indicators of crop WFs. I rely on the total amount of agricultural fertilizer consumption (kg/ha) to account for country-level nonpoint emissions. I incorporate different time-invariant country-specific characteristics, including land size, geography and agricultural terrain, through country fixed effects in the empirical model. I apply year fixed effects to account for changing environmental policies common to countries such as climate change agreements, and the adoption of agricultural best management practices. Finally, I use annual weather controls to proxy for stochastic environmental variables at the country level. These controls influence farming production decisions (Wimmer et al., 2024), and contribute to understanding the relationship between landscapes and environmental quality (Edwards et al., 2015). Consistent with literature (McArthur and McCord, 2017; Paudel and Crago, 2021), I further include variables that affect both crop yields and environmental outcomes. These characteristics include the share of agricultural land, life expectancy at birth, total fertility rate and agricultural machinery, tractors per sq. km of arable land.

2.2 Data

I construct a cross-country panel dataset for empirical analysis. My country-level economic variables, collected from the World Bank's World Development Indicators (WDI) database,[2] are available for each year from 1961 to 2020. These variables include fertilizer consumption (kilograms per hectare of arable land), cereal yields (kilograms per hectare), agricultural land (% of land area), average precipitation in depth (mm per year) and temperature, agricultural machinery (tractors per 100 sq. km of arable land), agricultural value added per worker (constant 2015 US$), GDP per capita (constant 2015 US$), total life expectancy at birth (years) and total fertility rate (births per woman). The measure of cereal yields focuses on crops harvested for dry grains only and includes wheat, rice, maize, barley, oats, rye, millet, sorghum, buckwheat and mixed grains. The fertilizer consumption variable includes nitrogenous, potash and phosphate fertilizers and excludes animal and plant manures.

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[2] The dataset is available at https://data.worldbank.org/.

I also obtain year-level global indices of fertilizer and natural gas prices from the Commodity Price Data available from the World Bank.[3] These prices are measured near the point of production, and do not include transportation costs. The indices are constructed in real US dollar terms and set to 100 for a base year (2015 in our data). A country-level average agriculture-weighted cost-distance to the nearest fertilizer production site is available from McArthur and McCord (2017). Specifically, McArthur and McCord (2017) calculate the minimum cost-adjusted distance from each grid cell within a country to the nearest fertilizer production site (among sixty-three unique locations in the world where fertilizers are produced), including the average for each country weighting each grid cell by its area planted to staple crops. This procedure also adjusts for relative transport cost between land and water based on findings from Limao and Venables (2001). Details regarding the computation of the agriculture-weighted cost-distance to the nearest fertilizer production site are available from McArthur and McCord (2017).

My first set of country-level environmental variables, accessible from the WDI database, is available for each year from 1990 to 2020. These variables include agricultural methane emissions (thousand metric tons of CO_2 equivalent), agricultural nitrous oxide emissions (thousand metric tons of C_2 equivalent), total annual freshwater withdrawals (billion cubic meters) and agricultural share of annual freshwater withdrawals (%). Agricultural nitrous oxide and methane emissions are produced through fertilizer use, animal waste management, agricultural waste burning and savanna burning. Freshwater withdrawals do not count evaporation losses from storage basins, and include withdrawals for irrigation and livestock production.

My second set of environmental variables that includes country-level WF of crops for each year from 1990 to 2019 is available from Mialyk et al. (2024). WF-related metrics allow researchers to assess agricultural water consumption and productivity. Mialyk et al. (2024) apply a global process-based crop model to quantify consumptive WFs of 175 individual crops at a 5 arcmin resolution over the 1990–2019 period, and classify WFs into green (water from precipitation) and blue (from irrigation or capillary rise). I employ four different country-level annual averages of unit WFs (cubic meters per ton) for my empirical analysis: green unit WFs, blue unit WFs from capillary rise, blue unit WFs from irrigation and the sum of the green and blue unit WFs. I explore WF of all crops combined, and cereal-specific WF for our research.

Figure 1 presents kernel density plots of key agricultural and environmental indicators across countries belonging to different income levels classified by the World Bank. Figure 1a and b indicates that both cereal yields and fertilizer consumption exhibit larger mean values in high-income countries compared to low-income countries. In Fig. 1c and d, methane and nitrous emissions exhibit a much larger variance in high-income countries,

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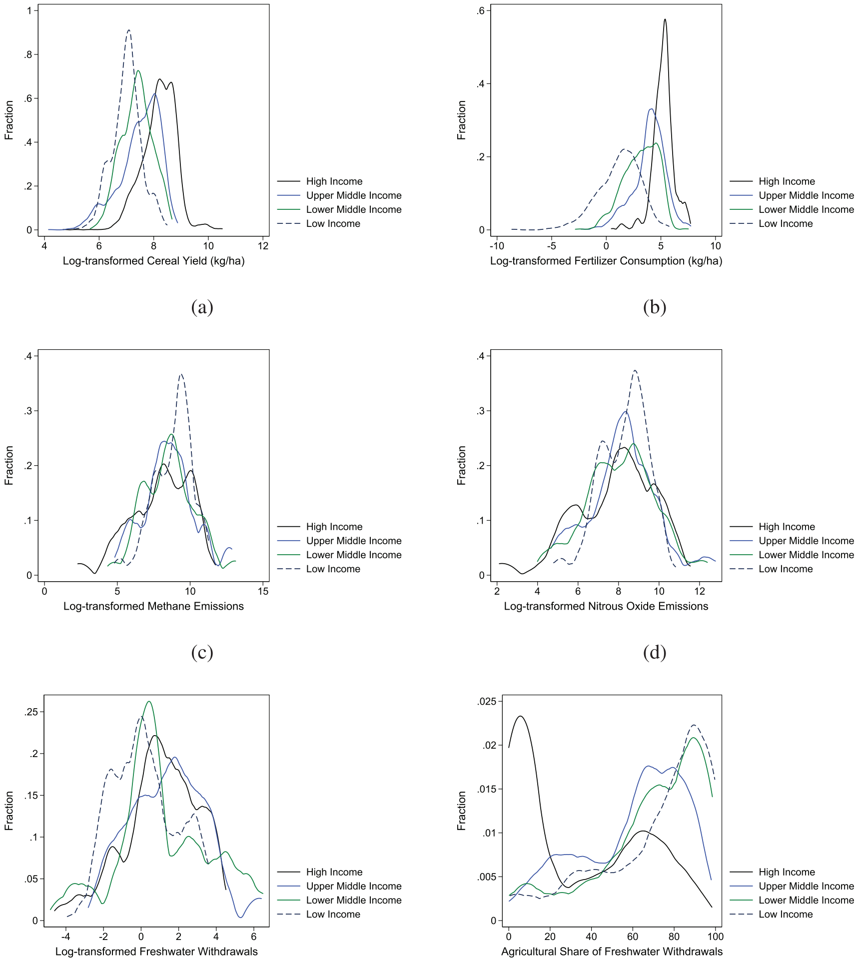
[3] The dataset is available at https://www.worldbank.org/en/research/commodity-markets.



(a) (b)

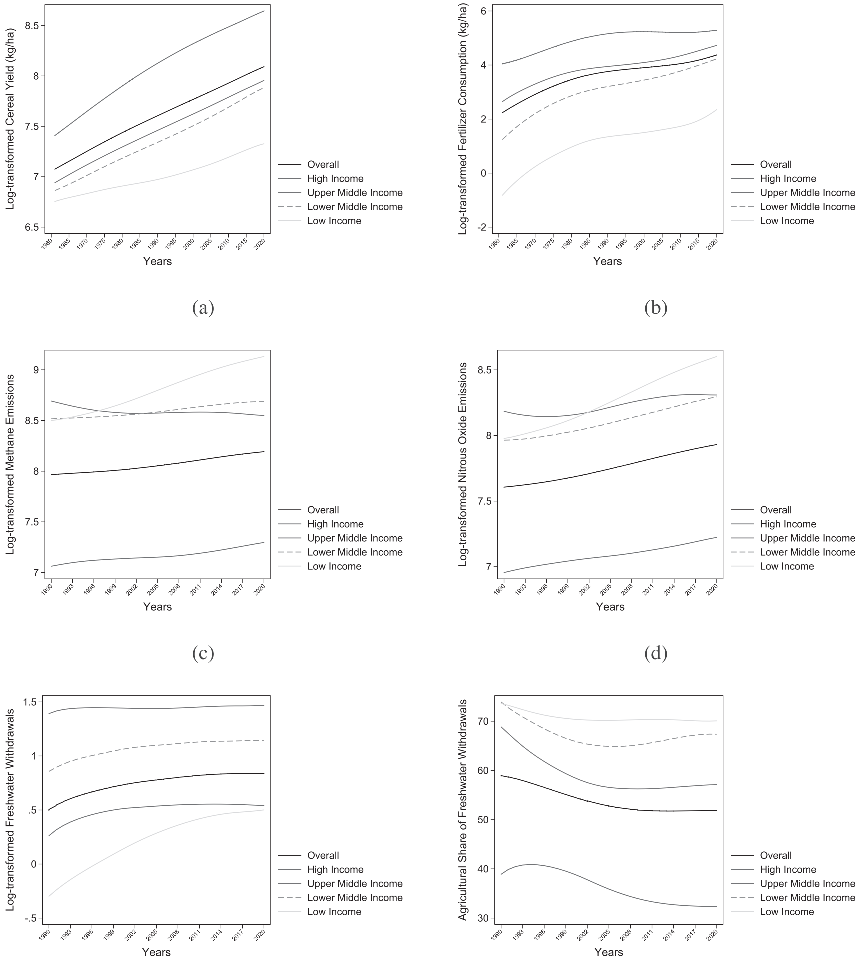
(c) (d)

(e) (f)

Fig. 1. Kernel density plot of agricultural and environmental indicators across countries belonging to different income levels classified by the World Bank.

but have larger average values in low-income countries. These figures illustrate that environmental emissions are worse in low-income countries, and agricultural gains are the largest in high-income countries. Figure 1e and f presents kernel density plots of freshwater withdrawals and conclude that there exists substantial heterogeneity across countries belonging to different income levels.

Figure 2 presents temporal variation in all the indicators above among countries belonging to different income levels. This figure illustrates disparities in both economic and environmental variables between high-income and low-income countries consistent throughout the entire sample period, except



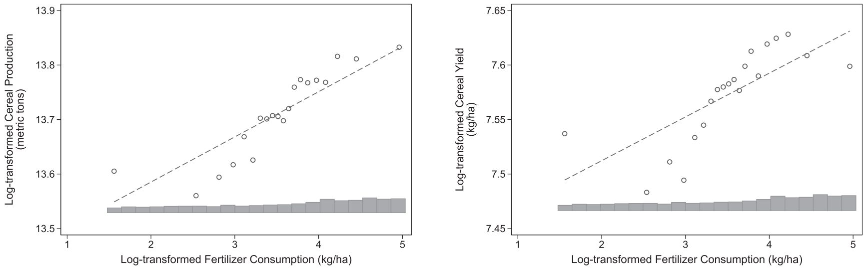
(a) (b)

(c) (d)

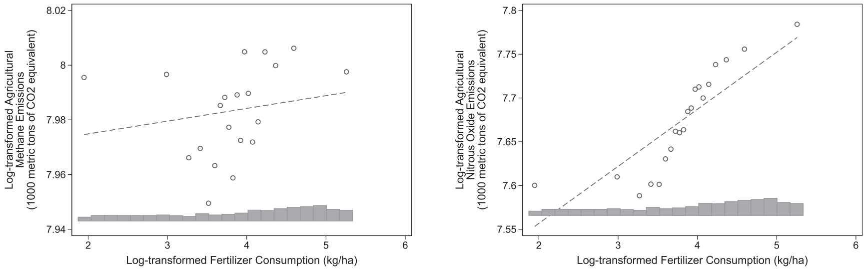
(e) (f)

Fig. 2. Temporal variation in agricultural and environmental indicators across countries belonging to different income levels classified by the World Bank.

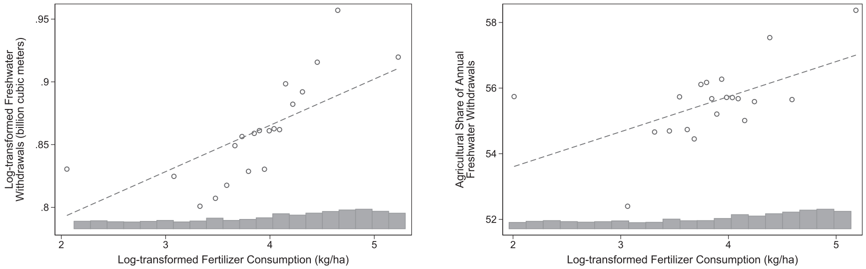
for freshwater withdrawals, which exhibit a decreasing gap between these comparison groups. Finally, Fig. 3 presents binned scatterplots between fertilizer consumption and agro-environmental outcomes, including the underlying distribution of fertilizer consumption. The figure provides descriptive evidence on a positive relationship between (i) fertilizer consumption, cereal yields and cereal production and (ii) fertilizer consumption, pollutant emissions and freshwater withdrawals. This nonparametric visual illustration calls for a rigorous examination on both economic and environmental effects of fertilizer consumption.



(a) Cereal production (b) Cereal yield



(c) Agricultural methane emissions (d) Agricultural nitrous oxide



(e) Water withdrawals (f) Share of water withdrawals

Fig. 3. Binned scatterplots between fertilizer consumption and agro-environmental outcomes. Notes: The binned scatterplot denotes the nonparametric relationship between agricultural fertilizer use and agro-environmental outcome, including the underlying distribution.

2.3 Empirical strategy

I begin with a standard ordinary least squares (OLS) estimation to evaluate the impact of agricultural fertilizer consumption on economic and environmental variables, as shown below

$$\ln Y_{it} = \beta \ln F_{it} + \mathbf{X}^{'}_{it}.\theta + \eta_i + \delta_t + \epsilon_{it}, \tag{4}$$

where Y_{it} is the outcome for an individual country i in year t. Y_{it} includes (i) cereal yields, (ii) GDP per capita, (iii) agricultural value added per worker,

(iv) agricultural methane emissions, (v) agricultural nitrous oxide emissions, (vi) freshwater withdrawals for agricultural purposes and (vii) crop WFs. β, the parameter of interest, captures the effect of a percentage change in fertilizer consumption on a percentage change in the outcome variable. The equation also includes country fixed effects (η_i) that account for time-invariant unobserved determinants of agricultural and environmental outcomes at the country level, and year fixed effects (δ_t) that capture time-varying differences in each outcome. Finally, $\mathbf{X}_{it}$ controls for weather variables, agricultural machinery and tractors, total life expectancy at birth and total fertility rate. I cluster standard errors at the country level.

I note that estimated β is prone to different types of biases. First, unobserved characteristics such as agronomic knowledge are likely correlated with both cereal yields and levels of agricultural inputs, biasing the coefficients of interest in a standard OLS setup. Second, higher agricultural production may induce behavioral decisions to apply more fertilizers, creating the problem of reverse causality. Third, country-level variables on yields and fertilizer consumption may suffer from measurement errors, resulting in an underestimation of the true impact of fertilizer consumption on economic and environmental variables. This suggests that the OLS estimate is biased downwards. These concerns related to omitted variable bias, reverse causality and attenuation bias highlight the need to instrument for a country's agricultural fertilizer consumption.

Following insights from Werker et al. (2009) and McArthur and McCord (2017), I make use of the following exogenous variables to create a valid instrument: (i) the ratio between global fertilizer prices and natural gas prices, which exploits annual fluctuations in prices to generate temporal variation exogenous to country-specific conditions and (ii) country-specific average agriculture-weighted cost-distance to the nearest fertilizer production site, which provides a source of exogenous cross-sectional variation. According to McArthur and McCord (2017), countries closer to fertilizer plants are susceptible to variation in agricultural input prices compared to the transport costs incurred. I, therefore, instrument for a country's fertilizer consumption with global fertilizer price shocks interacted with agriculture-weighted cost-distance to the nearest fertilizer production site.

Figure A1 presents a nonparametric relationship between agricultural fertilizer consumption and global fertilizer price shocks interacted with the inverse of each country's cost-distance to the nearest fertilizer production site. The first stage below estimates the determinants of agricultural fertilizer consumption:

$$\ln F_{it} = \lambda \ln \left(\frac{P_t^f / P_t^n}{\mathrm{Dist}_i} \right) + \mathbf{X}_{it}^{'}.\theta + \eta_i + \delta_t + \epsilon_{it}, \tag{5}$$

where P_t^f is global fertilizer price in year t, P_t^n is global natural gas price in year t and Dist_i is the agriculture-weighted cost-distance to the nearest fertilizer production site for country i. Rest of the variables are same as in (4). We estimate β using the fitted value of fertilizer consumption $\hat{F}_{it}$ generated from the first-stage regression, as shown below

$$\ln Y_{it} = \beta \ln \hat{F}_{it} + \mathbf{X}^{'}_{it}.\theta + \eta_i + \delta_t + \epsilon_{it}. \tag{6}$$

Four potential concerns about the validity of the IV merit discussion. First, the issue of global business cycles has implications on whether the IV meets exclusion restrictions. For example, it is likely that the distance to the closest fertilizer production sites might reflect possible repercussions of global business cycles on each country based on its proximity to large economies. If this is true, variation in commodity prices may influence economic outcomes of each country through exchange rates to the dollar. To address this issue, I include the exchange rate as one of the control variables in (5) and find that the inclusion does not alter the statistical significance of the IV (more on Table A1). Because my estimated β in (6) remains robust and statistically significant when controlling for exchange rates, I am confident that the chosen instrument remains a valid choice.

Second, it is possible that the location of fertilizer plants is endogenous to improved economic gains. To the extent that economic changes in a nearby location result in higher fertilizer consumption, the IV will mistakenly reflect the endogenous location dynamics. To investigate this issue further, I run baseline regressions with the exclusion of countries that have major fertilizer production sites: the USA, Canada, Argentina, Egypt, Russia, India, the Netherlands, Brazil, France, Belgium, Germany, Sweden, Finland, Italy and Libya. It is, however, reassuring that the slope coefficients from the IV regressions on outcome variables of interest remain almost the same. For example, the estimated elasticity of cereal yields with respect to fertilizer consumption in the second stage is 0.33, and the estimate is statistically significant at the 1 per cent level. This allows me to conclude that the regression results (shown in the next section) are not driven by major fertilizer-producing countries. More importantly, this suggests that my identification is directly coming from cross-country relative distances to fertilizer production sites among countries that do not produce fertilizers.

Third, recent literature on weak IV points out that the Anderson–Rubin (AR) test should be used in lieu of the *t*-test from the two-stage least squares (2SLS) estimation to account for the issue of power asymmetry (Keane and Neal, 2023, 2024). Power asymmetry implies that 2SLS standard errors are either artificially small when the 2SLS estimate is close to OLS or large when the 2SLS estimate is far from OLS. Because the "AR test has correct size even when instruments are weak, and it largely avoids the power asymmetry problem" (Keane and Neal, 2024), I run the AR test as an additional sensitivity analysis to ensure that my baseline results are robust. This provides further confidence in the validity of the main findings of the study.

Fourth, I acknowledge certain limitations of my research design in the context of recent literature on shift-share designs (Goldsmith-Pinkham et al., 2020; Borusyak et al., 2022, 2025). Because my distance variable gives rise to the "incomplete shares" issue, I adopt the guideline provided by Borusyak et al. (2022) of controlling for the sum of shares with year fixed effects and sub-region fixed effects, and find that the results are consistent with main findings. Additionally, I am unable to conduct a special "exposure-robust" approach of simply running a particular shift-level 2SLS estimation in the context of my country-year-level data. These caveats need to be taken into account in relation to interpreting the results of the study.

3. Results

3.1 Economic effects of fertilizer consumption

I begin with an exploration of the relationship between agricultural fertilizer consumption and cereal yields. Across the first four columns of Table 1, the OLS estimates indicate that a 10 per cent increase in the use of fertilizer led to a 0.31 per cent increase in cereal yields, with estimated elasticities ranging between 0.03 and 0.13 across different specifications. While these estimates highlight a strong relationship between agricultural inputs and yields, they suffer from omitted variable bias and attenuation bias as mentioned in the preceding section.

To account for the endogeneity of fertilizer consumption, I apply the IV approach. My first-stage regression results in column (6) of Table 1 show that a 10 per cent decrease in the global price shocks interacted with the inverse of the agriculture-weighted average cost-distance to N fertilizer production site results in a 6.9 per cent increase in the consumption of fertilizers. This estimate is statistically significant at the 1 per cent level, with a Kleibergen–Paap F-statistic of 17.24. To illustrate the economic significance of this estimated parameter, I select two countries that lie one standard deviation above and below the cost-distance measure: Malawi and Bangladesh, respectively. For example, if there is a 10 per cent negative price shock to global fertilizer prices, my first-stage regression coefficients imply that fertilizer use increases by 1.45 kg/ha in Malawi and by 8.24 kg/ha in Bangladesh. These estimates are both economically and statistically meaningful, and are in line with literature (McArthur and McCord, 2017).

My 2SLS estimates indicate a positive and strong relationship between fertilizer consumption and cereal yields. Column (7) of Table 1, which accounts for weather controls, demographics, country and year fixed effects, shows that a 10 per cent increase in agricultural fertilizer consumption led to a 3.3 per cent increase in cereal yields. Economically, this estimate corresponds to an increase in cereal yields of approximately 79.86 kg/ha. For additional context, I note that a 3.3 per cent increase in cereal yields translates to approximately 42.62 kg/ha in Malawi and 91.07 kg/ha in Bangladesh, respectively.

It is worth pointing out that the slope coefficients increase in magnitude from the OLS specification to the 2SLS estimation procedure. I believe this is not surprising for two main reasons. First, fixed effect estimates suffer from attenuation bias, especially in settings that involve the use of aggregate agri-

Table 1. Impact of agricultural fertilizer use on cereal yields.

	Dependent variable (kg/ha):						
	OLS ln cereal yields				First stage ln fertilizer		2SLS ln cereal yields
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
ln fertilizer (kg/ha)	0.1384^{***}	0.0368^{**}	0.0368^{**}	0.0308^{**}			0.3309^{***}
	(0.0184)	(0.0164)	(0.0164)	(0.0146)			(0.0575)
Share of global fertilizer price/ Cost-adjusted distance					-0.9663^{***}	-0.6976^{***}	
					(0.1051)	(0.1680)	
Weather controls	No	No	Yes	Yes	No	Yes	Yes
Additional controls	No	No	No	Yes	No	Yes	Yes
Year fixed effects	No	Yes	Yes	Yes	Yes	Yes	Yes
Country fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	3,706	3,706	3,706	3,706	3,706	3,706	3,706
Kleibergen–Paap F-statistic					84.51	17.24	
Adjusted R-squared	0.8311	0.8806	0.8807	0.8864	0.8572	0.8663	0.8852

Notes: Share of global fertilizer price is the ratio between global fertilizer price index and natural gas prices. Cost-adjusted distance is each country's cost-distance to the nearest fertilizer production site, weighting each grid cell within a country by the percentage of the cell planted to staple crops. Additional controls include agricultural land (% of land area), life expectancy at birth (years), total fertility rate (births per woman) and agricultural machinery (tractors per 100 sq. km of arable land). Standard errors (in parentheses) are clustered by country across all specifications. *** indicates significance at the 1 per cent level, ** indicates significance at the 5 per cent level and * indicates significance at the 10 per cent level. The t-statistic from the second-stage regression of 5.76 gives the Anderson–Rubin (AR) test of $H_0 : \beta = 0$, and a valid confidence interval of [0.21, 0.44] obtained by inverting the AR test.

cultural data across countries belonging to different income levels, resulting in measurement error (Jerven 2010; Paudel and Crago, 2021). Second, a potential violation of the exclusion restriction may induce larger 2SLS slope coefficients. To the extent that omitted variables are correlated to the instrument, the documented effect of fertilizers on yields might instead be the effect of omitted variables on yields. I, however, find that my 2SLS estimates are robust to including controls for exchange rates to the dollar. For example, Table A1 shows that the first-stage regression involves a Kleibergen–Paap F-statistic of 35.29, and the elasticity of cereal yields with respect to fertilizer consumption is 0.22 with a statistical significance at the 1 per cent level. This gives me further confidence that the exclusion restriction is not violated through having fertilizer prices correlated to global business cycles.

I further document clear patterns of heterogeneity across continents, decades and income levels. First, I break down my IV estimates across continents to explore geographical heterogeneity in yield effects of fertilizer consumption. Table A2 presents these results for Africa, Asia, Europe and Americas, respectively.[4] These findings show that positive gains in cereal yields from fertilizer consumption are mostly driven by countries in Africa and Europe, although the estimated impact in other continents is positive in magnitude. Columns (2) and (6) show that a 10 per cent increase in agricultural fertilizer consumption led to a gain in cereal yields of 2.73 per cent in Africa and of 3.86 per cent in Europe.

Second, I explore heterogeneity in yield gains across countries belonging to different income levels classified by the World Bank: high-income, upper-middle-income, lower-middle-income and low-income. Table A3 shows that increases in yield in response to fertilizer consumption are positive and statistically significant across all four income sub-groups. It is worth noting, however, that the estimated elasticity parameter in high-income countries is much larger compared to low-income countries. For example, Columns (2) and (8) show that a 10 per cent increase in fertilizer consumption led to a 6.7 per cent increase in cereal yields in high-income countries and a 2.84 per cent increase in low-income countries. This is important because Marenya and Barrett (2009) argue that poorer farmers are likely to cultivate soils deficient in soil organic matter, causing fertilizer interventions to exacerbate income inequality. While I do not investigate changes in income inequality, my findings indicate that gains in cereal yields are more visible in high-income countries compared to low-income counterparts. Third, I show that positive effects of fertilizer consumption on cereal yields persist across decades. These consistent findings across time in Table A3 suggest that the relationship between fertilizer consumption and cereal yields is strong and robust.

I also evaluate other key agricultural and economic indicators to investigate the overall effects of fertilizer consumption. Although I do not have data on crop-specific fertilizer applications, I evaluate the impact of fertilizer

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[4] Due to small sample size concerns, I do not break down estimates across North and South America.

consumption on yields of four specific crops: maize, potato, rice and wheat. Table A4 shows that elasticities of crop-specific yields with respect to fertilizer consumption are positive and statistically significant, supporting the main results presented above. In addition, I delve into changes in GDP per capita and agricultural value from the use of fertilizers. Table A5 illustrates that a 1 per cent increase in fertilizer consumption led to a 9.76 per cent increase in GDP per capita and a 4.51 per cent increase in agricultural value per worker. Overall, these results provide strong evidence that fertilizer use resulted in economic development through gains in yields, GDP per capita and agricultural value.

Before I delve into the environmental effects of fertilizer consumption, I acknowledge that the heterogeneity in the effects of fertilizers on agricultural variables of interest (such as yields) across space and time may possibly reflect the presence of nonlinear effects. This further brings about concerns related to the role of unobserved heterogeneity that can affect the validity of the IV approach. Solutions to these complex empirical issues, critical for internal validity of research designs, are ongoing research topics in applied econometrics (Mogstad and Torgovitsky, 2024), and are beyond the scope of this study. I, therefore, believe that the interpretation of our IV estimates is subject to these caveats.

3.2 Environmental effects of fertilizer consumption

I explore environmental effects of fertilizer consumption in two ways. First, I focus on agricultural nitrous oxide emissions and methane emissions. This is important because scientists acknowledge the linkage between rates of nitrogen fertilizer application and GHG emissions (Williams and Shumway, 2000; Snyder et al., 2009; Chataut et al., 2023). To the extent that yields increase in response to higher consumption of agricultural fertilizers, I hypothesize that these emissions increase from fertilizer use. Second, I explore agricultural freshwater withdrawals and WFs of crops. Notably, overuse and low efficiency in applying chemical fertilizers and pesticides are associated with larger values of crop WFs Xu et al. (2019). While these indicators help assess water, food sustainability and agricultural freshwater appropriation, I know relatively little about the degree to which fertilizer use results in these environmental externalities. For example, if an increase in cereal yields from high fertilizer consumption exists at the cost of large freshwater withdrawals and volumes of water consumption, these subsequent environmental changes in response to agricultural inputs have implications on sustainable development (Paudel and Crago, 2021).

I begin with an examination on agricultural nitrous oxide emissions and the total amount of agricultural freshwater withdrawals. Column (4) of Table 2 illustrates that a 10 per cent increase in the use of fertilizers led to a 3.09 per cent increase in agricultural nitrous oxide emissions over a 15-year long period from 2006 to 2020. I note that this effect is positive (0.31) for the entire sample but not statistically significant. I also do not find a significant relation-

Table 2. Environmental impact of agricultural fertilizer use.

	Dependent variable (kg/ha):							
	ln agricultural nitrous oxide (thousand metric tons of CO_2 equivalent)				ln water withdrawal (billion cubic meters)			
	OLS (1)	2SLS (2)	1990–2005 2SLS (3)	2006–2020 2SLS (4)	OLS (5)	2SLS (6)	1990–2005 2SLS (7)	2006–2020 2SLS (8)
ln fertilizer (kg/ha)	0.0685***	0.3104	−0.5501	0.3091***	0.0376***	1.5288***	2.5423***	−0.0812−0.0812
	(0.0155)	(0.1885)	(0.6112)	(0.0808)	(0.0140)	(0.0945)	(0.1341)	(0.1216)
Weather controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Additional controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Country fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Notes: Additional controls include agricultural land (% of land area), life expectancy at birth (years), total fertility rate (births per woman) and agricultural machinery (tractors per 100 sq. km of arable land). Standard errors (in parentheses) are clustered by country across all specifications. *** indicates significance at the 1 per cent level, ** indicates significance at the 5 per cent level and * indicates significance at the 10 per cent level.

ship between fertilizer consumption and nitrous oxide emissions in the first fifteen periods of the sample, allowing me to conclude that the problem of emissions linked with fertilizers has become worse in recent decades. I believe multi-year period level analysis can reveal potential structural change in the agricultural sector (such as the adoption of best management practices to minimize agricultural pollutants) that can, in turn, affect the linkage between fertilizer consumption and nitrous oxide emissions.

In relation to the amount of freshwater withdrawals for agricultural purposes, I find a strong and positive relationship. My IV specification in Column (6) indicates that a 10 per cent increase in the use of fertilizers led to a 15.29 per cent increase in freshwater withdrawals during the entire sample period. I, however, observe in Table A6 that the effects of fertilizer consumption on agricultural methane emissions and agricultural share of freshwater withdrawals (in terms of percentage) are not statistically distinguishable from zero. These estimates provide sufficient evidence to conclude that not all environmental indicators exacerbate from fertilizer consumption, although the environmental effects of fertilizers on agricultural nitrous oxide emissions and total freshwater withdrawals are strong and both economically and statistically significant.

I further explore geographical heterogeneity in fertilizer-induced changes in agricultural nitrous oxide emissions and freshwater withdrawals. Table 3 breaks down our IV estimates for Africa, Asia, Europe and Americas, respectively. I observe two specific patterns from Panel A. First, the estimated increase in agricultural nitrous oxide emissions from fertilizers is the largest in Asia (with an elasticity of 1.64). Second, I find a strong decrease in agricultural nitrous oxide emissions from fertilizers in Europe. While a clear identification of the channel behind this documented effect in Europe is beyond the scope of this study, I speculate that the adoption of field-level best management practices in Europe has escalated in the last two decades in light of policy discussions around climate change mitigation. For example, improvements documented in the European setting have been attributed to agricultural policy targeted at the environment, improved environmental legislation, and new market opportunities (Stoate et al., 2009).

Panel B of Table 3 presents IV estimates on the effects of fertilizer consumption on agricultural freshwater withdrawals across Africa, Asia, Europe and Americas. I find that the estimated impact of fertilizers on freshwater withdrawals is driven by countries in Africa (with an elasticity of 2.58) and South and North America (with an elasticity of 2.12). Columns (2) and (8) show that a 10 per cent increase in the use of fertilizers led to a 25.89 per cent increase in freshwater withdrawals in Africa, and a 21.26 per cent increase in South and North America. These estimates are statistically significant at the 1 per cent level. Similar to Panel A, Panel B shows that the effect of fertilizers on freshwater withdrawals in Europe is negative, but statistically insignificant.

Without making any causal claims, I characterize regions with higher elasticity values as those with higher baseline values of pollutants. This line of reasoning is similar in the context of water pollution from fertilizers. For

Table 3. Heterogeneous environmental impact of agricultural fertilizer use across geographical regions.

	Dependent variable:							
	Africa		Asia		Europe		Americas	
	OLS (1)	2SLS (2)	OLS (3)	2SLS (4)	OLS (5)	2SLS (6)	OLS (7)	2SLS (8)
	Panel A: ln agricultural nitrous oxide (thousand metric tons of CO_2 equivalent)							
ln fertilizer (kg/ha)	0.0137	−0.0202	0.0954**	1.6415***	0.1948***	−1.0426**	0.1551***	0.2684
	(0.0093)	(0.4670)	(0.0353)	(0.4656)	(0.0318)	(0.4258)	(0.0404)	(0.4629)
Weather controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Additional controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Country fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Panel B: ln water withdrawal (billion cubic meters)							
ln fertilizer (kg/ha)	0.0024	2.5887***	0.0642***	0.5876	0.0350	−1.3142	0.1286	2.1259***
	(0.0125)	(0.5230)	(0.0198)	(0.4210)	(0.0688)	(0.8187)	(0.0777)	(0.3662)
Weather controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Additional controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Country fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Notes: Additional controls include agricultural land (% of land area), life expectancy at birth (years), total fertility rate (births per woman) and agricultural machinery (tractors per 100 sq. km of arable land). Standard errors (in parentheses) are clustered by country across all specifications. *** indicates significance at the 1 per cent level, ** indicates significance at the 5 per cent level and * indicates significance at the 10 per cent level.

example, higher nutrient pollution elasticity estimates with respect to fertilizers resulting in eutrophication in regions such as the Upper Mississippi River Basin tend to have higher historical fluxes (Sinha et al., 2017). My findings on the geographical heterogeneity of estimates highlight that areas with high estimated elasticity values will benefit more from fertilizer management programs. The regulation involving nutrient management plans in Wisconsin is a case in point. I believe that such areas will experience larger improvements in environmental indicators in response to a reduction in agricultural fertilizer consumption.

Finally, I investigate the environmental impact of agricultural fertilizer use on WF of crops. I make use of four different country-level annual averages of unit WFs (cubic meters per ton) for my empirical analysis: green unit WFs, blue unit WFs from capillary rise, blue unit WFs from irrigation and the sum of the green and blue unit WFs. Table 4 breaks down my IV estimates for WF of all crops combined in Panel A, and cereal-specific WF in Panel B. Across all the columns pertaining to 2SLS estimates, I find that the impact of fertilizer consumption on different indicators of crop WFs is not statistically distinguishable from zero. I find a similar observation when I look into WFs only for cereals in Panel B. I, therefore, do not have sufficient evidence to claim that higher fertilizer consumption results in crop production in an unsustainable manner.

4. Discussion

4.1 Comparison to studies

The majority of studies focused on environmental implications of agricultural inputs make use of *ex ante* simulation models (Thorp et al., 2007; Gowda et al., 2008; Iho and Laukkanen, 2012; Hendricks et al., 2014; Bostian et al., 2015; Pozzer et al., 2017; Schulte-Uebbing et al., 2022). To the best of my knowledge, this study is similar in spirit to Paudel and Crago (2021) and McArthur and McCord (2017), in which the authors construct empirical models using observed data (as opposed to simulated data) on agricultural fertilizer use. As such, I compare my estimates with findings from these two studies to provide additional context to our contributions.

First, Paudel and Crago (2021) aggregate both fertilizer and water quality observations at the watershed level to empirically tease out the relationship between nitrogen and phosphorus fertilizers and subsequent concentrations of nitrogen and phosphorus pollutants in water sites across the USA over a 55-year time period from 1951 to 2005. While they do not instrument for agricultural fertilizer use, their fixed effects OLS estimates illustrate that a 10 per cent increase in the use of nitrogen and phosphorus fertilizers leads to a 1.52 per cent increase in the concentration of nitrogen and a 1.37 per cent increase in the concentration of phosphorus across watersheds (Paudel and Crago, 2021). Although I do not investigate water quality effects of agricultural fertilizer consumption, my OLS estimates for a variety of outcome variables are much

Table 4. Environmental impact of agricultural fertilizer use on WF of crops.

	Dependent variable: ln WF (cubic meters per ton)							
	Green		Blue 1		Blue 2		Total	
	OLS (1)	2SLS (2)	OLS (3)	2SLS (4)	OLS (5)	2SLS (6)	OLS (7)	2SLS (8)
	Panel A: All crops							
ln fertilizer (kg/ha)	0.0159*	−0.2831	0.0213	0.1683	−0.0454**	−0.1499	0.0055	−0.3698
	(0.0089)	(0.2793)	(0.0178)	(0.5759)	(0.0199)	(0.5791)	(0.0082)	(0.2315)
Weather controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Additional controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Country fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Panel B: Cereal only							
ln fertilizer (kg/ha)	0.0206	0.5363	0.0312	−0.5954	−0.0526	0.5924	0.0186	0.6234
	(0.0272)	(1.1119)	(0.0437)	(1.6192)	(0.0565)	(1.2528)	(0.0273)	(1.0900)
Weather controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Additional controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Country fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Notes: WF variable definitions are based on Mialyk et al. (2024). Green refers to green unit WF, blue 1 refers to blue unit WF from capillary rise, blue 2 refers to blue unit WF from irrigation and total refers to the sum of green and blue unit WFs. Additional controls include agricultural land (% of land area), life expectancy at birth (years), total fertility rate (births per woman) and agricultural machinery (tractors per 100 sq. km of arable land). Standard errors (in parentheses) are clustered by country across all specifications. *** indicates significance at the 1 pre cent level, ** indicates significance at the 5 pre cent level and * indicates significance at the 10 pre cent level.

smaller in magnitude. Two caveats are worth highlighting, however. First, my unit of analysis is at the country level. Second, I employ 2SLS estimation, which is beyond the scope of Paudel and Crago (2021). Overall, my findings are in line with Paudel and Crago (2021) in that environmental externalities from agricultural fertilizer consumption can be large, and future research may benefit from quantifying environmental consequences of agricultural inputs in different settings.

Second, McArthur and McCord (2017) use country-level data on fertilizers, yields and other economic indicators in 5-year intervals using a similar identification strategy to conclude that agricultural productivity is a key driver of structural transformation. Although my econometric model is similar to McArthur and McCord's (2017), my research objectives are different. First, I quantify environmental consequences of agricultural fertilizer consumption. Second, I present heterogeneity in both agricultural and environmental outcomes across geographical locations, decades and income categories. My estimates do not imply that countries should simply avoid fertilizers to minimize environmental degradation. Rather, my findings fill the gap in prior literature, focused on economic effects of agricultural inputs, that has largely ignored environmental implications.

4.2 Economic and policy implications

These results provide substantial evidence to conclude that while fertilizers enhance economic gains through increased yields and GDP per capita, they create environmental damages through a rise in nitrous oxide emissions and freshwater withdrawals. To illustrate the economic significance of fertilizer-induced damages on the environment, I combine my estimated agricultural nitrous oxide emission elasticity with statistics based on global chemistry-climate models. Specifically, Pozzer et al. (2017) show that a 50 per cent change in agricultural emissions (notably the release of nitrogen from fertilizer use in air) is associated with air pollution-related annual deaths of approximately 250,000 people around the world. Applying my emission elasticity of 0.31 to the model from Pozzer et al. (2017), I find that a 10 per cent increase in fertilizer consumption causes an increase in mortality attributable to air pollution of approximately 15,450 annual deaths worldwide through increased agricultural nitrous oxide emissions. I argue that the true effects of fertilizer consumption on mortality through a rise in nitrous oxide emissions are likely much larger in magnitude, given that global nitrogen fertilizer use has increased eight-fold over the last 65 years (Lu and Tian, 2017).

From a policy perspective, the supply of sufficient food without hurting the environment is important. Rich agronomic literature concludes that chemical fertilizer overuse ends up polluting air instead of boosting crop growth (Xu et al., 2019). As such, it is imperative that one pays special attention to both levels of fertilizer consumption and efficient usage of agricultural inputs. Several complementary actions can enhance yields and preserve the environment (Quiñones et al., 2007; Xu et al., 2019; Paudel and Crago, 2021; Schulte-Uebbing et al., 2022). Some of these actions involve the application of slow-release fertilizers, the adoption of nutrient management techniques such as soil testing and balanced fertilization, and a careful consideration of fertilization timing, re-distribution of N inputs and the recycling of nutrients. My estimates are useful for benefit-cost analyses that assess agro-environmental policies aimed at mitigating climate change.

5. Concluding remarks

In this article, I investigate the relationship between fertilizer consumption, agricultural productivity and environmental pollution using cross-country panel data. To account for the endogeneity of agricultural fertilizer use, I interact global fertilizer price shocks with the inverse of each country's cost-distance to the nearest fertilizer production site to construct a valid IV. My first-stage regression estimate illustrates that a 10 per cent decrease in the global price shocks interacted with the inverse of the agriculture-weighted average cost-distance to N fertilizer production site results in a 6.9 per cent increase in the consumption of fertilizers.

I also show that a 10 per cent increase in the use of fertilizers led to a 3.3 per cent increase in cereal yields (approximately 79.86 kg/ha increase), with clear patterns of heterogeneity across continents, decades and income levels. I further find that a 10 per cent increase in the use of fertilizers induced a 3.09 per cent increase in agricultural nitrous oxide emissions over a 15-year long period from 2006 to 2020, and a 15.28 per cent increase in water withdrawals for agricultural purposes over the entire sample period. I also note that the effects of fertilizer consumption on four different indicators of crop WFs, which assess agricultural water consumption and productivity, are not statistically distinguishable from zero.

My findings conclude that fertilizers enhance economic gains through increased yields, but at the same time create environmental damages through a rise in nitrous oxide emissions and freshwater withdrawals. It is, however, beyond the scope of this study to determine the extent to which environmental pollution from fertilizer application results in spatially heterogeneous economic damages. I believe that future researchers can make use of my estimated externalities from fertilizer use to generate country-specific economic damages associated with agricultural nitrous oxide emissions.

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Supplementary data

Supplementary data are available at *ERAE* online.

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