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Research Article

Keywords: inorganic fertilizer, manure, India, Nepal, Bangladesh

Posted Date: February 22nd, 2021

DOI: https://doi.org/10.21203/rs.3.rs-206349/v1

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Abstract

Fertilizer, though one of the most essential inputs for increasing agricultural production, is a leading cause of nitrous oxide emissions from agriculture, contributing significantly to global warming. Therefore, understanding factors affecting farmers' use of fertilizers is crucial to develop strategies to improve its efficient use and to minimize its negative impacts. Using data from 2,558 households across the Indo-Gangetic Plains in India, Nepal, and Bangladesh, this study examines the factors affecting farmers' use of organic and inorganic fertilizers for the two most important cereal crops – rice and wheat. Together, these crops provide the bulk of calories consumed in the region. As nitrogen (N) fertilizer is the major source of global warming and other environmental effects, we also examine the factors contributing to its overuse. We applied multiple regression models to understand the factors influencing the use of inorganic fertilizer, Heckman models to understand the likelihood and intensity of manure use, and a probit model to examine the over-use of N fertilizer. Our results indicate that various socio-economic and geographical factors influence the use of inorganic fertilizer in rice and wheat. Across the study sites, N fertilizer over-use is the highest in Haryana (India) and the lowest in Nepal. Across all locations farmers reported a decline in manure application, concomitant with a lack of awareness of the principles of appropriate fertilizer management that can limit environmental externalities. Educational programs highlighting measures to improving nutrient-use-efficiency and reducing the negative externalities of N fertilizer over-use are proposed to address these problems.

Keywords: inorganic fertilizer; manure; India; Nepal; Bangladesh

1. Introduction

Achieving food security, addressing climate change, and halting environmental and natural resource degradation are among the key challenges faced by the agricultural sector in efforts to achieve sustainable development goals (SDGs[1]) and the Paris Agreement to limit global temperature increase to below 2 ºC (IPCC, 2014). Fertilizer use, particularly nitrogen (N), is one of the important land management practices to increase crop production and improve soil fertility. Thus, the use of soil fertility enhancing amendments to supply essential nutrients in crop production is of clear importance. Along with the nutrient supply from soil organic matter, crop residues, wet and dry deposition, and biological nitrogen fixation, synthetic fertilizer is a primary source of essential nutrients in crop production.

The success of the Green Revolution (GR) in 1960s to increase food production and to reduce hunger world-wide was made possible, partly due to increasing use of chemical fertilizer (Erisman *et al.*, 2008). However, excessive chemical fertilizer use during and post GR caused a number of environmental and ecological problems such as soil acidification, degradation, and water eutrophication, severely undermining the sustainability of agriculture (Lu and Tian, 2017). The loss of applied nutrients into the environment resulted in the fertilizer-induced emission of nitrous oxide (N_2O) from agricultural production, a major source anthropogenic greenhouse gas emissions (Sutton *et al.*, 2013). Around 60% of nitrogen pollution is estimated to originate from crop production alone, particularly through nitrogen (N) fertilizer application (Sapkota *et al.*, 2018b). Hence, agricultural development pathways need to address these concerns, in addition to climate change adaptation and mitigation (van Beek *et al.*, 2010; Aryal *et al.*, 2020a; Aryal *et al.*, 2020b).

[1] https://sustainabledevelopment.un.org/

In South Asia (SA), use of N fertilizer has been increasing over the last fifty plus years (FAO, 2013). Increased use of fertilizer together with irrigation and improved genetics were core to the GR philosophy that aimed to increase crop productivity in SA (Firdousi, 1997; Pingali, 2012; Benbi, 2017; Roy, 2017). Food-grain production in India increased from 82 million tons in 1960 to 284 million tons in 2018/19, rendering the country largely self-sufficient in cereals (GoI, 2020). Yet to achieve this, rates of fertilizer application have increased dramatically (Benbi, 2017; Roy, 2017). For instance, in Punjab and Haryana states of India, fertilizer-N use increased from meager 2-8 kg N ha^{-1} in 1960s to more than 160-180 kg N ha^{-1} in 2017 (Benbi, 2017).

Many farmers in SA are unaware of scientifically recommended rates of fertilizer application. Rather, they apply fertilizers when and where they believe them to be necessary, often in quantities and with elements based on what are available and affordable at markets (Takeshima *et al.*, 2016; Kishore *et al.*, 2019). Further, recommendations for fertilizer rates tend to be based upon small-plot crop yield response data that are extrapolated over large geographic areas without considering spatial variability in the nutrient supplying capacity of the soils and temporal variability due to management factors (Ladha *et al.*, 2020). Heavy subsidies for N fertilizer relative to other nutrients, and the lack of adequate knowledge on fertilizer management have resulted in unbalanced fertilizer application (Kishore *et al.*, 2019). Inappropriate and unbalanced nutrient addition not only reduces nutrient use efficiency (NUE) and profitability (Krupnik *et al.*, 2004; Ladha *et al.*, 2005), but also increases environmental risks associated with the loss of unused nutrients through emissions, leaching or run-off (Sapkota et al., 2014) . SA has one of the lowest NUE in the world (Ladha *et al.*, 2020). Average efficiency of fertilizer N in India has been reported to be 30-40% in rice and 50-60% in other cereals (Brar et al., 2011; Dobermann, 2006).

Opportunities exist to improve NUE through adoption of better fertilizer management practices such as adjusting application rates based on more precise estimate of plant demand, using the right form of fertilizer, and applying fertilizer using right method so that it is delivered directly to the root zone (Dobermann and Witt, 2004). A recent study in India showed that adoption of precision nutrient management technologies would substantially reduce fertilizer N consumption, thereby reducing GHG emission of 17.5 Mt CO2e per year with an estimated cost saving of 100 USD per t CO2e abated. (Sapkota *et al.*, 2019). Also, the application of manures contributes to the retention of synthetic fertilizer N and reduction of losses, mainly through gradual improvements in soil structure and ability to store nitrogen for slow release from soil organic matter (Krupnik *et al.*, 2004; Ladha *et al.*, 2005; Ladha *et al.*, 2020).

Realization of the benefits of improved fertilizer and organic matter management depends on the extent to which farmers are aware of and able to implement new appropriate agronomic management techniques. Farmers' use of different management practices are difficult to predict and depends largely on the socio-economic and cultural context under which they operate (Aryal *et al.*, 2018c; Sapkota *et al.*, 2018a). Understanding farmer behavior towards use of fertilizer and manure is crucial because improving N fertilizer use efficiency can substantially lower the carbon footprints of agriculture (Liu *et al.*, 2016). Though methods to improve the NUE continue to be developed, inefficient use of fertilizer persists. To date, relatively little is known about farmers' behavior towards fertilizer and manure use in South Asia (Stuart *et al.*, 2014; Sapkota *et al.*, 2018a).

This study explores the factors affecting the use of inorganic (Urea and Di-ammonium Phosphate) and organic (Manure) fertilizers in rice and wheat production in SA, using data from 2,550 households spread across Bangladesh, India and Nepal. Also, it examines the factors associated with the overuse of N fertilizer (both inorganic and organic) in rice and wheat. This study contributes to the existing literatures in several ways. Firstly, it is the first study that assesses the factors explaining farmers' fertilizer use behavior across these countries, while controlling for farmer characteristics, socio-economic factors, and farmland characteristics. Secondly, as the over-use of N fertilizer is one of the major reasons behind nitrous oxide emission and other negative environmental externalities, we examine the factors explaining its over-use using both quantitative and qualitative methods. It helps us to provide insights in designing low emission agricultural development and making investments consistent with the SDGs.

2. Study area and data

This study used data collected from a survey of 2,500 households across Indo-Gangetic plains of Bangladesh, India and Nepal in 2013. The data was collected through multistage sampling. In the first stage, three South Asian countries were purposively selected as they comprise approximately 84% of the land area allocated to rice and wheat in the Ingo-Gangetic Plains (Timsina and Connor, 2001). In the second stage, three districts in Bangladesh (Bagerhat, Jhalokhati, and Satkhira), one district in the Terai (plain lands) region of Nepal (Rupandehi), one district in Bihar state (Vaishali) and one district in Haryana state in India (Karnal) were selected. A total of 38 villages were selected for the study: 14 from Bangladesh, 12 from Bihar (India), 13 from Haryana (India) and 12 from Nepal (Table 1).

[Insert here Table 1]

In Bangladesh, agricultural input data come from 1,182 rice fields, cultivated by 630 households. In Nepal, the same data were collected from 1,576 rice and 977 wheat fields operated by 631 households, respectively. In Haryana, dataset included information from 665 rice and 667 wheat fields operated by 630 households and in Bihar 1,299 rice and 1,604 wheat fields, operated by 641 households were registered. Therefore, we analyze the factors affecting the use of fertilizer for rice and wheat in Nepal and India, and only for rice in Bangladesh. Furthermore, we collected qualitative information about the use organic and inorganic fertilizers, and possible reasons for their inappropriate use through two focus group discussions in each of the study sites.

3. Empirical methods

3.1 Multiple regression models: to analyze the factors affecting urea and DAP use in rice and wheat

As all sampled farmers growing rice and wheat applied urea and DAP, we used multiple regression models to analyze the factors affecting the use of these fertilizers in each crop. Farmers' use of inorganic fertilizers can be affected by several factors including household characteristics, socio-economic variables, market access and information, and farm characteristics including soil fertility status, irrigation, and soil depth (Shrestha *et al.*, 2013; Fishman *et al.*, 2016; Kpadonou *et al.*, 2019; Ward *et al.*, 2019). We included country dummy to capture the differences in fertilizer subsidy policy and price controls. Therefore, following empirical model is estimated:

$$Y_i = \alpha + \beta X_h + \gamma X_s + \delta X_k + \psi X_f + \varepsilon \qquad (1)$$

Where Y_i denotes the amount of urea (DAP) applied per hectare (kg ha^{-1}) of rice or wheat produced per season, X_h is a matrix of household characteristics including age, education and gender of the household head, X_s is a matrix of the ownership of and access to economic resources, X_k represents a matrix of knowledge enhancing activities such as participation in agricultural trainings and access to extension services, in addition to access to and market information and markets, and X_f refers to biophysical and farm characteristics including soil depth, soil fertility, access to irrigation, and distance from homestead to the rice or wheat field. $\alpha, \beta, \gamma, \delta$ and ψ are unknown parameters to be estimated, and ε is the stochastic error term. We controlled for possible hetereskedasticity using Huber-white robustness test and checked for multi-collinearity using variance influence factor (Wooldridge, 2010).

3.2 Heckman two-step model: to analyze the factors affecting the application of manures to rice and wheat fields

Considering that many rice and wheat fields did not receive manure, we applied Heckman two-step model to acknowledge censoring in the data (Heckman, 1979). The Heckman mdoel consists of two sequential decisions: first, a household decides whether or not to apply manure, and second, if they do apply it, they also need to decide how much to apply. Hence in the first step, we estimate a probit model with a dichotomous dependent variable (0 if manure is not applied and 1 if it is applied). In the second step, we analyze the factors influencing the quantity of manure used. Given that farmers applying manure have made the decision to use manure, we base this analysis on a sub-set of the data. As such, we assume that unobserved factors, which differentiate users from non-users, can also influence the amount of manure applied, resulting in selection bias. Consequently, we control for the self-selectivity bias described by using Inverse Mills Ratio (Heckman, 1979). The first step (selection mechanism) in a Heckman two-step model is:

$$z^* = \gamma w + \upsilon \tag{2}$$

As z^* is not directly observable, we assume idiosyncratic criteria are applied by farmers. z^* may be the difference in expected returns between applying and not applying manure. Therefore, a binary variable z is defined which takes on the value of one if the household decides to apply manure and zero otherwise.

$$z = \gamma w + \upsilon, \quad \text{where } z = 1 \text{ if } z^* > 0 \text{ and } z = 0 \text{ otherwise.} \tag{2a}$$

Therefore, $\text{Prob}(z=1) = \text{Prob}(z^* > 0) = \text{Prob}(\upsilon > -\gamma w) = \Phi(\gamma w)$, where Φ is the cumulative distribution at γw.

The second step in the Heckman model is given by:

$$y = \beta x + \varepsilon \tag{3}$$

Equation 3 is observed only if $z^* > 0$. When υ and ε follow a bivariate normal distribution with mean of zero, standard deviation σ and correlation ρ, we get:

$$E\left[y \middle| z=1\right] = E\left[y \middle| z^* > 0\right] = \beta x + \rho\sigma\lambda(\gamma w) \tag{4}$$

where λ is the Inverse Mills Ratio (IMR) $\left[\lambda = \phi(\gamma w)/\Phi(\gamma w)\right]$ i.e., the ratio of the value of density function of a standard normal distribution and cumulative distribution function calculated at γw. In equation 4, $\rho\sigma$ is equal to the regression coefficient on the IMR, β_λ. Inclusion of IMR in the second-stage as an explanatory variable helps correct selection bias. After this, ordinary least-square method can be used for estimation as follows (see Wooldridge 2010):

$$y = \beta x + \beta_\lambda \lambda + \varepsilon \tag{5}$$

Where β_λ is the coefficient of the IMR. Statistically significant IMR implies selection bias and confirms the appropriateness of Heckman's two-step model, supporting the hypothesis that the set of variables influencing the likelihood to adopt can be different from variables affecting the intensity of its use.

3.3 Probit model: to analyze factors influencing the over-use of N Fertilizer

We applied probit model to examine the factors associated with the over-use of N in rice and wheat. To obtain the total amount of N applied, we take the sum of nitrogen from urea, DAP and manure, accounting for their standard nutrient composition at 46%, 18% and 0.5%, respectively. For defining over-application of N, we followed the findings from (Sapkota *et al.*, 2018a) in Bihar and Haryana in India and adapted it for our study sites. According to their study, wheat farmers who applied more than 140 kg N ha^{-1} suffered a yield penalty and had high greenhouse gas emissions intensity. Similarly, rice yield leveled off with increased N application beyond 100 kg N ha^{-1}. Based on (Sapkota et al., 2018a), we created two variables, (1) 'over-use of N for rice' and (2) 'over-use of N for wheat'. The variable first is a binary variable with value of one if the amount of nitrogen applied is more than 120 kg N ha^{-1} in rice fields, and zero otherwise. Similarly, the variable 'over-use of N for wheat' is a binary variable with value of one if the amount of nitrogen applied is more than 140 kg N ha^{-1} in wheat plots and zero otherwise. Hence, we applied probit model combining all locations together (for details, see (Wooldridge, 2010)).

3.4 Variables and hypotheses

We have eight dependent variables in our analysis: urea applied to rice and wheat, respectively, DAP applied to rice and wheat, respectively, decision to use manure in rice and wheat, respectively, as well as the quantity of manure applied in rice, and wheat, respectively. The use of manure in rice and wheat are binary variables, while others are continuous.

3.4.1. Explanatory variables

Based on the theoretical framework and the previous literature on technology adoption, we included explanatory variables in the empirical analysis (Takeshima *et al.*, 2016; Aryal *et al.*, 2018b; Aryal *et al.*, 2018c; Pingali *et al.*, 2019; Ward *et al.*, 2019). A description of explanatory variables and hypotheses about their effects can be found below.

3.4.1.1. Household characteristics

Household characteristics including education, age, and gender of household head, family size, and migration can influence technology adoption decisions. Educated individuals are assumed to be able to more easily acquire new information and are more likely to adopt (Chowdhury *et al.*, 2014). Past studies indicate that they are more likely to use chemical fertilizer (Omamo *et al.*, 2002; Takeshima *et al.*, 2016). Further, elderly farmers apply more fertilizer relative to manure, as its use requires less labor compared with manure application. Conversely, with longer experience in agricultural management and benefits of organic matter in improving soil fertility, older farmers have also been observed to prefer manure (Waithaka *et al.*, 2007). Rural out-migration reduces the availability of household members to perform farm tasks; however, it also increases access to alternative income streams through remittances that can assist in purchasing fertilizer.

3.4.2. Economic and social capital

Economic capital consists of land, livestock, farm assets, household endowments and off-farm income sources, whereas social capital can include membership in village institutions such as farmer cooperatives/clubs. To capture the effect of wealth on the use of fertilizer and manure, we constructed household asset index (AI) using principal component analysis (for details, see https://www.stata.com/manuals13/mvpca.pdf). Wealthier households with higher index values are hypothesized to be more likely to use more fertilizer (Omamo *et al.*, 2002; Waithaka *et al.*, 2007). By alleviating cash constraints, access to off-farm income and remittances was also hypothesized to facilitate the use of fertilizer (Pingali *et al.*, 2019).

3.4.3. Market, institutional services, and training

Access to markets and institutional services can influence transactions costs and the degree of farmers' knowledge and access to information, thereby influencing technology adoption (Chowdhury *et al.*, 2014; Aryal *et al.*, 2018a; Aryal *et al.*, 2018c). Though extension staff is mobile, lack of sufficient staff to cover all the geographical territory is common in SA. We therefore consider distances to village markets and to extension service offices as proxies for accesses to markets and information services, respectively. Households farther from input markets conversely tend to use less fertilizer (Zhou *et al.*, 2010). Farmers' participation in agriculture-related trainings and educational programs also influences technology adoption (Aryal *et al.*, 2018c).

3.4.5. Farm land characteristics

To control for the potential effects of land attributes on fertilizer/manure use, we included farmers' tenure status, soil fertility, soil depth, land slope, irrigation status, and distance to plot from homestead in the analysis. Distant plots require increased transaction costs due to the price of purchasing transport for inputs. Fields far from the household are also more difficult to monitor. Therefore, input use was hypothesized to be inversely related to distance from the household to the field. Farmers want to supply adequate inputs to fields that they can more closely monitor and intervene in with management to achieve greater productivity. Fields that farmers perceive as being less fertile may also receive more manure compared to fertile ones because manure releases nutrients slowly and can improve soil physical and chemical properties over time (Waithaka *et al.*, 2007).

4. Results and discussion

4.1. Descriptive statistics

Considerable differences were observed in the application of urea and DAP across study sites (Table 2). The average amount of urea applied to rice was 315 kg ha^{-1} in Haryana (India), while it is only 205 kg ha^{-1} in Nepal. The average amount of DAP applied in rice was highest in Haryana (130 kg ha^{-1}), followed by Bihar (95 kg ha^{-1}), Bangladesh (65 kg ha^{-1}), and then Nepal (62 kg ha^{-1}). The average amount of urea applied in rice is much higher in Bangladesh compared to Bihar and Nepal. Generally, average rates of urea and DAP applied in both rice and wheat were lowest in study sites in Nepal when compared with India and Bangladesh.

Unlike urea and DAP, farmers did not apply manure to all fields in the survey sample. In Bihar, (India) and Nepal, 47% rice plots received manure, while 26% received manure additions in Bangladesh. Manure was applied in 24% of plots cultivated to wheat in Nepal. Across all locations, farmers in focus groups indicated that their use of manure is decreasing. They reported that educated young household members are less interested in carrying manure to plots and as a result, use of chemical fertilizer is increasing over time. In Haryana, the average amounts of manure use in rice and wheat fields were 1,899 and 1,680 kg ha^{-1}, respectively while they were 925 and 1,250 kg ha^{-1} in rice and wheat fields in Bihar.

[Insert here Table 2]

On the average, age of household heads ranges between 47 and 51 years. Nepal had the highest percentage of illiterate household heads (48%), while Haryana (India) has the lowest percentage of illiterate household heads (22%). Almost 38% of the sample households in Nepal had at least one member migrated for employment, while only 11% indicated out-migration from Haryana.

Average landholding size in Haryana was 3.33 ha, much greater than in other sites (0.44 to 0.51 ha). Livestock holdings in the study locations exhibited similar trends, with the highest in Haryana (3.81) followed by Nepal (1.25), Bangladesh (0.92) and Bihar (0.70). Access to credit is relatively better in Bangladesh (69%) compared with other locations (34-44%).

Farmland characteristics substantially vary across study sites. Farmers in Haryana self-described that almost 90% of their plots have fertile soil, whereas only 24% of farmers in Bangladesh suggested that their soil was fertile. Access to irrigation facilities varied considerably, with all farmers in Haryana indicating they could access irrigation, while 95% in Bihar, 56% in Nepal and 76% in Bangladesh could access irrigation reliably.

4.1 Factors influencing the amount of urea and DAP use in rice and wheat

The factors influencing the amount of urea used in rice are, in most cases, similar to the ones affecting DAP (Table 3). Gender, education and migration are key household characteristics significantly affecting the amount of urea applied in rice. Compared to female-headed households (FHHs), male-headed households (MHHs) in Bihar and Bangladesh applied significantly higher rates of urea in rice. However, MHHs in Nepal applied significantly less urea and DAP in rice compared to their FHHs counterparts. This result is somewhat expectable, as Nepalese women face fewer restrictions in carrying out agricultural activities than in India or Bangladesh, where socio-cultural norms may inhibit them from doing so (Mallick and Rafi, 2010; Mahmud *et al.*, 2012; Aryal *et al.*, 2014). Additionally, male out-migration has substantially changed the traditional gender norms in Nepal (Sugden *et al.*, 2018; Spangler and Christie, 2020). Compared to illiterate household heads, those with secondary and higher education also applied more urea and DAP to rice. This finding does not corroborate with (Zhou *et al.*, 2010) and (Adesina, 1996). Rural out-migration also appears to reduce fertilizer use in Bihar and Bangladesh, while it conversely increased fertilizer use in Nepal. Male out-migration negatively influenced fertilizer use in Bihar, India and Bangladesh as fertilizer application is mainly the men's task in these countries.

[Insert here Table 3]

Farm size was positively associated with the amount of both urea and DAP applied in rice. Households with more livestock and wealthier households (measured in terms of AI) in all study locations except Haryana have applied more urea and DAP. Access to credit is positively associated with the application of urea and DAP in rice in Bangladesh, while the reverse was found in Bihar. Off-farm income, market access and training all positively influenced the application of urea and DAP across all locations. These findings suggest that it may be preferential for government policy to focus on facilitating additional opportunities for off-farm employment and income generation, increasing market access, and training rather than on access to credit.

Farmers applied less urea and DAP to fields they indicated were more inherently fertile in comparison to those they deemed as fertile. Irrigation was positively associated with fertilizer rates in Bangladesh and Nepal, but not in Bihar. Farmers with secured tenure also tended to apply higher rates of fertilizer compared to those who rented-land. Most farmers are found to use of Urea and DAP as complementary inputs in rice farming. We also observed that factors affecting the amount of urea and DAP applied to wheat (Table 4) are generally similar to that of rice in all countries (see Table 3).

[Insert here Table 4]

4.2 Factors determining the adoption and intensity of manure use in rice and wheat

Wald chi-square tests for the Heckman two-step models were significant at 1% level (Tables 5 and 6), indicating the validity of the models in explaining observed differences in farmers' decision to adopt manure in rice and wheat. The Inverse Mills Ratio was highly significant in all models, implying that manure use intensity depends on the likelihood of farmers to decide to apply manure. Sets of the observed factors appear to affect the likelihood of farmers' choice to utilize manure. These factors differed from the ways they influence the rates of manure used among the subset of farmers who chose to apply manure. Furthermore, some factors appear to have contradictory effects on the choice to apply manure *vis-à-vis* its application rate. As several factors influencing the adoption and intensity of adoption of manure in rice (Table 5) and wheat (Table 6) are similar, we describe their results together.

[Insert here Table 5]

Compared to FHHs, MHHs in Bihar, Bangladesh and Nepal appear to be more likely to choose to use manure, but the rates of application are higher among MHHs in Bangladesh and Nepal only. Farmers' educational levels have differential impacts on the likelihood to use and rate of application. Household heads with primary education (relative to no formal schooling) were more likely to apply manure, though the same variable failed to influence the amount of manure applied. Household heads with secondary and higher educational levels were conversely less likely to apply manure. However, if they do apply manure, the rates of use were higher than those with no or primary education only.

[Insert here Table 6]

The likelihood of manure application increased with land size, but the rate of application was inversely related. Farmers reported that the young and educated generation tend not to prefer labour-intensive approaches such as manure application. Livestock ownership, the major source of manure, was unsurprisingly positively associated with both likelihood and intensity of manure use in all sites. Access to credit had variable effects manure use: no impact was observed in Haryana, while negative and positive impacts on were found in Bihar relative to Bangladesh and Nepal. Factors such as off-farm income, market access, training and membership in village institutions also increased the use of manure in both crops.

Farmers are also less likely to apply manure they perceived of as being highly saline. Use of organic amendments has however been shown to help mitigate the effects of salinity on crop productivity (Xu *et al.*, 2014; Ding *et al.*, 2020). Educational programs could be of use in saline-affected locations where farmers have access to manure and can afford labor to apply it, although application over multiple seasons may be required for desirable impacts (Ding *et al.*, 2020). Those who did apply manure also used lower rates. Similar is the findings for plots that are located farther from homestead. In contrast, farmers were more likely to adopt manure in fields they perceived of having greater soil depth. In Bangladesh and Nepal, irrigation was also positively associated with both the likelihood and rate of manure use. Compared to rented fields, farmers with tenure also had greater rates of manure application.

4.4 Factors affecting the over-use of N fertilizer

A total of 33.6% of rice fields in our data were reported by farmers as receiving more than 120 kg N ha^{-1} and 18.5% of the wheat fields received more than 140 kg N ha^{-1} (see appendix: Tables A1 and A2). Though the critical value of N that is used here for defining over-use of N may vary across sites, we believe it to be rational here as our objective is to examine the factors contributing to the over-use of N. Moreover, we estimated the models by changing the critical value of N for rice as more than 100 kg N ha^{-1} and for wheat 120 kg N ha^{-1}, the variables significantly affecting the over-use of N in rice and wheat remained almost same. Therefore, we analyzed the factors affecting over-use of fertilizer by combining data from all locations (Table 7).

[Insert here Table 7]

Compared to FHHs, MHHs appear to be more likely to over-use N. Household heads with secondary and higher educational levels also appear to have a higher likelihood to over-use of N (significant at 5% and 1% level). Land size, off-farm income, and wealth were also significantly and positively associated with the over-use of N.

Households that are farther from market are perhaps unsurprisingly less likely to over-use N fertilizer. Training on fertilizer management is negatively associated with the N over-use. Farmers are not likely to over-use N fertilizer in plots they consider as having higher inherent fertility levels, or that have deeper soil profiles. Over-use of N fertilizer does appear to increase with access to irrigation, a consistent findings as observed in the states with successful GR. Across the study locations, Nepal has lowest percentage of over-use of N in both rice and wheat. All other countries conversely have a greater likelihood of overusing N.

Overall, a wide variation is observed across the study sites regarding the over-use of N fertilizer in rice and wheat. The findings indicate that training on fertilizer management is more crucial than formal education to reduce the over-use of N. This also calls for a new study focusing on the institutional analysis including the information and support that farmers get from extension agents to regularly update the fertilizer need for their farm, information on soil testing and nutrient adjustment as per requirement, and increased access to nutrient management tools.

4.5 Farmer focus group findings

Our discussions with farmers in the study villages confirmed the complex interactions of variables that conditions decisions on fertilizer use. Although many farmers indicated that they could not clearly understand or 'separate' the impact of a single production factor such as fertilizer to distil its implication for overall crop productivity, they did however clearly indicate that they understand the importance of fertilizer but lack knowledge on its balanced application. Therefore, they are more likely to go for over-application of N, mainly from urea, ignoring other nutrients.

Farmers reported that government subsidy plays important role in fertilizer use. In all South Asian countries exempting Sri Lanka, government subsidy is higher on urea than on other fertilizers. In focus groups, farmers indicated that this has a strong influence on their application of fertilizer N at rates that are often higher than required. Together, the uneven subsidy structure also works as disincentives in using recommended rates of secondary and micronutrients. This is in line with the findings of (Sapkota *et al.*, 2018a).

Farmers also reported that increase in formal education level may not necessarily reduce the over-use of N fertilizer as more educated family members have more non-farm opportunities and may not stay as involved in agriculture. Therefore, agricultural training, awareness raising, appropriate extension services – which can be delivered by public and also by the private sector – and interventions to increase farmers' knowledge of nutrient responses to plant are important to encourage change in farmers' knowledge and behavior towards fertilizer use to reduce inefficiencies (Sapkota *et al.*, 2018a; Afrad *et al.*, 2019; Ananth *et al.*, 2019). Some farmers also reported that traditional extension service by government institution is not very effective in providing recent advancement in fertilizer management properly and thus, there is a need to mobilize local youth clubs to update the recent developments in soil fertility management.

Very few participants were aware of possibility of non-point water pollution due to nitrogen leaching from over-use of N and its negative human health and environmental impacts. This underscores the importance of programs to educate farmers on the principles of efficient fertilizer management – perhaps coupled with appropriate nutrient management policy (Kishore *et al.*, 2019).

5. Conclusions and policy implications

This study revealed that various factors influence the amount of fertilizer (urea and DAP) and manure application in rice and wheat in South Asia. Wealth, gender, education, migration, access to market, training, and off-farm income sources are some of the key factors influencing the application of chemical fertilizer and manure. Economic and elements of social capital are primarily positively correlated with increased chemical fertilizer use. Discussions with farmers show that they prefer using off-farm income to purchase agricultural inputs rather than credit. Thus, public policy that create off-farm income generation opportunities are likely to be of use – particularly for resource poor and smallholder farm families – when increasing fertilizer use are the goal. Conversely, where farmers routinely over-apply fertilizers, or practice imbalanced application, more complex policy and development interventions may be needed, including educational programs, direct training, and behavioral nudging methods that may encourage more rational use. Similarly, few farmers in the study locations appeared to have sophisticated knowledge on the negative effects of fertilizer over-use. Thus, training on fertilizer management, along with the dissemination of knowledge on negative externalities of its inappropriate use is likely to be important in preventing unsound over-use.

Another crucial finding is that application of manure is decreasing in all locations. Perhaps surprisingly, where farmers have higher levels of education, our data suggest that they are more likely to opt out of manure application to rice and wheat fields. Combined with evidence on decreasing concentrations of soil organic matter in our study countries, this is arguably concerning, and indicates the need for appropriate educational and extension programs, methods to offset the high labor demand and costs of manure application, possibly through scale-appropriate machinery options to encourage educated and young farmers to use manure when and where it is most needed to maintain long-term soil fertility.

Ethical Approval

This study is based on survey methods involving interviewing farmers to answer questions about their socioeconomic and farming activities. Like all socioeconomic surveys (or any data collection that involves collecting data from family or community representatives) Institutional Research Ethics Committee (IREC) of International Maize and Wheat Improvement Centre (CIMMYT) classified it as low risk and approved the study. Entire research methods were performed in accordance with the relevant guidelines and regulations issued by CIMMYT institutional research ethics committee (IREC).

Consent to Participate

Each questionnaire of this study had a front page section that required informed consent for interview before the interview could proceed. Interviewers were trained and under instructions to read aloud the consent statement to each interviewee before the interview could advance. Participants were informed that they were under no obligations to answer any questions or they could stop the interview at any time, without giving any reasons and ask that any partial data recorded be removed from the records. This way the survey was consistent with CIMMYT-IREC policies and those generally applied in low-risk social science research.

Consent to Publish

Before the interview could proceed, we obtained informed consent from the participant that the data will be analyzed and a paper will be published. No personal information will be shared and published. This way the survey was consistent with CIMMYT-IREC policies and those generally applied in low-risk social science research.

Acknowledgments and Funding

This work was carried out by International Maize and Wheat Improvement Center (CIMMYT) as part of the CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS) with support from CGIAR Fund Donors and through bilateral funding agreements. For details, please visit https://ccafs.cgiar.org/donors. Further support was also provided by the USAID and Bill and Melinda Gates Foundation (BMGF) supported Cereal Systems Initiative for South Asia (CSISA) project, and the CGIAR Research Program on Wheat Agri-Food Systems (CRP WHEAT). We thank field teams for collecting data in Bangladesh, India and Nepal. The views expressed here are those of the authors and do not necessarily reflect the views of the authors' institutions, CCAFS, or BMGF, or USAID, and shall not be used for advertising purposes.

Authors Contributions

- **Jeetendra Prakash Aryal:** Led the preparation of data collecting instruments, survey design and data collection (both quantitative survey and focus group discussion), conceptualization, analysis and write up
- **Tek Bahadur Sapkota:** Contributed in the research idea formulation, and write up of the paper and project management
- **Timothy J. Krupnik**: Contributed in conceptualization, write up of the paper
- **Dil Bahadur Rahut:** Contributed in the interpretation of the result and the write up of the paper, provided input in the development of the instrument
- **ML Jat:** Contributed in the write up of the paper
- **Clare M. Stirling:** Contributed in the write up of the paper

Competing Interests

Authors do not have any competing interest

Availability of data and materials

Authors do not have the right to share the data. However, it will be made available to the reader upon request.

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Tables for South Asia fertilizer paper

Table 1: Study villages and sample size (n)

Bangladesh[1]		Bihar-India: Vaishali district		Haryana-India: Karnal district		Nepal: Rupandehi district	
Village name	n	Village name	n	Village Name	n	Village name	n
Boro Galua (J)	32	Bhatha Dasi	63	Anjanthali	67	Aahirauli	50
Burigoalini (S)	45	Bilandpur	68	Bir Narayana	49	Bairiyan	50
Chandipur (S)	66	Dedhpur	46	Barthal	41	Bhaglapur	32
Dumuria (S)	64	Dhabhaich	46	Churni Jagir	20	Dewapar	59
Durgapur (J)	8	Laxminarayanpur	44	Darar	25	Dhakdahi	92
Gabgasia (B)	66	Mirpur	55	Garghi Jattan	46	Haraiya	47
Gopalpur (J)	32	Mukundpur	69	Hathlana	46	Hati Bangai	33
Hatsala (S)	28	Panapur Camp	56	Mohri Jagir	40	Mahuwari	71
Horinagor (S)	45	Raja Pakar	70	Nanhara	43	Parasi Thuga	66
Jagannathpur (J)	64	Rampur Ratnagar	45	Pakhana	80	Razadh	36
Joka (B)	40	Rasalpour	48	Sandhir	64	Rehara	48
Sreefal Kathi (S)	45	Varishpur	31	Sanwat	45	Samrahana	47
Tarabunia (J)	45			Sounkra	60		
Teligati (B)	50						
Total sample HHs	630		641		626		631
No. of rice plots	1182		1299		665		1576
No. of wheat plots	0		1544		667		977

Note: [1]B, J, and S denotes for Bagerhat, Jhalokathi and Satkhira districts in Bangladesh, respectively.

Table 2: Description of variables used in the study

Variables	Haryana		Bihar		Bangladesh		Nepal		Overall		Variable Description
	Mean	S.D	Mean	S.D	Mean	S.D.	Mean	S.D.	Mean	S.D.	
Dependent Variables											
Urea_rice (C)	315	93	210	87	285	101	205	91	254	93	Amount of urea applied in rice (kg ha^{-1})
Urea_wheat (C)	320	96	225	79	na	na	210	73	252	82	Amount of urea applied in wheat (kg ha^{-1})
DAP_rice (C)	130	49	95	53	65	29	62	45	88	44	Amount of DAP applied in rice (kg ha^{-1})
DAP_wheat (C)	125	35	110	51	na	na	79	43	104	43	Amount of DAP applied in wheat (kg ha^{-1})
Manure_rice (C)	1899	1409	925	1586	1120	950	1362	1102	1326	1261	Amount of manure applied in rice (kg ha^{-1})
Manure_wheat (C)	1680	1233	1250	955	na	na	1030	725	1320	971	Amount of manure applied in rice (kg ha^{-1})
Manure_r (D)	0.46	0.49	0.47	0.50	0.26	0.36	0.47	0.49	0.42	0.45	1 if manure is applied in rice plots
Manure_w (D)	0.25	0.29	0.43	0.48	na	na	0.24	0.34	0.31	0.36	1 if manure is applied in wheat plots
Independent Variables											
Household (HH) characteristics											
Male headed HH (D)	0.97	0.17	0.91	0.29	0.90	0.30	0.78	0.41	0.89	0.31	1 if male headed house and 0 if female
Age of HH head (C)	49	13	51	14	47	13	50	14	49	13.45	Age of household in years
Education of HH head (D)	0.67	0.47	0.62	0.49	0.71	0.45	0.51	0.5	0.63	0.48	1 if HH went to school and 0 otherwise
Illiterate	0.22	0.41	0.38	0.49	0.29	0.45	0.48	0.50	0.22	0.41	Illiterate
Primary education	0.19	0.39	0.09	0.29	0.33	0.47	0.19	0.38	0.33	0.47	Up to primary education (Grade 1-5)
Secondary education	0.40	0.49	0.38	0.48	0.31	0.46	0.28	0.45	0.34	0.48	Up to secondary education (Grade 6-10)
Higher education	0.18	0.38	0.15	0.36	0.07	0.26	0.05	0.22	0.12	0.32	Higher secondary or above education (Grade 11 and above)
Education of Spouse (D)	0.51	0.5	0.3	0.46	0.63	0.48	0.22	0.41	0.42	0.49	1 if HH's spouse went to school and 0 otherwise
AEC (C)	4.46	1.79	0.89	0.17	3.27	1.27	4.57	2.19	3.28	2.15	Household labor worked in agriculture
Family Size (C)	6.03	2.47	6.05	2.65	4.67	1.68	6.39	3.08	5.78	2.61	Total members in family
Food Security status (D)	1	0.07	0.69	0.46	0.72	0.45	0.89	0.3	0.82	0.37	1 if HH is food secure and 0 otherwise
Migration (D)	0.11	0.31	0.28	0.45	0.23	0.42	0.38	0.48	0.25	0.43	1 if HH has migrant member and 0 otherwise
Economic and social capital											
Land Size (C)	3.33	3.81	0.51	0.41	0.44	0.48	0.49	0.85	1.1	2.32	Total land operated in ha
TLU (C)	3.81	5.7	0.70	0.74	0.92	1.19	1.25	1.54	1.63	3.27	Livestock owned in tropical livestock unit
Asset index (C)	0.93	0.61	0.30	0.53	0.43	0.75	0.45	0.68	0.53	0.59	Household asset index [1]
Access to credit (D)	0.4	0.49	0.34	0.48	0.69	0.46	0.44	0.49	0.47	0.5	1 if taken loan in last 24 months and 0 otherwise
Non-Agricultural income (D)	0.15	0.36	0.47	0.5	0.16	0.36	0.38	0.49	0.29	0.45	1 if HH has income from non-agriculture source, 0 otherwise
Farm labor income (D)	0.01	0.09	0.04	0.19	0.13	0.34	0.04	0.18	0.05	0.22	1 if works as on farm labor, 0 otherwise

Non-Farm labor income (D)	0.03	0.18	0.25	0.43	0.19	0.38	0.15	0.34	0.15	0.36	1 if works as non-farm labor, 0 otherwise
Membership (D)	0.35	0.48	0.09	0.28	0.39	0.49	0.45	0.52	0.32	0.47	1 if any family member is member in any institution in village and 0 otherwise
Access to market and agriculture extension service, and training											
Distance to input market (C)	6.43	3.07	4.69	4.67	3.54	4.02	4.39	5.81	6.07	5.21	Distance to nearest input market from house (in km)
Distance to agriculture extension office (C)	5.25	2.84	5.04	3.66	9.16	8.79	3.72	3.56	6.78	6.80	Distance to agriculture extension service from house (in km)
Training (D)	0.22	0.41	0.52	0.5	0.04	0.18	0.02	0.15	0.2	0.4	1 if HH has received training on improved seeds, soil & water management, crop rotation, minimum tillage, 0 otherwise
Farmland characteristics											
Soil fertility (D)	0.91	0.23	0.46	0.50	0.24	0.35	0.37	0.49	0.48	0.39	1 if good and 0 otherwise
Soil depth (D)	0.38	0.19	0.15	0.36	0.42	0.49	0.09	0.38	0.27	0.41	1 if deep and 0 if shallow
Land slope (D)	0.91	0.29	0.47	0.50	0.75	0.43	0.56	0.47	0.68	0.46	1 if gentle slope and 0 if medium/steep slope
Irrigation (D)	0.99	0.07	0.92	0.17	0.76	0.46	0.56	0.38	0.75	0.45	1 if irrigated and 0 if rainfed
Soil salinity (D)	0.16	0.47	0.04	0.18	0.45	0.49	0.07	0.31	0.19	0.38	1 if soil salinity high and 0 if low
Land ownership (D)	0.88	0.33	0.75	0.43	0.62	0.48	0.89	0.32	0.78	0.37	1 if owner-operated plot and 0 if leased-in
Distance to plot (C)	1.39	0.99	0.76	1.06	0.59	0.82	0.87	1.15	0.81	0.83	Average distance from homestead to farm plot (in km)

Notes:

1. C and D refer to continuous and dummy variables, respectively.
2. na refers to not applicable.
3. To capture the effect of wealth on the use of urea, DAP and manure by the farm household, we constructed household asset index using principal component analysis (for detail, see https://www.stata.com/manuals13/mvpca.pdf). We included most of the household assets such as tractor, car, television, water pump, motorbike, etc. for constructing household asset index.
4. Adult equivalent
5. Tropical livestock unit (TLU): calculated using Chilonda, P., Otte, J., 2006. Indicators to monitor trends in livestock production at national, regional and international levels. Livestock research for Rural Development 18. Article number 117. Accessed at http://www.lrrd.org/lrrd18/8/chil18117.htm

Table 3: Factors influencing amount of Urea (kg ha^{-1}) and DAP (kg ha^{-1}) used in rice in the study sites

	Urea (kg ha^{-1})				DAP (kg ha^{-1})			
	Haryana	Bihar	Bangladesh	Nepal	Haryana	Bihar	Bangladesh	Nepal
Household (HH) characteristics								
Male headed HH	19.76	22.17**	21.04***	-18.08***	4.04	8.12***	5.17***	-7.35***
	(21.36)	(11.02)	(7.06)	(6.07)	(6.56)	(2.14)	(1.95)	(2.33)
Age of HH head	0.32	4.81	1.47	3.31	0.73	-0.10	-0.37	-1.10
	(0.39)	(8.45)	(2.31)	(5.78)	(0.75)	(0.17)	(0.49)	(1.12)
Primary education	1.70	10.22*	7.63	9.70**	-4.56	3.61**	2.59	2.35***
	(9.26)	(5.41)	(8.12)	(4.33)	(5.83)	(1.67)	(1.83)	(0.81)
Secondary education	15.23***	13.72**	10.12**	18.87***	5.09**	3.63**	1.92**	2.04***
	(5.07)	(6.14)	(4.05)	(7.06)	(2.02)	(1.72)	(0.80)	(0.63)
Higher education	22.10**	28.75***	26.81***	20.35**	4.86***	3.97***	2.32***	2.83***
	(10.89)	(9.07)	(8.78)	(10.01)	(1.55)	(1.23)	(0.78)	(0.91)
Family size (AEC)	-20.49	-27.11	6.80**	17.49	-6.49	-5.51	2.53*	-7.88
	(39.23)	(28.71)	(3.05)	(16.74)	(14.40)	(8.11)	(1.40)	(8.01)
Migration	-11.29	-20.16***	-15.21**	25.08***	-6.19	-2.50**	-3.16**	4.21***
	(7.45)	(5.03)	(6.01)	(8.14)	(7.58)	(0.98)	(1.50)	(1.09)
Economic and social capital								
Land size	47.93***	22.15***	29.36***	25.11***	10.44***	7.21***	3.57**	5.40*
	(9.24)	(7.01)	(10.12)	(6.17)	(3.30)	(2.45)	(1.54)	(2.93)
Livestock owned	9.28**	5.46**	4.42**	4.04***	2.39	2.98***	4.13**	3.24***
	(4.01)	(2.24)	(2.00)	(1.14)	(1.92)	(1.03)	(2.01)	(1.21)
Asset index	5.34	4.17**	7.03***	2.82***	3.15	3.29**	3.10***	2.06**
	(6.76)	(1.98)	(2.59)	(0.76)	(3.31)	(1.31)	(1.09)	(0.83)
Credit access	-17.83	-6.74**	4.18***	5.74	-4.55	-3.12**	2.04***	-2.55
	(16.91)	(2.85)	(1.58)	(6.85)	(3.18)	(1.30)	(0.58)	(3.24)
Off-farm income	7.57***	12.48***	5.32**	11.81***	3.29**	3.54***	2.46***	2.53***
	(2.33)	(3.57)	(2.17)	(2.86)	(1.39)	(1.11)	(0.91)	(0.89)
Membership	4.84	5.08**	-18.84	4.84***	3.65	2.91**	5.14	2.63***
	(5.15)	(2.02)	(13.85)	(1.25)	(5.28)	(1.29)	(5.51)	(0.88)
Access to market, extension service and training								

Distance to input market	-7.98***	-10.01***	-9.25***	-11.71***	-6.01***	-3.26**	-4.05***	-5.20***
	(2.78)	(3.04)	(2.37)	(3.14)	(1.35)	(1.50)	(0.98)	(1.04)
Distance to extension service	-0.80	-1.73	-3.48	-2.31	-0.60	-2.45	-0.87	-1.60
	(0.95)	(1.87)	(4.62)	(3.11)	(0.41)	(3.12)	(0.89)	(1.57)
Training	-3.53	5.61***	7.30**	5.02***	4.84**	6.16***	3.25***	2.93**
	(6.43)	(1.32)	(3.00)	(1.43)	(2.06)	(1.95)	(1.10)	(1.45)
Farm land characteristics								
Soil fertility	-10.10***	-15.21***	-12.44**	-9.07**	-4.22***	-2.83***	-5.72***	-6.01***
	(3.09)	(5.11)	(6.01)	(4.28)	(1.05)	(1.01)	(2.13)	(1.98)
Soil depth	-4.13	-12.07**	-10.39**	-9.22*	-3.35	-2.62***	-4.53***	-4.85***
	(7.07)	(5.14)	(4.72)	(5.41)	(3.27)	(0.97)	(1.27)	(1.40)
Land slope	5.33	9.53	7.81	6.72	4.21	3.35	2.18	3.41
	(10.62)	(9.21)	(8.18)	(8.29)	(4.85)	(4.07)	(3.66)	(3.30)
Irrigation	na	29.54	39.12***	36.41***	na	8.71	13.95***	11.85***
	na	(33.45)	(12.37)	(11.83)	na	(8.60)	(3.77)	(2.91)
Soil salinity	10.15***	5.15	15.39***	4.15	7.99**	-3.99	5.84***	-2.75
	(2.49)	(7.19)	(5.12)	(6.14)	(3.41)	(3.63)	(2.05)	(3.17)
Land ownership	15.10**	22.01***	27.41***	18.05*	10.22**	12.83***	9.01***	9.42***
	(6.44)	(7.09)	(9.07)	(10.01)	(5.05)	(4.10)	(3.04)	(2.81)
Distance to plot	-11.95***	-18.07***	-17.58***	-21.17***	-7.85***	-9.25***	-8.53***	-7.15***
	(3.08)	(5.14)	(5.13)	(5.06)	(1.53)	(2.04)	(2.17)	(1.91)
Amount of urea applied	na	na	na	na	0.19***	0.13***	0.07**	0.09***
	na	na	na	na	(0.05)	(0.04)	(0.03)	(0.03)
Amount of DAP applied	0.55***	0.46***	0.17***	0.21***	na	na	na	na
	(0.17)	(0.11)	(0.03)	(0.05)	na	na	na	na
Constant	143.45***	115.37	122.21***	107.08***	89.34***	67.90***	46.15***	43.26***
	(31.41)	(20.24)	(24.04)	(29.37)	(22.21)	(19.40)	(11.65)	(11.33)
R-squared	0.53	0.59	0.47	0.64	0.61	0.68	0.51	0.66
Number of observations	667	1299	1182	1576	667	1299	1182	1576

Note: Standard errors in parenthesis. *, **, and ** refer to 10%, 5%, and 1% level of significance, respectively. 'na' refers to not applicable.

Table 4: Factors influencing amount of Urea (kg ha^{-1}) and DAP (kg ha^{-1}) used in wheat in the study sites

	Urea (kg ha^{-1})			DAP (kg ha^{-1})		
	Haryana	Bihar	Nepal	Haryana	Bihar	Nepal
Household (HH) characteristics						
Male headed HH	22.68	18.09**	-21.32***	7.12	10.08***	-5.18**
	(25.45)	(9.10)	(7.12)	(7.23)	(2.81)	(2.50)
Age of HH head	0.46	6.75	5.24	0.93	-0.85	-2.13
	(0.51)	(7.04)	(4.91)	(0.92)	(0.94)	(2.10)
Primary education	3.67	9.36***	11.51**	-6.11	3.01***	3.35***
	(5.92)	(3.21)	(5.24)	(6.07)	(1.02)	(0.96)
Secondary education	12.17**	17.23***	15.46***	7.10**	4.52**	3.12***
	(6.03)	(4.10)	(5.13)	(3.31)	(2.03)	(0.89)
Higher education	24.08***	19.14***	18.19***	5.14***	4.61***	2.96***
	(7.02)	(5.17)	(6.42)	(1.28)	(1.50)	(0.97)
Family size (AEC)	-15.94	-13.28	-22.47	-11.46	-7.63	-8.78
	(16.11)	(12.97)	(23.19)	(13.22)	(8.92)	(8.25)
Migration	-13.42	-24.20***	19.25***	-7.16	-4.54**	7.23***
	(9.73)	(4.31)	(5.80)	(7.95)	(1.25)	(2.42)
Economic and social capital						
Land size	25.24***	27.08***	19.50***	12.40***	9.20***	6.71***
	(7.51)	(7.74)	(5.42)	(4.16)	(3.15)	(2.09)
Livestock owned	11.14***	8.79***	6.58***	3.56***	5.89***	5.20***
	(3.89)	(3.04)	(2.01)	(0.98)	(1.81)	(1.43)
Asset index	7.85	7.50***	3.51**	4.69	5.23***	2.21***
	(7.76)	(2.10)	(1.72)	(4.37)	(1.31)	(0.84)
Credit access	-12.33	-4.28*	4.08	-3.15	-4.12***	-3.57
	(13.61)	(2.55)	(3.85)	(3.45)	(1.47)	(3.33)
Off-farm income	11.10***	8.92***	15.01***	6.21***	7.11***	5.63***
	(3.30)	(2.54)	(3.69)	(2.08)	(2.45)	(1.39)
Membership	5.73	4.25**	5.91***	5.19	4.81**	3.95***
	(5.44)	(1.97)	(1.30)	(5.13)	(1.88)	(0.98)
Access to market, extension service and training						

Distance to input market	-10.77***	-17.15***	-14.50***	-7.01***	-8.53**	-10.24***
	(3.14)	(4.10)	(3.36)	(2.30)	(2.57)	(3.15)
Distance to extension service	-2.96	-3.27	-1.67	-0.96	-3.45	-2.93
	(3.98)	(4.13)	(2.56)	(0.94)	(3.32)	(2.87)
Training	8.34**	3.96***	7.02***	5.04**	7.06***	4.90**
	(3.63)	(1.25)	(2.08)	(2.25)	(2.14)	(1.85)
Farm land characteristics						
Soil fertility	-17.51***	-12.42***	-11.90***	-7.20***	-5.08***	-6.78***
	(5.11)	(3.28)	(3.59)	(2.12)	(1.39)	(1.68)
Soil depth	-5.09*	-9.21***	-7.50***	-4.89	-4.42***	-5.05***
	(2.68)	(3.10)	(2.41)	(4.73)	(1.06)	(1.53)
Land slope	7.08	8.23	4.65	3.80	3.89	4.74
	(9.60)	(8.44)	(6.88)	(4.71)	(4.11)	(5.30)
Irrigation	na	21.59	30.20***	na	9.15	13.50***
	na	(24.32)	(8.73)	na	(10.01)	(3.21)
Soil salinity	15.05***	6.86	6.33	8.50**	-4.74	-2.95
	(3.61)	(7.04)	(6.44)	(3.56)	(4.63)	(3.47)
Land ownership	14.50**	25.27***	12.01**	9.02**	13.33***	10.14***
	(5.69)	(6.25)	(5.21)	(4.15)	(3.85)	(2.98)
Distance to plot	-10.04***	-20.55***	-23.50***	-6.81***	-10.92***	-9.55***
	(3.10)	(5.25)	(6.01)	(1.61)	(2.48)	(2.01)
Amount of urea applied	na	na	na	0.17***	0.11***	0.15***
	na	na	na	(0.04)	(0.03)	(0.03)
Amount of DAP applied	0.61**	0.45***	0.28***	na	na	na
	(0.19)	(0.13)	(0.10)	na	na	na
Constant	155.23***	121.33***	113.04***	71.35***	63.14***	47.26***
	(29.87)	(22.19)	(24.97)	(16.41)	(15.08)	(12.37)
R-squared	0.57	0.59	0.45	0.65	0.48	0.62
Number of observations	667	1544	977	667	1544	977

Note: Standard errors in parenthesis. *, **, and ** refer to 10%, 5%, and 1% level of significance, respectively. 'na' refers to not applicable.

Table 5: Factors influencing adoption and amount of manure used in rice in the study sites (Heckman two-step model)

	Haryana		Bihar		Bangladesh		Nepal	
Variables	Adoption	Intensity	Adoption	Intensity	Adoption	Intensity	Adoption	Intensity
Household (HH) characteristics								
Male headed HH	0.09	-271.19	0.40**	-351.33	0.29**	151.51**	0.35**	220.22**
	(0.17)	(305.04)	(0.18)	(335.99)	(0.13)	(61.33)	(0.14)	(105.10)
Age of HH head	-0.03	21.51	-0.01*	11.15	-0.09***	9.37	-0.10**	8.14
	(0.13)	(18.81)	(0.00)	(7.79)	(0.03)	(10.70)	(0.04)	(8.31)
Primary education	0.28***	134.17	0.46***	155.71	0.34***	234.18	0.38***	184.16
	(0.10)	(213.04)	(0.14)	(316.02)	(0.11)	(242.02)	(0.09)	(213.10)
Secondary education	-0.19**	264.56**	-0.23**	364.55**	-0.21***	205.17**	-0.31**	195.22**
	(0.09)	(112.15)	(0.10)	(175.15)	(0.07)	(95.42)	(0.15)	(83.14)
Higher education	-0.12***	298.16***	-0.12	304.79**	-0.12	271.83**	-0.12	276.79**
	(0.03)	(100.21)	(0.13)	(152.31)	(0.13)	(135.30)	(0.13)	(122.26)
Family size (AEC)	0.39***	109.58	0.36***	153.28**	0.25***	201.58**	0.41***	185.58**
	(0.13)	(256.75)	(0.10)	(76.75)	(0.09)	(96.75)	(0.11)	(84.23)
Migration	0.04	103.70	-0.16*	-203.70**	-0.13**	-214.08**	-0.19**	-195.03**
	(0.07)	(122.95)	(0.09)	(89.23)	(0.06)	(101.11)	(0.09)	(91.12)
Economic and social capital								
Land size	0.23***	-201.09	0.43***	-199.37*	0.51***	-205.51**	0.39***	-185.72**
	(0.06)	(230.22)	(0.08)	(112.30)	(0.17)	(97.30)	(0.12)	(75.14)
Livestock owned	0.53***	289.01**	0.31***	270.19***	0.25***	270.15***	0.35***	300.09***
	(0.06)	(124.71)	(0.10)	(101.11)	(0.04)	(94.17)	(0.07)	(99.38)
Asset index	-0.09	35.33	0.16**	235.33**	0.27***	151.74**	0.21**	135.33**
	(0.08)	(134.92)	(0.07)	(104.27)	(0.09)	(71.32)	(0.10)	(61.92)
Credit access	-0.07	130.08**	-0.15*	290.86*	0.22**	150.54**	0.19***	175.80***
	(0.13)	(63.51)	(0.09)	(166.54)	(0.10)	(69.14)	(0.07)	(59.66)
Off-farm income	0.42***	-182.47	0.47***	-171.41	0.33***	-166.78	0.27***	-153.77
	(0.12)	(206.32)	(0.14)	(226.13)	(0.10)	(168.23)	(0.09)	(154.09)
Membership	0.23*	-150.41	0.35***	-189.24	0.47***	-171.41	0.19***	-187.02
	(0.11)	(186.22)	(0.09)	(226.13)	(0.14)	(189.01)	(0.06)	(211.26)
Access to market, extension service and training								
Distance to input market	0.06***	16.63	0.10***	125.16***	0.09***	161.07***	0.13***	152.60**

	(0.01)	(27.52)	(0.03)	(39.27)	(0.03)	(51.27)	(0.04)	(67.15)
Distance to extension service	0.01	-20.27	0.13	-19.60	0.08	-22.03	0.12	-33.10
	(0.01)	(21.56)	(0.18)	(20.41)	(0.10)	(25.01)	(0.21)	(35.25)
Training	0.18*	146.28	0.22**	164.82**	0.15**	146.28**	0.25**	154.83**
	(0.10)	(154.60)	(0.09)	(79.45)	(0.07)	(70.60)	(0.10)	(72.01)
Farm land characteristics								
Soil fertility	0.58***	-314.12**	0.26***	-331.01*	0.34***	-290.13**	0.29***	-243.31**
	(0.08)	(135.27)	(0.06)	(185.21)	(0.11)	(144.45)	(0.09)	(109.21)
Soil depth	0.60***	-442.80	0.53**	-272.39	0.41***	-248.45	0.38***	-215.44
	(0.13)	(283.92)	(0.23)	(271.83)	(0.11)	(239.97)	(0.10)	(220.02)
Land slope	0.01	-37.49*	0.07	-82.14***	0.21	-67.49**	0.14	-41.49*
	(0.01)	(22.73)	(0.09)	(19.22)	(0.22)	(31.73)	(0.13)	(22.73)
Irrigation	na	na	-0.38	145.01	0.37***	318.01***	0.41***	250.01**
	na	na	(0.41)	(151.50)	(0.12)	(110.50)	(0.09)	(115.27)
Soil salinity	-0.39***	-319.02***	-0.40***	-223.13**	-0.34***	-285.45**	-0.25***	-201.23**
	(0.11)	(87.32)	(0.13)	(102.97)	(0.10)	(112.28)	(0.09)	(98.43)
Land ownership	0.61***	396.09**	0.49***	301.25***	0.42***	250.89***	0.47***	199.15**
	(0.20)	(175.41)	(0.16)	(101.01)	(0.13)	(96.28)	(0.15)	(91.14)
Distance to plot	-0.38***	-459.18**	-0.27***	-350.51***	-0.31***	-259.02**	-0.41***	-249.05**
	(0.09)	(182.21)	(0.08)	(98.10)	(0.10)	(110.48)	(0.12)	(102.48)
Constant	4.73***	536.45***	5.44***	442.36***	3.46***	336.21**	4.91***	350.35**
	(1.69)	(164.23)	(2.10)	(102.62)	(1.25)	(164.29)	(1.82)	(155.71)
Mills lambda		-0.073***		-0.092***		-0.107***		-0.113***
		(0.017)		(0.023)		(0.041)		(0.037)
Wald Chi-square (23)	178.39***		168.83***		193.21***		159.11***	
Prob > chi2	0.000		0.000		0.000		0.000	
Number of observations (plots)	665	306	1299	611	1182	307	1576	740

Note: Standard errors in parenthesis. *, **, and ** refer to 10%, 5%, and 1% level of significance, respectively. 'na' refers to not applicable.

Table 6: Factors influencing adoption and amount of manure used in wheat in the study sites (Heckman two-step model)

	Haryana		Bihar		Nepal	
Variables	Adoption	Intensity	Adoption	Intensity	Adoption	Intensity
Household (HH) characteristics						
Male headed HH	-0.31	-254.21	0.27**	-271.51	0.24***	241.27**
	(0.33)	(295.41)	(0.11)	(319.13)	(0.09)	(112.05)
Age of HH head	-0.05	19.15	-0.06**	23.45	-0.13***	11.21
	(0.17)	(20.63)	(0.03)	(24.12)	(0.05)	(11.34)
Primary education	0.22**	173.24	0.37***	185.55	0.41***	199.68
	(0.09)	(203.13)	(0.11)	(301.16)	(0.11)	(201.31)
Secondary education	-0.23**	312.21***	-0.27**	293.55**	-0.19	201.91**
	(0.09)	(117.25)	(0.13)	(145.15)	(0.09)	(97.38)
Higher education	-0.19***	268.17***	-0.12	271.04*	-0.17	209.73**
	(0.06)	(98.61)	(0.14)	(141.31)	(0.13)	(101.06)
Family size (AEC)	0.27***	153.51*	0.29***	161.83**	0.32***	192.24**
	(0.08)	(79.15)	(0.10)	(72.66)	(0.11)	(91.22)
Migration	0.01	-116.12	-0.22***	-220.24**	0.12**	-205.11**
	(0.03)	(129.28)	(0.08)	(101.01)	(0.05)	(97.27)
Economic and social capital						
Land size	0.25***	-260.17*	0.39***	-205.31**	0.41***	-198.28***
	(0.07)	(156.21)	(0.12)	(97.33)	(0.14)	(71.14)
Livestock owned	0.49***	277.14**	0.38***	255.51***	0.29***	271.15***
	(0.11)	(120.71)	(0.12)	(85.22)	(0.07)	(95.39)
Asset index	-0.09	75.56	0.17***	254.11**	0.19**	122.30**
	(0.10)	(113.34)	(0.05)	(123.27)	(0.09)	(60.29)
Credit access	-0.12	110.08**	-0.21***	274.07*	0.21***	181.07***
	(0.13)	(51.05)	(0.08)	(150.04)	(0.07)	(60.16)
Off-farm income	0.37***	-195.02	0.42***	-198.01	0.31***	-157.54
	(0.12)	(198.06)	(0.13)	(207.26)	(0.10)	(160.04)
Membership	0.31**	-171.28	0.27***	-199.18	0.24***	-192.31
	(0.15)	(179.20)	(0.09)	(208.81)	(0.06)	(198.61)
Access to market, extension service and training						
Distance to input market	0.09***	28.25	0.13***	105.45***	0.17***	141.09**
	(0.02)	(29.04)	(0.04)	(31.09)	(0.04)	(65.07)
Distance to extension service	0.07	-42.11	0.21	-25.14	0.12	-33.10
	(0.09)	(51.50)	(0.23)	(27.43)	(0.21)	(35.25)
Training	0.22**	153.42	0.25***	150.02**	0.33**	142.83**
	(0.10)	(156.04)	(0.07)	(70.41)	(0.11)	(64.07)
Farm land characteristics						
Soil fertility	0.37***	-300.18***	0.18***	-250.01*	0.26***	-261.34**
	(0.11)	(110.02)	(0.06)	(146.01)	(0.08)	(109.11)
Soil depth	0.45***	-275.17	0.43**	-251.41	0.32***	-198.15
	(0.13)	(278.08)	(0.19)	(259.17)	(0.10)	(201.04)
Land slope	0.07	-60.41**	0.10	-76.06***	0.11	-46.09**
	(0.06)	(30.05)	(0.09)	(24.91)	(0.13)	(22.73)

Irrigation	na	na	-0.40	152.09	0.27***	271.05**
	na	na	(0.43)	(157.50)	(0.09)	(130.17)
Soil salinity	-0.41***	-295.42***	-0.24***	-210.74**	-0.27***	-210.31**
	(0.12)	(81.32)	(0.08)	(100.97)	(0.09)	(97.44)
Land ownership	0.58***	291.09**	0.39***	285.09***	0.42***	201.36**
	(0.19)	(146.41)	(0.13)	(97.22)	(0.14)	(99.18)
Distance to plot	-0.27***	-350.18***	-0.29***	-311.01***	-0.33***	-260.14***
	(0.09)	(120.21)	(0.10)	(94.21)	(0.08)	(91.08)
Constant	5.29***	610.81***	3.98**	421.14***	4.85***	371.61***
	(1.74)	(200.63)	(1.81)	(141.01)	(1.62)	(141.71)
Mills lambda		-0.044***		-0.051***		-0.321***
		(0.007)		(0.010)		(0.102)
Wald Chi-square (23)	173.21***		167.96***		158.54***	
Prob > chi2	0.000		0.000		0.000	
Number of observations (plots)	667	167	1544	689	977	235

Note: Standard errors in parenthesis. *, **, and ** refer to 10%, 5%, and 1% level of significance, respectively. 'na' refers to not applicable.

Table 7: Factors influencing the over-use of N fertilizer (kg ha^{-1}) in rice and wheat

Variables	Rice	Wheat
Household (HH) characteristics		
Male headed HH	0.30**	0.39***
	(0.15)	(0.14)
Age of HH head	0.02	0.00
	(0.03)	(0.00)
Primary education (base category: illiterate)	0.11	0.13
	(0.19)	(0.21)
Secondary education (base category: illiterate)	0.12***	0.10**
	(0.04)	(0.05)
Higher education (base category: illiterate)	0.31***	0.27**
	(0.09)	(0.11)
Family size (AEC)	0.16**	0.29
	(0.07)	(0.31)
Migration	0.07	0.10
	(0.08)	(0.11)
Economic and social capital		
Land size	0.28***	0.31***
	(0.10)	(0.09)
Livestock owned	0.09**	0.15***
	(0.04)	(0.05)
Asset index	0.17***	0.12**
	(0.05)	(0.6)
Credit access	-0.22	0.18
	(0.23)	(0.20)
Off-farm income	0.09***	0.07***
	(0.03)	(0.02)
Membership	0.13	0.10**
	(0.12)	(0.05)
Access to market, extension service and training		
Distance to input market	-0.11***	-0.13***
	(0.03)	(0.04)
Distance to extension service	0.06	0.11
	(0.07)	(0.13)
Training on fertilizer management	-0.11***	-0.12***
	(0.03)	(0.04)
Farm land characteristics		
Soil fertility	-0.11***	-0.08***
	(0.03)	(0.02)
Soil depth	-0.13**	-0.15***
	(0.05)	(0.03)
Land slope	-0.11	0.14
	(0.12)	(0.16)
Irrigation	0.46***	0.39***
	(0.15)	(0.13)

Soil salinity	-0.09	-0.13
	(0.08)	(0.12)
Land ownership	0.17***	0.21***
	(0.05)	(0.06)
Distance to plot	-0.12***	-0.06***
	(0.04)	(0.02)
Study locations dummy		
Haryana (base category: Nepal)	0.39***	0.35***
	(0.10)	(0.11)
Bihar (base category: Nepal)	0.18***	0.21***
	(0.06)	(0.07)
Bangladesh (base category: Nepal)	0.29***	na
	(0.09)	na
Constant	-3.11***	-2.13***
	(0.63)	(0.55)
LR chi (26)	173.62	163.78
Prob > chi2	0.000	0.000
Pseudo R-Squared	0.23	0.20
Censored observations	3777	2675
Uncensored observations	937	513
Total number of observations	4712	3188

Note: Standard errors in parenthesis. *, **, and ** refer to 10%, 5%, and 1% level of significance, respectively. 'na' refers to not applicable.

Appendix

Table A1: Average N fertilizer applied in rice (in kg ha^{-1})

Study sites	Urea (A)	DAP (B)	Manure 0.5%N (C)	2%N (D)	Total N A+B+C	A+B+D
Haryana	144.9	23	9.51	37.98	177.4	205.88
Bihar	96.6	17.1	4.625	18.5	118.3	132.2
Nepal	94.3	11.6	6.81	27.24	112.3	133.14
Bangladesh	131.1	11.7	5.6	22.4	148.4	165.2

Table A2: Average N fertilizer applied in wheat (in kg ha^{-1})

Study sites	Urea (A)	DAP (B)	Manure		Total N	
			0.5%N (C)	2%N (D)	A+B+C	A+B+D
Haryana	147.2	22.5	8.4	33.6	178.1	203.3
Bihar	103.5	19.8	6.25	25	129.6	148.3
Nepal	96.6	14.22	5.15	20.6	115.9	131.4

Table A3: Factors influencing the over-use of N from inorganic fertilzer only (kg ha^{-1}) in rice and wheat

Variables	Rice	Wheat
Household (HH) characteristics		
Male headed HH	0.34*	0.41**
	(0.18)	(0.17)
Age of HH head	0.01	0.00
	(0.03)	(0.00)
Primary education (base category: illiterate)	0.06	0.09
	(0.13)	(0.11)
Secondary education (base category: illiterate)	0.09***	0.17**
	(0.02)	(0.09)
Higher education (base category: illiterate)	0.22**	0.18**
	(0.10)	(0.08)
Family size (AEC)	0.32	0.29
	(0.38)	(0.31)
Migration	0.07	0.10
	(0.08)	(0.11)
Economic and social capital		
Land size	0.31***	0.42***
	(0.14)	(0.09)
Livestock owned	-0.15***	-0.12***
	(0.03)	(0.04)
Asset index	0.13***	0.11**
	(0.04)	(0.5)
Credit access	-0.12	-0.09
	(0.08)	(0.13)
Off-farm income	0.09***	0.06***
	(0.03)	(0.02)
Membership	0.01	0.11**
	(0.01)	(0.05)
Access to market, extension service and training		
Distance to input market	-0.16***	-0.19***
	(0.05)	(0.03)
Distance to extension service	0.05	0.10
	(0.07)	(0.13)
Training on fertilizer management	-0.07***	-0.09***
	(0.02)	(0.03)
Farm land characteristics		
Soil fertility	-0.08***	-0.07***
	(0.03)	(0.02)
Soil depth	-0.12**	-0.15***
	(0.05)	(0.03)
Land slope	-0.15	0.12
	(0.12)	(0.16)
Irrigation	0.52***	0.59***
	(0.15)	(0.14)

Soil salinity	-0.10	-0.11
	(0.08)	(0.12)
Land ownership	0.21***	0.18***
	(0.05)	(0.06)
Distance to plot	-0.11***	-0.07***
	(0.03)	(0.02)
Study locations dummy		
Haryana (base category: Nepal)	0.43***	0.37***
	(0.11)	(0.13)
Bihar (base category: Nepal)	0.21***	0.24***
	(0.07)	(0.06)
Bangladesh (base category: Nepal)	0.29***	na
	(0.11	na
Constant	-2.09***	-1.85***
	(0.67)	(0.58)
LR chi (26)	161.21	183.63
Prob > chi2	0.000	0.000
Pseudo R-Squared	0.21	0.17
Censored observations	3777	2675
Uncensored observations	937	513
Total number of observations	4712	3188

Note: Standard errors in parenthesis. *, **, and ** refer to 10%, 5%, and 1% level of significance, respectively. 'na' refers to not applicable.

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