Factors Affecting Farmers’ Use of Inorganic Fertilizers and Manure in South Asia

Jeetendra Prakash Aryal
International Maize and Wheat Improvement Centre: Centro Internacional de Mejoramiento de Maiz y Trigo

Tek Bahadur Sapkota
International Maize and Wheat Improvement Centre: Centro Internacional de Mejoramiento de Maiz y Trigo

Timothy J. Krupnik
International Maize and Wheat Improvement Centre: Centro Internacional de Mejoramiento de Maiz y Trigo

Dil Bahadur Rahut (✉ dilbhutan@gmail.com)
Asian Development Bank Institute

Mangi Lal Jat
International Maize and Wheat Improvement Centre: Centro Internacional de Mejoramiento de Maiz y Trigo

Clare M Stirling
Mondelez International

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

License: This work is licensed under a Creative Commons Attribution 4.0 International License. Read Full License
Factors affecting farmers’ use of inorganic fertilizers and manure in South Asia

Jeetendra Prakash Aryal¹, Tek Bahadur Sapkota¹, Timothy J. Krupnik², Dil Bahadur Rahut³*, Mangi Lal Jat², Clare M. Stirling¹

¹International Maize and Wheat Improvement Center (CIMMYT)El Batan, Mexico
²International Maize and Wheat Improvement Center (CIMMYT), Dhaka, Bangladesh
³Asian Development Bank Institute (ADBI), Tokyo, Japan
⁴International Maize and Wheat Improvement Center (CIMMYT), Delhi, India

*Corresponding author:
Asian Development Bank Institute (ADBI),
Kasumigaseki Building, Level 8,
3 Chome-2-5 Kasumigaseki, Chiyoda City,
Tokyo 100-6008
Email: drahut@adbi.org
dilbhutan@gmail.com
Factors affecting farmers’ use of inorganic fertilizers and manure in South Asia

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 °C (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 \textit{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\(_2\)O) from agricultural production, a major source anthropogenic greenhouse gas emissions (Sutton \textit{et al.}, 2013). Around 60\% of nitrogen pollution is estimated to originate from crop production alone, particularly through nitrogen (N) fertilizer application (Sapkota \textit{et al.}, 2018b). Hence, agricultural development pathways need to address these concerns, in addition to climate change adaptation and mitigation (van Beek \textit{et al.}, 2010; Aryal \textit{et al.}, 2020a; Aryal \textit{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 Indo-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:

\[ Y_i = \alpha + \beta X_{h,i} + \gamma X_{s,i} + \delta X_{k,i} + \psi X_{f,i} + \varepsilon \]  

Where \( Y_i \) denotes the amount of urea (DAP) applied per hectare (kg ha\(^{-1}\)) of rice or wheat produced per season. \( X_{h,i} \) is a matrix of household characteristics including age, education and gender of the household head, \( X_{s,i} \) is a matrix of the ownership of and access to economic resources, \( X_{k,i} \) 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 $X_j$ 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 $\psi$ are unknown parameters to be estimated, and $\varepsilon$ is the stochastic error term.

We controlled for possible heteroskedasticity 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 model
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:

$$z^* = \gamma w + \nu$$  \hspace{1cm} (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.
\[ z = \gamma w + \nu, \quad \text{where } z = 1 \text{ if } z^* > 0 \text{ and } z = 0 \text{ otherwise.} \quad (2a) \]

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

The second step in the Heckman model is given by:

\[ y = \beta x + \epsilon \quad (3) \]

Equation 3 is observed only if \( z^* > 0 \). When \( \nu \) and \( \epsilon \) follow a bivariate normal distribution with mean of zero, standard deviation \( \sigma \) and correlation \( \rho \), we get:

\[ E[y|z = 1] = E[y|z^* > 0] = \beta x + \rho \sigma \lambda(\gamma w) \quad (4) \]

where \( \lambda \) is the Inverse Mills Ratio (IMR) \( \lambda = \phi(\gamma w)/\Phi(\gamma w) \) i.e., the ratio of the value of density function of a standard normal distribution and cumulative distribution function calculated at \( \gamma w \). In equation 4, \( \rho \sigma \) is equal to the regression coefficient on the IMR, \( \beta_\lambda \). 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):

\[ y = \beta x + \beta_\lambda \lambda + \epsilon \quad (5) \]

Where \( \beta_\lambda \) 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/mv pca.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.

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).
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 on manure use: no impact was observed in Haryana, while negative and positive impacts 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.

References

Adesina, A.A., 1996. Factors affecting the adoption of fertilizers by rice farmers in Côte d'Ivoire. Nutrient Cycling in Agroecosystems 46, 29-39.

Afrad, S.I., Wadud, F., Babu, S.C., 2019. Chapter 2 - Reforms in agricultural extension service system in Bangladesh. In: Babu, S.C., Joshi, P.K. (Eds.), Agricultural Extension Reforms in South Asia. Academic Press, pp. 13-40.

Ananth, P.N., Barik, N.K., Babu, S.C., Dash, A.K., Sundaray, J.K., 2019. Chapter 7 - Can institutional convergence force agricultural development in pluralistic extension systems: a case of Krishi Vigyan Kendra (the farm science center) in India. In: Babu, S.C., Joshi, P.K. (Eds.), Agricultural Extension Reforms in South Asia. Academic Press, pp. 141-165.

Aryal, J.P., Farnworth, C.R., Khurana, R., Ray, S., Sapkota, T., 2014. Gender dimensions of climate change adaptation through climate smart agricultural practices in India. Innovation in Indian Agriculture: Ways Forward, New Delhi, India: Institute of Economic Growth (IEG), New Delhi, and International Food Policy Research Institute (IFPRI), Washington DC.

Aryal, J.P., Jat, M.L., Sapkota, T.B., Khatri-Chhetri, A., Kassie, M., Rahut, D.B., Maharjan, S., 2018a. Adoption of multiple climate-smart agricultural practices in the Gangetic plains of Bihar, India. International Journal of Climate Change Strategies and Management 10, 407-427.

Aryal, J.P., Rahut, D.B., Jat, M.L., Maharjan, S., Erenstein, O., 2018b. Factors determining the adoption of laser land leveling in the irrigated rice–wheat system in Haryana, India. Journal of Crop Improvement 32, 477-492.

Aryal, J.P., Rahut, D.B., Maharjan, S., Erenstein, O., 2018c. Factors affecting the adoption of multiple climate-smart agricultural practices in the Indo-Gangetic Plains of India. Natural Resources Forum 42, 141-158.

Aryal, J.P., Rahut, D.B., Sapkota, T.B., Khurana, R., Khatri-Chhetri, A., 2020a. Climate change mitigation options among farmers in South Asia. Environment, Development and Sustainability 22, 3267-3289. https://doi.org/10.1007/s10668-10019-00345-10660.

Aryal, J.P., Sapkota, T.B., Rahut, D.B., Jat, M.L., 2020b. Agricultural sustainability under emerging climatic variability: the role of climate-smart agriculture and relevant policies in India. International Journal of Innovation and Sustainable Development 14, 219-245.

Benbi, D.K., 2017. 6 - Nitrogen Balances of Intensively Cultivated Rice–Wheat Cropping Systems in Original Green Revolution States of India. In: Abrol, Y.P., Adhya, T.K., Aneja, V.P., Raghuram, N., Pathak, H., Kulshrestha, U., Sharma, C., Singh, B. (Eds.), The Indian Nitrogen Assessment. Elsevier, pp. 77-93.

Chowdhury, A.H., Hambly Odame, H., Leeuwis, C., 2014. Transforming the Roles of a Public Extension Agency to Strengthen Innovation: Lessons from the National Agricultural Extension Project in Bangladesh. The Journal of Agricultural Education and Extension 20, 7-25.

Ding, Z., Kheir, A.M.S., Ali, M.G.M., Ali, O.A.M., Abdelaal, A.I.N., Lin, X.e., Zhou, Z., Wang, B., Liu, B., He, Z., 2020. The integrated effect of salinity, organic amendments, phosphorus fertilizers, and deficit irrigation on soil properties, phosphorus fractionation and wheat productivity. Scientific Reports 10, 2736.
Dobermann, A., Witt, C., 2004. The evolution of site-specific nutrient management in irrigated rice systems of Asia. In: Dobermann, A., Witt, C., Dawe, D. (Eds.), Increasing Productivity of Intensive Rice Systems through Site-Specific Nutrient Management. Science Publisher Inc., and International Rice Research Institute (IRRI), p. 410.

Erisman, J.W., Sutton, M.A., Galloway, J., Klimont, Z., Winiwarter, W., 2008. How a century of ammonia synthesis changed the world. Nature Geoscience 1, 636-639.

Firdousi, N., 1997. Green Revolution in Bangladesh: Production Stability and Food Self-Sufficiency. Economic and Political Weekly 32, A84-A89.

Fishman, R., Kishore, A., Rothler, Y., Ward, P.S., Jha, S., Singh, R.K.P., 2016. Can Information Help Reduce Imbalanced Application of Fertilizers in India? Experimental Evidence from Bihar. IFPRI Discussion Paper 01517, South Asia Office, Environment and Production Technology Division, International Food Policy Research Institute (IFPRI), New Delhi, India.

GoI, 2020. Agricultural situation in India. Ministry of Agriculture and Farmers’ Welfare (MAFW), Government of India (GOI). http://agriculture.gov.in/.

Heckman, J., 1979. Sample Selection as a Specification Error. Econometrica 47, 153-161.

IPCC, 2014. Climate change 2014: Impacts, Adaptation and Vulnerability; Contribution of Working Group II to the Fifth Assessment Report, Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press Cambridge, UK; New York, NY, USA.

Kishore, A., Alvi, M., Krupnik, T.J., 2019. Development of Balanced Nutrient Management Innovations in South Asia: Lessons from Bangladesh, India, Nepal, and Sri Lanka. CSISA Policy and Research Note | 14.

Kpadonou, R.A.B., Barbier, B., Owiyo, T., Denton, F., Rutabingwa, F., 2019. Manure and adoption of modern seeds in cereal-based systems in West African drylands: linkages and (non)complementarities. Natural Resources Forum 43, 41-55.

Krupnik, T.J., Six, J., Ladha, J.K., Paine, M.J., van Kessel, C., 2004. An assessment of fertilizer nitrogen recovery efficiency by grain crops In: Mosier, A.R., Syers, K.J., Freney, J.R. (Eds.), Agriculture and the Nitrogen Cycle. The Scientific Committee Problems of the Environment, Island Press, Covel, California, USA, pp. 193–207.

Ladha, J.K., Jat, M.L., Chakraborty, D., Pradhan, P., Krupnik, T.J., Sapkota, T.B., Rana, D.S., Tesfaye, K., Gérard, B., 2020. Achieving the Sustainable Development Goals in Agriculture: The Crucial role of Nitrogen in Cereal-Based Systems. Advances in Agronomy (In press).

Ladha, J.K., Pathak, H., J. Krupnik, T., Six, J., van Kessel, C., 2005. Efficiency of Fertilizer Nitrogen in Cereal Production: Retrospects and Prospects. Advances in Agronomy. Academic Press, pp. 85-156.

Liu, C., Cutforth, H., Chai, Q., Gan, Y., 2016. Farming tactics to reduce the carbon footprint of crop cultivation in semiarid areas. A review. Agronomy for Sustainable Development 36, 69.

Lu, C., Tian, H., 2017. Global nitrogen and phosphorus fertilizer use for agriculture production in the past half century: shifted hot spots and nutrient imbalance. Earth Syst. Sci. Data 9, 181-192.

Mahmud, S., Shah, N.M., Becker, S., 2012. Measurement of Women's Empowerment in Rural Bangladesh. World Development 40, 610-619.

Mallick, D., Rafi, M., 2010. Are Female-Headed Households More Food Insecure? Evidence from Bangladesh. World Development 38, 593-605.

Morello, T.F., Piketty, M.-G., Gardner, T., Parry, L., Barlow, J., Ferreira, J., Tancredi, N.S., 2018. Fertilizer Adoption by Smallholders in the Brazilian Amazon: Farm-level Evidence. Ecological Economics 144, 278-291.

Omamo, S.W., Williams, J.C., Obare, G.A., Ndiwa, N.N., 2002. Soil Fertility Management on Small Farms in Africa: Evidence from Nakuru District, Kenya. Food Policy 27, 159-170.
Pingali, P., Aiyar, A., Abraham, M., Rahman, A., 2019. Agricultural Technology for Increasing Competitiveness of Small Holders. In: Pingali, P., Aiyar, A., Abraham, M., Rahman, A. (Eds.), Transforming Food Systems for a Rising India. Springer International Publishing, Cham, pp. 215-240.

Pingali, P.L., 2012. Green revolution: impacts, limits, and the path ahead. Proceedings of the National Academy of Sciences of the United States of America 109, 12302-12308.

Roy, T., 2017. The Green Revolution. In: Roy, T. (Ed.), The Economy of South Asia: From 1950 to the Present. Springer International Publishing, Cham, pp. 155-181.

Sapkota, T.B., Aryal, J.P., Khatri-Chhetri, A., Shirsath, P.B., Arumugam, P., Stirling, C.M., 2018a. Identifying high-yield low-emission pathways for the cereal production in South Asia. Mitigation and Adaptation Strategies for Global Change 23, 621-641.

Sapkota, T.B., Jat, M.L., Stirling, C., 2018b. Climate smart fertilizer management in smallholder production systems. Fertilizer Focus (Jan-Feb).

Sapkota, T.B., Vetter, S.H., Jat, M.L., Sirohi, S., Shirsath, P.B., Singh, R., Jat, H.S., Smith, P., Hillier, J., Stirling, C.M., 2019. Cost-effective opportunities for climate change mitigation in Indian agriculture. Science of The Total Environment 655, 1342-1354.

Shrestha, N., Raes, D., Sah, S.K., 2013. Strategies to Improve Cereal Production in the Terai Region (Nepal) during Dry Season: Simulations With Aquacrop. Procedia Environmental Sciences 19, 767-775.

Spangler, K., Christie, M.E., 2020. Renegotiating gender roles and cultivation practices in the Nepali mid-hills: unpacking the feminization of agriculture. Agriculture and Human Values 37, 415-432.

Stuart, D., Schewe, R.L., McDermott, M., 2014. Reducing nitrogen fertilizer application as a climate change mitigation strategy: Understanding farmer decision-making and potential barriers to change in the US. Land Use Policy 36, 210-218.

Sugden, F., Seddon, D., Raut, M., 2018. Mapping historical and contemporary agrarian transformations and capitalist infiltration in a complex upland environment: A case from eastern Nepal. Journal of Agrarian Change 18, 444-472.

Sutton, M.A., Bleeker, A., Howard, C.M., Bekunda, M., Grizzetti, B., De Vries, W., Van Grinsven, H.J.M., Abrol, Y.P., Adhya, T.K., Billen, G., Davidson, E.A., Datta, A., Diaz, R., Erisman, J.W., Liu, X.J., Onema, O., Palm, C., Raghuram, N., Reis, S., Scholz, R.W., Sims, T., Westhoek, H., Zhang, F.S., 2013. Our nutrient world: the challenge to produce more food and energy with less pollution. Global Overview of Nutrient Management., Centre for Ecology and Hydrology, Edinburgh on behalf of the Global Partnership on Nutrient Management and the International Nitrogen Initiative.

Takeshima, H., Adhikari, R.P., Kaphle, B.D., Shivakoti, S., Kumar, A., 2016. Determinants of Chemical Fertilizer Use in Nepal: Insights Based on Price Responsiveness and Income Effects. IFPRI Discussion Paper 01507, Development Strategy and Governance Division, International Food Policy Research Institute, New Delhi, India.

Timsina, J., Connor, D.J., 2001. Productivity and management of rice–wheat cropping systems: issues and challenges. Field Crops Research 69, 93-132.

van Beek, C.L., Meerburg, B.G., Schils, R.L.M., Verhagen, J., Kuikman, P.J., 2010. Feeding the world's increasing population while limiting climate change impacts: linking N2O and CH4 emissions from agriculture to population growth. Environmental Science & Policy 13, 89-96.

Waithaka, M.M., Thornton, P.K., Shepherd, K.D., Ndiwa, N.N., 2007. Factors affecting the use of fertilizers and manure by smallholders: the case of Vihiga, western Kenya. Nutrient Cycling in Agroecosystems 78, 211-224.

Ward, P.S., Gupta, S., Singh, V., Ortega, D.L., Gautam, S., Guerena, D., Shrestha, R., 2019. What is the Intrinsic Value of Fertilizer? Experimental Value Elicitation and Decomposition
in the Hill and Terai Regions of Nepal. International Food Policy Research Institute IFPRI Discussion Paper 01812, International Food Policy Research Institute, USA.

Wooldridge, J.M., 2010. Econometric analysis of cross section and panel data. MIT press, Second Edition. Cambridge, Massachusetts, London, England.

Xu, H., Huang, X., Zhong, T., Chen, Z., Yu, J., 2014. Chinese land policies and farmers’ adoption of organic fertilizer for saline soils. Land Use Policy 38, 541-549.

Zhou, Y., Yang, H., Mosler, H.-J., Abbaspour, K.C., 2010. Factors affecting farmers' decisions on fertilizer use: A case study for the Chaobai watershed in Northern China. Consilience, 80-102.

Tables for South Asia fertilizer paper

Table 1: Study villages and sample size (n)

| Village name     | n | Village name     | n | Village name     | n | Village name     | n |
|------------------|---|------------------|---|------------------|---|------------------|---|
| Boro Galua (J)   | 32| Bhattha 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| Rasalpur         | 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: 'B, J, and S denotes for Bagerhat, Jhalokathi and Satkhira districts in Bangladesh, respectively.
| Variables                      | Haryana | Bihar | Bangladesh | Nepal | Overall | Variable Description                                                                 |
|-------------------------------|---------|-------|------------|-------|---------|--------------------------------------------------------------------------------------|
| **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_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**     |         |       |            |       |         |                                                                                      |
| 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  
| 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/mv pca.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) |
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)    | (3.15)     | (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***  
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***   
Amount of DAP applied   | 0.55***  | 0.46***   | 0.17***   | 0.21***    | na       | na       | na        | na        
(0.17)                   | (0.11)   | (0.03)    | (0.05)    | (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** |                  |               |        |                |               |        |
|                                      |          |          |          |          |          |          |
|--------------------------------------|----------|----------|----------|----------|----------|----------|
|                                      | -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*** |
|                                      | (24.32)  | (8.73)   | (10.01)  |           | (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)   |           |           |           |
| 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)

| Variables                  | Haryana | Bihar | Bangladesh | Nepal |
|----------------------------|---------|-------|------------|-------|
| **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** |
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*** |
|                      | (0.000)   | (0.000)   | (0.000)   | (0.000)   |
| 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)

| Variables                              | Haryana | Bihar | Nepal |
|----------------------------------------|---------|-------|-------|
| **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) |       |
| Wald Chi-square (23)      | 173.21***| 167.96***| 158.54***|
| Prob > chi2               | 0.000  | 0.000  | 0.000  |
| Number of observations    | 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** | -0.11***| -0.13*** |
| 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)  |
| Variable                        | Coefficient 1 | Coefficient 2 | Standard Error Coefficient 1 | Standard Error Coefficient 2 |
|--------------------------------|---------------|---------------|-----------------------------|-----------------------------|
| 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 fertilizer 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*

| Country                        | Parameter 1 | Parameter 2 |
|-------------------------------|-------------|-------------|
| 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.
Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Appendix.docx