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Yield Gains from Balancing Fertilizer Use

Evidence from Eastern India

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Abstract

As with most agricultural inputs, the optimal use of fertilizer leverages the production complementarities between different types of nutrients. Wide variation in the intensity of nutrient application rates suggests there are potentially large productivity gains to be had from rebalancing fertilizer use across nutrient types even under a fixed expenditure budget. Using detailed information on a large sample of rice fields across three states in eastern India, this paper investigates whether a more balanced use of fertilizer—measured as the ratio of potash to nitrogen applied to a field—can lead to higher yields and revenues. To address the endogeneity of fertilizer application decisions, the analysis exploits the fact that nitrogen-based fertilizers demanded by Indian farmers are mostly produced domestically in a limited number of manufacturing plants, while all potash-based fertilizers must be imported by ship from abroad. Instrumenting for the ratio of potassium-to-nitrogen fertilizer applied on a field with the relative travel distances between farmers' villages and both the nearest urea production plant and the nearest international port, the paper estimates the impact of more balanced fertilizer use on yields and revenues. The estimates show that at median levels of fertilizer use, and keeping the level of expenditure on fertilizers constant, rebalancing fertilizer application choices such that the potassium-to-nitrogen ratio of fertilizer is doubled would lead to a 4.8 percent increase in yield.

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Yield Gains from Balancing Fertilizer Use: Evidence from Eastern India

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1. Introduction

A key driver of improvements in agricultural productivity across the developing world has been the widespread adoption of inorganic fertilizers, which have been recognized for their role in enhancing food production and driving structural transformation processes (Beaman et al., 2013; Duflo, Kremer, & Robinson, 2008; Ghose, Fraga, & Fernandes, 2023; McArthur & McCord, 2017). However, even at modestly high levels of input use, the effectiveness of fertilizer starts to hinge on leveraging the production complementarities between different types of nutrients (Ye et al., 2021). The overuse of a single type of fertilizer leads to diminishing returns, reductions in future productivity due to soil acidification, and has negative environmental and health externalities (Bobbink et al., 2010; Diaz & Rosenberg, 2008; Guo et al., 2010; Ward et al., 2018). While promoting the adoption of fertilizer use still has large rates of private and social returns in some settings, especially in Sub-Saharan Africa (Carter, Laajaj, & Yang, 2021), the inefficiently high and mostly unbalanced use of nitrogen-based fertilizers is becoming an increasingly pressing concern in major agricultural producers such as the U.S., China, and India (Cui et al., 2018; West et al., 2014).

In this paper we study the impacts of fertilizer imbalance on agricultural productivity in the context of Indian agriculture. Using detailed microdata from a large sample of rice fields in three states in eastern India—Andhra Pradesh, Bihar, and Odisha—we first document the large differences in application rates of different types of fertilizer nutrients used by farmers. Across all surveyed fields, the median nitrogen application rate is 7.9 times higher than the median potassium application rate.[1] This observation is consistent with the wide variation in nutrient application levels observed for the whole country across regions, farmers, and nutrient types (Bora, 2022). High nitrogen use relative to other types of nutrients—a secular trend in Indian agriculture—has been further reinforced by the imposition of differential subsidies across fertilizer types that distort optimal input choices by affecting relative prices (Chand & Pandey, 2009; Chatterjee & Kapur, 2017; Garg & Saxena, 2022).

We then investigate how much would correcting these imbalances improve agricultural production. In particular, we investigate the effect that a more balanced application of nutrients—measured by the ratio of potash (K_2O) to nitrogen (N) applied to a field—would have on agricultural yields and farmers' revenues.

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[1] In a state-level comparison of fertilizer use across India, Chand and Pavithra (2015) also find large gaps in application rates of K relative to N for the three states analyzed in our paper. Moreover, by considering the combination of state-level cropping patterns and crop-specific nutrient recommendations, the authors are able to compute 'normative' desired nutrient ratios. While there is wide variation across states on the distance to this normative benchmark, the three states analyzed in our paper have substantially lower observed K-to-N ratios than what the normative measure indicates.

We motivate this question by noting the production complementarities observed in the data between the use of different types of nutrients, and showing the strong relationship between K-to-N ratios, yields, and revenues. To assess the causal nature of these associations and account for the endogeneity in fertilizer application decisions, our econometric strategy exploits the fact that the large majority of nitrogen-based fertilizers demanded by Indian farmers are produced domestically in a limited number of manufacturing plants, while the entirety of potash-based fertilizers must be imported by ship from abroad. Based on this fact, we instrument for the K-to-N nutrient ratio applied in each field with the relative travel distances between farmers' villages and *i)* the nearest urea manufacturing plant, and *ii)* the nearest international seaport. This approach leverages idiosyncratic geographical constraints in the supply chain of different types of fertilizer—as in McArthur and McCord (2017)—and provides plausible exogenous variation in the relative costs, availability, and application rates of different nutrients across space.

Our 2SLS estimates show that, unconditional on the baseline level of fertilizer use, a one-standard-deviation increase in the K-to-N ratio leads to a 16% increase in rice yields. This effect is roughly ten times larger than the one obtained from OLS estimates and suggests that the benefits of shifting fertilizer use towards more nutrient-balanced applications are potentially much larger than what simple correlations suggest. Based on these estimates, a back-of-the-envelope calculation shows that, at median fertilizer application rates and prices, rebalancing fertilizer choices such that the total level of expenditure on fertilizer is kept constant, but the K-to-N ratio is doubled, would lead to a 4.8% increase in yields, or, at mean values, of 0.204 tons/ha per season. We find that these yield increases are accompanied by positive, but imprecisely estimated, impacts in farmer revenue. These results align with the economic literature on agricultural input complementarities (Abay et al., 2018; Bohr et al., 2024) and provide empirical evidence in support of policies that aim to optimize fertilizer use as a pathway to improving farm productivity.

The main contribution of this paper is to present causal evidence on the impacts of balancing fertilizer application choices on agricultural output. While our empirical strategy leverages variations in relative costs of fertilizer types, and so speaks most directly to policies that improve input choices by altering relative nutrient prices, our estimates also suggest that—even at current prices—rebalancing fertilizer demand could raise yields without the need to increase expenditure levels.

We thus explore additional factors that may explain why farmers do not select a more balanced fertilizer bundle. Using a complementary dataset with survey responses from farmers in Odisha, we present evidence suggesting that lack of farmer knowledge about nutrient diversity might be one of the main barriers preventing more efficient input use. We argue that interventions that provide general information to farmers on the benefits of balancing nutrient application and help them identify the different types of fertilizer that can provide such balance may be a cost-effective policy to improve agricultural productivity. In this sense, this paper also contributes to the literature studying the impacts of digital extension services on agricultural productivity (Beg, Islam, & Rahman, 2024; Corral et al., 2020; Fabregas et al., 2025; Gars et al., 2025; Harou et al., 2022; Islam & Beg, 2021) by highlighting that general-knowledge information deliveries might be both more cost-effective and a prerequisite to the delivery of more complex, granular information based on the specific characteristics of individual plots.

In the next section of the paper, we describe the different data sources used for the analysis. Section 3 introduces the context of the study and describes the motivating facts. Section 4 outlines the empirical strategy, including its motivation and details. Section 5 presents and discusses the estimation results, and Section 6 concludes.

2. Data

We investigate the relationship between fertilizer balance and agricultural productivity using detailed farmer-level surveys collected and harmonized between 2017 and 2019 by several research teams affiliated with the *Cereal Systems Initiative for South Asia* (CSISA). We use farmer-level data originally compiled by Coggins et al. (2025) to study nitrogen use efficiency across several rice-growing regions across three South Asian countries, and we refer to this data throughout as the *CSISA-NUE* dataset. Given the nature of our empirical strategy, we focus only on farmers within India. Our selected sample contains information for smallholder farmers that cultivated rice fields between 2017 and 2019 across three eastern Indian states: Andhra Pradesh, Odisha, and Bihar.[2]

The *CSISA-NUE* dataset contains farmer-reported data on the household's largest rice plot during the most recent monsoon season. The sampling frame was designed to select districts of high relative importance for food security goals at the state level. Within these districts, rice fields were chosen to ensure the sample was representative of rice field conditions across the district. Each survey collected farmers' responses on plot size, rice output, farmgate prices for rice—which we use to compute measures of revenue per hectare—and detailed information on application rates of different types of fertilizer. The dataset also offers either directly collected or harmonized publicly available secondary data on a large number of plot- and household-level variables related to demographic characteristics, market access, irrigation status, seed availability, soil quality perceptions, and weather outcomes. Summary statistics of the full list of variables

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[2] While we refer to the region as Bihar throughout, this subsample of plots also includes villages from several districts in eastern Uttar Pradesh, namely Ballia, Chandauli, Deoria, Ghazipur, Gorakhpur, Kushinagar, Maharajganj, Mau, and Siddharthnagar. Additionally, while the original dataset also contains information on fields in the Punjab-Haryana region, we exclude this subsample from this study due to a higher prevalence of missing values in some surveyed villages, primarily caused by travel restrictions during the COVID-19 pandemic.

used for this study are shown in Table A1 in the appendix. Crucially, the *CSISA-NUE* dataset also contains GPS-recorded coordinates for each surveyed field.

Our empirical strategy, described in detail in Section 4, leverages variation in farmers' relative travel distance to both urea manufacturing plants and international seaports. Information on the location of major urea manufacturing plants was obtained by reviewing official government communications that provide an exhaustive list of all major fertilizer manufacturing units operating across the country, with fertilizer production capacity disaggregated by urea, DAP, NPK complex, and ammonium sulfate.[3] Only facilities recorded as urea producers were included in the analysis, and each of them was geolocated using Google Maps based on the state of operation, company name, and name of plant location. A total of 33 locations across 14 states were identified and geolocated as major urea manufacturing plants. Major international port locations were obtained from the *Manual on Port Statistics* (2015), produced by the Transport Research Wing of the Ministry of Road Transport and Highways. This document includes a comprehensive list of the 13 designated major international ports in operation across the country.

Since the *CSISA-NUE* dataset does not explicitly record the administrative unit in which a surveyed field is located, we overlay field-level coordinates with the village-level shapefiles constructed by the *SHRUG* project (Asher et al., 2021), and assign fields to their corresponding village, tehsil (i.e., a group of villages), and district. Given that coordinates in the *CSISA-NUE* are censored for confidentiality, and we cannot directly observe the exact distance of each household to the nearest road, we aggregate individual-level coordinates at the village level and define our distance instruments to be common to all fields within a village. Further, since our question of interest relates to the intensive margin of fertilizer use—that is, how, conditional on fertilizer adoption, rebalancing fertilizer use can lead to productivity improvements—we exclude fields with no fertilizer use (less than 2% of observations). Our final estimation sample consists of 12,255 farmers across 2,917 villages and 68 districts within the three states.

Combining each village location with manufacturing plant and international port locations, we calculated travel distances by road using road network data from the *Open Source Routing Machine* (OSRM) platform. We follow the methodology used by Baragwanath et al. (2024), and implement Dijkstra's algorithm to find the shortest path between a pair of nodes through a weighted graph, where weights represent average speeds for different road categories. Figure 1 displays the spatial distribution of sample villages and their computed shortest travel routes to urea plants and international ports.

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[3] Unstarred question No. 2172 made to the Minister of Chemicals and Fertilizers at the request of the Lok Sabha. Answered on 29.07.2022.

We collect fertilizer price information by nutrient from the 2017–2020 round of the *Crop Cultivation Surveys* (CCS) conducted by the Department of Agriculture in India. These surveys collect detailed input-use information at the farmer-crop level across all seasons over three years. By combining expenditures by nutrient type with total input usage, we compute tehsil-level average nutrient prices (value per kg) for both nitrogen- and potassium-based fertilizers. To calculate travel distances to the nearest urea plant and the nearest major port, we assign each *CCS* tehsil the corresponding *SHRUG* coordinates by matching state, district, and tehsil names across both datasets.

We complement our analysis using data from two additional sources. We use annual district-level information of fertilizer application rates by nutrient from the *ICRISAT-TCI* District-Level Database (DLD) for Indian Agriculture and Allied Sectors. Additionally, while discussing the possible drivers of fertilizer imbalance, we present some statistics from a baseline survey collected in the state of Odisha as part of the impact evaluation of the *Rejuvenating Watersheds for Agricultural Resilience through Innovative Development* (REWARD*)* watershed management project.[4] This survey, conducted between January and February 2024, has information on a wide range of household- and plot-level characteristics of farmers. In particular, the survey tests farmers' knowledge on topics related to soil health and fertilizer application best practices and covers topics ranging from knowledge on different types of fertilizer and the specific nutrient deficiencies they address, to the importance of crop rotations, and the potential hazard of fertilizer overapplication.

3. Context and Motivating Facts

Indian agriculture has experienced significant productivity gains over the past five decades, largely driven by the Green Revolution and the widespread adoption of modern inputs such as high-yielding variety seeds, irrigation, and chemical fertilizers (Evenson & Gollin, 2003). Fertilizer use, in particular, has been heavily subsidized by the Indian government, which currently spends between US$10 billion and US$11 billion a year on fertilizer subsidies alone (Zaveri, 2025). Beyond the obvious pressures on government budgets, excess fertilizer use has become an increasing concern, given that the overapplication of nitrogen-based fertilizers can lead to environmental degradation and reductions in long-term agricultural productivity due to soil acidification (Guo et al., 2010), has negative impacts on biodiversity and human health (Bobbink et al., 2010; Diaz & Rosenberg, 2008; Ward et al., 2018), and constitutes a significant fraction of global greenhouse gas emissions (Menegat, Ledo, & Tirado, 2022).

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[4] For more information on the *REWARD* project visit: https://rewardiiswc.in/about_reward.php, and https://projects.worldbank.org/en/projects-operations/project-detail/P172187.

Long-term trends in fertilizer consumption in India reflect a sustained increase in usage since the 1960s, but with compositional changes at the nutrient level which have evolved over time in response to changing subsidy regimes and price liberalization. As shown in panel (a) of Figure 2, the demand for potash and phosphorus fertilizers experienced a notable acceleration in the second half of the 2000s, reflecting a growing recognition of their role in balanced soil nutrition. Following the policy shift in 2010 when the government lowered subsidies for P and K fertilizers but not for nitrogen-based ones, the sharp increase in the price of K and P fertilizers significantly altered fertilizer application patterns. Overall fertilizer expenditure—in levels and as a share of total spending in agricultural inputs—increased as farmers adjusted to new price structures while the overall use of P and K fertilizers declined, reversing earlier trends of rising application rates. Consequently, the K-to-N ratio, which had steadily grown throughout the 1990s and reached an average of 1:4 by the late 2000s, dropped to approximately 1:8 following the subsidy reforms as shown in panel (c) of Figure 2. Average K-to-N ratios across the country have had only minor increases in the second half of the 2010s.

These adjustments highlight the sensitivity of fertilizer use to policy changes and suggest that price distortions rather than agronomic considerations have played a central role in shaping nutrient application decisions. While subsidies have ensured high adoption rates among farmers and contributed to the secular improvements in yields and food security outcomes, they have also led to distortions in the relative use of different types of fertilizers (Garg & Saxena, 2022). The imbalance between different soil nutrients used, particularly the excessive application of nitrogen relative to potassium, is an underexplored issue in Indian agriculture that could be limiting agricultural productivity. This is largely due to the strong complementarities between these two nutrients based on agronomical and physiological characteristics of crops, particularly rice (Akter et al., 2024; Ye et al., 2021). Given that macronutrients play a complementary role in plant growth and crop output, farmers should, given any level of expenditure, prefer a balanced mixture of fertilizers instead of exclusively applying a single type of nutrient.

Using data from the *CSISA-NUE* surveys, we show that the unbalanced use of fertilizers is prevalent. Figure 3 illustrates the magnitude of this imbalance at the field level. Nitrogen application rates are significantly higher than those of potash across all regions. Median nitrogen application rates across the full sample are 7.9 times higher than median potash application rates (123 kg/ha for N vs. 15.5 kg/ha for K), with the general pattern observed as well within states. As shown in Table A1, while the average plot size in the sample is relatively small (ranging from 0.24 hectares in Bihar to 0.49 hectares in Andhra Pradesh) the dispersion in K-to-N ratios is large both within and across states.

We further explore if the potential for complementarity gains between nutrients is suggested in the data by regressing observed yields and revenues on nutrient application rates, their square, and the interaction between fertilizer types. To reduce the influence of omitted confounders, these regressions further include village and year fixed effects plus the set of plot- and household-level controls explained in detail in Section 2. Table 1 presents the correlations between yields, specific nutrient use and nutrient type interaction. The estimates show a strong positive association of both nitrogen and potash application with farmers' yields and revenue per hectare. Column 1 indicates that, on average, each additional kilogram of nitrogen applied per hectare is associated with an increase in yield of approximately 4.36 kg/ha, while the effect of potassium application is even larger at 6.05 kg/ha (column 3). Results in column 2 show that returns seem to have diminishing marginal effects, at least for nitrogen application. In contrast, the interaction term between nitrogen and potassium (columns 5 and 10) shows a positive and precisely estimated complementarity effect between these two nutrients, consistent with results from agronomic trials.

The coefficient on the interaction term suggests that a more balanced application—where potassium use increases alongside nitrogen—can enhance the effectiveness of nitrogen, leading to greater yield and revenue improvements. In particular, as Table 2 shows, increasing the ratio of K application relative to N is strongly associated with yield and revenue gains. Higher K-to-N ratios are linked to increased productivity and revenue per hectare, both unconditionally (Columns 1 and 3) and when controlling for nitrogen application levels.

While apparently large, and distant from the standard agronomical recommendation, differences in application rates by nutrient are not by themselves informative on whether the chosen nutrient composition is suboptimal. The soil nutrient needs of each field are determined by crop choice and soil characteristics, and optimal nutrient composition can vary widely across agroclimatic regions (NAAS, 2009). Moreover, observed correlations between more balanced nutrient application rates and higher yields do not imply the causal impact of rebalancing fertilizer use on productivity is necessarily positive, since both fertilizer choice and yields might be affected by unobserved confounders. Despite the inclusion of a large battery of controls at the village, household, and plot levels, the observed correlation between the K-to-N ratio and productivity outcomes might still suffer from endogeneity. Unobserved factors—such as differences in farmer-specific knowledge, or access to complementary agricultural inputs—could simultaneously influence both fertilizer application decisions and yields, leading to biased estimates. Additionally, farmers experiencing higher yields due to unobserved factors may be more likely to experiment with rebalancing their fertilizer use, making it difficult to disentangle the causal effect of the K-to-N ratio from farmers' decisions.

To address these concerns, the next section outlines our empirical strategy which leverages the idiosyncratic geography of fertilizer supply chains to instrument for K-to-N application rates. By exploiting exogenous variation in the relative availability and cost of different fertilizers across regions, we estimate the effect of higher K-to-N ratios on agricultural output.

4. Empirical Strategy

Our objective is to estimate the causal impact of the K-to-N ratio in fertilizer use on field-level outcomes such as yield and revenue per hectare. Since fertilizer application choices are endogenous to other factors that also affect productivity, we exploit spatial cross-sectional variation in farmers' relative travel distance to both urea manufacturing plants and international seaports, where potash-based fertilizer imports enter the country. We use these distances as instruments for the ratio of observed fertilizer application rates.[5]

This empirical strategy is motivated by the observation that local agricultural input prices are strongly associated with travel costs and market access measures (Aggarwal et al., 2024; Bonilla Cedrez et al., 2020), and is most closely related to the strategy used by (McArthur & McCord, 2017), which interacts travel costs with variations in international fertilizer prices across time to assess the impact of changes in agricultural productivity on overall growth. Our approach only leverages the cross-sectional variation in transport costs between different locations and in that sense, similar to Nunn (2008), relies on the assumption that—given that both urea manufacturing plants and major international ports have to be located in places with specific geographical characteristics—the location of the source of supply of different fertilizer types is not influenced by the location of the sources of demand. In other words, the intuition behind our identification strategy relies on the assumption that the combination of relative distances from a farmer's field to both the nearest urea plant and the nearest seaport affects agricultural productivity only through its impact on the availability and prices of different fertilizers, thereby influencing farmers' nutrient application choices. The effect of fertilizer composition on production is identified under the assumption that the ratio of plant-to-port distance is unrelated to other characteristics that also influence agricultural output such as soil quality, weather, or farmers' idiosyncratic productivity, and only affects production through the impact it has on relative prices.

4.1 Motivation for the instrumental variable approach

To validate this intuition, we use data from the Cost of Cultivation Surveys (CCS) and analyze the relationship between farmers' travel distances to the nearest international port and urea manufacturing plant with both fertilizer prices and application rates. Figure 4 shows the relationship between (demeaned) average fertilizer prices and road distances from villages to urea plants, international ports, and their ratio. Prices for nitrogen-based fertilizer have a strong positive relationship with distance to the closest urea manufacturing plant, while this distance has no clear relationship with potash-based fertilizer prices. Both

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[5] Figure A1 in the appendix shows total domestic production and consumption of fertilizers by nutrient time between 1960–2022. For the 2017–2020 period 26.8% of all nitrogen-based fertilizers were imported, while effectively 100% of potassium-based fertilizers were sourced from abroad. In 2020, the main sources of potash fertilizers where Canada (29% of total imports), Lithuania (17%), the Russian Federation (14%), Jordan (12%), Israel (12%), and Belarus (11%).

N and K prices are positively correlated with distance to the nearest international port. As a consequence, the correlation between fertilizer prices and the plant-to-port ratio of distances is negative for K prices while being close to null for N prices.

The relationship depicted in Figure 4 suggests that village-level variation in distances to both plants and ports influences relative fertilizer prices and availability. We further explore this relationship by estimating a regression between fertilizer prices and distances that includes both district-level and year fixed effects. This allows us to restrict the comparison between distances and prices to villages within the same district, and to account for time-specific events that might impact fertilizer prices on any given year. The results, displayed in Table 3, support the intuition behind our identification strategy. We find that minimum travel distances by road from each sampled village to (i) an international port and (ii) a urea manufacturing plant are significantly correlated with fertilizer prices and application rates in a way that aligns with the sourcing mechanisms of each nutrient.

Although the maximum retail price (MRP) of urea is fixed nationwide under the Government of India's Urea Pricing Policy, data from the CCS reveal that unit values paid for nitrogen-based fertilizers vary significantly across villages and even across households within districts. The price dispersion observed in urea may reflect local charges and last-mile delivery costs. While the price subsidy policy reimburses primary freight from plant or port to the district railhead, any secondary movement from the railhead to the village outlet is only partially compensated—and is sometimes routed through rail rather than the cheaper freight-on-road option. Deviations from the prescribed logistics channels can impose additional costs not covered by stipulated freight subsidies.[6] Additionally, price dispersion within districts and villages can may increase and persist over time due to imperfections in secondary markets, as documented by Chatterjee & Kapur, 2017 for staple-crop output prices.

Panel A of Table 3 shows the relationship between travel distances and fertilizer unit values (expressed in rupees/kg). The results indicate that greater distances from international ports are strongly associated with higher potash prices. A 1% increase in the distance to the nearest port is associated with a 6.33% increase in unit values for K when year and district fixed effects are included, while greater distances from international ports show no statistically significant relationship with N prices. In contrast, a higher distance to urea manufacturing plants is associated with significantly higher N prices but is not associated with variation in K prices. The overall pattern is consistent with the geographical differences of nutrient supply

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[6] "Transportation of Urea through Freight on Road." Unstarred question No. 3008 made to the Minister of Chemicals and Fertilizers at the request of the Lok Sabha. Answered on 13.12.2024.

chains, as urea is domestically produced, while potash-based fertilizers are entirely imported and variations in their cost should not be affected by the proximity of villages to the nearest urea plant.

As shown in panel B, the relationship of urea plant distance with respect to fertilizer application rates is not as precisely estimated. Farmers in villages farther from urea plants have lower but imprecisely estimated N application rates, suggesting that—at current price levels—demand for nitrogen-based fertilizers might be relatively price insensitive. Rather surprisingly, the negative relationship between distance to urea plants and application rates is also observed for potassium-based fertilizers. For its part, distance to international ports is strongly associated with lower K application rates and *higher* application rates of N, which suggests a potential substitution effect—as potassium fertilizers become more expensive, farmers may compensate by increasing nitrogen use, even if this may not be agronomically optimal.

Taken together, these results provide strong empirical support for our proposed instrumental variable strategy. They demonstrate that geographical constraints on fertilizer supply chains affect both the cost and demand for different nutrients in ways that are exogenous to unobserved productivity shocks. This validates our approach of using relative distances to urea plants and ports as instruments for fertilizer application choices, allowing us to better isolate the causal impact of K-to-N ratios on agricultural productivity outcomes.

4.2 Estimation

Formally, let i index farmers in village j, district d, and year t. We are interested in estimating the impact of the K-to-N ratio of fertilizer use (R_{ijdt}) on some field-level outcome, (y_{idjt}). We estimate the two-stage least squares (2SLS) model:

$$y_{idjt} = \beta_0 + \ \beta_1 R_{idjt} + X'_{idjt}\delta + \ \gamma_d + \gamma_t + \varepsilon_{idjt}, \tag{1}$$

with first-stage equation:

$$R_{idjt} = \alpha_0 + Z'_j\gamma + X'_{idjt}\delta + \gamma_d + \gamma_t + \epsilon_{idjt}, \tag{2}$$

where Z'_j is a vector composed of *i*) the minimum travel distance between village j and the nearest urea manufacturing plant, *ii*) the minimum travel distance between village j and the nearest international port, and *iii*) the ratio of both distances. We further show that our results are robust to including an extensive set of farmer-, field-, and village-level controls (denoted as X'_{ijdt}) such as schooling level, household structure, distance to output markets, availability of irrigation, type of rice varietal planted, weather realizations, and farmer's perceived soil quality. In our preferred specification we also include the level of N-based fertilizer application rates as part of the vector of controls. The coefficient of interest (γ) is identified under the assumption that, conditional on the set of covariates, the combination of distances to urea manufacturing plants, international ports, and their ratio affects yields and revenues only through its impact on nutrient application rates. To account for spatial correlation in farmer outcomes, we cluster all standard errors at the village level.

Panel A of Table 4 presents the first-stage results. These regressions show that both distance to ports and distance to urea manufacturing plants are strongly correlated with observed K-to-N ratios. While distances in levels alone are strong predictors of the endogenous variable of interest, including both of them and their ratio as the vector of instruments allows us to make a stronger case regarding the validity of the instrument: while many unobserved confounders might be related to distance from ports and, to a lesser extent, to distance from fertilizer plants, it is unlikely that the relative distance of both to a village affects yields in any other way than through the composition of fertilizer nutrients used. Given that the strength of the instrument when using the combination of the three variables remains at acceptable levels (the value of the Kleibergen-Paap F statistic is 12.4), we use the three-variable vector of distances as our preferred instrument for the 2SLS estimation.

Panel B of Table 4 shows the reduced-form results of regressions of travel distances measures on log yields. A greater distance from ports negatively affects yields, while distance to plants is not statistically significantly different from zero. The coefficient on the port-to-plant distance on yields is also negative, which indicates the presence of both non-linearities and interaction effects in the combined impact of both distances on the outcome. The joint vector of village-level distance variables has a strong negative association with field-level yields, which supports our proposed instrumental variable approach. Taken together, the results show that geographical constraints of fertilizer supply chains influence both the cost and application rates of different nutrients in ways that are unrelated to unobserved productivity shocks. This validates our approach of using relative distances to urea plants and ports as instruments for farmers' fertilizer application choices, allowing us to better isolate the causal impact of K-to-N ratios on agricultural productivity outcomes.

5. Results

5.1 Main results

Table 5 presents our main results on the impact of K-to-N ratios on yields and revenues. Column 1 presents the estimated effect without conditioning on baseline nitrogen application, while column 2 controls for nitrogen application levels. The 2SLS estimates show that increasing K-to-N ratios has a large, positive impact on yields, even when controlling for baseline nitrogen use. On average, a one-percentage-point increase in the K-to-N ratio leads to a 0.41% and 0.67% increase in rice output per hectare, depending on whether the effect is estimated across all fields or within levels of N application rates. These effects are substantially larger to the ones obtained from OLS estimates (Panel A), which indicate that a one-percentage-point increase in the K-to-N ratio to be associated to just a 0.03% and 0.07% increase yields, again depending on whether the effect is estimated controlling or not for baseline nitrogen rate. Given the observed K-to-N ratios in our sample, the 2SLS point estimates indicate that—unconditional on the baseline amount of nitrogen fertilizer application—a one-standard-deviation increase in the K-to-N ratio causes yields to increase by about 16%, or 0.68 tons/ha per season at mean values. This effect is 9.5 times larger than what OLS estimates imply. These results suggest the benefits, in terms of increases in aggregate output, from shifting fertilizer use towards more nutrient-balanced applications are potentially much larger than what simple correlations suggest.

Columns 3 and 4 of Table 5 show that the observed increases in yields are accompanied by positive, but imprecisely estimated, impacts in farmer revenue. While large in magnitude, the 2SLS estimates on the effect of K-to-N ratios on revenue per hectare are less precisely estimated and do not allow us to discern a clear impact of rebalancing fertilizer use on farmers' revenues. The lack of precisely estimated increases in revenues could be driven by a larger degree of measurement error in the revenue variable, perhaps caused by larger imprecisions in the collection of farmgate prices in the survey. Larger measurement error could explain why the magnitude of the estimated 2SLS coefficients is at least as large as OLS coefficients—and for the specification that controls for baseline N application rates (column 4 of Table 5), substantially larger—yet less precisely estimated.

The relatively noisy impact of K-to-N ratios on revenue per hectare might also be driven by general equilibrium effects related to lower output prices driven by expanded production. Given the observed large impacts of more balanced fertilizer choices on output, markets where excess production cannot be as easily commercialized in other locations should also experience simultaneous reductions in output prices, thus hampering revenues. It could be that—as with many other interventions impacting the net output of agricultural firms—whether rebalancing fertilizer use leads to sustained increases in farmers' revenues and profits might depend on the relative openness of the local economy and the capacity of producers to move excess production across markets. Similar to our results, other studies evaluating the impact of fertilizer subsidies also find positive and precisely estimated impacts on output, but show that estimates on consumption (Carter, Laajaj, & Yang, 2021) or profits (Beaman et al., 2013) are usually noisier.

How economically significant are the estimated impacts on yields? To assess this question, we propose a simple back-of-the-envelope calculation that provides a (lower-bound) approximation of the potential output gains to be had from balancing fertilizer use. This exercise is based on the sample's median fertilizer application rates and prices and calculates how much would yields vary given changes in K and N application rates such that the level of expenditure in fertilizers is kept constant. This requirement implies that increases in K use must be compensated by proportional reductions in N. Relying on the estimated 2SLS coefficients, we then compute how much would yields change if this rebalancing of K vs. N were to take place.

Median fertilizer application rates for N and K in our sample (shown in Table A1) are, respectively, 122.8kg/ha and 15.49kg/ha. At median fertilizer prices (computed from the *CCS* and shown in Table A3 in the appendix), these levels of input use imply an expenditure of 2,442rs/ha. Maintaining this level of expenditure constant but *doubling* the K-to-N ratio—that is, going moving from an application ratio of 0.126 to one of 0.252—would require increasing K application rates to 26.03kg/ha and lowering N application rates to 103.14kg/ha. Based on the 2SLS point estimates on the effect of both K-to-N ratios and N levels on yield, this rebalancing of fertilizer use implies an increase in yields of 4.8%, or 0.204 tons/ha per season.[7]

While only illustrative, this calculation highlights the potential output gains that could be had from policies that induce farmers to apply more potassium-based fertilizers even if this implies reducing the amount of nitrogen application. It is important to note that this estimate does not include the direct impact on yields of increasing the *level* of K application, so it constitutes a lower-bound estimate of the total effect of balancing fertilizer composition on total output.

5.2 Why don't farmers balance their fertilizer use?

The fact that, on average, farmers could reallocate their input choices and increase yields without requiring higher expenditure levels raises the question of what type of underlying constraints may be preventing the adoption of a more balanced nutrient mix.

One potential barrier to more balanced fertilizer adoption may be the inconsistent availability of potassium-based fertilizers, especially in more remote markets. Given that potash fertilizers are entirely imported logistical disruptions in its supply chain can make this nutrient less accessible in certain regions. Even when farmers recognize the benefits of a more balanced fertilizer application, they may struggle to obtain potash at the right time in the planting cycle. Another possible market failure preventing wider use of K-based

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[7] Specifically, based on the coefficients shown in column 2 of Table 5 we assume that the change in average yield is given by

$$\Delta\bar{y} = \hat{\beta}_1 \Delta(K/N) + \hat{\delta}_N \Delta N,$$

where $\hat{\beta}_1$, and $\hat{\delta}_N$ are estimated from equation (1). The computed changes in K and N use that maintain expenditure levels constant while doubling the K/N ratio imply that $\Delta\bar{y} = 0.67 \times (0.126) + 0.00184 \times (-19.623) = 0.048$. Household-level median prices for K and N in the *CCS* for the states of Andhra Pradesh, Bihar and Odisha during the 2017–2020 are, respectively, 30Rs/kg and 16.11Rs/kg.

fertilizers might be related to information asymmetries and concerns about input quality. Studies have shown that farmers often face difficulties in assessing the reliability and effectiveness of agricultural inputs, which leads to adverse selection and lower demand (Bold et al., 2017). Imperfect information regarding the quality of imported K-based fertilizers might lead to under-adoption and lower application rates.

Beyond issues of availability and trust, a more fundamental barrier may be a lack of knowledge about the agronomic benefits of balanced fertilizer use. Using data from the *REWARD* project baseline survey of farmers in the state of Odisha, we present evidence suggestive of the fact that i) farmers have on average very limited awareness of the role of potassium in crop growth, and ii) farmers who demonstrate greater knowledge about the importance of potassium tend to achieve higher yields and revenues. Table A4 in the appendix shows the rate of correct responses for all questions in the fertilizer knowledge module of the survey. In general, knowledge about fertilizer use and soil health is relatively low, with an average correct response rate of only 26%. Particularly for knowledge on potassium-based fertilizers only 45.4% of surveyed farmers could correctly identify fertilizers which supply potassium suggesting that lack of basic information on the importance of nutrient diversity for soil health is a significant factor in explaining current fertilizer application patterns.

The responses from the *REWARD* survey also show that farmers who are more knowledgeable about potassium-based fertilizers cultivate plots with higher yields and higher revenues. Table A4 in the appendix presents the estimates from plot-level OLS regressions an indicator for whether the farmer cultivating the plot correctly identifies K-based fertilizers on yields, revenue per hectare, and net revenue per hectare, defined as revenue net of total expenditures in variable inputs. After the inclusion of crop- and season-level fixed effects, these estimates show that farmers correctly able to correctly identify K-based fertilizers tend to have plots with 1.3kg/ha higher yields, producing 6,909.2 Rs/ha per season more net revenue. While correlational only, these associations hint at the importance of general fertilizer knowledge on better fertilizer use and consequently higher output levels.

We take these results as suggestive of knowledge constraints being one of the principal drivers of unbalanced fertilizer use. Interventions targeted at improving farmers' general agronomic knowledge on the importance of diversifying nutrient application and enhancing their capacity to correctly identify which fertilizers supply which nutrients may be more cost-effective than delivering granular information based on plot-specific characteristics that may be too complex to operate on (Beg, Islam, & Rahman, 2024; Fabregas et al., 2025). Digital extension services could be used to disseminate practical, localized guidance on nutrient management, similar to successful interventions implemented in other agricultural contexts (Corral et al., 2020; Harou et al., 2022; Islam & Beg, 2021). Addressing these informational barriers may not only lead to higher yields but also raise overall farm profitability, reduce environmental externalities and improve long-term soil health.

5.3 Robustness

Our preferred specification only leverages variation across villages within districts and further controls by year-specific characteristics as well as for a large battery of household and plot control variables. However, the inclusion of these controls is not pivotal for the qualitative conclusions of our analysis. Table A2 in the appendix shows how results vary according to the set of controls and fixed effects included for both the OLS and the 2SLS specifications. The inclusion of increasingly more stringent controls reduces the magnitude of the OLS point estimates and tends to increase the magnitude of the 2SLS coefficients. All coefficients for the effect of K-to-N ratios on yields remain positive and precisely estimated throughout, with 2SLS estimates being larger than OLS by a factor that goes from about 1.3 for specification without fixed effects or controls (columns 1-2), to a factor of about 12 for regressions with fixed effects but no controls.

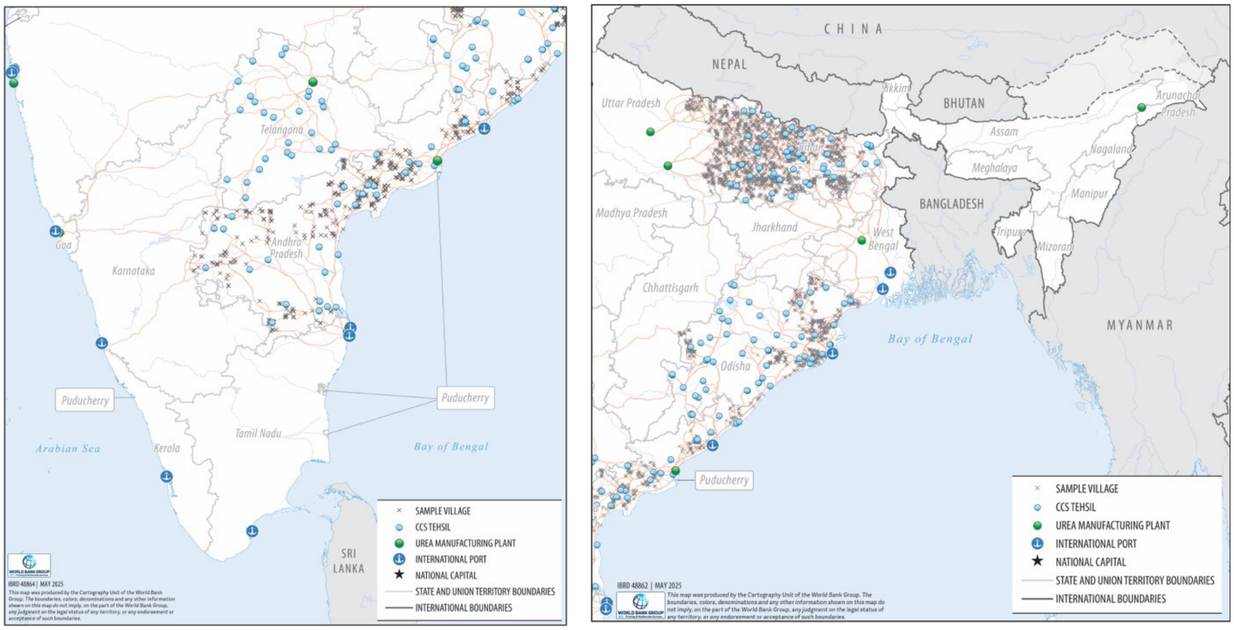
6. Conclusion

The combination of nitrogen overapplication and limited use of other essential nutrients is an underexplored issue that appears to be limiting agricultural productivity in India, the world's largest rice exporter and one of the world's main contributors to food security goals. The main objective of this paper has been to show that rebalancing nutrient use would induce large improvements in yields. Despite the clear agronomic benefits of a more balanced K-to-N ratio, and the observation that these benefits can potentially be obtained without increases in input expenditures, imbalances in fertilizer application are prevalent. Our results further suggest that a combination of several different mechanisms might be impeding the adoption of a more agronomically efficient choice of nutrients. Policy makers should consider recalibrating existing subsidies, promoting educational campaigns that encourage farmers to adopt more balanced fertilization practices, as well as undertaking investments in infrastructure that improve the accessibility to diverse nutrient types. Existing evidence from different contexts suggests there is wide scope for policies that lead to more balanced—and potentially less costly—fertilizer choices that achieve productivity gains and reduce environmental externalities (Coggins et al., 2025; Nayak et al., 2024; Sapkota et al., 2021).

We conclude by suggesting two important questions for future research. First, while lack of information seems to play a key role in explaining why many farmers do not choose a more diverse nutrient basket, measuring the relative importance of all factors currently impeding this input reallocation from taking place—i.e., understanding whether price incentives are more or less effective than information delivery in improving nutrient balance—constitutes a key input to inform policy design. A second open question relates to the aggregate and distributional effects of nudging farmers' fertilizer use away from domestically produced nitrogen-based fertilizers and towards imported potash-based fertilizers. Parallel to the positive effects on yield and output growth, changes in the relative demand for different nutrients are bound to have distributional impacts across farmers, input manufacturers, and government expenditure levels. By reducing levels of excess nitrogen, these changes in demand would also have impacts on long-run soil health, biodiversity, and greenhouse gas emissions, all of which should be accounted for to assess the net welfare impacts of policies that rebalance fertilizer use.

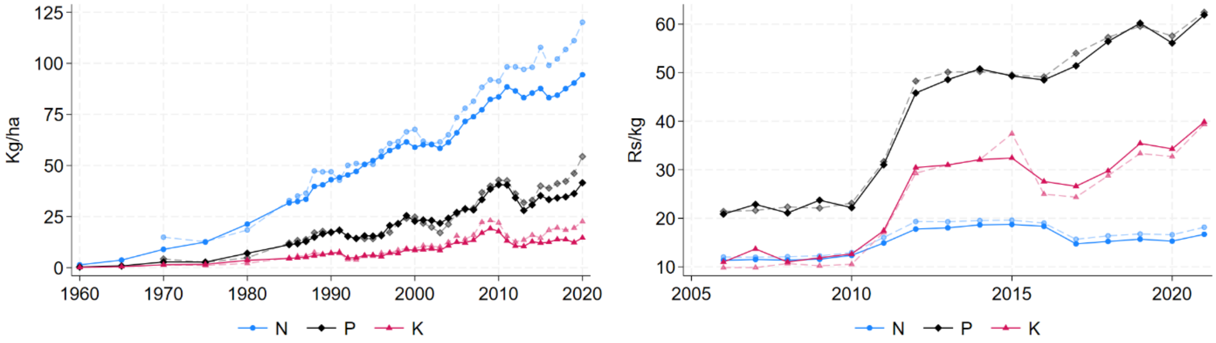
Tables and Figures

Figure 1. Minimum travel distances between sample villages, urea manufacturing plants, and international ports



Notes: Minimum road travel distances in kilometers between the closest urea manufacturing plant (green dots), and international port (dark blue dots) to each sample village in the *CSISA-NUE* dataset (crosses), and each sample tehsil in the *CCS* (light blue dots). Orange lines denote shortest route to a urea plant or to a major port.

Figure 2. Fertilizer demand and price trends by nutrient

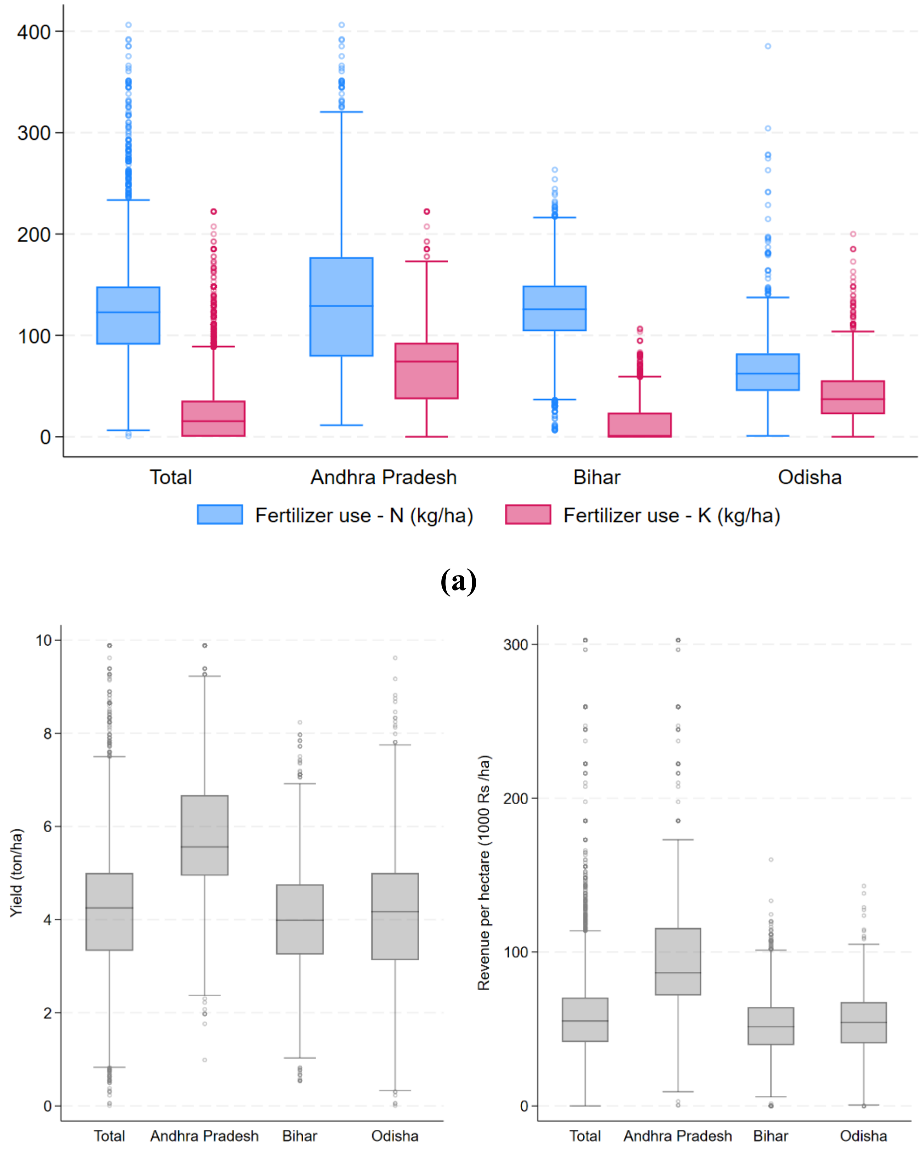


(a) Fertilizer use **(b) Fertilizer prices**

(c) K-to-N ratio of fertilizer use **(d) Fertilizer spending as share of total input expenditure**

Notes: Solid lines in all figures show nation-wide averages, while dashed lines represent averages for the states of Andhra Pradesh, Bihar, and Odisha only. Panel (a): Fertilizer use by nutrient type based on data from the *ICRISAT-TCI* District-Level Database (DLD) for Indian Agriculture and Allied Sectors. Panel (b): Average fertilizer prices by nutrient (total expenditure / quantity applied) across cultivation units surveyed in each round of the *Cost of Cultivation Surveys* (CCS) 2006–2020. Panel (c): K-to-N ratio of potash-based over nitrogen-based fertilizers based on data from *DLD*. Panel (d): Average expenditure in all types of fertilizer as a fraction of total agricultural input expenditures across cultivation units surveyed in the *CCS*. All prices in nominal Indian rupees.

Figure 3. Distribution of yield, revenue per hectare, and nutrient application rates by state

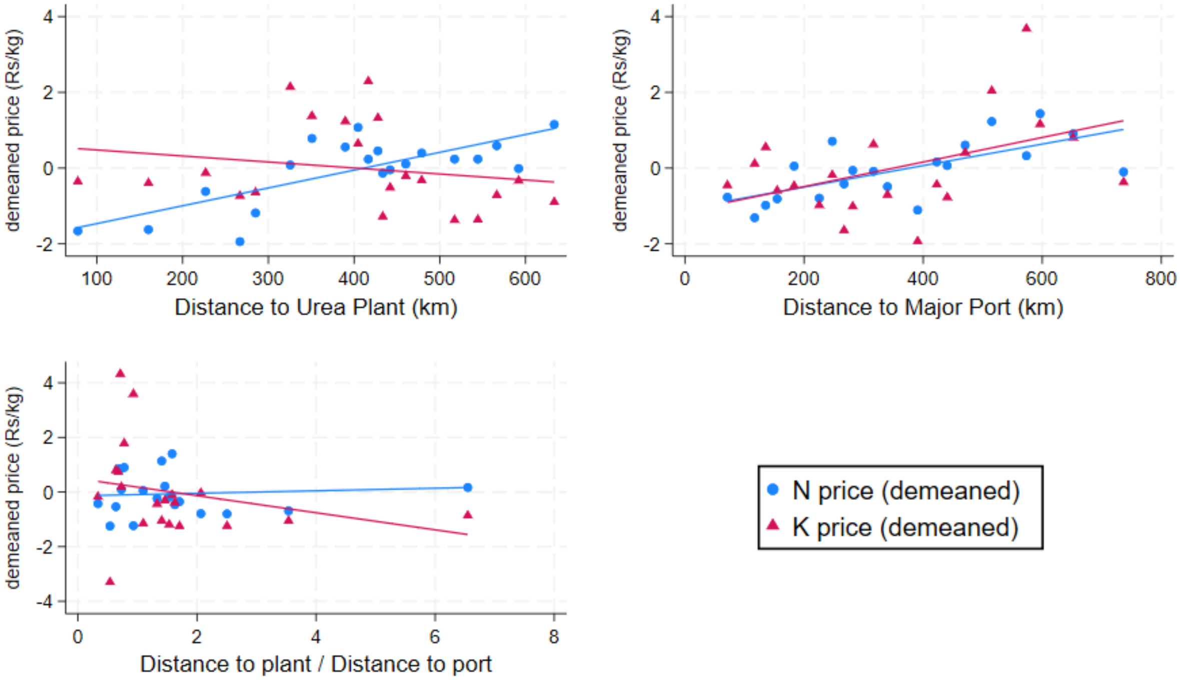


(a)

(b) **(c)**

Notes: Distribution of nutrient application rates (panel a), yields (panel b), and revenues per hectare (panel c) for the sample of farmers in the *CSISA-NUE* database. Yields are measured for each farmer's main rice plot during the season. Horizontal lines within each box denote median values, box edges denote respectively the 25th and 75th percentiles (Q1-Q3), end of whisker lines denote respectively upper and lower adjacent values (Q3 + 1.5(Q3-Q1), Q1 – 1.5(Q3-Q1)). Observations above the 99.9th percentile of each variable's distribution excluded from plot.

Figure 4. Fertilizer prices and village distance to plants, ports and distance ratio



Note: Binned scatterplot of fertilizer prices by nutrient vs. village-level distances to nearest urea plant, international port, and the ratio of both distances. Fertilizer prices aggregated at the household level from the *CCS* 2017–2020 rounds. Prices demeaned to account for differences in price levels between N- and K-based fertilizers. Distance variables measured at the village level based on data from the *OSRM* platform.

Table 1. Correlation of yields and revenue per hectare with nutrient application rates

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
	Yield (Kg/ha)					Revenue per hectare (Rs/ha)				
N applied (kg/ha)	4.36*** (0.300)	5.55*** (0.648)			3.23*** (0.347)	53.39*** (4.766)	68.17*** (10.284)			40.50*** (5.533)
N squared (kg/ha)^2		-0.004** (0.002)					-0.046 (0.028)			
K applied (kg/ha)			6.05*** (0.545)	5.96*** (0.894)	1.70* (0.963)			81.57*** (8.592)	81.23*** (14.126)	37.59** (15.236)
N squared (kg/ha)^2				0.001 (0.006)					0.003 (0.088)	
N * K					0.02*** (0.005)					0.18** (0.079)
Obs.	11,531	11,531	11,531	11,531	11,531	11,393	11,393	11,393	11,393	11,393
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Village FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Plot and Household Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Notes: Regions included are Andhra Pradesh, Bihar, and Odisha. "Plot and Household Controls" denotes a vector of controls consisting of gender and educational level of farmer, total area farmed by household, number of household members, distance to output market, availability of irrigation, type of rice varietal planted, total precipitation, number of dry and wet days, average dry- and wet-spell length, farmer's perceived soil texture, quality, and drainage. Standard errors in parentheses. * $p<0.10$, ** $p<0.05$, *** $p<0.01$.

Table 2. Correlation of yields and revenue per hectare with K/N ratios

	(1)	(2)	(3)	(4)
	Yield (Kg/ha)		Revenue per hectare (Rs/ha)	
K/N ratio	85.29 (52.07)	244.3*** (52.49)	2452.7*** (818.4)	4457.6*** (828.9)
N quantity applied (kg/ha)		4.646*** (0.306)		58.62*** (4.858)
Obs.	11531	11531	11393	11393
Year FE	Yes	Yes	Yes	Yes
Village FE	Yes	Yes	Yes	Yes
Plot and Household Controls	Yes	Yes	Yes	Yes

Notes: Regions included are Andhra Pradesh, Bihar, and Odisha. "Plot and Household Controls" denotes a vector of controls consisting of gender and educational level of farmer, total area farmed by household, number of household members, distance to output market, availability of irrigation, type of rice varietal planted, total precipitation, number of dry and wet days, average dry- and wet-spell length, farmer's perceived soil texture, quality, and drainage. Standard errors in parentheses. * $p<0.10$, ** $p<0.05$, *** $p<0.01$.

Table 3. Travel distance to international ports and urea manufacturing plants vs. fertilizer prices and application rates

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Panel A: Nutrient Unit Values (Rs/kg)								
	log Unit Value K (Rs/kg)				log Unit Value N (Rs/kg)			
log distance to port	0.0175***	0.0633***			0.0476***	0.0109		
	(0.00499)	(0.0225)			(0.00282)	(0.0135)		
log distance to urea plant			-0.0153***	-0.0258			0.0757***	0.0234**
			(0.00545)	(0.0189)			(0.00349)	(0.0114)
Obs.	4026	4026	4026	4026	7340	7340	7340	7340
Year FE	No	Yes	No	Yes	No	Yes	No	Yes
District FE	No	Yes	No	Yes	No	Yes	No	Yes

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Panel B: Nutrient Application Rates (kg/ha)								
	log K applied (kg/ha)				log N applied (kg/ha)			
log distance to port	-1.421***	-0.253**			0.287***	0.254***		
	(0.0245)	(0.126)			(0.00616)	(0.0318)		
log distance to urea plant			0.656***	-0.413***			-0.214***	-0.0110
			(0.0475)	(0.136)			(0.0114)	(0.0346)
Obs.	12,255	12,253	12,255	12,253	12,255	12,253	12,255	12,253
Year FE	No	Yes	No	Yes	No	Yes	No	Yes
District FE	No	Yes	No	Yes	No	Yes	No	Yes
Plant and Household Controls	No	Yes	No	Yes	No	Yes	No	Yes

Notes: Panel A: Unit value data by nutrient computed from the *Cost of Cultivation Surveys* as the ratio of reported household-level expenditure over amount used for each fertilizer nutrient. Regressions weighted by the survey's cluster factor expansion weights. Distances measured from each *CCS'* tehsil (group of villages) centroid. Panel B: Nutrient application rate variables computed from the *CSISA-NUE* farmer-level dataset and defined in log(x+1) transformation. Distances measured from the average coordinates of all households within the same village. "Plot and Household Controls" denotes a vector of controls consisting of gender and educational level of farmer, total area farmed by household, number of household members, distance to output market, availability of irrigation, type of rice varietal planted, total precipitation, number of dry and wet days, average dry- and wet-spell length, farmer's perceived soil texture, quality, and drainage. Regions included are Andhra Pradesh, Bihar, and Odisha. Standard errors in parentheses. * p<0.10, ** p<0.05, *** p<0.01.

Table 4. First stage and reduced form relationship with distance instrumental variables

	(1)	(2)	(3)	(4)
Panel A: First Stage - Dependent Var: K/N ratio				
Distance to port	-0.878***			-0.872***
	(0.155)			(0.149)
Distance to plant		-0.390***		-0.143
		(0.146)		(0.138)
Plant-to-port distance ratio			0.00291	-0.00443
			(0.00732)	(0.00681)
Obs.	12,255	12,255	12,255	12,255
Kleibergen-Paap F-stat	32.2	7.17	.16	12.37
Panel B: Reduced Form - Dependent Var: log Yield (kg/ha)				
Distance to port	-0.350*			-0.540***
	(0.189)			(0.200)
Distance to plant		0.0892		0.279
		(0.185)		(0.194)
Plant-to-port distance ratio			-0.0117**	-0.0174***
			(0.00465)	(0.00521)
Obs.	12,255	12,255	12,255	12,255
R^2	.34782	.3474	.34775	.34876
Year FE	Yes	Yes	Yes	Yes
District FE	Yes	Yes	Yes	Yes
Plot and Household Controls	Yes	Yes	Yes	Yes

Notes: Regions included are Andhra Pradesh, Bihar, and Odisha. Distances are defined in thousands of kilometers. "Plot and Household Controls" denotes a vector of controls consisting of gender and educational level of farmer, total area farmed by household, number of household members, distance to output market, availability of irrigation, type of rice varietal planted, total precipitation, number of dry and wet days, average dry- and wet-spell length, farmer's perceived soil texture, quality, and drainage. Standard errors clustered at the village level in parentheses. * $p<0.10$, ** $p<0.05$, *** $p<0.01$.

Table 5. Yield and Revenue returns of increasing K/N ratios

	(1)	(2)	(3)	(4)
Panel A: OLS	log Yield (Kg/ha)		log Revenue per hectare (Rs/ha)	
K / N Ratio	0.0336*	0.0704***	0.0384*	0.0691***
	(0.0177)	(0.0173)	(0.0206)	(0.0207)
N quantity applied (kg/ha)		0.00114***		0.000948***
		(0.000121)		(0.000130)
Obs.	12255	12255	12060	12060
Panel B: 2SLS				
K / N Ratio	0.411*	0.664***	0.0330	0.155
	(0.211)	(0.256)	(0.270)	(0.320)
N quantity applied (kg/ha)		0.00183***		0.00105**
		(0.000329)		(0.000408)
Obs.	12,255	12,255	12,060	12,060
Year FE	Yes	Yes	Yes	Yes
District FE	Yes	Yes	Yes	Yes
Plot and Household Controls	Yes	Yes	Yes	Yes
Kleibergen-Paap F-stat	12.37	10.39	12.13	10.18

Notes: Regions included are Andhra Pradesh, Bihar, and Odisha. "Plot and Household Controls" denotes a vector of controls consisting of gender and educational level of farmer, total area farmed by household, number of household members, distance to output market, availability of irrigation, type of rice varietal planted, total precipitation, number of dry and wet days, average dry- and wet-spell length, farmer's perceived soil texture, quality, and drainage. Standard errors clustered at the village level in both first and second stages in parentheses. * p<0.10, ** p<0.05, *** p<0.01.

Table 6. *REWARD* survey – K-fertilizer knowledge vs. yield and revenue

	(1)	(2)	(3)	(4)	(5)	(6)
	Yield (Kg/ha)		Revenue ($Rs/ha)		Net Revenue (Revenue - Variable input costs)	
Q17: Your soil test results also require application of K. What type of fertilizer can you choose to do so?	99.06** (42.89)	110.1*** (39.14)	2638.4*** (901.2)	2546.3*** (860.8)	5817.9*** (846.7)	5710.7*** (827.9)
Obs.	11,175	11,175	11,162	11,162	11,160	11,160
Household controls	No	Yes	No	Yes	No	Yes
Crop FE	No	Yes	No	Yes	No	Yes
Season FE	No	Yes	No	Yes	No	Yes

Notes: Estimates of OLS regressions of a dummy variable indicating if the farmer cultivating the plot correctly identifies K-based fertilizers on yields, revenue per hectare, and net revenue per hectare, defined as revenue net of total expenditures in variable inputs. Columns 2, 4, and 6 include controls for household dependency ratio, household head age and education level, an indicator for whether the household head is female, owns a mobile phone, or belongs to a farmer's organization, plus crop, and season fixed effects. Standard errors in parentheses. * p<0.10, ** p<0.05, *** p<0.01.

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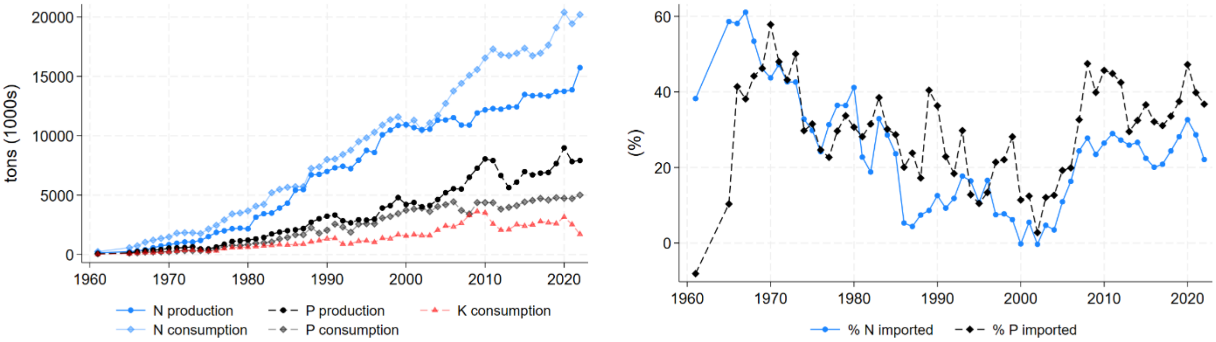
Appendix

Additional Figures and Tables

Figure A1. Production and consumption of fertilizer by nutrient type – National level



(a) Total production and consumption **(b) Fraction of consumption imported**

Notes: Data from the *Fertilizer Association of India* (FAI). Years indicate levels consumed and produced from April to March of the following year. Nitrogen production levels exclude N produced for non-agricultural purposes. Note the entire requirement of K consumption is met through imports.

Table A1. *CSISA – NUE* sample of rice farmers: Descriptive statistics

	Andhra Pradesh	**Bihar**	**Odisha**	**Total**
Area of farmer's largest plot (ha)	0.491	0.237	0.320	0.280
	[0.405]	[0.182]	[0.202]	[0.202]
	(0.531)	(0.244)	(0.363)	(0.324)
Yield (kg/ha)	5787.680	4058.302	4190.949	4302.672
	[5559.862]	[3985.564]	[4170.000]	[4250.206]
	(1830.140)	(1121.916)	(1665.085)	(1429.595)
Revenue per hectare (Rs/ha)	105376.755	52202.712	54512.965	59604.087
	[86486.750]	[51397.840]	[54375.000]	[55250.000]
	(57561.704)	(17729.787)	(22813.173)	(32643.653)
Fertilizer use - N (%)	1.000	1.000	1.000	1.000
	[1.000]	[1.000]	[1.000]	[1.000]
	(0.000)	(0.000)	(0.000)	(0.000)
Fertilizer use - P (%)	0.959	0.912	0.932	0.921
	[1.000]	[1.000]	[1.000]	[1.000]
	(0.197)	(0.283)	(0.252)	(0.270)
Fertilizer use - K (%)	0.925	0.424	0.959	0.550
	[1.000]	[0.000]	[1.000]	[1.000]
	(0.263)	(0.494)	(0.198)	(0.498)
Fertilizer use - N (kg/ha)	137.286	126.433	68.296	121.398
	[130.224]	[125.749]	[62.270]	[122.762]
	(74.392)	(33.730)	(42.159)	(46.463)
Fertilizer use - P (kg/ha)	72.297	48.038	44.248	50.836
	[66.101]	[50.014]	[42.626]	[51.164]
	(42.657)	(23.120)	(30.118)	(28.607)
Fertilizer use - K (kg/ha)	67.369	12.301	44.635	23.213
	[74.132]	[0.000]	[37.066]	[15.490]
	(39.463)	(16.774)	(31.921)	(30.541)
K/N Ratio	0.614	0.104	0.726	0.241
	[0.502]	[0.000]	[0.638]	[0.136]
	(0.442)	(0.153)	(0.507)	(0.362)
K/P Ratio	1.074	0.289	1.170	0.497
	[1.184]	[0.000]	[0.870]	[0.326]
	(0.843)	(0.438)	(1.120)	(0.716)
P/N Ratio	0.614	0.391	0.705	0.455
	[0.544]	[0.418]	[0.659]	[0.418]
	(0.346)	(0.204)	(0.436)	(0.286)
Distance to major port (km)	301.875	621.620	162.750	528.060
	[342.303]	[613.700]	[155.009]	[555.861]
	(127.285)	(134.492)	(81.848)	(211.760)
Distance to urea plant (km)	266.167	303.684	414.467	311.042
	[276.002]	[299.596]	[403.087]	[303.394]
	(111.318)	(83.441)	(106.386)	(98.318)
Plant/port distance ratio	1.030	0.517	3.585	0.927
	[0.967]	[0.574]	[2.424]	[0.632]
	(0.601)	(0.180)	(3.295)	(1.482)
Farmer is male (%)	0.939	0.975	0.979	0.970
	[1.000]	[1.000]	[1.000]	[1.000]
	(0.240)	(0.157)	(0.142)	(0.169)
Farmer's educ level: None (%)	0.347	0.257	0.137	0.256
	[0.000]	[0.000]	[0.000]	[0.000]
	(0.476)	(0.437)	(0.344)	(0.436)
Farmer's educ level: Primary (%)	0.372	0.302	0.393	0.321
	[0.000]	[0.000]	[0.000]	[0.000]
	(0.483)	(0.459)	(0.489)	(0.467)
Farmer's educ level: Secondary (%)	0.207	0.331	0.372	0.319
	[0.000]	[0.000]	[0.000]	[0.000]
	(0.405)	(0.471)	(0.484)	(0.466)
Farmer's educ level: Tertiary (%)	0.074	0.109	0.097	0.103
	[0.000]	[0.000]	[0.000]	[0.000]
	(0.262)	(0.312)	(0.297)	(0.304)
Number of household members	4.516	7.900	5.746	7.211
	[4.000]	[8.000]	[5.000]	[7.000]
	(1.443)	(2.688)	(2.338)	(2.812)
Total area farmed by household	1.742	1.159	1.118	1.232
	[1.012]	[0.759]	[0.809]	[0.809]
	(2.171)	(1.479)	(1.214)	(1.576)
Distance to output market	13.997	4.543	4.025	5.740

	[13.000]	[3.000]	[3.000]	[4.000]
	(10.666)	(3.875)	(4.088)	(6.226)
Irrigation availability (%)	0.949	0.983	0.572	0.933
	[1.000]	[1.000]	[1.000]	[1.000]
	(0.220)	(0.129)	(0.495)	(0.251)
Type of rice variety: Basmati (%)	0.000	0.003	0.000	0.002
	[0.000]	[0.000]	[0.000]	[0.000]
	(0.000)	(0.052)	(0.000)	(0.045)
Type of rice variety: Hybrid (%)	0.146	0.301	0.074	0.255
	[0.000]	[0.000]	[0.000]	[0.000]
	(0.353)	(0.459)	(0.262)	(0.436)
Type of rice variety: Improved (%)	0.663	0.691	0.871	0.707
	[1.000]	[1.000]	[1.000]	[1.000]
	(0.473)	(0.462)	(0.335)	(0.455)
Type of rice variety: Traditional (%)	0.190	0.005	0.055	0.035
	[0.000]	[0.000]	[0.000]	[0.000]
	(0.392)	(0.073)	(0.228)	(0.185)
Total yearly precipitation (mm)	923.115	1155.455	1748.747	1190.692
	[928.088]	[1090.043]	[1757.070]	[1110.824]
	(344.246)	(223.052)	(100.340)	(315.571)
Days without rainfall	271.457	292.356	253.428	285.245
	[270.000]	[293.000]	[253.000]	[290.000]
	(12.199)	(7.487)	(7.504)	(15.640)
Days with rainfall	93.547	72.644	111.573	79.755
	[95.000]	[72.000]	[112.000]	[75.000]
	(12.197)	(7.487)	(7.504)	(15.640)
Average length of dry spell	18.039	18.636	16.742	18.346
	[17.917]	[18.333]	[16.417]	[18.067]
	(2.603)	(2.945)	(2.309)	(2.900)
Average length of wet spell	8.656	8.202	8.842	8.334
	[8.200]	[7.750]	[8.750]	[8.000]
	(1.913)	(1.935)	(1.296)	(1.886)
Perceived soil texture: Light	0.060	0.081	0.075	0.078
	[0.000]	[0.000]	[0.000]	[0.000]
	(0.237)	(0.273)	(0.263)	(0.268)
Perceived soil texture: Medium	0.778	0.822	0.843	0.818
	[1.000]	[1.000]	[1.000]	[1.000]
	(0.416)	(0.383)	(0.364)	(0.386)
Perceived soil texture: Heavy	0.162	0.097	0.082	0.104
	[0.000]	[0.000]	[0.000]	[0.000]
	(0.369)	(0.296)	(0.275)	(0.306)
Perceived soil quality: Low	0.037	0.040	0.056	0.041
	[0.000]	[0.000]	[0.000]	[0.000]
	(0.189)	(0.195)	(0.231)	(0.198)
Perceived soil quality: Medium	0.810	0.867	0.902	0.863
	[1.000]	[1.000]	[1.000]	[1.000]
	(0.392)	(0.340)	(0.298)	(0.344)
Perceived soil quality: High	0.153	0.094	0.042	0.096
	[0.000]	[0.000]	[0.000]	[0.000]
	(0.360)	(0.291)	(0.200)	(0.294)
Perceived drainage: very lowland	0.028	0.003	0.045	0.011
	[0.000]	[0.000]	[0.000]	[0.000]
	(0.164)	(0.054)	(0.208)	(0.104)
Perceived drainage: lowland	0.079	0.133	0.254	0.139
	[0.000]	[0.000]	[0.000]	[0.000]
	(0.269)	(0.340)	(0.436)	(0.346)
Perceived drainage: mediumland	0.717	0.772	0.659	0.752
	[1.000]	[1.000]	[1.000]	[1.000]
	(0.451)	(0.420)	(0.474)	(0.432)
Perceived drainage: upland	0.177	0.092	0.041	0.098
	[0.000]	[0.000]	[0.000]	[0.000]
	(0.382)	(0.289)	(0.198)	(0.297)
Number of farmers	1,627	9,263	1,365	12,255

Notes: Descriptive statistics for the sample of farmers in the *CSISA-NUE* database. Yields are measured for each farmer's largest plot during the season. Rainfall data comes from the Climate Hazard Group InfraRed Precipitation (*CHIRPS*) dataset. Median values in square brackets, standard deviation in parentheses.

Table A2. Yield and Revenue returns of increasing K/N ratios – Varying sets of controls

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
	log Yield (Kg/ha)						log Revenue per hectare (Rs/ha)					
Panel A: OLS												
K / N Ratio	0.112***	0.200***	0.037**	0.075***	0.034*	0.070***	0.230***	0.334***	0.046**	0.077***	0.038*	0.069***
	(0.017)	(0.017)	(0.018)	(0.018)	(0.018)	(0.017)	(0.026)	(0.027)	(0.021)	(0.021)	(0.021)	(0.021)
N applied (kg/ha)		0.002***		0.001***		0.001***		0.002***		0.001***		0.001***
		(0.000)		(0.000)		(0.000)		(0.000)		(0.000)		(0.000)
Obs.	12,255	12,255	12,255	12,255	12,255	12,255	12,060	12,060	12,060	12,060	12,060	12,060
Panel B: 2SLS												
K / N Ratio	0.139***	0.281***	0.531**	0.823***	0.411*	0.664***	0.294***	0.468***	0.205	0.389	0.033	0.155
	(0.029)	(0.031)	(0.218)	(0.268)	(0.211)	(0.256)	(0.037)	(0.041)	(0.274)	(0.328)	(0.270)	(0.320)
N applied (kg/ha)		0.002***		0.002***		0.002***		0.003***		0.001***		0.001**
		(0.000)		(0.000)		(0.000)		(0.000)		(0.000)		(0.000)
Obs.	12,255	12,255	12,255	12,255	12,255	12,255	12,060	12,060	12,060	12,060	12,060	12,060
Kleibergen-Paap F	401.39	427.51	12.35	10.37	12.37	10.39	397.53	423.61	12.22	10.26	12.13	10.18
Year FE	No	No	Yes	Yes	Yes	Yes	No	No	Yes	Yes	Yes	Yes
District FE	No	No	Yes	Yes	Yes	Yes	No	No	Yes	Yes	Yes	Yes
Plot and Household Controls	No	No	No	No	Yes	Yes	No	No	No	No	Yes	Yes

Notes: Regions included are Andhra Pradesh, Bihar, and Odisha. "Plot and Household Controls" denotes a vector of controls consisting of gender and educational level of farmer, total area farmed by household, number of household members, distance to output market, availability of irrigation, type of rice varietal planted, total precipitation, number of dry and wet days, average dry- and wet-spell length, farmer's perceived soil texture, quality, and drainage. Standard errors clustered at the village level in parentheses. * p<0.10, ** p<0.05, *** p<0.01.

Table A3. Fertilizer prices by nutrient: Descriptive statistics

	(1)	(2)	(3)	(4)	(5)	(6)
Nutrient	**N**		**P**		**K**	
Panel A: Plot level						
N = 17,408	16.361	16.271	56.844	57.522	28.984	28.779
	[16.427]	[16.358]	[55.501]	[55.502]	[29.687]	[30.000]
	(2.354)	(2.315)	(9.046)	(9.504)	(33.193)	(9.786)
Panel B: Plot level - rice only						
N = 10,429	16.574	16.281	57.570	58.204	28.219	28.364
	[16.488]	[16.328]	[55.501]	[55.502]	[28.030]	[29.334]
	(2.305)	(2.222)	(9.920)	(9.990)	(4.258)	(4.341)
Panel C: Household level						
N = 7,342	15.917	15.903	56.105	56.869	28.875	28.981
	[16.193]	[16.110]	[55.502]	[55.502]	[30.000]	[30.000]
	(2.126)	(2.133)	(7.717)	(8.437)	(6.514)	(6.605)
Survey weights	No	Yes	No	Yes	No	Yes

Notes: Average fertilizer prices by nutrient (total expenditure / quantity applied) for cultivation units surveyed in the 2017–2020 rounds of the *Cost of Cultivation Surveys* (CCS) for the states of Andhra Pradesh, Bihar, and Odisha. Panel A: all cultivation units included in survey. Panel B: Cultivation units planted with rice only. Panel C: Prices aggregated across units cultivated by the same household. Columns 1, 3, and 5 show unweighted averages, while columns 2, 4, 6 show averages with survey weights. Median values in square brackets, standard deviation in parentheses.

Table A4. ***REWARD*** **survey – fertilizer knowledge test questions**

Question	Share of correct answers
Q01: Which of the below are reasons to have your soil tested:	8.40%
Q02: Legumes are good for soil health but require how much N?	24.40%
Q03: Your soil is light color – what does this say about its fertility status	57.10%
Q04: Your soil is deficient in organic matter. Which of the following should you do?	78.80%
Q05: If your plants suffer from nitrogen deficiency, which part of leaves will turn yellow first?	33.40%
Q06: If you see such symptoms, what would be an appropriate fertilizer to apply:	9.00%
Q07: Chemical vs Organic fertilizers - Which of the following is correct:	0.70%
Q08: Your soil has been characterized as very acidic. What can you do to reduce the harmful effects:	2.70%
Q09: A neighbor says one reason for soils to become more acid is overapplication of fertilizers. Is he correct?	54.40%
Q10: Which crops can suitably be grown on acid soils (choose all that apply)?	2.60%
Q11: What are advantages of direct seeding of rice:	27.20%
Q12: What is the appropriate seeding rate for direct seeding of rice?	67.90%
Q13: If your plant looks like [Picture], which nutrient is lacking?	8.90%
Q14: Which of the following fertilizer should you apply to fix this?	11.30%
Q15: Soil test results ask to apply 46 kg N/ha. How much Urea will meet this recommendation?	48.00%
Q16: The soil test also asks to apply 20 kg of P per ha. Will of Urea help meet this requirement?	1.20%
Q17: Your soil test results also require application of K. What type of fertilizer can you choose to do so?	45.10%
Mean Test Score (Index with values from 0 to 100)	41.446
Number of surveyed farmers	5,187

Notes: Proportion of 5429 farmers surveyed in the Odisha *REWARD* baseline survey who correctly answer each question in the baseline knowledge test. A multiple-choice question is defined as correctly answered if all of the available correct answers, and none of the available incorrect answers, are selected. Q15, which accepts a continuous numerical value as response, is defined as correctly answered if the answer falls within a range of 50kg plus or minus the correct value.