

# Fixing Nitrogen

## Agricultural Productivity, Environmental Fragility, and the Role of Subsidies

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## Abstract

Nitrogen fertilizer is essential for boosting agricultural yields and food production. However, agricultural subsidies often drive the inefficient application of fertilizer, leading to significant costs for farms, the environment, and economies. Scientific evidence indicates that nitrogen pollution has exceeded safe planetary boundaries, making it one of the world's largest externalities. Yet, the global economic costs and consequences of subsidized nitrogen fertilizer use remain poorly understood. This paper combines data on subsidies, satellite-derived measures of crop productivity, nitrogen usage, water quality, and spatial and administrative data sets to provide globally comprehensive empirical estimates of the long-term costs of fertilizer use and the role of subsidies. The results show that in regions with large input subsidies, nitrogen overapplication diminishes crop

productivity returns and increases nitrogen runoff into waterways, with lasting implications for human health and labor productivity. More than half of global agricultural production occurs in areas with high subsidized nitrogen use, where the marginal benefit of additional fertilizer is negative. This indicates significant potential to reduce fertilizer use without adversely affecting crop yields. Globally, up to 17 percent of nitrogen pollution in water is linked to inefficient input subsidies, contributing to hypoxic zones and harmful algal blooms. Conversely, decoupled subsidies not tied to production reduce these harmful spillovers. These findings underscore the enduring consequences of nitrogen fertilizer, how well intentioned but poorly designed subsidies can aggravate nitrogen waste, and the potential of policies to pave the path to reform.

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Fixing Nitrogen:  
Agricultural Productivity, Environmental Fragility, and the Role of  
Subsidies

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## 1. Introduction

There are few innovations that have transformed the world as much as nitrogen. Since the start of the 20th century, humans have been successful at making *'Brot aus Luft'* or 'bread from air' by transforming atmospheric nitrogen in the air into ammonia, a form of reactive nitrogen which plants can use. A hundred years since the ingenious experiment in nitrogen fixation by Haber and Bosch, nitrogen has been poured into the ground as fertilizer. One result of the experiment is already clear. It has more than doubled the global rates of nitrogen fixation, enabled a 30–50 percent increase in yields, and supported the lives of several billion people who otherwise might have died prematurely, or never been born at all (Erisman et al. 2008; Stewart et al. 2005).

The ability to produce fertilizers at scale, coupled with large fertilizer subsidies, has led to a steady increase in the consumption of nitrogenous fertilizers. Since the 1960s, nearly all of the growth in fertilizer use has been in Asia, particularly in China and India. This coincides with the onset of the Green Revolution, when government policies actively began to support a system of domestic price controls by way of large subsidies that distorted market prices.

In many countries fertilizer subsidies comprise some of the largest expenditure items in government budgets. India currently spends a staggering US\$10 billion to US\$11 billion a year on fertilizer subsidies (Chatterjee, Kapur, Sekhsaria, Subramanain, 2022), roughly five times more than what had been recorded 15 years earlier (Gulati and Banerjee 2015). Nearly 70 percent of this amount is allocated to nitrogen, causing a large gap between global and Indian domestic prices. In China, subsidies to the fertilizer industry averaged almost US\$7 billion per year from 2008 to 2010, substantially depressing fertilizer prices.<sup>2</sup> In Mexico, the government created the Programa de Fertilizantes (Fertilizers Program) in 2019 with an initial budget of around US\$75 million to support and supply smallholder farmers up to 600 kg of fertilizer per year (Ding et al., 2021). In regions like Africa, which accounts for just 1.5 percent of the world's consumption of nitrogen, governments of at least 10 African countries that account for more than half of the region's population currently spend nearly US\$600 million to US\$1 billion annually on subsidies, representing about 14–26 percent of their national budgets allocated for agriculture (Jayne and Rashid 2013; Jayne et al., 2018).<sup>3</sup> These magnitudes, however, obscure the mixed track record in implementation, the vast disparities of fertilizer use across regions and between small and big farmers, and their uncertain effectiveness due to differences in soil composition.

The rationale for the large resources devoted to fertilizer subsidies is often to stimulate agricultural production, benefit poor rural households, stabilize food prices, and boost food security. At the same time, it also provides politicians with a demonstrable way to show support to their constituents.<sup>4</sup> In the developing world, the economic case often rests on perceived market failures that might cause farmers to inefficiently use low levels of fertilizer. For instance, studies suggest that fertilizer markets can be prone to market failure due to high sunk costs of fertilizer producers, high transaction costs associated with poor market infrastructure, low demand by farmers because of liquidity constraints or imperfect information

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<sup>2</sup> In 2015, China took steps to phase out production subsidies for fertilizer by 2017. In 2017, the Chinese Ministry of Agriculture initiated a pilot program to replace chemical fertilizers with organic fertilizer for the production of fruits, vegetables, and tea in 100 counties. Under this program, subsidies are provided to organic fertilizer manufacturers to increase affordability and uptake (Huang, Gulati, and Gregory 2017; Searchinger et al., 2020).

<sup>3</sup> Input subsidy programs in Africa were largely phased out in the 1980s and 1990s but were revitalized in the 2000s. Ten countries currently implement second-generation subsidy programs. Despite recent evidence casting significant doubt on its touted success, Malawi's Agricultural Input Subsidy Program, known as the "Malawi miracle," is considered a watershed moment which sparked resurgence of input subsidies in the other African countries in the mid to late 2000s (Jayne and Rashid 2013; Jayne et al., 2018).

<sup>4</sup> Globally, input subsidies have become instruments of political expediency (Chatterjee, Kapur, Sekhsaria, Subramanain, 2022; Takeshima and Liverpool-Tasie, 2015).

and uncertainty about the returns to fertilizers (Duflo, Kremer, and Robinson 2011; Carter et al. 2013; Abay et al. 2017). In such contexts, economically rational farmers respond to price incentives provided by subsidies and increase their fertilizer application rates.

On the other hand, with exceptionally low prices of fertilizers, subsidies may also encourage farmers to deviate from optimal levels, resulting in an overuse of fertilizers beyond recommended rates (Schultz et al., 1964).<sup>5</sup> It may also lead to a failure to supply the right amount of fertilizer at the right time – a problem that seems to be pervasive in developing countries where technical know-how is low (Duflo, Kremer, and Robinson 2011).<sup>6</sup> This is especially salient for nitrogen fertilizer, which when compared to other fertilizers, calls for greater information to determine the appropriate timing and scale of application. In part, this is because nitrogen in forms available for crops is highly volatile and can leave the soil very quickly.

Subsidized or distorted prices in combination with the inability of farmers to precisely gauge the amount of application needed may result in over application as well as incorrectly timed application (Islam and Beg, 2021). Indeed, several studies show that fertilizer subsidies have increased fertilizer use intensity as well as overuse (Huang, Gulati and Gregory, 2017).<sup>7</sup> Oftentimes, this balance is tilted on the side of nitrogen since it is much more heavily subsidized than other fertilizers.<sup>8</sup>

But like people, plants need a variety of nutrients to thrive. The right mineral fertilizers applied appropriately can alleviate nutrient deficiencies in soils and increase crop yields. While mineral fertilizers provide higher and more plant accessible nutrients, organic minerals also provide carbon, which contributes to healthy soils and better crop productivity (Gram et al., 2020; Barrett and Bevis, 2015). However, subsidy driven applications of nitrogenous fertilizer appear to be causing nutrient imbalances in many regions of the world as farmers apply significantly more nitrogen compared to other primary nutrients like potassium and phosphorous or other secondary and micro-nutrients (Kurdi et al., 2020; Gautam, 2015).

The imbalanced use of fertilizers has created widespread deficiency of secondary and micro-nutrients such as zinc, sulfur, iron, and manganese in the soil that ultimately limits the ability of farmers to use fertilizers profitably (Jayne and Rashid, 2013; Goyal and Nash, 2017; Giné et al., 2019; Kishore et al., 2021) and can also impact the nutritional content of crops and food consumed by people (De Groote et al., 2021).<sup>9</sup> This is of salience in Africa where the variation in soil quality is particularly high (Carter et al. 2015), and where the presence of acidic soils requires secondary and micro-nutrients, organic amendments, and

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<sup>5</sup> With exceptionally low subsidized prices of fertilizers, economically rational farmers respond to price incentives but can end up significantly overusing fertilizers, especially if the technical efficiency of the average farmer is low.

<sup>6</sup> In addition, critics also argue that subsidies can discourage product innovation by fertilizer companies; crowd out commercial market purchases of fertilizers and crowd out productive investments in agricultural research and development (Gulati and Banerjee, 2015). Less commonly cited criticisms include misdiagnosed market failures—for example, using fertilizer subsidy to solve a transport cost problem that would be better addressed by investment in infrastructure (Gautam, 2015; Smale and Thériault, 2018).

<sup>7</sup> For example, some studies have found that the maintenance of low and stable fertilizer prices in China has contributed to its overuse in the past to a “moderate” or a “significant” extent (Cassou et al., 2017).

<sup>8</sup> For example, subsidy regimes in countries like Bangladesh, India, Nepal, and Sri Lanka have been found to incentivize excessive application of urea and underapplication of phosphorus and potassium fertilizers (in India and Nepal), micronutrients, and organic inputs (Islam and Beg, 2021; Kishore et al., 2021; Gulati and Banerjee, 2015; Huang et al., 2017).

<sup>9</sup> Zinc deficiency in soils, for example, is an important constraint to crop production, and the most ubiquitous micronutrient deficiency in crops worldwide. At the same time, zinc deficiency is one of the most common micronutrient deficiencies in humans, with over 2 billion people estimated to be at risk worldwide (Hotz and Brown, 2004). In Malawi, low-zinc soils and maize puts semi-subsistence farming families at risk of zinc deficiency (Chilimba et al., 2012; Bevis, 2018). In Bangladesh, rice farmers with low-zinc soil and low-zinc rice have lower zinc status themselves (Mayer et al., 2007; Bevis, 2018). A recent working paper by Bevis, Kim, and Guerená (2022) finds national-level large-scale evidence on a bounded causal relationship between soil zinc status and child stunting, which is the primary clinical symptom of zinc deficiency, in Tarai Nepal, highlighting the enigma of South Asian micronutrient malnutrition partially driven by soil zinc deficiency.

lime supplements for better soil management (Smale and Theriault, 2018). Blanket recommendations and subsidy programs that heavily focus on nitrogen without careful attention to soil or agronomic conditions can thus fail to address the relevant limiting factors for plant growth specific to local contexts (Smale and Theriault, 2018).<sup>10</sup>

Yet, despite the ubiquity of fertilizer subsidies as an agricultural policy tool and the magnitude of resources devoted to them, little is known about their long-term impacts, or the externalities and waste imposed due to their ineffective use (Gautam et al., 2022). Lopsided subsidies for fertilizers which substantially lower the prices of nitrogen relative to other nutrients can promote inefficient and ineffective use. Such excess use and inefficiencies in application means that not all of the nitrogen that is applied on fields gets absorbed by crops. This is because there is a limit to how much a plant can produce based on nitrogen alone.<sup>11</sup> Due to the unique chemistry of the nitrogen cycle, the remaining excess of reactive nitrogen then gets lost to the surrounding environment in its multiple chemical forms—as nitrites and nitrates polluting the waterways; as anhydrous ammonia or nitrogen oxide negatively impacting air quality; and as nitrous oxide, exacerbating climate change and stratospheric ozone depletion (Kanter 2018).<sup>12</sup>

Using disaggregated grid cell-level datasets on nitrogen fertilizer, yields and water quality, combined with administrative data on subsidies from 1995-2013 covering about 150 countries, the paper highlights these unintended but significant long-term costs of fertilizer subsidies. In doing so, the results focus on how ineffective application of nitrogen fertilizer can hurt agricultural productivity as well as impair freshwater resources.

The rest of the paper is organized as follows. Section 2 describes the data and empirical strategy used in this analysis. Section 3 presents the main results demonstrating the impact of nitrogen fertilizer on agricultural productivity, and pollution in the waterways along with the overall impact of subsidies. Finally, Section 4 concludes with policy implications and discusses the way forward.

## 2. Data and Empirical Strategy

To study the impact of nitrogen fertilizer on agricultural productivity, the paper uses a grid cell-level data set covering the entire world. For the analysis, the land area is split into grid cells measuring 0.5 degrees on each side, which is approximately 56 × 56 kilometers at the equator. The sample period extends from 2000 to 2013. The following equation is estimated at the global scale:

$$\ln(NPP_{it}) = \alpha_1 + \sum_{b=2}^9 \beta_b Q_{it} + X'_{it} \lambda + f_c(t) + \theta_t + \gamma_i + \epsilon_{it} \quad (1)$$

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<sup>10</sup> Due to the heavy focus on urea, studies have shown that the Mali subsidy program failed to address the more limiting factor for crop growth, which in some cases was phosphorus rather than nitrogen (Smale and Thériault, 2018). Similarly, a Tanzania field study that conducted soil testing found that sulfur was deficient in all the plots and remained a critical limiting factor for growth in maize yields. Yet, national fertilizer recommendations mandated by the government did not include sulfur (Harou et al., 2021).

<sup>11</sup> Fertilizers are essential for plant growth but beyond a point, adding more fertilizer may not be able to boost yield.

<sup>12</sup> For this reason, the fallout of nitrogen pollution is considered one of the most important environmental issues of the twenty-first century (Kanter 2018). Recent estimates suggest that nitrogen may be the world's largest global externality, even surpassing carbon (Keeler et al. 2016).

Cells are indexed by  $i$  and years by  $t$ . Thus, the unit of observation is the grid cell-year. Here  $NPP_{it}$  is net primary productivity in gridcell  $i$  in year  $t$ . NPP, which can be measured from satellite imagery, is used to measure agricultural performance following the past literature since it provides a common unit of productivity across different crop types (Zaveri, Russ, and Damania, 2020). NPP is linearly related to the amount of solar energy that plants absorb over a growing season and is measured in grams of carbon per square meter. NPP is combined with a land cover data set developed by the European Space Agency's Climate Change Initiative, which provides information on 37 land cover classes globally at a 300-meter grid. This ensures that plant productivity as measured by NPP is only captured in grid cells that contain significant amounts of agriculture and avoids attributing impacts to forests or other natural habitats.

Data on average annual nitrogen fertilizer used per hectare of cropland is sourced from Lu and Tian (2017). Previous work by McArthur and McCord (2017)<sup>13</sup> finds that a 1 kg/ha increase in fertilizer causes an 8-9 kg/ha increase in yields. This translates to a 10 percent increase in nitrogen fertilizer use, boosting global yields by about 29-32 percent. However, a continuous measure of nitrogen usage can mask heterogeneity in impacts on yields due to the presence of subsidies. This is because although fertilizer subsidies may have enabled fertilizer usage and hence agricultural productivity, subsidies can incentivize farmers to apply more than they need such that the beneficial impacts of nitrogenous fertilizers on productivity can begin to wane beyond a point. To demonstrate the non-linear effects of nitrogen use on agricultural productivity at the global scale, a continuous measure of nitrogen fertilizer use is replaced with indicators for whether the log values of nitrogen usage lie within nine different quantile bins  $Q_{it}$  to assess impacts across the global fertilizer distribution. The quantile coefficients,  $\beta_b$ , are our coefficients of interest. The first quantile is omitted and becomes the reference quantile.

A plethora of other factors can also affect the relationship between nitrogen fertilizer and yields. Weather data taken from the *Terrestrial Air Temperature and Precipitation Version 4.01* compiled by the University of Delaware (Willmott and Matsuura 2001) has been widely used in the economics literature (Dell Jones and Olken 2012, Burke Hsiang and Miguel 2015, among others). This data set provides monthly total precipitation and temperature at a 0.5-degree spatial resolution. Data are available for each month between 1901 and 2014.

Control variables include rainfall and temperature from the *Terrestrial Air Temperature and Precipitation Version 4.01* compiled by the University of Delaware (Willmott and Matsuura 2001). Various fixed effects and time trends are included to isolate the impact of nitrogen fertilizer as much as possible from other factors.  $\theta_t$  are year fixed effects,  $\gamma_i$  are grid cell fixed effects,  $f_c(t)$  are country-specific time trends,  $X'_{it}$  is a vector of other control variables, including precipitation shocks, a quadratic term for mean annual temperature (°C), and log of population. These controls account for baseline differences in yield and other factors that vary by year. These are meant to control for changes in agricultural policies, development levels, input availability, technological levels, and time-invariant factors such as terrain

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<sup>13</sup> The authors utilize the economic geography of fertilizer production and transport costs to countries' agricultural heartlands to construct a time-varying instrument for fertilizer use globally for deriving causal estimates of the impacts of fertilizer on economic growth.

slope, and soil type. Standard errors are clustered at the administrative level to account for spatial and temporal correlation in the disturbance terms.

To the extent that unobservable factors like farmers' agronomic know-how might be correlated with both yields and inputs, the estimation could lead to an underestimation of the impact of increasing fertilizer use on yields, and therefore these results should be interpreted as lower bound estimates.

To account for the varying distribution of nitrogen usage in each region, equation (1) is modified to estimate region level regressions based on regional-specific quintiles. In the regional analysis, five quintiles are used and the middle or third quintile is omitted and becomes the reference quintile. The responsiveness of yield to the first, second, fourth and fifth quintiles are therefore measured relative to quintile three. Note that depending on the spread of the distribution of fertilizer in each region, the third quintile may or may not represent the optimum level of nitrogen.

To estimate the impact of nitrogen fertilizer on water pollution, equation 1 is modified to examine the total impact of nitrogen fertilizer use on water pollution spillovers. The sample period for this analysis extends from 1995 to 2013. A considerable body of literature has attempted to explain how human and environmental changes impact freshwater quality. Many of these pollution elasticities are available for individual countries or case specific studies but have not previously been quantified at the global level for water pollution. This paper employs a global gridded dataset of nitrogen fertilizer and nitrogen pollution in water to calculate the change in water quality for every percentage change in nitrogen fertilizer use.

The following equation is estimated at the global scale where  $i$  denotes grid cell and  $t$  denotes year:

$$\ln(WQ_{it}) = \alpha_1 + \beta_1 \ln(N_{it}) + \mathbf{X}'_{it} \boldsymbol{\lambda} + f_c(t) + \theta_t + \gamma_i + \epsilon_{it} \quad (2)$$

Water quality data is sourced from GEMStat which is a globally harmonized database on freshwater quality developed by UNEP-GEMS, maintained by the International Centre for Water Resources and Global Change (ICWRGC) and hosted by the Federal Institute of Hydrology in Koblenz, Germany ([www.gemstat.org](http://www.gemstat.org)). Data from river monitoring stations in the GEMStat database are used to measure concentrations of nitrogen in rivers. Total nitrogen in water,  $WQ_{it}$ , is measured using a combination of nitrates and nitrites, and aggregated to the 0.5-degree grid to match the resolution of nitrogen fertilizer data,  $N_{it}$ . Various other factors can also affect the relationship between nitrogen fertilizer and water quality. Control variables, including various fixed effects and time trends, are included to isolate the impact of nitrogen fertilizer as much as possible from other factors:  $\theta_t$  are year fixed effects,  $\gamma_i$  are grid cell fixed effects,  $f_c(t)$  are country-specific time trends. Finally,  $\mathbf{X}'_{it}$  is a vector of other control variables, including annual rainfall, temperature, runoff, and log of population. In some specifications, the extensive or intensive margin of land use such as cropped area and yields are also included. Together, these controls account for baseline differences in water quality patterns and other factors that vary by year. These are meant to control for changes in agricultural policies, development levels, input availability, technological levels, and time-invariant factors such as terrain slope, soil type, and distance to coast or water bodies.

To provide a better sense of the overall and direct effect of agricultural subsidies on water resources, analysis is undertaken for the sample of countries for which subsidy data is available. A major challenge with quantifying support in agriculture is the difficulty in obtaining consistent measurements of such support across all developed and developing countries. Agricultural support estimates are obtained from a combined database following Gautam et al. (2022). It is important to distinguish between agricultural supports that are coupled to input use and output levels versus those that are decoupled from production and provided as direct payments to farmers. Coupled subsidies incentivize production and provide direct subsidies on output or input that create incentives to increase output. In contrast, decoupled supports are not linked to production and avoid altering incentives to change input or output levels. Instead, they provide direct income support to producers, thus acting as lump sum subsidies and are less distortionary.

To separate producer support into coupled and decoupled payments, country-level estimates of annual support to agricultural producers from the OECD's Producer Support Estimates (PSE) database data are obtained from the OECD's Composition of Producer Support Estimate tables. These estimates are used to construct coupled and decoupled support as shares of the total value of production. PSE are defined as the annual monetary value of gross transfers from consumers and taxpayers to agricultural producers, measured at the farm gate level, arising from policy measures that support agriculture. They are available for 24 countries and the European Union.

In certain parts of the world, like South Asia and Sub-Saharan Africa, aggregate coupled support can be negative due to the inclusion of market price support, a variable in the database that accounts for trade measures and policies such as export bans which can lead to a net tax on producers, when global (free trade) prices exceed the domestic price. For this reason, three measures of coupled subsidies are used in the analysis. In one variant, market price support is removed to focus only on the portion of the subsidy that amounts to direct producer support. In the second variant, only support on inputs is included, and in the third variant, only market price support is included. This country-level data is then combined with water quality data and the following equation is estimated:

$$\ln(WQ_{ct}) = \alpha_1 + \beta_1 \text{share}(\text{coupled support}_{ct}) + \beta_2 \text{share}(\text{decoupled support}_{ct}) + \theta_t + \gamma_c + \epsilon_{ct}$$

where  $WQ_{ct}$  is total nitrogen in water in country  $c$  and year  $t$  measured by taking the mean value of water quality for all grid cells in a country in a given year. Coupled supports and decoupled supports are estimates of annual Producer Support Estimates from the OECD, separated into those tied to production incentives and those decoupled from output levels. The equation includes country fixed effects,  $\gamma_c$  to account for time-invariant differences between countries, such as geography and climate, as well as year fixed effects,  $\theta_t$ , to account for common time trends. Standard errors are clustered at the regional level to account for spatial and temporal correlation.

Although this analysis provides insight into the association between producer support and water quality, it is not clear whether the estimated effects can be interpreted as causal because levels of producer support are not randomly assigned but rather endogenously determined in response to conditions facing producers and consumers. To partially address this concern, a placebo test is conducted that estimates the effect of future producer support (i.e. PSE in time  $t + 1$ ) on total nitrogen in water. If

producer support levels are determined in response to some omitted variable that also influences water quality directly, we should expect to see a detectable effect of future PSE on water quality today.

### 3. Results

#### Agricultural Productivity

Table 1 presents the impacts on yields across the fertilizer distribution and Figure 1 provides a visualization of the estimates in Table 1 and plots the global response curve. The results show that nitrogen fertilizer can have significant but heterogeneous effects on yields across the fertilizer distribution. The response of yields to increasing levels of nitrogen application gradually rises till it reaches a peak after which it falls, indicating diminishing productivity. This means that yields are increasing but require increasing amounts of nitrogen to achieve this. Going from quantile 1 to quantile 2 (or 7) of nitrogen usage increases yields by about 10 (or 20) percent, but the increase slows down thereafter such that going from quantile 1 to quantile 8 (or 9) increases yields by only 17 (or 13) percent (respectively). Put simply, at low and moderate levels of use, nitrogen fertilizer has the intended beneficial impact on yields, but at high applications, there is a law of diminishing returns whereby extra nitrogen has a diminishing effect on yields.

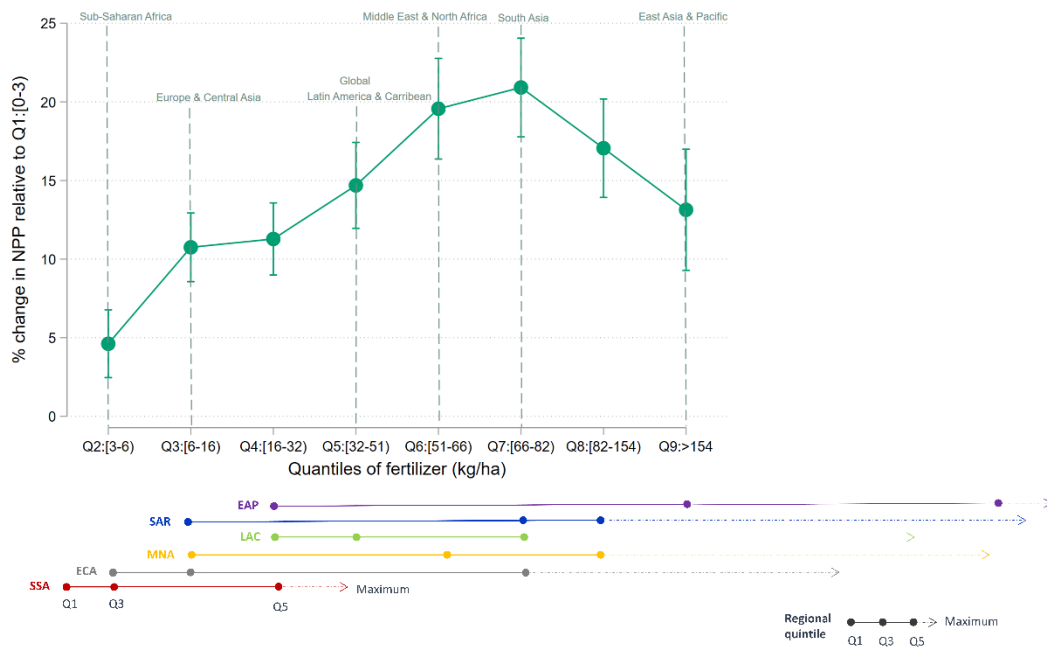
*Table 1 Global response of agricultural yields to quantiles of nitrogen fertilizer (grid cell-level analysis)*

	Log NPP on cropland		
	(1)	(2)	(3)
N fertilizer (Q2)	0.0480*** (0.013)	0.0423*** (0.013)	0.0462*** (0.013)
N fertilizer (Q3)	0.1205*** (0.013)	0.1132*** (0.013)	0.1075*** (0.013)
N fertilizer (Q4)	0.1195*** (0.014)	0.1151*** (0.014)	0.1128*** (0.014)
N fertilizer (Q5)	0.1417*** (0.017)	0.1457*** (0.016)	0.1469*** (0.017)
N fertilizer (Q6)	0.1874*** (0.020)	0.1910*** (0.019)	0.1956*** (0.019)
N fertilizer (Q7)	0.2000*** (0.019)	0.2046*** (0.019)	0.2091*** (0.019)
N fertilizer (Q8)	0.1494*** (0.019)	0.1577*** (0.019)	0.1705*** (0.019)
N fertilizer (Q9)	0.1096*** (0.023)	0.1108*** (0.023)	0.1314*** (0.023)
N	94724	94724	94724
Year FE	Y	Y	Y
Grid cell FE	Y	Y	Y
Country Trends	Y	Y	Y
R-sq	0.927	0.930	0.932
Adj R-sq	0.921	0.924	0.927

Note: Dependent variable is log of NPP in cropland pixels where cropland makes up more than half of the share of the total land area (55%). All regression models include grid cell fixed effects; year fixed effects; country specific trends. Controls for contemporaneous precipitation shocks (i.e. Whether annual precipitation in the grid cell was at least 1 SD higher or lower than the long-run mean of the grid cell), temperature, and population are added in turn in columns 1, 2 and 3 respective with the last column including all controls. Statistical significance is given by +P < 0.10, \*P < 0.05, \*\*P < 0.01, and \*\*\*P < 0.001.

Figure 1 also highlights the median level of nitrogen usage for various regions, with regional response curves depicted in Figure 2 to obtain a more complete picture of the differences in the spread of the nitrogen distribution across the world. Figure 1 shows that regions like East Asia and South Asia are at the high end of the global nitrogen fertilizer distribution, while Sub-Saharan Africa is at the low end of the distribution. South Asia, for example, is operating at the peak global response level, indicating that about half of the areas within these regions are on the decreasing return parts of the global response curve. The median level of nitrogen usage in East Asia is at the 95<sup>th</sup> percentile of the global level of nitrogen usage and is situated on the decreasing part of the global response curve, indicating that much of the region is already facing the brunt of diminishing returns. This is not surprising given the long history of nitrogen fertilizer use in these regions.

Figure 1: Change in agricultural productivity due to nitrogen fertilizer, by quintiles



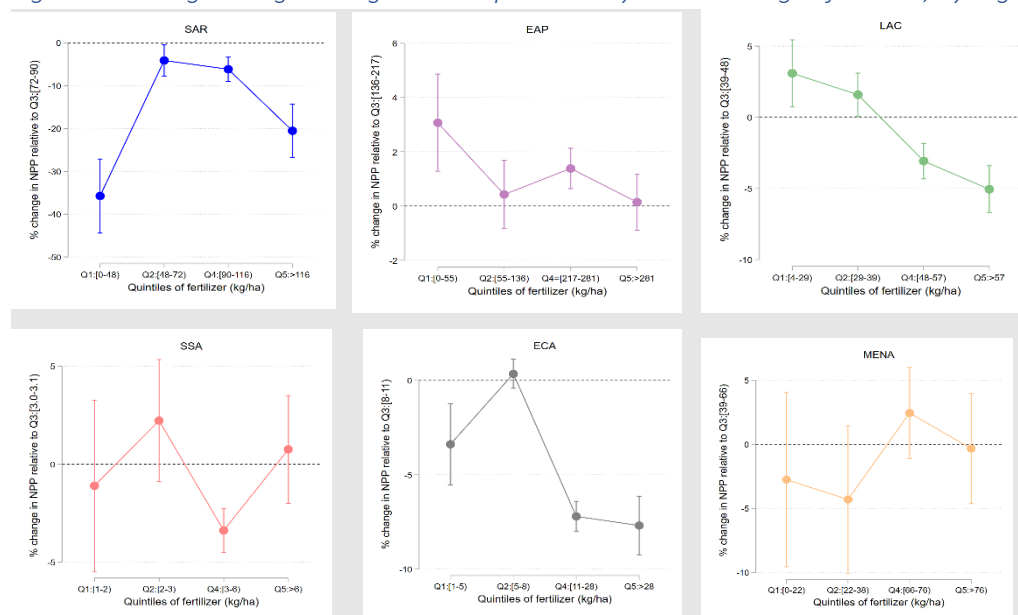
Note: This figure shows point estimates and 95 percent confidence intervals of coefficients obtained for different quantiles of nitrogen fertilizer usage from the second to the ninth quantile relative to the omitted first quantile. Vertical lines indicate where the median values of nitrogen fertilizer usage lie for the global sample, and the different regions. Horizontal lines and dots below the graph indicate the bottom, middle and top region-specific quintiles based on the regional distribution of fertilizer usage. NPP= net primary productivity

On the other hand, the median level of nitrogen usage in Sub-Saharan Africa is only a fraction of the global median. Many of the countries in this region get low yields *and* apply only small amounts of nitrogen to their crops. While a decline in overall fertilizer use would lead to significantly reduced productivity for the region, with potentially serious consequences for food security, blanket recommendations and a sole focus on the application of nitrogenous fertilizers warrant further scrutiny. The responsiveness of yields to nitrogenous fertilizers, in particular, is therefore still uncertain due to differences in soil composition

and acidity of African soils.<sup>14</sup> Balanced and soil-specific fertilizers can go a long way in helping African farmers to maximize their farming ventures' returns on investment.

Figure 2 demonstrates the region-level response curves. In certain regions like Latin America and East Asia and Pacific, the amount of nitrogen usage is high across most of the region and the diminishing returns in the upper quintiles relative to the returns in the middle quintile can be stark. In these regions going from the middle 3<sup>rd</sup> quintile to the lowest 1<sup>st</sup> quintile improves productivity by 3 to 4 percent. Further increases of nitrogen fertilizer use beyond the 3<sup>rd</sup> quintile diminish yields. In regions like South Asia, there are significant spatial disparities across the region with areas of both low and high usage of nitrogen fertilizer. Therefore, going from the middle 3<sup>rd</sup> quintile to the lowest 1<sup>st</sup> quintile or the highest 5<sup>th</sup> quintile of nitrogen usage shows a decrease in productivity of about 35 or 20 percent, respectively. In Europe and Central Asia, both low and high quintiles of nitrogen usage can decrease yields, relative to the middle quintile. The response curves in Sub-Saharan Africa and the Middle East and Africa remain largely noisy. This is perhaps reflective of the vast uncertainty and heterogeneity surrounding yield responses across the African continent.

Figure 2: Change in regional agricultural productivity due to nitrogen fertilizer, by region specific quintiles



Note: This figure shows point estimates and 95 percent confidence intervals of coefficients obtained for different quintiles of nitrogen fertilizer usage from the first to the fifth quintile relative to the omitted third quintile.

Overall, these results demonstrate that crop production is becoming less efficient at using nitrogen fertilizer. This is qualitatively consistent with field-level agronomic data that also show decreasing returns to nitrogen fertilizer use. Underlying these results is the critical metric of nitrogen use efficiency, an indicator that describes how much of the fertilizer that is used reaches a harvested crop. A variety of studies have tried to evaluate the exact value of nitrogen use efficiency. In India, studies suggest that only 32 percent is absorbed by plants, compared with 52 percent in Europe and 68 percent in Canada and the United States (Zhang et al. 2015). A recent global meta-analysis finds that nitrogen use efficiency has decreased by 22 percent since 1961 and remains stubbornly low at around 46 percent (Zhang et al., 2021). According to an average of 13 global databases, of the 161 teragrams of nitrogen applied to agricultural

<sup>14</sup> Studies suggest that in acidic soils root growth can be stunted and essential nutrients can be strongly bound in the soil solution, rendering them unavailable to plants. However, with adequate soil management (e.g., liming), fertilizer use can be profitable on soils that would otherwise be acidic (Jayne and Rashid, 2018).

crops, only 73 teragrams of nitrogen made it to the harvested crop (Zhang et al. 2021). This means that almost two-thirds of all nitrogen applied to crops gets wasted. The European Union Nitrogen Expert Panel recommends nitrogen use efficiency of around 90 percent as an upper limit, indicating that a vast amount of the nitrogen that is poured into fields is getting wasted.

In sum, there exists an optimum level of nitrogenous fertilizer application that can vary with field conditions and combinations of other inputs. Policies intended to help increase productivity but without careful consideration for local conditions can inadvertently exacerbate the unbalanced and ineffective use of nitrogenous fertilizers. Subsidizing the wrong type of fertilizer or subsidizing fertilizers in areas where fertilizer use is already well above levels that maximize its value can impose substantial costs on productivity and provide lower returns to farmers, leading to wasted fertilizers and government spending.

### Water Quality

The massive increase in nitrogen fertilizers has, in turn, impacted many of the world's water bodies. As described earlier, because of excess use and inefficiencies in application, not all nitrogen applied on fields is absorbed by crops. Runoff of excess nitrogen increases concentrations of nitrate and nitrite in the waters. These can lead to cyanobacteria-related algal blooms. Conspicuous to the eyes, cyanobacteria can be deadly— they can emit neurotoxins and hepatotoxins such as microcystin and cyanopeptolin, which are toxic to humans, animals, and other aquatic life (Damania et al., 2019). Previous remote sensing analysis has shown that the world experienced on average nearly two such episodes of massive cyanobacteria-related algal bloom per year in 421 of the world's largest lakes between 2002 and 2012, highlighting the recurring problem of fertilizer overuse, agricultural runoff and subsequent deterioration in water quality (Damania et al., 2019).<sup>15</sup> Large algal blooms can devastate ecosystems, often resulting in hypoxia or dead zones, a condition that arises when water bodies lack sufficient oxygen. The legacy effects of nitrogen pollution on the environment can also endure decades after nitrogen inputs have ceased, with long time lags between the adoption of conservation measures and any measurable improvements in water quality (Van Meter et al. 2018; Basu et al., 2022). Not surprisingly, according to the FAO, in many countries the biggest source of water pollution today is agriculture — not cities or industry — while worldwide, the most common chemical contaminant found in groundwater aquifers is nitrate from farming (Mateo-Sagasta et al., 2017).

The results in Table 2 show that an increase in agricultural fertilizer use leads to substantial deterioration in water quality such that there is a strong and positive impact of nitrogen fertilizer use on the concentration of nitrogen in water. These estimates are robust across multiple specifications with elasticities ranging from 0.16 to 0.34, suggesting that a 10 percent increase in nitrogen fertilizer leads to a 1.6 to 3.4 percent increase in the concentration of nitrogen pollutant. These pollution elasticities are consistent with estimates from prior econometric literature that find adverse effects of nitrogen fertilizer use on water quality in country-specific settings (Paudel and Crago, 2021).<sup>16</sup>

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<sup>15</sup> Although the dominant source of nitrogen pollution in the water is the agriculture sector, many other diverse sources also contribute to its proliferation from livestock waste, fossil fuel combustion to untreated wastewater. As cities grow and become denser, the threats of nitrogen leaching from below-ground septic tanks, human sewage, urban wastewater, and urban stormwater runoff are also expanding.

<sup>16</sup> The authors construct an empirical model on determinants of ambient water quality using over 2.9 million pollution readings and find that a 10 percent increase in the use of nitrogen fertilizers (kg) leads to a 1.47 percent increase in the concentration of nitrogen (mg/l) across the U.S. water sites.

Table 2 Impact of nitrogen fertilizer on water pollution (grid cell-level analysis)

	Log (Total nitrogen in water)			
	1	2	3	4
log(Nitrogen in grams per sq m)	0.1686** (0.073)	0.2745** (0.108)	0.3437* (0.197)	0.3466** (0.169)
N	1461	1343	1037	1037
Grid Cell FE	Y	Y	Y	Y
Country-Year FE	Y	Y	Y	Y
Share Cropland		Y		Y
Log NPP			Y	Y
Adj. Rsq	0.703	0.706	0.759	0.759
RMSE	0.606	0.609	0.553	0.553

Notes: Dependent variable is log of total nitrogen water pollution in a grid cell. All regression models include grid cell fixed effects; country-year fixed effects; controls for precipitation, temperature, runoff, and log population. In some specifications both the extensive (share of cropland) and intensive margins of agriculture (Log of NPP on cropland) are included as controls. Statistical significance is given by +P < 0.10, \*P < 0.05, \*\*P < 0.01, and \*\*\*P < 0.001.

Finally, Table 3 and Figure 3 demonstrate the overall impact of subsidies on total nitrogen in water. The results show that coupled producer support has a positive and significant impact on nitrogen pollution levels across various definitions of coupled support. Further, the results show that even when the

Table 3 Impact of agricultural subsidies on water pollution (country-level analysis)

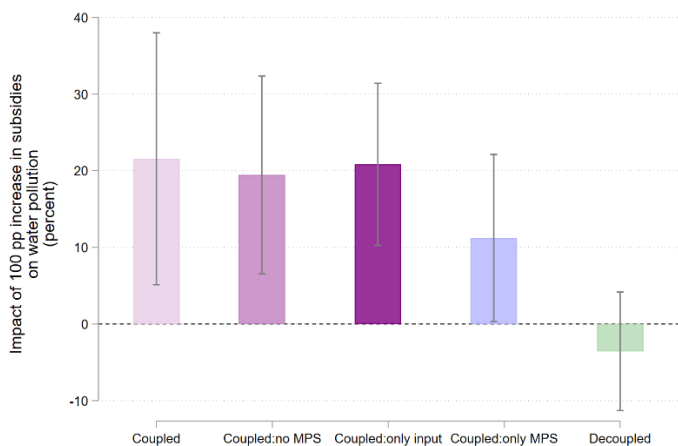
X: Share of Value of Production	Y: IHS(Total nitrogen in water)				
	1	2	3	4	5
Decoupled PSE	-0.0122 (0.016)	-0.0254+ (0.014)	-0.0245+ (0.015)	-0.0249+ (0.014)	-0.0264 (0.016)
Decoupled PSE [t+1]					0.0011 (0.016)
Coupled PSE (def1)	0.0065* (0.003)				
Coupled PSE (def2)		0.0143* (0.006)			
Coupled PSE (def3)			0.00572+ (1.71)		
Coupled PSE: Variable input support				0.0733** (0.022)	0.0861** (0.032)
Coupled PSE: Variable input support [t+1]					-0.0192 (0.034)
N	117	117	117	117	117
Country FE	Y	Y	Y	Y	Y
Year FE	Y	Y	Y	Y	Y
R-sq	0.957	0.956	0.956	0.958	0.958
Adj R-sq	0.937	0.934	0.935	0.937	0.936

Notes: Dependent variable is inverse hyperbolic sine of total nitrogen water pollution in a gridcell. All regression models include country fixed effects and year fixed effects. Def1 includes all coupled support, Def2 includes coupled support minus market price support, Def3 includes only market price support. Statistical significance is given by +P < 0.10, \*P < 0.05, \*\*P < 0.01, and \*\*\*P < 0.001. Following Bellemare and Wichman (2020), the coefficients are converted into elasticities as follows:  $\hat{\epsilon}_{yx} =$

$$\hat{\beta}_x \frac{\sqrt{y^2+1}}{y}$$

definition of coupled subsidies is restricted to input support, the magnitude of the effect on pollution remains stable and similar to the magnitudes that correspond to broader definitions of coupled subsidies. A 100 percentage point increase in the share of coupled support for inputs leads to about a 20 percent increase in nitrogen pollution in water. These effects are quantitatively meaningful and amount to input support explaining approximately 17 percent of nitrogen pollution in the past 30 years across the global sample. On the other hand, when the definition of coupled support is restricted to market price support (MPS), the impacts on pollution are reduced by up to half. Unlike the results of these

Figure 3: The effect of subsidy on water pollution



Note: This figure shows point estimates of the impact of a 100 percentage point increase in the share of coupled or decoupled subsidy over the total value of production on total nitrogen pollution in water with 90 percent confidence intervals using estimates from Table 3. MPS= market price support

coupled support measures, decoupled support has muted or statistically insignificant impacts.

Since levels of producer support are not randomly assigned, a potential concern is that subsidies themselves are endogenously determined and that in reality other unobserved variables that are correlated with subsidies are really to blame. The placebo test in column 5 of Table 3 checks whether future levels of producer support are associated with higher levels of nitrogen pollution in water. Results show that the estimates on future producer support are small and insignificant, suggesting that the results are not simply picking up generic correlations between producer support and nitrogen pollution, providing further confidence in the result.

Following Paudel and Crago (2021), these elasticities can be used to estimate the effect of an increase in nitrogen water pollution on the size of the hypoxic zone to illustrate their economic significance.

Applying the statistics reported in Hendricks et al. (2014) and Obenour et al. (2012),<sup>17</sup> a 100 percentage point increase in coupled input support, on average, can result in an increase of about 2,173 square

<sup>17</sup> Hendricks et al. (2014) use regression estimates from Obenour et al. (2012) and report that a 0.23 percent increase in nitrogen concentration translates to an increase of 25 square miles in the size of the hypoxic zone with a standard error of 5.45 square miles.

miles in the size of the hypoxic zone globally. This amounts to almost 30-40 percent of the measured size of the “dead zone” in the Gulf of Mexico, considered one of the largest dead zones in the world.

These spillover effects on water also have implications for human health. Although it is known that nitrogen in water is responsible for fatally inflicting what is known as blue baby syndrome, which starves infants’ bodies of oxygen, studies have also shown that those that survive endure longer-term damage throughout their lives. Exposure to nitrogen pollution in early life can result in stunted growth and impaired development of infants, which could lead to poor productivity of future generations (Zaveri et al., 2020; Jones, 2019). Using prior estimates, this implies that globally, a 10 percentage point increase in coupled input support and the subsequent release of nitrates into the water poses a risk large enough to wipe out up to 2.7 to 3.5 percent of labor productivity especially in areas where input subsidies make up the largest share of the value of production in the global sample.

Understanding how subsidies impact water pollution can therefore also shine a light on the influence of subsidies on population health outcomes and a country's forgone human capital accumulation. Though these estimates are broad and imprecise, they suggest that fertilizer policies and vast fertilizer subsidies require careful scrutiny particularly in places where nitrogen use exceeds optimal levels for plant growth.

#### 4. Policy Implications and the Way Forward

Nitrogen balances across the developing world run the gamut from acute deficiencies to extreme excesses. In general, farmers struggle to apply just the right amount of fertilizer. Even in advanced economies like the EU which has reduced nitrogen waste over the past several decades, progress continues to stagnate.<sup>18</sup> How nitrogen is managed over the coming decades will determine whether humanity can return to being within the nitrogen planetary boundary—a level of human interference beyond which damage to ecosystems and human health could increase dramatically, perhaps permanently—without jeopardizing food security. Not surprisingly, improved nitrogen management is encapsulated in several of the Sustainable Development Goals (SDGs) from ending hunger (SDG 2) to protecting the environment and human health (SDGs 6, 12, 13, 14 and 15). Therefore, it is critical that better modes of nitrogen management be developed, deployed, and adopted globally in areas that use too much, to areas that use too little fertilizer (Kanter et al., 2020b). Well-designed policy that encourages experimentation can also help. For instance, research suggests that subsidies need not be permanent or universal to benefit farmers in substantial ways. Instead, temporary input subsidies can be useful to experiment and learn about best management practices (Carter et al., 2019).

On the farm, there is scope for improving management of inputs within existing technology and resources by employing best management practices such as the 4 R’s to improve nitrogen use efficiency: using the right nutrients, at the right rate, at the right time and in the right place. Overall, better fertilizer management through optimal quantity and timing of application can minimize wastage, lower the direct fertilizer expense and associated environmental costs, and can also improve productivity by maintaining soil quality and ensuring nitrogen is available when it is most beneficial for plant growth (Islam and Beg, 2022). Methods that harness accumulated nitrogen legacies within the soil profile in areas where soil nitrogen availability is high could also lower fertilizer application rates without notable declines in crop yields and contribute to cost savings and environmental benefits (Basu et al., 2022). Since the ability of legacy nitrogen stores to sustain crop yields would vary spatially, tailored approaches are needed (Basu

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18 <https://www.eea.europa.eu/airs/2018/natural-capital/agricultural-land-nitrogen-balance>

et al., 2022). Precision agriculture's focus on tailoring management decisions to site-specific conditions can help refine these strategies such that they are more responsive and respectful of agricultural heritage and cultural practices (Kanter et al., 2019). Low-cost, manual approaches such as seed priming and fertilizer micro-dosing can concentrate scarce resources in the vicinity of the plant, ensuring greater nitrogen uptake and leaving less nitrogen available to be lost to the environment. Other low-cost techniques suited to both low- and high-nitrogen smallholder systems include leaf color charts and chlorophyll meters (Kanter et al., 2019).

However, the adoption of more efficient and sustainable intensification management practices is not inevitable.<sup>19</sup> Studies have pointed to various reasons for why the adoption is often slow or minimal. These include perceived technological and financial barriers due to lack of information, farmers' reticence to overturn or augment long-running practices due to lock-in as well as the inherent complexity in dealing with volatile nutrients like nitrogen that make it difficult to know the precise nitrogen needs of plants throughout the season (Jack and Tobias, 2017; Kanter et al., 2019). Changing farmers' practice surrounding the over- or underapplication of nitrogen, therefore, requires combining the right information with the right incentives, training, and farmer education services.

China provides a notable example of success in educating and training farmers on good management practices. In a decade-long trial, researchers worked with 20.9 million smallholder farmers across the country to see if they could increase crop yields while also reducing the environmental impacts of farming. A combination of outreach program and workshops — about 14,000 over 10 years — helped to convince the farmers to adopt the recommendations (Cui et al., 2018). Results show that in the decade from 2005 to 2015, average yields of maize, rice and wheat increased by around 11 percent. At the same time, nitrogen fertilizer use *decreased* by around one-sixth— saving 1.2 million tons of nitrogen. By producing more crops and needing less fertilizer, this experiment provided an economic return of US\$12.2 billion (Cui et al., 2018). More recently, China has also phased out nitrogen fertilizer subsidy and is instead funding improvements in nitrogen and manure management with promising early results (Ji et al., 2020).

On the other hand, in India, the launch of a large-scale soil health card (SHC) program in 2015 that tested 23.6 million soil samples and distributed 93 million SHC results and fertilizer recommendations to farmers proved to be less successful. Without adequate education of what the data meant or how to apply the information, farmers failed to optimize the use of fertilizers (Fishman et al., 2016). Instead, when the SHCs were simplified and made more user-friendly, and farmers were given repeated access to extension services, there was a significant improvement in farmers' comprehension of soil health information along with a small, but significant, increase in the adoption of more balanced nutrient applications (Cole and Sharma, 2017). Similarly, in Bangladesh, a simple rule-of-thumb training that deployed colored leaf charts to guide fertilizer application was found to be successful at reducing fertilizer usage by 8 percent without compromising yields. The behavioral intervention amounted to a savings of 180,000 metric tons of nitrogenous fertilizer, worth \$80 million or 14 percent of Bangladesh's input subsidy budget (Islam and Beg, 2021).

Increasingly, new data through satellite technology coupled with the rapid rise in mobile-phone penetration<sup>20</sup> in rural areas has opened new opportunities to connect farmers more easily to extension services and to empower them with timely and accurate information on fertilizer recommendations

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<sup>19</sup> Broadly, three assumptions are often made concerning adoption: (1) smallholder farmers will understand the benefits of improved practices, (2) even with an understanding of the benefits, there is an assumption that they will trust the quality and reliability of the information, (3) farmers will be able to act on their altered preferences without being constrained by other factors that may affect their choices (Fishman et al., 2016).

<sup>20</sup> Even among the poorest 20 percent in developing countries, which tend to live overwhelmingly in rural areas, 70 percent have access to mobile phones—more than the share that have access to improved sanitation or electricity in their homes.

(Kanter et al., 2019; Singh et al., 2018).<sup>21</sup> With increased availability and affordability, data from satellite sensors such as the European Space Agency's SENTINEL-2 Multi Spectral Imager and the series of sensors from Planet's Dove satellites are being explored to bring satellite monitoring to the individual-field level. Recent research has shown that data from low-cost satellite sensors can help predict crop yields at the individual-field scale, which can serve as crucial information for farmers to inform their agricultural-management practices and help them make decisions about where and when to apply fertilizer (Jain et al., 2019). Building the capacity of local agricultural-extension officers to appreciate the usefulness of these datasets and apply them in practice will be critical (Dash, 2019).

Other initiatives and technologies, such as nitrogen-fixing bacteria, efficiency enhancing fertilizers or fertilizer deep placement that targets fertilizer right at the source also show promise. At the same time, even as countries focus attention on best management practices on-farm, there is an increasing need to extend attention to off-farm actors across the agricultural value chain that are capable of influencing farm-level nitrogen management (Kanter et al., 2020a).

For example, since 2015, the Government of India has made efforts to improve nitrogen use efficiency in agriculture and has mandated manufactures of urea, a type of nitrogen fertilizer that is commonly applied in India, to produce neem-coated urea. Neem-coating helps to reduce leakages by making it more difficult for black marketers to divert urea to industrial consumers (Government of India, 2016). At the same time, it has the potential to benefit farmers. Since neem acts as a nitrification inhibitor, it allows a more gradual release of nitrogen into the soil, thereby improving nitrogen use efficiency. Neem, however, is one of many possible compounds and the responses of different crops under different conditions can be highly variable (Searchinger et al., 2020).

Another technique developed by the International Fertilizer Development Center is using fertilizer deep placement that enhances the efficiency of nutrient delivery to crops. The method buries nitrogen fertilizer into the soil, which feeds nitrogen directly into a plant and reduces losses. However, the potential to scale such technology in regions like Africa may be more limited due to the nature of the soils that can hinder the pathways of nutrient distribution (Cox et al., 2015). Expanding frontier agricultural technologies such as insect and hydroponic farming that have minimal land and water footprints and employ circular economy principles is increasingly being seen as an attractive option to enhance food security and livelihood opportunities, especially in Africa and countries affected by fragility, conflict, and violence. Waste from insects can also be fed back into the food system as organic fertilizers to help improve soil health (Verner et al., 2021). More research on these new technologies and initiatives is needed to better understand their efficacy across different locales, and to quantify the environmental and economic consequences of such measures.

Several countries have taken steps to reduce problems related to fertilizer use using a mix of instruments. For instance, since the early 1990s, Denmark has reduced its nitrogen balance by 56 percent, although its agricultural productivity has continued to increase over this period. Policy makers used a portfolio of strategies, including targets for reductions of nitrogen discharges, fertilizer accounting systems, nitrogen quota systems to regulate use, bans on manure application on bare fields, fertilizer taxes for non-agricultural uses, as well as agricultural environmental schemes and advisory services (OECD, 2021).

Ultimately, there is no easy solution for curbing nitrogen waste, given the diversity of agricultural, climatic and political systems across the world. Nevertheless, as the challenge mounts and world population grow, it is urgent to close efficiency gaps, and explore policy options on and off-farm that make it possible to

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<sup>21</sup> For example, UjuziKilimo, a Kenyan company, uses simple ground sensors to provide nitrogen recommendations via text messaging. A Nigerian company, Hello Tractor, connects farmers with tractor services via apps and text messaging (Kanter et al., 2019).

increasingly decouple agricultural production from its environmental impacts. Central to this will be the design of agricultural subsidies that profoundly influence the structure, function and trajectory of agriculture-food systems. As this paper has demonstrated, even when eminently justifiable, poorly designed subsidies are enmeshed in tradeoffs suggesting the need to clearly analyze the benefits and costs of whether, what, and how to subsidize.

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