CLOSING YIELD GAPS IN SOUTH ASIAN WHEAT PRODUCTION (BIHAR, INDIA AND TERAI OF NEPAL)

BY

ALEXANDER GUY PARK

DISSERTATION

Submitted in partial fulfillment of the requirements
for the degree of Doctor of Philosophy in Crop Sciences
in the Graduate College of the
University of Illinois at Urbana-Champaign, 2018

Urbana, Illinois

Doctoral Committee:

Professor Adam Davis, Chair
Andrew McDonald, Cornell University
Professor German Bollero
Associate Professor Maria Villamil
Assistant Professor Cameron Pittelkow

ABSTRACT

Rising wheat consumption and recurring climate extremes threaten food security in the Eastern Indo-Gangetic Plain. Closing wheat yield gaps in this region through agronomic practices currently available to farmers can contribute to a more secure future in this region. In Nepal and Bihar, India, a set of complementary management practices were associated with higher yields, namely: 1) early sowing with long maturing varieties, 2) higher rates of N, P and particularly K application, 3) transitions to zero-till for crop establishment, and 4) encouraging more frequent irrigation. Financial and policy support for infrastructure and agricultural inputs, extension, research and development of private service networks made a marked improvement in yield outcomes in Bihar.

Nepal is at a crossroads of diminishing farm-labor and inadequate investment into farming operations that, among other factors, have stagnated domestic wheat yield. Cultural and economic constraints have hindered the widespread adoption of more expensive precision agriculture technologies like zero-till that have the capacity to improve labor and farm input efficiencies. To capture the benefits from added precision of application but with the ability to fit within the current semi-mechanized seed bed preparation and tillage system, we introduced a low-cost, chest mounted seed and fertilizer. We found that simple mechanization caused yield efficiencies to be positive and significant for nitrogen and phosphate. Seed rates using this method were positively associated with seedling density. This led to both yield and profit being more predictable for farmers. Conversely, hand-applied inputs caused a disassociation between inputs and end of season yield and therefore added a large measure of risk to their farming operations.

Nepali farmers endure many types of risks in producing wheat. Some, such as those affiliated with socioeconomic and demographic pressures, they have little control over. Other sources of risk, such as stresses associated with particular agronomic practices, can be mitigated through better management. In this research, we found that waterlogging stress early in wheat phenology reduced yield. This was attributed to farmers applying flood irrigation to the crop to the point of ponding at early wheat growth stages when the plants were more vulnerable. Waterlogging stress was exacerbated by the common practice of applying seed and fertilizer by hand which created in-field heterogeneity of nutrient distribution, thereby reducing individual plant access to nutrients and making them less resilient to waterlogging stress. Two different solutions, one a technological intervention and the other a change in irrigation practices, reduced this stress. The first was the introduction of a chest-mounted spreader that added a greater measure of uniformity to input application and reduced the impact that waterlogging stress had on crop productivity by ensuring greater availability of nutrients across fields. The second was a delay in the timing of flood irrigation to coincide with greater crop maturity. Plants at the tillering development stage (zadoks stage 20) demonstrated a greater resilience to waterlogging stress and promoted greater yield. At the policy level, increasing the availability of diesel pumps on the landscape, and splitting irrigations, would offer farmers greater flexibility in their management to reduce crop stresses and overall risk.

ACKNOWLEDGEMENTS

We acknowledge the Bill and Melinda Gates Foundation, the United States Agency for International Development, and the United States Agency for International Development's Borlaug Fellowship program administered through Purdue University for funding this study. We want to offer a special thanks to Dr. Andrew McDonald for making a concerted effort to make all of this research possible through financial, managerial and emotional support throughout a difficult project. Without Dr. McDonald, this research would not have been possible. We also thank Shalin Acharaya, Sailesh Sigdel, and Anurag Pandey for their help in collecting data and managing a challenging field campaign. Mention of trade names or commercial products in this publication is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.

In dedication to my family, friends and mentors that supported me through my research.

TABLE OF CONTENTS

CHAPTER 1: INTRODUCTION

1.1 Yields in the Eastern Indo Gangetic Plains

The Indian state of Bihar and the Terai region of Nepal produce about half the grain yield of their neighboring Indian states on the Eastern Indo Gangetic Plains. While there have been gains in productivity in these regions over the past twenty years, Bihar and the Terai of Nepal lag behind the yield gains observed in adjacent Uttar Pradesh, Punjab, and Haryana over the same period (Food and Agricultural Organization, 2017; Paulsen et al., 2012). There is evidence that poor adoption of better management practices in cereals production is a leading cause of these differences in yield (Joshi et al., 2012; Special Task Force on Bihar, 2008). The differences in the level of adoption of better technologies and practices reflect two different sets of government policies and levels of agricultural investment. Here we highlight some of the major factors that we believe led to these different yield outcomes. Understanding these factors provides context as to why critical agronomic practices are not being adopted, and incorporate these factors potential influence into any future interventions so that their likelihood of adoption is higher by making them more customized to the unique socioeconomics and policies of Bihar and Nepal.

1.1.1 The State of Agriculture in Nepal

The current state of Nepali agriculture masks the early success of its agricultural economy. In the early 1960s Nepal had the highest yield per hectare in south Asia, contributing up to 80% of its Gross Domestic Product (Food and Agricultural Organization, 2017; Sharma, 1999). The collapse of Nepali agriculture came on the heels of inconsistent economic policies that jumped between heavily regulated to market driven between decades. Since the mid-1950s these policies prioritized economic growth in urban centers, manifesting in the government spending only 26% of its development expenditures in agricultural regions (Karan et al., 1994; National Planning Commission, 2000; Sharma, 2006b). An unbalanced investment in the agriculture sector was accompanied by an undercutting of both farmer profitability and supporting agribusiness. Grain sales were controlled by government entities which set prices below international prices, thereby discouraging farmers from entering commercial production of cereals because of low return on investment (Sharma, 2006a). High duties on raw materials needed for local manufacturing of agricultural machines and tools negatively affected agribusiness (Joshi et al., 2012).

The lack of investment in agribusiness and the farming sector has led to a sharp contraction of affordable fertilizer to farmers. Access to fertilizer and development of private supply markets has been hampered by two policies: 1) The Nepali government became heavily involved in the supply of fertilizer by setting up corporations in the public sector in the 1970s, effectively limiting development of private suppliers that could better react to changes in market demand (Sharma, 2006a), and 2) the current market of government subsidized fertilizer does not meet farmer demand, with an average of 140,000 tons supplied between 2009-2011 compared to farmer demand of 586,000 tons (Joshi et al., 2012). The resulting limitations of access to fertilizer has left 75-80% of Nepali farmers reliant on gray market sources from India (Pandey, 2014). While there have been encouraging signs of privatization in the seed supply market, 90% of farmers still use informal seed systems and/or seed from their previous crop (Joshi et al., 2012).

The policies that hampered the development of mechanization, and seed and fertilizer markets have effectively mired agricultural investment in Nepal. Evidence of this are noticeable in the rates of adoption of different management practices. Nepal is the least mechanized among all south Asian countries, with farmers largely reliant on semi-mechanization (Pingali, 2007). Semi-mechanization is the process of applying inputs such as seed and fertilizer on fields by hand, which are then incorporated by cultivators or rotovation (Manandhar et al., 2009). Adoption of seed bed preparation and tillage technologies with greater precision of input application such as zero tillage was reported by 3% of farmers in a recent production survey (Park et al., 2018). Low adoption of new mechanization technologies like zero tillage has been partially attributed to the lack of a local machining and manufacturing availability to maintain the equipment and cultural intractability (Joshi et al., 2012; Metz, 1995).

Fertilizer rates and choice of seed also reflect Nepal's current slow progress towards agricultural intensification. Farmers on the Terai of Nepal – the most productive agricultural region bordering India – used 40% less Nitrogen, 26% less Phosphate, and 70% less Potassium compared to farmers in neighboring Bihar, India (Park et al., 2018). When aggregating for the entire country, fertilizer use has been documented to be as low as 19 kg ha^{-1}, compared with 136 kg ha^{-1} in India (Gulati et al., 2010). Farmers in Nepal have little access to "modern" varieties of (PBW, HD, and HUW lineages) that possess disease and heat resistance traits which make them common in India in favor of traditional varieties (Park et al., 2018).

In response to limited opportunities for economic advancement in farming, agricultural laborers and farmers in the 1990s began leaving the sector en masse in search of more lucrative work abroad (Central Bureau of Statistics, 2009; Seddon et al., 2002). This exodus accelerated with the Maoist revolution of the early 2000s in what became for many people an essential livelihood strategy (Maharjan et al., 2013). This departure of farm labor was found to dramatically reduce the productivity of Nepali agriculture on a farm by farm basis. For every laborer that left a household in which they were part of the labor pool, total crop productivity dropped 11% (Maharjan et al., 2013). Losses in farm productivity from departing labor are set to continue, with 19% of the Nepali population involved in the remittance economy in 2008 (Central Bureau of Statistics, 2009). As household revenue from remittances have risen there has been little evidence that it has improved Nepali agriculture. Maharjan et al., 2013 found that rural Nepalis were not reinvesting this remittance money into their farms with more inputs like fertilizer or mechanization.

As labor becomes more scarce in the Nepali agricultural economy, labor bottlenecks have emerged as an increasing problem. Labor bottlenecks occur when there are labor shortages, and are especially problematic during critical times of agricultural operations (Pingali, 2007). Bottlenecks often occur around seed bed preparation, sowing, top dressing and harvesting when demand for labor is high. Delays in these operations have real consequences to the productivity of the wheat system in Nepal and south Asia. A common example is the late sowing of wheat which can reduce yields by 0.7% for every day delayed past an optimum sowing window due to late season heat stress (Ortiz-Monasterio et al., 1994). Solutions to labor bottlenecks is increasingly taking the form of mechanization in south Asian agricultural systems, which is contrasted to Nepal being the least mechanized south Asian country (Pingali, 2007, 2010).

Agriculture in Nepal faces constraints from multiple factors. Bad economic policy and limited development of domestic agribusiness has had a cascading effect which has both reduced the labor pool leading to bottlenecks and caused farmers to not invest in their farm operations. When they chose to invest, they are faced with an inadequate supply of inputs like improved varieties and fertilizer. Agronomic solutions towards improving productivity in the country will need to account for these constraints in their design, with a focus on increasing the efficacy of farm inputs. This is important because major changes to the current agricultural policy environment are unlikely in the near future, and any intervention that relies on using more inputs will not reflect their availability in the farming system.

1.1.2 The State of Agriculture in Bihar, India

Bihar is the 6th largest producer of wheat in all of India, but has seen erratic growth in wheat production per hectare over the last 20 years (Food and Agricultural Organization, 2017). This erratic productivity has been associated with changing importance of wheat in the Indian diet relative to over cereals (Paulsen et al., 2012). Three of the biggest challenges to raising the supply of wheat to meet this growing demand are seed development, access to credit and inputs.

Investment by the Bihar State government in agricultural research has been limited. While the average Indian state invests approximately 0.4% of its state GDP to agricultural research, Bihar allocates 0.2% (Special Task Force on Bihar, 2008). This has led to approximately 75% of seed production in Bihar coming from outside sources of unknown quality, which had led to only 27% of seed used in Bihar meeting germination requirements (Bihar Department of Agriculture, 2011). Lower domestic production of seed has led to a limited availability of quality seed, which has emerged as a major constraint to farming (Kumbhare and Singh, 2011). Poor quality of wheat weed available from reputable dealers forces farmers to use seed from their previous wheat crop for next seasons planting. The inability to access high quality seed has emerged as the leading concern of farmers within the production system (Special Task Force on Bihar, 2008).

Another major problem confronting farmers in Bihar is lack of available credit. Formal credit sources within the agricultural sector are considered inadequate. In Bihar there is an estimated need of Rs. 113 billion to support agricultural investment in the state, while banks only provide 3% of this value (Special Task Force on Bihar, 2008). Local financial institutions have been wary to provide lines of credit to farmers in Bihar because of the high cost of servicing the loans, which include limited reliable information about farmer's equity, high cost of obtaining this information, and high supervision costs related to the farmers (Infrastructure Leasing & Financial Services, 2008). The lack of reliable credit from formal sources forces farmers to seek credit from other sources, including those that charge very high interest rates (Special Task Force on Bihar, 2008). The inability of farmers to reinvest in their operations is part of the reason why productivity in the region has been stagnant (Unnati and Pragati, 2009).

The costs associated with labor, fertilizer and irrigation also have been found to constrain investment into farms (Special Task Force on Bihar, 2008). Improving the efficacy of these inputs rather than applying more has been argued as a pragmatic approach towards increasing yields of wheat in the state of Bihar (Unnati and Pragati, 2009). While farmers in Bihar apply more fertilizer than farmers in neighboring Nepal, rates are lower than those in the highest producing wheat states of Punjab and Haryana (Bihar Department of Agriculture, 2012). A survey in Bihar found that the high cost of fertilizers was the second most significant constraint to wheat production (Special Task Force on Bihar, 2008).

The high cost of diesel has become an increasingly important constraint to irrigation in Bihar. Although irrigation is widely available to farmers, only 57% of the harvested area in Bihar is irrigated (Janaiah and Hossain, 2013). This has been attributed to the rising cost of diesel fuel needed to run irrigation pumps (Commission for Agricultural Costs and Prices, 2011). Even though many farmers have access to irrigation, drought stress remains a significant problem in Bihar.

Labor is the largest expense for farmers in Bihar (31%) (Paulsen et al., 2012). Wages for agricultural labor have increased by as much as 20% per annum over the last decade (Commission for Agricultural Costs and Prices, 2011). This has coincided with a relatively low level of mechanization in Bihar, which has one of the lowest levels of mechanization compared to other Indian states. In Punjab, farmers have approximately 56 tractors per 1000 hectares compared to Bihar where there are 5 tractors per 1000 hectares (Special Task Force on Bihar, 2008). Because thigh costs and limited access to quality seed, fertilizer and mechanized equipment are limiting factors in the production of wheat in Bihar, the interventions most likely to succeed and be adopted with will be associated with improving the efficacy of the inputs, rather than increasing the rate of inputs.

1.1.3 Suitable Interventions

Acknowledging the current levels of agricultural investment in Nepal and Bihar, and the economic and policy forces that that have had a major influence on this lower investment, there are two criteria that any technological or agronomic intervention needs to meet. First, it would have to improve input efficiencies – making better use of the little that is available – because we have a reasonable expectation that inadequate fertilizer and seed levels will remain the status quo into the near future. Second, a successful intervention needs to improve labor efficiency to alleviate decreasing supply and increasing costs in Bihar and Nepal. More specifically to Nepal, any intervention would need to fit within the current semi-mechanized system, and be simple and inexpensive enough to avoid the problems that have limited adoption of more advanced technologies like zero tillage in Nepal. Incorporating the concepts of greater efficiency across farm inputs within an intervention acknowledges that farmers have limited access to capital in both Nepal and Bihar, and that by improving the efficacy of every input through an intervention is a way for farmers to improve yields without significant investment. This intervention strategy that focuses on changing existing practices or introducing simple technologies has shown to be successful in increasing adoption by farmers in the developing world in the past (ATTRA, 2018).

1.2 Literature Cited

1. ATTRA, (2018) Sustainable Agriculture, in: National Center for Appropriate Technology (Ed.), Master Publication List.
2. Bihar Department of Agriculture, (2011) SeedNet India Portal.
3. Bihar Department of Agriculture (2012) Fertilizer.
4. Commission for Agricultural Costs and Prices, (2011) Price policy for rabi crops: The marketing season 2012-2013, in: India, G.o. (Ed.).
5. Food and Agricultural Organization, (2017) FAOSTAT, in: Nations, U. (Ed.). United Nations, Rome, Italy.
6. Infrastructure Leasing & Financial Services, (2008) Food processing in Bihar: The road ahead, in: Bihar, T.G.o. (Ed.).
7. Janaiah, A., Hossain, M. (2013) Farm-level sustainability of intensive rice-wheat system: Socioeconomic and policy perspectives.
8. Joshi, K.D., Conroy, C., Witcombe, J.R., (2012) Agriculture, seed, and innovation in Nepal: Industry and policy issues for the future. International Food Policy Research Institute, Washington, D.C., pp. 1-60.
9. Kumbhare, N.V., Singh, K. (2011) Adoption behaviour and constraints in wheat and paddy production technologies. Indian Res. J. Ext. Edu 11, 41-44.
10. Paulsen, B.J., Chew, K., Gugerty, M.K., Anderson, C.L., (2012) Wheat value chain: Bihar, in: Evans School of Policy and Research Brief No. 202 (Ed.), Seattle, Washington.
11. Pingali, P., (2007) Agricultural Mechanization: Adoption Patterns and Economic Impact, in: Evenson, R., Pingali, P. (Eds.), Handbook of Agricultural Economics, Oxford, pp. 2779-2805.
12. Pingali, P., (2010) Agriculture Renaissance: Making “Agriculture for Development” Work in the 21st Century, in: Pingali, P., Evenson, R. (Eds.), Handbook of Agricultural Economics. Elsevier, Oxford, pp. 3867-3894.
13. Special Task Force on Bihar, (2008) Bihar’s agriculture development: Opportunities & challenges, in: India, G.o. (Ed.).
14. Unnati, K.k., Pragati, D.k., (2009) National Food Security Mission. Department of Agriculture and Cooperation. Government of India, New Delhi.

CHAPTER 2: PRIORITIES FOR WHEAT INTENSIFICATION IN THE EASTERN INDO-GANGETIC PLAINS

2.1 Introduction

Increasing yields of the rice-wheat cropping system in South Asia is important to the food security of more than a billion people. Two regions in the Eastern Indo-Gangetic Plains (EIGP) of South Asia, the Indian state of Bihar and the Terai of Nepal, are half as productive as the adjacent Indian states of Punjab and Haryana (FAO, 2016; Indian Ministry of Agriculture, 2017). Increasing yields in these two regions to more closely approximate those in Punjab and Haryana will be critical to the regional food security of the EIGP because of rising demand for wheat products from increasing population, changing diets and rising personal income (Paulsen et al., 2012). Nepal and Bihar have wheat yield potential (Y_p) similar to Punjab and Haryana based on soil and climactic properties (Aggarwal et al., 2000), presenting an opportunity to identify agronomic practices that lead to higher productivity.

Understanding the causes of yield loss in farmers' fields, and the capacity of agronomic practices to reduce those losses, can empower farmers to make the right decisions that improve their food security. The concept of yield gaps has emerged as a useful analytical tool in development agriculture because it provides a relativistic measure of yield, allowing researchers to deploy interventions that reduce yield gaps (Lobell et al., 2009) Yield gaps are typically calculated as the difference between the Y_p and average yields of farmers (Y_a) within a spatially explicit area, with the difference being called model-based yield gap (YG_M) (van Ittersum and R.Rabbinge, 1997). Yield potential has been argued to be most accurately calculated by crop models because they can simulate growing conditions for a given location and crop variety for several years to estimate long-term average potential (van Ittersum et al., 2013). On-farm production practice and crop yield surveys can be used in combination with YG_M to identify which management and site factors contribute to better yield outcomes.

In order to identify technological and management entry points that reduce YG_M in wheat production, the Cereal Systems Initiative for South Asia (CSISA – www.csisa.org) conducted on-farm production practice and crop yield surveys across 1,181 farmer's fields within 109 villages in Bihar and the Terai region of Nepal (Figure 2.1). CSISA is part of a collaborative effort between CGIAR centers (CIMMYT, IRRI, and IFPRI) and national partners in South Asia (Nepal, India, Bangladesh). Surveys were conducted in April and May of 2012, 2013 and 2016 (limited resources prevented sampling in 2014 and 2015). Sampling occurred in areas where CSISA project interventions were ongoing and included both farmers who were implementing new technologies and those that were not. Although the sampling design was not completely random (e.g. including areas outside of CSISA working domain), we assume the large number of farmers included in the study across significant environmental and socioeconomic boundaries is representative of the diversity of management and environments found in the EIGP. Data from these surveys were used for three purposes: 1) Determine YG_M for the EIGP, Bihar, Terai of Nepal, and environments therein; 2) Identify and prioritize stand out agronomic practices that reduce YG_M across different political and environmental boundaries; 3) Provide context on how agricultural policy and Per Capita Income may influence the adoption of successful agronomic practices that emerge in our study.

2.2 Methodology

2.2.1 Study Location and Cropping System

The study area was located in fourteen districts of the Terai region of Nepal bordering the Indian states of Bihar and Uttar Pradesh, and twelve districts in the Indian state of Bihar. The study area climate is sub-tropical, with a mean annual temperature between 20 and 25 °C and an average annual rainfall of approximately 1,400 to 2,000 mm which mostly falls during the summer monsoon (WFP, 2010). All fields in the study received at least one irrigation during the wheat growing season. The dominant annual cropping pattern in the survey area is the rice-wheat rotation and covers approximately 33% and 42% of the total rice and wheat area in the EIGP (Mahajan and Gupta, 2009). Wheat is largely sown in November and harvested in March or April.

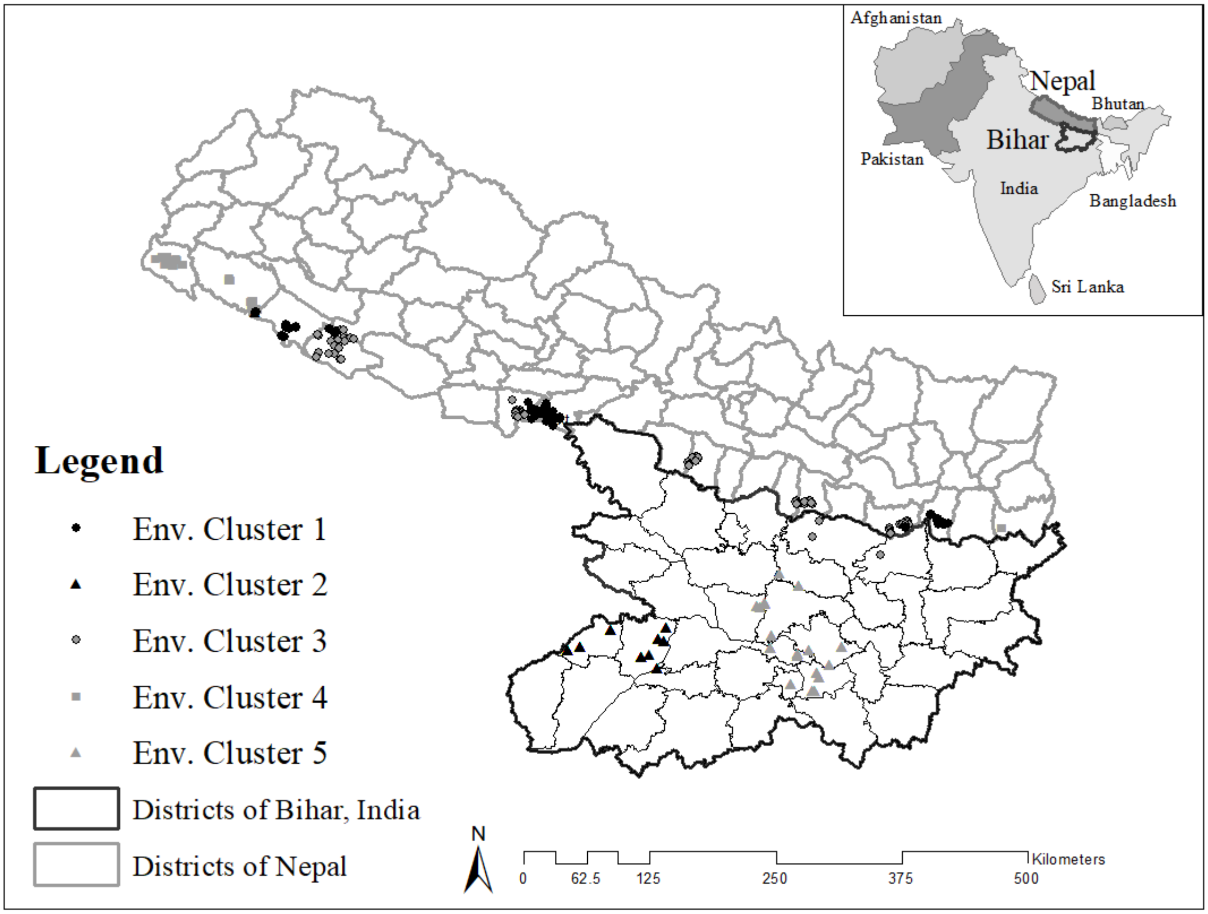

Figure 2.1. On-farm production practice and yield estimation surveys taken at 1,181 farms in 109 villages in Bihar, India and the Terai Region of Nepal. Surveys taken in 2012, 2013, and 2016, but not universally replicated yearly at all locations. Five environmental clusters created from k-means cluster analysis are shown. Environmental clusters two and five are found in Bihar, while one and three are found in Nepal. Environmental cluster four was predominantly found in Nepal, while three villages in Bihar were classified as environmental cluster four.

2.2.2 Survey Data

Data was collected on tillage and crop establishment type (rotovation, cultivation, or zero-till); Nitrogen (N), Phosphate (P), Potassium (K) and seed input rates in kg ha^{-1}; number of irrigations during the growing season; wheat variety and maturity rating; date of sowing; and wheat grain yield in kg ha^{-1}. Yield samples were corrected for moisture content using a *wile 55* moisture meter or equivalent. District level Per Capita Income for 2014 estimates in USD ($)

were determined from each country's Bureau of Statistics (MSPI, 2015; Sharma et al., 2014). Per Capita Income was included in this analysis because there are a host of management decisions associated with wealth for agricultural intensification and risk bearing capacity that are difficult to fully capture in production surveys. Its inclusion was an attempt to include some of these latent variables and their associated effects on management decisions within our analysis.

2.2.3 Yield Potential

A previous study by Aggarwal et al. 2000 used model-based methods to estimate the Y_p of rice and wheat in the Indian States of Punjab, Haryana, West Bengal, Uttar Pradesh and Bihar. In this study, we used wheat Y_p estimates from the simulations conducted Aggarwal et al. 2000 for Bihar that were planted during an optimum sowing window with no water limitations. Varieties of the same lineage commonly found in our study were used by Aggarwal et al. 2000 to estimate Y_p. We used the same Y_p values from Indian districts bordering Nepal as a reasonable proxy for the Nepali farmers in our study because the two regions share very similar agroecological characteristics (Pathak et al., 2003).

2.2.4 Farmer-Based and Model-Based Yield Gaps

The large sample collected by CSISA allows for a modification of the farmer-based yield gap (YGF) which is calculated as the difference between area-averaged Ya and maximum farm yields (Lobell et al., 2009). Instead we treated YGF as an individual value per farmer independent of Ya, and is the difference between their yields and that of the maximum farmer in their respective village. In our calculation of YG_F, the maximum yielding farmer in each village has a YG_F value of 0 kg ha^{-1}, while all other farmers within that village had a negative value as a measure of the difference between their yields and that of the maximum yielding farmer. YG_F were calculated for the i^{th} farmer within the j^{th} village as

$$YG_{F_{ij}} = Farmer\ yield_{ij} - Maximum\ yield_j$$

We do not consider maximum farmer yield within our calculation of YG_F as an approximation of Y_p. This is because highest yielding farmers are often unable to achieve optimal yields for a given variety with their management practices, and is therefore not an adequate measure of Y_p (Ittersum et al., 2013). However, we treated YG_F as a relative measure of yield performance with the assumption that similar development and environmental conditions exist at the village level, and that differences between the maximum yielding farmer and all other farmers within a village were a result of different agronomic practices (Fischer et al., 2009). We then determined the YG_M of different political units and/or environments by finding the difference between area-averaged Y_a and Y_p as estimated from Aggarwal et al. 2000. Estimations of YG_M for the EIGP, Bihar, Nepal and their environments were compared against each other to determine if there were agricultural practices that had the potential to improve yields in other parts of the EIGP.

2.2.5 Elite and Low-Performing Farmers

Once we had identified agronomic practices that were important in predicting YG_F for all the farmers within a political unit or environment, we wanted to identify how the farmers with the lowest and highest YG_F used these selected practices relative to each other, and to average yielding farmers. To determine the differences in implementations of the farmers with the lowest and highest YG_F, we isolated the farmers that were the top 10% of YG_F in each political unit and environment, as well as the lowest 10% YG_F values. These top farmers we identified as "elite farmers", while those in the bottom 10% were identified as "low-performing farmers".

2.2.6 Environmental Clusters

To understand the role environment has in affecting YG_F, five homogeneous environments were identified using k-means cluster analysis using R version v3.2.4 (R Core Team, 2017). Variables used to create the clusters were: Soil texture, organic matter, cation exchange capacity (CEC), bulk density (ISRIC, 2013), seasonal average of temperature minimum and maximum, seasonal average solar radiation (kJ $m^{-2}day^{-1}$) (WorldClim, 2017) and seasonal average of precipitation (CHG, 2016).

Clusters two and five were located in Bihar, while one, three and four were located in the Terai of Nepal with the exception of three villages that fell within Bihar (Figure 2.1). Cluster two and five in Bihar exhibited the most fertile soils, highest solar radiance, maximum temperature, and least precipitation (Figure A. 4). Clusters one and three appeared to be located at opposing sides of major river valleys along the Himalaya range. This may indicate different soil properties that were the result from alluvial activity. Cluster four was mostly located in western Nepal, and was characterized by sandy soils and low CEC values.

2.2.7 Analysis at Different Geographic Scales

To determine if the influence of agronomic practices affected YG_M differently across different political and environmental boundaries, we aggregated and analyzed farmers by political groupings based on country and the greater EIGP, and environmental groupings based on the cluster analysis. Hereafter, references to the Bihar, India and Nepal represent distinct political boundaries, while EIGP refers to a combination of both of these political units into a single feature which captures all farmers in the study.

2.2.8 Classification and Regression Tree Analysis

Classification and Regression Tree (CART) analysis was used to identify important associations between the dependent variable YG_F and independent variables including agronomic factors and Per Capita Income. The algorithm underlying CART repeatedly partitions a data set into more similar groups, and evaluates the impurity of the data before and after a split to determine if added model complexity reduces proportional error (Breiman et al., 1984). We implemented this procedure with 50-fold cross-validation in the ‘rpart’ package of R statistical software (R Core Team, 2017). Our method identified the most parsimonious models for the dependent variable YG_F following the ‘1-se’ rule (Venables and Ripley, 2002), in which the simplest model within one standard error from the minimum relative model error was selected as providing the best fit for the data with minimal splits. The output is presented graphically as a dichotomous tree.

2.2.9 Linear Mixed Effects Models

We conducted model selection from a pool of candidate models representing competing hypotheses underlying the cause of YG_F using the ‘nlme’ package in R version v3.2.4 (Pinheiro et al., 2017). This model building process was performed for political and environmental grouping. The most parsimonious model was selected by comparing the goodness of fit among models using maximum likelihood and simplification (Burnham and Anderson, 2002). In the global model (EIGP model), village was nested in environmental cluster, nested in year, nested in country.

There were three steps to the model simplification process. First, fixed effects for a geographic level were added to the model based on their selection from CART, with a full model then developed that incorporates random effects. Second, the number of random effects were reduced to see if the model fit improved. Third, if appropriate quadratic terms were added to fixed effects to test if optimum rates were begin used by farmers. The EIGP linear mixed effects model was used to calculate inter-class correlations that indicate the variability in YG_F explained at each hierarchical level within the random effects structure (Maindonald and Braun, 2007).

Term	Acronym (if used)	Description
Yield Potential	Y_p	yields obtainable under "ideal" conditions
Average Farmer Yields	Y_a	average farm yields
Model-based yield gap	YG_M	difference between Y_p and Y_a
Farmer-based yield gap	YG_F	YG_{Fif} = Farmer yield$_{ij}$ - Maximum yield$_j$
Elite farmers	Elite Farmers	top 10% of YG_F
Low-performing farmers	Low-performing farmers	bottom 10% of YG_F

Table 2.1. Commonly used terms, their acronyms if used, and a brief description.

2.2.10 Model Selection for Farmer-Based Yield Gap

Although agricultural decisions, environments and economics vary widely across the EIGP, we were able to construct hierarchical models to describe YG_F using linear mixed effects models for the different political and environmental units within our study. An example of model selection using maximum likelihood for the EIGP political grouping among five candidate models is shown in Table 1 whereby model five was the best supported. The fixed effects within the model consisted of both linear and quadratic terms. The linear terms within the model included: cultivar maturity, sowing date, Per Capita Income, K, number of irrigations, and the interaction effect between sowing date and cultivar maturity. A quadratic term for N rate was included in the fixed effects (Table 1.1). The random effects structure for this model contained nested terms for country, year, environmental cluster, and village. This model selection process was repeated for each political and environmental grouping, with final models represented by the parameter estimates found in Table A.1a-1g.

Table 2.2. Maximum likelihood selection among best linear mixed effects models of YG_F

Model	Fixed effects[a]	Random effects	df[b]	AIC	BIC	LL	w_i
1	dtm + sdoy + PCI + k.kgha	~ 1|country/year/cluster/village	9	19350	19396	-9666	8.8×10^{-83}
2	dtm * sdoy + PCI + k.kgha	~ 1|country/year/cluster/village	11	19049	19105	-9513	2.7×10^{-17}
3	dtm * sdoy + PCI + k.kgha + n.kgha + irrig + sd.kgha	~ 1|country/year/cluster/village	14	18987	19058	-9479	0.0006
4	dtm * sdoy + PCI + k.kgha + n.kgha + irrig + zt	~ 1|country/year/cluster/village	14	18977	19048	-9474	0.12
5	**dtm * sdoy + PCI + k.kgha + n.kgha + n.kgha^2 + irrig + zt**	**~ 1|country/year/cluster/village**	**15**	**18973**	**19049**	**-9471**	**0.88**

[a]Agronomic and economic variables as fixed effects. Environmental factors incorporated by clustering in agroecological zones. The symbol, ~1 indicates that fixed effects refer to model intercepts only.
[b]Model selection criteria abbreviations: AIC, Akaike's information criterion; BIC, Bayesian information criterion; LL, log likelihood; *wi*, Akaike weights, larger values indicate the probability that a given model represents the most parsimonious model (shown in bold) within the group.

2.3 Results and Discussion

2.3.1 Yield Comparisons

Yield potential estimates obtained from Aggarwal et al. 2000 were similar across the different political and environmental groups found within the study, with the EIGP averaging 6,897 kg ha^{-1} (Figure 2.2). The minimum Y_p estimates of 6,741 kg ha^{-1} were found in Bihar, while maximum estimates of 7,057 kg ha^{-1}were located in Nepal. Unlike Y_p, average farmer and elite farmer yields were not consistent across the political or environmental groupings. Average farmer yields in Bihar were 47% higher than those in Nepal. Elite farmers in Bihar performed 39% better than those in Nepal.

Average farm yields in environmental clusters two and five located in Bihar were 35% higher than Y_a of environmental clusters one, three and four located in Nepal. The consistency of Y_p across the EIGP, and the large differences in Y_a between the political and environmental groupings resulted in large variability of YG_M between Nepal and Bihar. Model based yield gaps for farmers in Bihar and Nepal were 2,628 kg ha^{-1} and 4,823 kg ha^{-1}, respectively. These values indicate that the surveyed farmers in Bihar were much closer to achieving the Y_p of their region compared to farmers in Nepal. The magnitude of difference in YG_M was similar for the environmental clusters located within a respective country. Elite farmers in cluster two were the closest to achieving the Y_p among all the political and environmental groupings. These elite farmers came within 16% of reaching the Y_p of their environmental cluster.

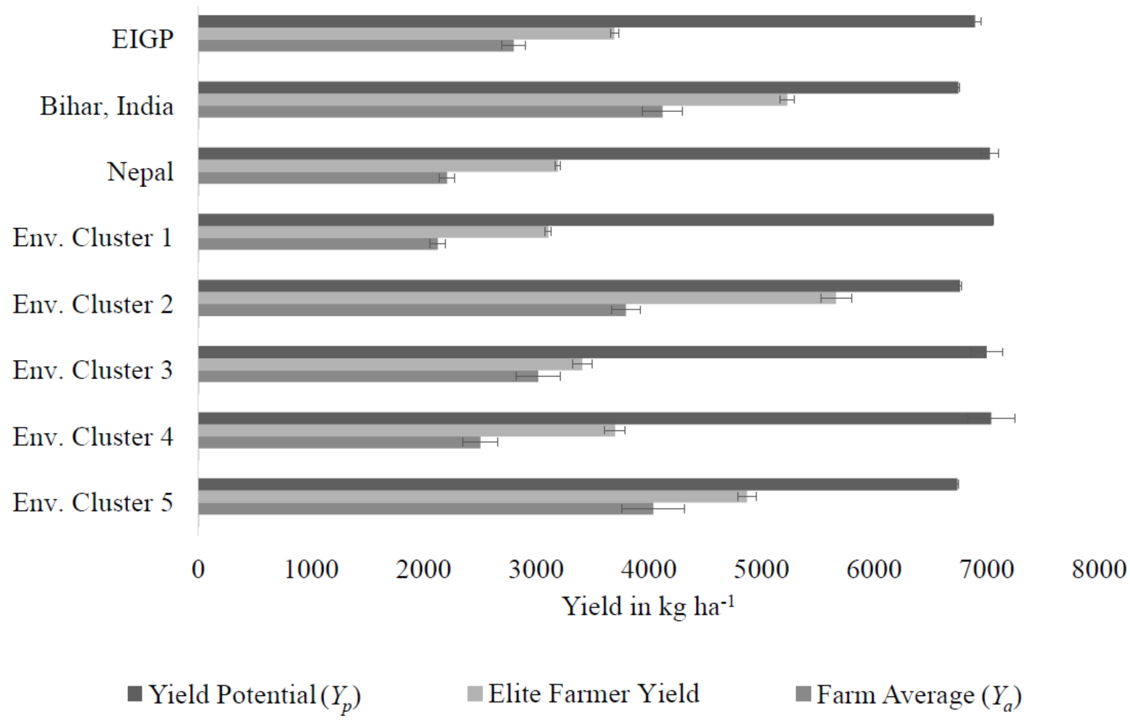

Figure 2.2. Yield potential (Y_p), elite farmer yields, and farmer average yields (Y_a) for the geographic levels of Eastern Indo-Gangetic Plains (EIGP), Bihar, India, the Terai of Nepal, and environmental clusters 1-5. Yield potential (Y_p) estimates were derived from Aggarwal et al. 2000. Standard error bars are included.

2.3.2 Agronomic Practices That Reduced Farmer-Based Yield Gaps

2.3.2.1 Soil Fertility

At the scale of the EIGP, K was the only nutrient that was found to have a significant, positive linear relationship that reduced YG_F in both linear mixed effects model and CART. For every kg ha^{-1} of K applied, YG_F were reduced by 6.5 kg ha^{-1} (Table 1.2); and application of 24 kg ha^{-1} or more of K reduced YG_F, on average, by 651 kg ha^{-1} (Figure 2.3). Farmers from both countries used little K in their fields, with only 48% of the surveyed farmers from Bihar, and 30% of Nepali farmers applying any K whatsoever (Figure 2.4a). We believe application of sufficient K emerged as an important agronomic practice within the study for two reasons. First, the cultural practice of removing straw from fields for fodder after harvest of grain prevents the return of the 80-85% of accumulated K stored in the wheat stem back to the field (Kumar and Goh, 1999). This common practice ensures a yearly net deficit of K if this nutrient is not added back as fertilizer. Second, mixed extension messages, subsidies that favor N, and the resulting incomplete farmer knowledge of the importance of K nutrition has led to a prioritization of N over K in the EIGP (Pandey, 2014; Singh et al., 2005).

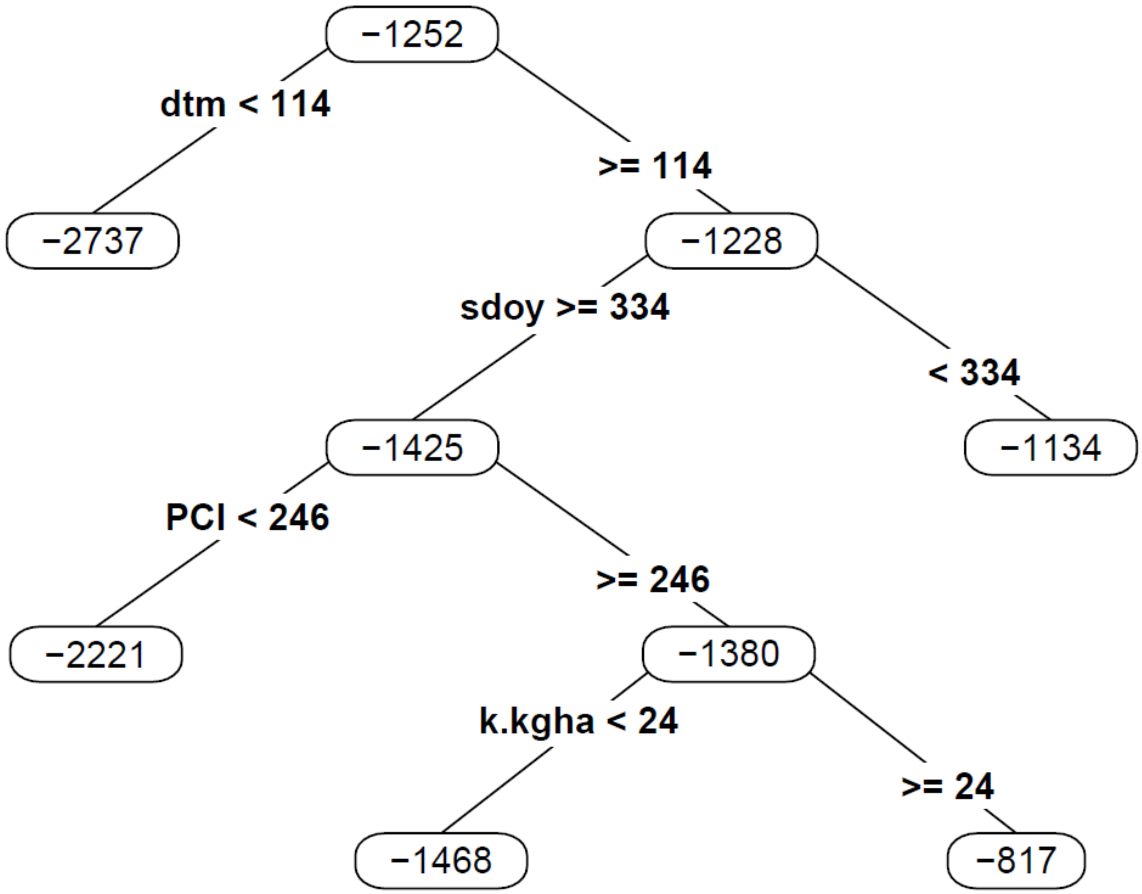

Figure 2.3. Classification and regression tree showing associations between the dependent variable farmer based yield gaps (YG_F) and independent variables retained in the most parsimonious model for the EIGP. Explanation of fixed effects parameters: dtm, days to maturity; sdoy, sowing day of year; PCI, Per Capita Income; k.kgha, K kg ha^{-1}.

Nitrogen, P and K were found to significantly affect YG_F in the political units of Bihar and Nepal (Figures 5 & 6, Table A.1a, 1b). We observed two major differences between farmers in Bihar and Nepal in how fertilizers were used, and how fertilizers affected YG_F. First, surveyed farmers in Bihar applied substantially more fertilizer (40% more N, 26% more P, and

70% more K) than in Nepal (Figure 2.4a & Table A. 3b, 3c). Second, fertilizers in Bihar had higher use efficiencies than those in Nepal (with the exception of K) (Table A. 1a,1b). These factors indicate that farmers in Bihar were not only applying more fertilizer, but that each kilogram of that fertilizer is more effective at closing YG_F compared to Nepal.

Table 2.3. Summary of random and fixed effects for the most parsimonious linear mixed effects model of YG_F

Fixed Effects[a]	Coefficient	SE	df	t-value	P-value	Random effects	SD
dtm	-0.68	15.53	1035	-0.04	0.97	Country	627.2
sdoy	-20.88	4.22	1035	-4.95	0.00	Year	214.5
PCI	-0.03	0.26	1035	-0.11	0.91	Env. Cluster	162.5
k.kgha	6.46	1.62	1035	3.99	0.00	Village	486.7
n.kgha	-0.97	2.57	1035	-0.38	0.71	Residual	671.8
$n.kgha^2$	0.03	0.01	1035	2.48	0.01		
irrig	217.18	44.19	1035	4.92	0.00		
zt	327.84	98.29	1035	3.34	0.00		
dtm*sdoy	0.71	0.37	1035	1.89	0.06		

[a]Explanation of fixed effects parameters: dtm, days to maturity; sdoy, sowing day of year; PCI, Per Capita Income; k.kgha, K kg ha^{-1}; n.kgha, N kg ha^{-1}; $n.kgha^2$, quadratic term of N kg ha^{-1}; irrig, number of irrigations; zt, zero till; dtm*sdoy, interaction effect between cultivar maturity and sowing day of year.

With the exception of cluster five and Bihar, statistically significant yield responses to N, P and K were linear in all environmental clusters. These linear responses indicate yield responses to additional fertilizer were maintained at the same level of efficiency across range of input use observed in this study. We found that environmental cluster five had a significant quadratic response of YG_F to N, indicating that farmers at the higher end of application rates (150-200 kg ha^{-1}) have reduced efficiencies.

In Nepal, insufficient supplies of government subsidized fertilizer and low levels of private sector investment have led to chronic shortages of fertilizer, resulting in 75-80% of

Nepali farmers becoming reliant on the informal trade of fertilizers from gray market sources in India (Pandey, 2014). In contrast to Bihar, lower fertilizer efficiencies observed in Nepal were likely a symptom of other poor agronomic practices (limited irrigation, late sowing, etc…) that persist due to prevailing agricultural policy and socioeconomic conditions. Conversely, investment by the Indian Government since the Green Revolution in fertilizer subsides has led to easier access to affordable fertilizer, with an imbalance of fertilizers in favor of N (Fan et al., 2008; Parayil, 1992). An indication of the effect of these policies may be reflected in the near significance of quadratic terms we found for N in Bihar and cluster five, respectively. These quadratic relationships in our models indicated that farmers were approaching a plateau where reduction in YG_F is diminishing with further additions of N (Ingestad, 1977). Here we underscore that these relationships were with respect to optimum growth as compared to economically optimal production.

2.3.2.2 Timely Sowing

Earlier sowing dates within our study were associated with smaller YG_F in the EIGP. If wheat was sown before November 30th (Julian day 334), farmers reduced their YG_F by 291 kg ha^{-1} (Figure 2.3). This effect was also observed in the linear mixed effects model; every day earlier a farmer sowed caused their YG_F to decrease by 21 kg ha^{-1} (Table 1.3). These results were largely consistent across both political units and environmental clusters (Table A. 1a, 1b, 1e, 1g). Early sowing is an important management decision as it relates to overcoming terminal heat stress, a major production constraint in the EIGP. Terminal heat stress occurs when temperatures exceed 31°C during flowering and grain filling stages, causing anther and pollen sterility that limits embryo development thereby creating sink limitations and low harvest indices

(Al-Khatib and Paulsen, 1984). Solutions to terminal heat stress largely come from earlier sowing (Lobell et al., 2013) and breeding for heat tolerance (Rane et al., 2007). Ortiz et al. 1994 found yield losses of 0.7% daily if wheat is sown past an optimum time window based on the cultivars' maturity rating. By sowing earlier, farmers can shift the development of wheat earlier into the year so that the crop has a greater chance of completing anthesis prior to heat stress. In some cases, sowing delays are caused by a knowledge gap among farmers of the vital importance of timely sowing to preserve yield potential of their wheat crop. In other cases, delays occur because of late harvesting of rice crop or due to persistently wet soils that prevent field access for sowing (Ladha et al., 2003).

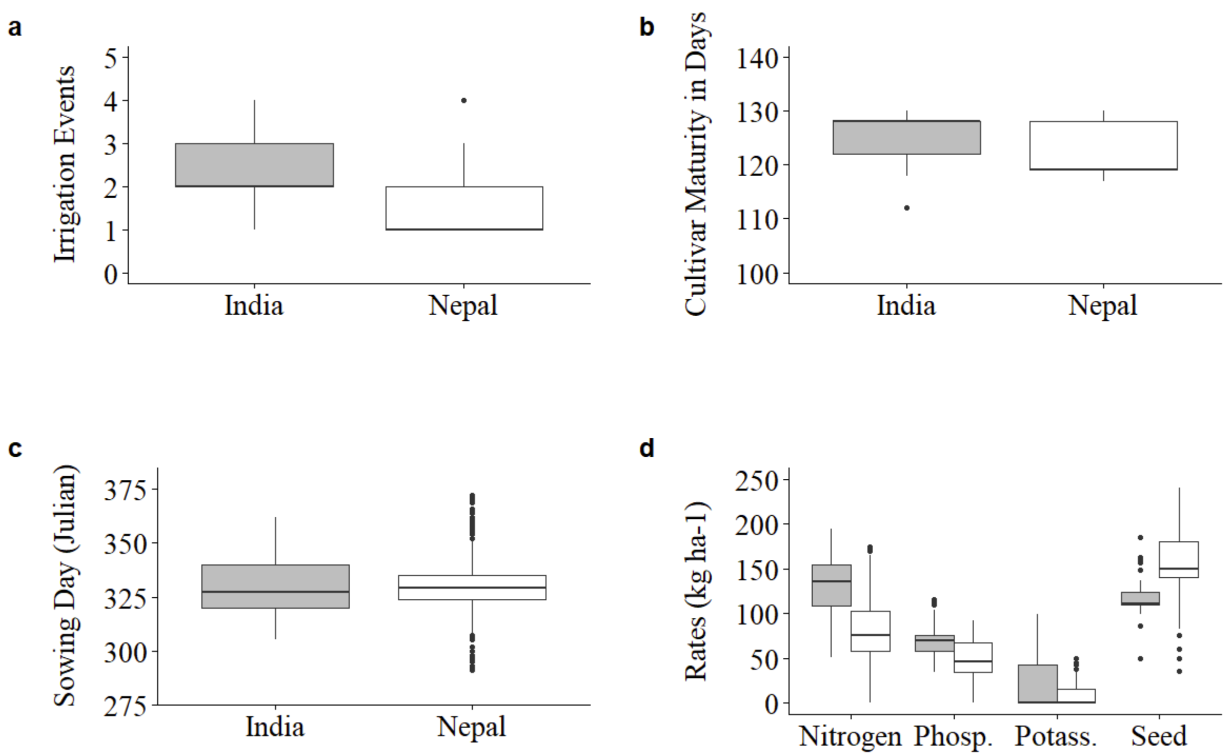

Figure 2.4. Differences among farmer inputs between Bihar, India and the Terai of Nepal a) irrigation; b) cultivar maturity rating; c) sowing day of year, d) Nitrogen, Potassium, Phosphate and seed rate in kg per ha^{-1}.

2.3.2.3 Cultivar Maturity

A longer cultivar maturity emerged as important towards closing YG_F in Bihar, but not Nepal. Farmers in Bihar on average used varieties which had maturity ratings four days (126 compared to 124 days) longer than Nepal ($F_{1,1179}$=141.6, p <0.01), and skewed towards higher maturity ratings (Figure 2.4b). Nepal on the other hand had the reverse distribution, and skewed towards using shorter maturity ratings. Benefits to farmers in Bihar occurred even when using varieties with maturities less than the average maturity, with a 1,044 kg ha^{-1} reduction in YG_F if they used a maturity of greater than or equal to 121 days (Figure 2.5). This effect was also observed in the linear mixed effects model, where the coefficient of cultivar maturity indicated that every extra day of maturity reduced YG_F by 75 kg ha^{-1} (Table A. 1a). Cultivar maturity was found significant in the environmental clusters located in Bihar, but not Nepal (Appendix 1c-1g).

We believe varieties with longer duration maturity ratings performed better within our study area because longer maturing varieties have been associated with slower vegetative growth that promotes total crop development and Y_p by preventing an early triggering of the reproductive phase (White and Hoogenboom, 2010). Longer maturing varieties can also accumulate more growing degree days which are related to end of season yield (Burke and Lobell, 2009).

Access to seeds with different traits, including different maturity ratings, were more limited in Nepal than Bihar. Farmers in Nepal overwhelmingly use informal seed systems for acquiring seed, with only 10% using formal seed suppliers (Joshi et al., 2012). The higher adoption rate of cultivars with greater maturity may indicate that Indian Government investments in extension, research and subsidies for seed (Parayil, 1992; Rane et al., 2007) may be making a difference in greater access to seed with longer maturity ratings in Bihar.

2.3.2.4 Sowing Date x Cultivar Maturity Interaction

In both the EIGP and environmental cluster two, we observed that there were yield benefits to pairing an early sowing date with a longer maturing variety. An interaction effect between sowing date and cultivar maturity that affected YG_F was found to be nearly significant for the EIGP political unit, and significant for environmental cluster two located in Bihar (Table 1.3 & Table A. 1d). Across the EIGP, we found that farmers which sowed before November 30th with a longer maturing variety (>=114 days) reduced their YG_F by 1,800 kg ha^{-1} compared to farmers that did not (Figure 2.3). In environmental cluster two, for every day increase in maturity rating of a cultivar planted at the earliest sowing date (November 9th), YG_F were reduced by 243 kg ha^{-1} (Table A. 1d). We suspect this is caused by a combination of the benefits of both early sowing and long maturing varieties: Reducing the risk from terminal heat stress, accumulating more growing degree days across a season, and allowing for a more total crop development by delaying the onset of an early reproductive phase.

Across the EIGP, 33% of farmers planted after November 30th while only 4% of farmers use cultivars with less than 114 day maturity rating. This information implies that there are still opportunities to reduce YG_F in the EIGP through earlier sowing, but is less telling of the improvements that can be made by using maturities longer than 114 days as the majority of farmers already do so. The importance of equitable access to seed with different maturities becomes clear when we investigate environmental clusters where elite farmers achieved yields closer to Y_p by using varieties with maturity ratings 12-14 days longer than the 114 day maturity rating (Table A. 3a-3g).

Elite farmers in environmental cluster two – coming to within 16% of Y_p – took advantage of this interaction by using cultivars with six more days of maturity (128 day compared to 122 day maturity rating), and sowing eleven days earlier than average yielding farmers (November 19th compared to November 30th) (Table A. 3e). Earlier sowing in cluster two can be partially attributed to it being the hottest, driest environmental cluster. This likely allowed famers to enter and prepare fields earlier after monsoon because of faster drying soils. These favorable conditions for earlier sowing were likely the reason elite farmers in environmental cluster two planted six days earlier and with cultivar maturity ratings three days longer than any of the other elite farmers in different environmental clusters. Elite farmers in cluster two provided evidence of using adaptive management by selecting late maturing cultivars to use in earlier sowing conditions.

2.3.2.5 Other Varietal Traits

Investigation into the varieties used in this study showed that farmers in Bihar used more "modern" varieties compared to farmers in Nepal. The PBW, HD, and HUW lineages accounted for 83% of the seed used in Bihar while in Nepal these accounted for 10%, with the remainder being varieties released in the 1970s and 80s (Bhatta, 2010) (Table A. 2a-2b). PBW 502 and PBW 343 together accounted for 52% of seed used in Bihar, while Bhrikuti was the most popular in Nepal (26%). In general, the modern varieties used in Bihar possess disease resistance and heat tolerance traits (Bhatta, 2010; Rane et al., 2007). Bhrikuti possesses disease resistance, but does not have heat tolerance traits (Bhatta, 2010; Hobbs and Rajbhandari, 1998).

2.3.2.6 Tillage and crop establishment type

In the EIGP, farmers that selected zero-tillage as their preferred tillage and crop establishment type reduced their YG_F by 328 kg ha^{-1} compared to those that used cultivation or rotovation (Table 1.3). Zero-tillage reduced YG_F by 375 kg ha^{-1} in Bihar (Table A.1a) and 697 kg ha^{-}1 environmental cluster five (Table A.1g), respectively. No tillage and crop establishment types (including cultivation or rotovation) were not found to significantly affect YG_F in Nepal or environmental clusters located therein (Table A. 1b).

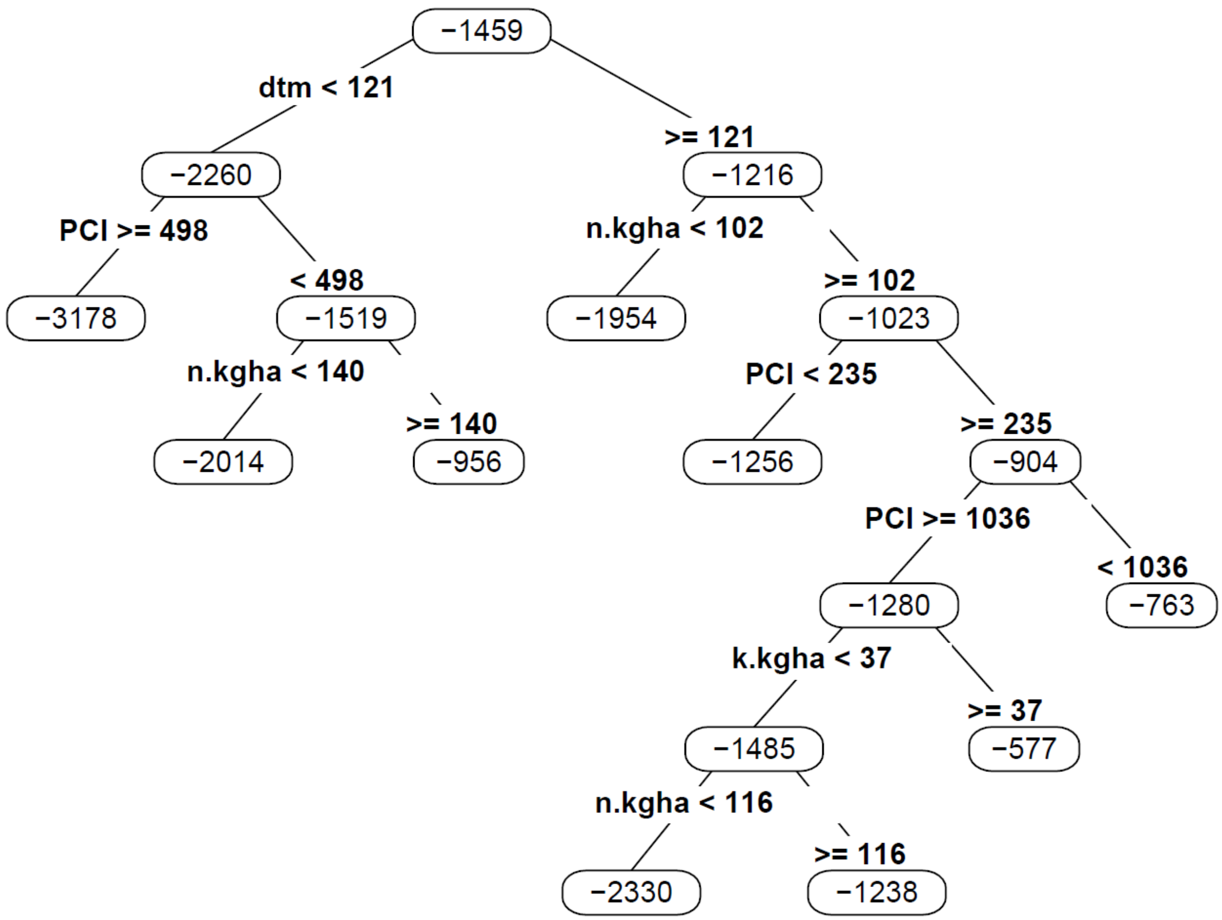

Figure 2.5. Classification and regression tree showing associations between the dependent variable farmer based yield gaps (YG_F) and independent variables retained in the most parsimonious model for the Bihar, India. Explanation of fixed effects parameters: dtm, days to maturity; sdoy, sowing day of year; PCI, Per Capita Income; k.kgha, K kg ha^{-1}; n.kgha, N kg ha^{-1}.

As the first agronomic operations of the season, tillage and crop establishment affects the timing of all subsequent operations and therefore strongly influences farmers' ability to preserve Y_p (Erenstein and Laxmi, 2008). Zero-till has been found in some studies to allow farmers to plant up to 8-25 days earlier than in conventional tillage in the EIGP (Singh et al., 2002). A recent study by (Keil et al., 2015) suggested a similar productivity gains in Bihar, India with zero-till leading to a 498 kg ha^{-1} yield gain compared to conventional tillage practices. In the EIGP and environmental cluster five we did not find a significant association between establishment type and sowing date in our study ($F_{1,1179}$=1.99, p = 0.16 & $F_{1,204}$=1.6, p =0.2, respectively) (Figure 2.4c). In Bihar, farmers using zero tillage planted five days later ($F_{1,363}$=5.9, $p < 0.05$) than those using conventional tillage. This data indicates yield gains associated with zero-till were not associated with earlier sowing in our study. It is likely that the yield gains we observed with the use of zero tillage were from the added measure of precision in the application of fertilizer and seed relative to these inputs being applied by hand when incorporated by conventional tillage (Erenstein and Laxmi, 2008).

One problem in assessing the effects of zero-till on crop productivity in developing countries is disentangling the confounding effects of other agricultural incentives often given alongside zero-till (e.g. fertilizer support) (Whitfield et al., 2015). We did not find evidence of this confounding effect among the zero-till users in Bihar, which applied 13% less N ($F_{1,363}$=30.1, $p < 0.01$), 27% less K ($F_{1,363}$=17.6, $p < 0.01$) and 10% more P ($F_{1,363}$=3.6, p = 0.06) than conventional tillage.

Because tractor ownership is limited to relatively large farmers, most farmers rely on zero-till service providers to access this service. A more organized private service provider network in Bihar has allowed the relatively new zero-tillage technology to rapidly increase in adoption (Keil et al., 2015). Higher adoption rates in Bihar have also been attributed to more aggressive governmental mechanization subsidy schemes (Erenstein and Laxmi, 2008) compared to those in Nepal (Joshi et al., 2012). The differences in policy and private service provider network may be a reason by 87% of farmers in Bihar used zero-tillage, while only 3% in Nepal among surveyed farmers.

2.3.2.7 Irrigation

Additional irrigation events were found to reduce YG_F in the EIGP, Nepal and Bihar (Table 1.3 & Table A.1a-1b). Irrigation of wheat in the EIGP is considered a necessary part of farming operations because of the low precipitation during the growing season (Chatrath et al., 2007). Although both Nepal and Bihar observed similar reductions in YG_F from irrigation (Table A.1a, 1b), Bihar on average applied roughly double the number of irrigations (Figure 2.4d). We suspect the extra irrigation in Bihar reflected adaptive management toward the hotter, drier climate, and a better capacity for cash investment compared to Nepal (Shah et al., 2006). Evidence of this adaptive management was observed in the relationship between maximum temperatures and number of irrigations. As average maximum temperatures rose so too did the number of irrigations in Bihar (b_1= 0.1, R^2=0.02, $F_{1,363}$ = 8.6, p<.01) while the opposite was true in Nepal (b_1= -0.37, R^2=0.1, $F_{1,814}$ = 92.2, p<.01). In Bihar, the benefits additional irrigations in Bihar diminished after two irrigations (Table A. 1a).

These results highlight the dichotomy between countries in the ability of farmers to access irrigation because of changes related to wealth differences and capacity to invest in fuel for farmers who require diesel for pumps (Shah et al., 2006). Since the Green Revolution, the Indian government heavily invested in irrigation projects, and continues to provide funding for canal installation and maintenance to provide year-round farmer access to irrigation. Irrigation policy in Nepal has left farmers on the Terai more reliant on diesel pumps than farmers in Bihar (Shah et al., 2006). Diesel fuel is one of the most expensive farming inputs, and subsidy schemes for it in Nepal have not been large enough to benefit farmers at scale in the Terai (Joshi et al., 2012).

2.3.2.8 Similar Production Environments, Different Outcomes

Inter-class correlations from the EIGP linear mixed effects model provide evidence that policy and socioeconomic differences were a major cause of differences we saw in YG_F. Ninety-three percent of the variation in YG_F were caused by the combined differences among agronomic, socioeconomic, temporal, and environmental factors that existed between Nepal and Bihar, India in our study. When assessed separately, year and environmental cluster accounted for 32% and 24% of this variation, respectively. We contend the variation not explained by year and environment can be attributed to the agricultural policy differences that exist between the Nepali and Indian governments that we have highlighted, and helps explains the large differences we observed in YG_M and Y_a in a farming environment with fairly homogeneous Y_p.

2.3.2.9 Per Capita Income and Government Policy

Using district level Per Capita Income, we saw signals that regional differences in wealth can affect YG_F. Reductions of YG_F in Nepal and its environmental clusters three and four were found to be positively associated with increases in district level Per Capita Income (Figure 2.6 & Table A. 1e-1f), indicating that farmers in richer districts had better yield outcomes. Conversely, farmers in Bihar from districts with lower Per Capita Income were able to achieve smaller YG_F than those from wealthier districts (Figure 2.5). Without Per Capita Income at the farmer scale, we lack the ability to make inferences beneath the district level when interpreting the effect Per Capita Income had on adoption of agronomic practices and YG_F. Nevertheless, we believe this result demonstrates the influence that relative wealth has on risk management in agriculture between Nepal and Bihar. In Bihar, farmers growing in poorer districts were able to reduce YG_F to a greater degree than those in richer districts through the adoption of better agronomic technologies and management. In Nepal, the positive association between smaller YG_F and district level wealth indicated that better management may be unavailable to poorer farmers. Taken together, these factors reflected that higher yields were more equitably achieved in India compared to Nepal.

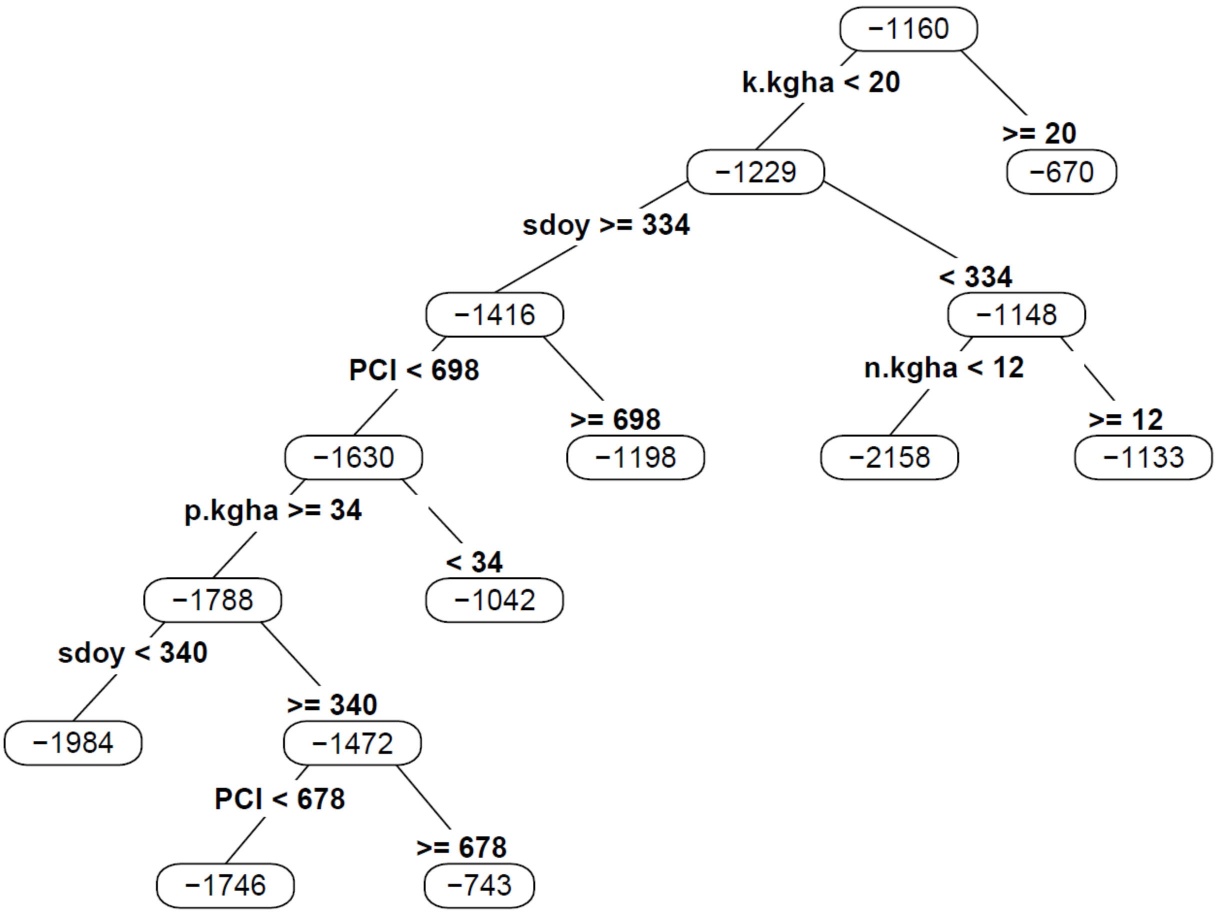

Figure 2.6. Classification and regression tree showing associations between the dependent variable farmer based yield gaps (YG_F) and independent variables retained in the most parsimonious model for the Terai of Nepal. Explanation of fixed effects parameters: dtm, days to maturity; sdoy, sowing day of year; PCI, Per Capita Income; k.kgha, K kg ha^{-1}; n.kgha, N kg ha^{-1}; p.kgha, P kg ha^{-1}.

In India, government incentives, support for infrastructure and private sector innovation, and subsidies effectively reduced the disposable income required to purchase inputs (Fan et al., 2008; Keil et al., 2015), thereby allowing farmers with smaller Per Capita Income to obtain and use the necessary inputs to meet crop needs. In general, this stood in contrast to those in Nepal where poorly executed and inconsistent agricultural development policies have contributed to slow growth of the agricultural economy (Sharma, 2006).

2.3.2.10 Synthesis and Stand out Agronomic Practices

In conclusion, our results indicate that four agronomic practices stood out to meaningfully reduce YG_M at different political and environmental levels of the study: 1) early sowing with long maturing varieties, 2) higher rates of N, P and particularly K, 3) transitions to zero-till for crop establishment, and 4) encouraging more frequent irrigation. We used two different types of models to identify how each of these practices affected farmers yield gaps at different political and environmental groupings. Financial and policy support for infrastructure and agricultural inputs, extension, research and development of private service networks made a marked improvement in yield outcomes in Bihar. These factors allowed farmers from Bihar in our study to have yields equivalent to those in Punjab and Haryana. A dissimilar agricultural policy and private sector environment existed in Nepal, which we believe limited their yield even though sharing similar Y_p with Bihar. This analysis should offer optimism for law makers in Nepal because of the evidence that changes in policy had meaningful impacts to reduce YG_M by improving adoption of better agronomic practices that we observed in Bihar. By focusing on the four agronomic practices we highlighted, policy makers in Nepal and India will help ensure gains in productivity and improve food security outcomes.

2.4 Funding

This work was supported by the Bill & Melinda Gates Foundation, Seattle, WA [grant number OPP1052535]; the United States Agency for International Development, Washington

D.C. [grant number BFS-G-11-00002]; and the United States Borlaug Fellows in Global Food Security Awarded to Purdue University, Washington D.C. [grant number A11023.2]

2.5 Acknowledgements

We acknowledge the Bill and Melinda Gates Foundation, the United States Agency for International Development, and the United States Agency for International Development's Borlaug Fellowship program administered through Purdue University for funding this study. We thank Dr. Mina Devkota-Wasti, Dr. Ram Malik, Gokul Paudel, and Madan Bhatta for their work in collecting and contextualization the data within this study.

2.6 Literature Cited

1. Aggarwal, P.K., Talukdar, K.K., Mall, R.K., (2000) Potential Yields of Rice-Wheat System in the Indo-Gangetic Plains of India. Rice-Wheat Consortium Series 10, New Delhi, India, pp. 1-16.
2. Al-Khatib, K., Paulsen, G.M. (1984) Mode of high temperature injury to wheat during grain development. Physiology Plant 61, 363-368.
3. Bhatta, M.R. (2010) National Wheat Research Program, Bhairahawa, Nepal.
4. Breiman, L., Friedman, J.H., Olshen, R.A., Stone, C.I. (1984) Classification and regression trees. Wadsworth, Belmont, Calif.
5. Burke, M., Lobell, D., (2009) Food Security and Adaptation to Climate Change: What Do We Know?, in: Burke, M., Lobell, D. (Eds.), Climate Change and Food Security: Adapating Agriculture to a Warmer World. Springer, New York, pp. 133-153.
6. Burnham, K.P., Anderson, D.R. (2002) Model selection and inference: a practical information-theoretic approach. Springer, New York.
7. Chatrath, R., Mishra, B., Ferrara, G.O., Singh, S.K., Joshi, A.K. (2007) Challenges to wheat production in South Asia. Euphytica 157, 447–456
8. CHG, (2016) Globaly Monthly Precipitation Data, in: Climate Hazards Group (Ed.), Climate Hazard Group InfraRed Precipitation (CHIRP) data archive, University of Santa Barbara.
9. Erenstein, O., Laxmi, V. (2008) Zero tillage impacts in India's rice–wheat systems: A review. Soil & Tillage Research 100, 1-14.
10. Fan, S., Gulati, A., Thorat, S. (2008) Investment, subsidies, and pro-poor growth in rural India. Agricultural Economics 39, 163-170.
11. FAO, (2016) Production quantities by country: Wheat, in: Division, S. (Ed.). Food and Agriculture Organization of the United Nations.
12. Fischer, R.A., Byerlee, D., Edmeades, G.O., (2009) Can Technology Deliver on the Yield Challenge to 2050? , in: Department, E.a.S.D. (Ed.). Food and Agriculture Organization of the United Nations, Rome, Italy, pp. 1-46.
13. Hobbs, P.R., Rajbhandari, N.P., (1998) Proceedings of the Rice–Wheat Research End-of-Project Workshop, in: Hobbs, P.R., Rajbhandari, N.P. (Eds.). Nepal Agricultural Research Council

(NARC), International Maize and Wheat Improvement Center (CIMMYT), and Rice-Wheat System Research Consortium, Hotel Shangri-La, Kathmandu, Nepal.
14. Indian Ministry of Agriculture, (2017) 5-Year (2010-11 to 2014-15) State-wise Normal Area, Production and Yield of Total Foodgrains., in: Ministry of Agriculture, G.o.I. (Ed.). Government of India, India.
15. Ingestad, T. (1977) Nitrogen and Plant Growth; Maximum Efficiency of Nitrogen Fertilizers. Ambio 6, 146-151.
16. ISRIC, (2013) SoilGrids: an automated system for global soil mapping, in: International Soil Reference and Information Centre (Ed.), World Soil Information.
17. Ittersum, M.K.v., Cassman, K.G., Grassini, P., Wolf, J., Tittonell, P., Hochman, Z. (2013) Yield gap analysis with local to global relevance—A review. Field Crops Research 143, 4-17.
18. Joshi, K.D., Conroy, C., Witcombe, J.R., (2012) Agriculture, seed, and innovation in Nepal: Industry and policy issues for the future. International Food Policy Research Institute, Washington, D.C., pp. 1-60.
19. Keil, A., D'souza, A., McDonald, A. (2015) Zero-tillage as a pathway for sustainable wheat intensification in the Eastern Indo-Gangetic Plains: does it work in farmers' fields? Food Security 7, 983-1001.
20. Kumar, K., Goh, K.M. (1999) Crop Residues and Management Practices: Effects on Soil Quality, Soil Nitrogen Dynamics, Crop Yield, and Nitrogen Recovery. Advances in Agronomy 68, 197-319.
21. Ladha, J.K., Dawe, D., Pathak, H., Padre, A.T., Yadav, R.L., Singh, B., Singh, Y., Singh, Y., Singh, P., Kundu, A.L., Sakal, R., Ram, N., Regmi, A.P., Gami, S.K., Bhandari, A.L., Amin, R., Yadav, C.R., Bhattarai, E.M., Das, S., Aggarwal, H.P., Gupta, R.K., Hobbs, P.R. (2003) How extensive are yield declines in long-term rice-wheat experiments in Asia? Field Crops Research 2003, 159-180.
22. Lobell, D.B., Cassman, K.G., Field, C.B. (2009) Crop Yield Gaps: Their Importance, Magnitudes, and Causes. Annual Review Environmental Resources 34, 179-204.
23. Lobell, D.B., Ortiz-Monasterio, J.I., Sibley, A.M., Sohu, V.S. (2013) Satellite detection of earlier wheat sowing in India and implications for yield trends. Agricultural Systems 115, 137-143.
24. Mahajan, A., Gupta, R.D., (2009) The Rice–Wheat Cropping System, in: A., M., R.D., G. (Eds.), Integrated Nutrient Management (INM) in a Sustainable Rice—Wheat Cropping System, Springer, Dordrecht.
25. Maindonald, J., Braun, J. (2007) Data Analysis and Graphics Using R: An Example-Based Approach, 2nd ed. Cambridge University Press, Cambridge.
26. MSPI, (2015) Indian states by Per Capita Income, in: Implementation, M.o.S.a.P. (Ed.). The Government of India, New Delhi, India.
27. Pandey, S.P. (2014) The role of fertilizer in transforming the agricultural economy of Nepal. ReSAKSS Asia 9.
28. Parayil, G. (1992) The Green Revolution in India: A Case Study of Technological Change. Technology and Culture 33, 737-756.
29. Pathak, H., Ladha, J.K., Aggarwal, P.K., Peng, S., Das, S., Singh, Y., Singh, B., Kamra, S.K., Mishra, B., Sastri, A.S.R.A.S., Aggarwal, H.P., Das, D.K., Guptaj, R.K. (2003) Trends of climatic potential and on-farm yields of rice and wheat in the Indo-Gangetic Plains. Field Crops Research 80, 223-234.
30. Paulsen, B.J., Chew, K., Gugerty, M.K., Anderson, C.L., (2012) Wheat value chain: Bihar, in: Evans School of Policy and Research Brief No. 202 (Ed.), Seattle, Washington.
31. Pinheiro, J., Bates, D., DebRoy, S., Sarkar, D., Team, R.C., (2017) {nlme}: Linear and Nonlinear Mixed Effects Models.
32. R Core Team, (2017) R: A language and environment for statistical computing, R Foundation for Statistical Computing. ISBN 3-900051-07-0, Vienna, Austria.

33. Rane, J., Pannu, R.K., Sohu, V.S., Saini, R.S., Mishra, B., Shoran, J., Crossa, J., Vargas, M., Joshi, A.K. (2007) Performance of Yield and Stability of Advanced Wheat Genotypes under Heat Stress Environments of the Indo-Gangetic Plains. Crop Science 47, 1561-1573.
34. Shah, T., Singh, O.P., Mukherji, A. (2006) Some aspects of South Asia's groundwater irrigation economy: analyses from a survey in India, Pakistan, Nepal Terai and Bangladesh. Hydrogeology Journal 14, 286-309.
35. Sharma, K. (2006) The political economy of civil war in Nepal. World Development 37, 1237-1253.
36. Sharma, P., Guha-Khasnobis, B., Khanal, D.R., (2014) Nepal Human Development Report 2014 Beyond Geography Unlocking Human Potential, in: Government of Nepal National Planning Commission & United Nations Development Programme (Ed.). Government of Nepal, Kathmandu, Nepal, pp. 1-142.
37. Singh, S.S., Prasad, L.K., Upadhayay, A., (2002) Root behaviour, water saving and performance of wheat under zero tillage in heavy soils of South Bihar, India, in: Malik, R.K., Balyan, R.S., Yadav, A., Pahwa, S.K. (Eds.), Management and Zero Tillage in Rice–Wheat Cropping System. CCSHAU, Hisar, India.
38. Singh, V.K., Dwivedi, B.S., Shukla, A.K., Chauhan, Y.S., Yadav, R.L. (2005) Diversification of rice with pigeonpea in a rice–wheat cropping system on a Typic Ustochrept: effect on soil fertility, yield and nutrient use efficiency. Field Crops Research 92, 85-105.
39. van Ittersum, M.K., Cassman, K.G., Grassini, P., Wolf, J., Tittonell, P., Hochman, Z. (2013) Yield gap analysis with local to global relevance—A review. Field Crops Research 143, 4-17.
40. van Ittersum, M.K., R.Rabbinge (1997) Concepts in production ecology for analysis and quantification of agricultural input-output combinations. Field Crops Research 52, 197-208.
41. Venables, W.N., Ripley, R.D. (2002) Modern Applied Statistics with S, 4th ed. Springer, Berlin, Germany.
42. WFP, (2010) The Food Security Atlas of Nepal. World Food Program. Government of Nepal, World Food Program.
43. White, J.W., Hoogenboom, G., (2010) Crop Response to Climate: Ecophysiological Models, in: Lobell, D., Burke, M. (Eds.), Climate Change and Food Security: Adapating Agriculture to a Warmer World. Springer, New York, pp. 59-80.
44. Whitfield, S., J.Dougill, A., C.Dyer, J., K.Kalaba, F., Leventon, J., Stringer, L.C. (2015) Critical reflection on knowledge and narratives of conservation agriculture. Geoforum 60, 133-142.
45. WorldClim, (2017) Global Climate Data, in: Hijmans, R.J., Cameron, S., Parra, J., Jones, P., Jarvis, A., Richardson, K. (Eds.).

CHAPTER 3: INCREASING YIELD STABILITY AND INPUT EFFICIENCIES WITH COST-EFFECTIVE MECHANIZATION IN NEPAL

3.1 Introduction

Nepal has the lowest cereal yield per hectare among the south Asian countries that provide the region with its domestic source of grain. The cause of Nepal's low yields has been attributed to a stunting of agricultural intensification caused by short-sighted development policies and socioeconomic crises (Karan et al., 1994; Sharma, 2006). Limited adoption of agronomic practices by farmers that increase yield are on a collision course with a diminishing labor market that will further undermine domestic food security if not addressed (Joshi et al., 2012; Seddon et al., 2002). Long-term solutions to these problems will require policy changes at the national level by the Nepali government, while more immediate solutions can be found by targeting appropriate technologies at ineffective agricultural practices. Here we document the effects of low-cost, simple mechanization (in the form of a chest-mounted seed and fertilizer spreader) on yield, yield variability, efficiencies and others metrics compared to the traditional hand application of inputs.

Stagnation of agricultural intensification in Nepal has exposed farmers to risk by preventing them from adopting better agronomic practices like appropriate management of soil fertility. Fertilizer rates for nitrogen (N), phosphate (P), and potassium (K) on the Terai of Nepal –the most productive and developed agricultural region adjacent India– are 40%, 26%, and 70% less, respectively compared to farmers in neighboring Bihar, India (Park et al., 2018). When fertilizer is applied, 75-80% of it comes from gray market sources from India (Pandey, 2014). The effects of inadequate supplies of affordable fertilizer to crop productivity in Nepal are compounded by decreasing availability of agricultural labor (Maharjan et al., 2013).

In response to limited opportunities for economic advancement in farming, agricultural laborers and farmers in the 1990s began leaving the sector en masse in search of more lucrative work abroad (Central Bureau of Statistics, 2009; Seddon et al., 2002). This trend has only accelerated, with 10% of the Nepali population working overseas in the remittance economy by 2014 (Kaphle, 2014; NIDS, 2018). This departure of farm labor was found to dramatically reduce the productivity of Nepali agriculture on a farm by farm basis. For every laborer that left a household in which they were part of the labor pool, total crop productivity dropped 11% (Maharjan et al., 2013). As labor becomes scarcer in the Nepali agricultural economy, labor bottlenecks have emerged as an increasing problem. Labor bottlenecks occur when there are labor shortages, and are especially problematic during critical times of agricultural operations (Pingali, 2007). Bottlenecks often occur around seed bed preparation, sowing, top dressing and harvesting. Delays in these operations have significant consequences to the productivity of the wheat system in Nepal and South Asia. A common example of a labor bottleneck in Nepal is the late sowing of wheat. Delays in sowing can reduce yields by 0.7% for every day delayed past an optimum sowing window due to late season heat stress (Ortiz-Monasterio et al., 1994). Solutions to labor bottlenecks increasingly take the form of mechanization, or technology more broadly, in most global agricultural systems (Pingali, 2010).

Immediate solutions to the specific problems of labor and fertilizer scarcity can be undertaken using technology that increase efficiencies. A technological solution that focuses on improving efficiency of inputs and labor best reflects the reality that an increase of both inputs and labor in Nepal is unlikely to increase in the near future because of the long-term political and socioeconomic roots of these problems (Sharma, 2006). To have a realistic chance of adoption at scale, technological solutions must be low-cost, simple for easy maintenance, and capable of fitting within the status quo of agricultural practices of Nepal. These criteria are part of successful agricultural development projects in the past that adapted appropriate technologies to the constraints of the local agricultural systems (ATTRA, 2018). Past development projects in Nepal that leveraged advanced agricultural technologies have often failed in the long-term because the supporting manufacturing, machinery, and agribusiness sectors were unable to maintain complex equipment or processes after the initial support for the introduction of the technology was completed (Maharjan et al., 2013; Metz, 1995).

A source of inefficiency in Nepal ripe for improvement with an appropriate technological intervention is the traditional practice of applying farm inputs by hand. We believe this traditional practice is a principal source of within-field variability and, we hypothesize, a prime contributor to resource use inefficiencies and yield gaps. An intervention that increases the precision and speed of application of seed and fertilizer would improve both input and labor efficiencies. We therefore sought to test if a simple, chest-mounted spreader could improve the following aspects of the farming system in our study relative to traditional methods: 1) improve uniformity of wheat yield within fields, 2) improve fertilizer efficiency of nitrogen and phosphate with respect to yield and an independent measure of crop vigor, 3) increase seed efficiency to seedling establishment and yield, and 4) increase labor efficiency. We then assessed whether the net effect of mechanization provided meaningful improvements to a farmer’s return on investments.

3.2 Methods

3.2.1 Overview

To test whether simple mechanization could improve fertilizer and seed efficiency compared to traditional hand applied methods on the Terai of Nepal, we split a group of 60 farmer participants into two treatment groups within a Completely Randomized Design. Thirty farmers received an application of farm inputs using a chest-mounted spreader, while the other 30 applied these inputs by hand.

3.2.2 Study Location and Timing

The study area was located near the town of Siddharthanagar in the district of Rupandehi in the Terai region of Nepal (27.5126° N, 83.4816° E) where the dominant annual cropping pattern is a rice-wheat rotation (Mahajan and Gupta, 2009). Trials began in November of 2016 with sowing and concluded in April 2017 when harvested. The study area climate is sub-tropical, with a mean annual temperature between 20 and 25 °C and an average annual rainfall of approximately 1,400 to 2,000 mm (WFP, 2010) which mostly falls during monsoon. All fields in the study received at least one irrigation during the wheat growing season.

3.2.3 Technological Intervention and Traditional Practices

We selected a chest-mounted spreader as our intervention to apply the granular inputs of urea, diammonium phosphate, and seed to farmer's fields. The model chosen was a (Model 2750, Manufacturer-EarthWay) spreader, commonly used to fertilize lawns in America and Europe. An agitator feeds granular material from a top mounted nylon hopper to the distribution plate where it is spread in a fanning action of approximately 45° in front of the user's chest who controls rate of application through speed of cranking and a flow control mechanism. Inputs were applied by travelling along the perimeter of the field with the left side of the fan overlapping the right side of the previous pass (Wolf and Smith, 1979). The current price for a single unit sold in the United States at the time of publication was $35 USD. This simple device was compared to the traditional method of applying fertilizer and seed by hand. In the traditional method, fertilizer or seed is placed in a container, which is applied by hand as the laborer walks up and down a field applying the input as uniformly as possible. Under both mechanized and traditional treatments, the inputs were then incorporated by either a cultivator or rotovator.

3.2.4 Experimental Design and Input Rates

Sixty farmers were selected at random for inclusion in a Completely Randomized Design trial, with the two treatments applied to 30 farms each. A single researcher applied farm inputs with the spreader, while farmers applied inputs to their own fields. Within each farmer's field, four 1 m2 subsamples were randomly established to capture heterogeneity of response variables across the season. As these were on-farm trials, researchers only controlled different application techniques of seed and fertilizer. All farmers were provided 3.75 kg of diammonium phosphate, and 4 kg of urea after it was determined that many farmers in the trials would have no fertilizer to apply whatsoever because of inadequate access or funding, thereby making the experiment irrelevant. If farmers were able to afford fertilizer, they almost always added the amount we provided them to their own supply, thereby increasing their rates (information that we recorded). The rates of fertilizer in these trials for N and P are 21% higher than those in a recent production survey (Park et al., 2018), and reflect the combining of farmer fertilizer with that provided by researchers. Seed was provided by farmers and represented 12 unique varieties. Field sizes ranged between 0.014 ha to 0.11 ha, and averaged 0.04 ha.

3.2.5 Normalized Difference Vegetation Index, End of Season Yield Estimates, and Seedling Density

Normalized Difference Vegetation Index (NDVI) was recorded bi-weekly throughout the wheat season at all subsamples because of its strong relationship with both plant uptake of fertilizer (Teal et al., 2006) and end of season yield (Wiegand and Richardson, 1990). Time constraints at the time of harvest necessitated a four-step model approach to estimate yield at all subsamples in farmers' fields. First, we harvested a single random subsample from each of the 60 fields within the study for an estimation of real yield. The yield of this sample was corrected for moisture content using a wile 55 moisture meter. Second, we fit a quadratic model to the seasonal NDVI curves with random effects in the intercept and linear term for each farm, and a random effect in the intercept for each subsample. Third, we estimated the seasonal maximum NDVI using these fitted curves for each subsample because of its strong relationship to end of season yield (Labus et al., 2002). Fourth, simple linear models were fit between maximum NDVI values and the real yield values from the harvested subsample stratified by variety to allow for adequate replication. The resulting predictions of final yield were used as the response variable in this study. Seedling density was determined by visual counts within each of the subsamples. Variability of seedling density was determined by calculating the variance of all four subsamples within a given field.

3.2.6 Seasonally Integrated Normalized Difference Vegetation Index

We calculated the area under the curve of an NDVI time series throughout the season to estimate seasonally integrated NDVI per sub-sample (R Core Team, 2017). Seasonally integrated NDVI is measure of crop vigor that is a strong proxy between fertilizer uptake and end of season biomass production and yield (Labus et al., 2002; Teal et al., 2006). We used values of seasonally integrated NDVI as a reasonable intermediary between crop vigor related to fertilizer uptake, fertilizer rates and end of season yield to better understand the mechanisms by which a more precise application of inputs affected wheat productivity.

3.2.7 Farmer Partial-Profit

The costs of inputs within the study were \$0.18 kg-1 urea, \$0.32 kg-1 diammonium phosphate, and \$0.28 kg-1 seed. We assumed the values of seed to be that of the wholesale price of wheat grain at the end of the 2016-2017 wheat season. Our calculation of profit was determined by multiplying the yield per hectare of a farmer by the wholesale price of wheat grain minus inputs of N, P and seed. Our calculation of profit is therefore only a partial measure of profit, because we were unable to measure the costs of other inputs such as irrigation, machinery, diesel, etc.

3.2.8 Bardiya Time Trials

A separate Completely Randomized Design trial was established to determine whether there was an improvement in labor efficiency between mechanized versus hand distributed treatments in Bardiya district on the Terai of Nepal in November 2015. Forty farmers were split between the two treatments, with each receiving the equivalent rate of 120 kg ha-1 in seed to be applied to fields. Each treatment was timed from beginning to completion of application of seed.

3.2.9 Environmental Data

Soil and atmospheric data were collected in an effort to control for their potential influence on interpretation of any interaction effects from the treatments. Bi-weekly volumetric soil moisture to a 1-meter depth was recorded through the growing season across all 60 farms, allowing for an estimation of the total seasonal abstraction of water through the soil profile. To account for potential differences in the effect of water stress, the Crop Water Stress Index was estimated at each subsample as soon as the wheat canopy closed till the initiation of senescence (Donald J. Garrot et al., 1994). A simple linear model was fit per field using the average of the Crop Water Stress Index values across the four sub-samples as the response variable plotted through time. The slope of the Crop Water Stress Index through time for each field gave an indication of the influence that water stress may have had on final yield, with greater slopes indicating a larger water stress and vice versa. A single weather station was installed within 1 km of the field sites to measure rainfall and heat throughout the growing season.

3.2.10 Statistical Analysis

Linear mixed effects models were used to determine slope by interaction effects for the two treatments (Pinheiro et al., 2017). These models were used to test for treatment effects between N, P and yield and seasonally integrated NDVI, seed rate and yield and density, N, P, and seed rates to partial-profit. We used a single random effect for the intercept of sub-sample within farm. General linear models were used to find slope by interaction effects by treatment for seed rate on the variability of seedling germination, and input costs on profit (R Core Team, 2017). A simple linear model was fit between the variability of seasonally integrated NDVI and yield. Partial correlations were used to calculate the pairwise partial correlation between two variables while controlling for the third variable (Kim, 2015). Variances and averages were determined for each field using the four sub-samples therein for yield and seasonally integrated NDVI. The coefficient of variation was used to determine if there were significant differences between treatments among the variability of yield, seasonally integrated NDIV, seedling density, and partial-profit (Krishnamoorthy and Lee, 2014). Analysis of Variance was used to test whether the time of application between two treatments were significantly different from each other and differences between treatment groups in amount of inputs.

3.3 Results

3.3.1 Stand Uniformity and Yield Stability

We found that an increase in the variability of seasonally integrated NDVI of subsamples within farmers' fields was negatively associated with end of season yield (b_1= -10.8, $F_{1,58}$=7.7, $p<0.01$) (Figure 3.1a). If farmers were able to grow a spatially uniform crop that had the yield of their most productive sub-sample, farmers would have achieved yields of 3,116 kg ha^{-1}. Under the observed heterogeneous stand conditions found in the study, farmers on average yielded 2,212 kg ha^{-1}. This variability of wheat stands within farmer's fields caused an average loss of 29% of their potential yield.

The variability of seasonally integrated NDVI was greater when farmers applied inputs by hand when compared with simple mechanization (21 compared to 15), but was not significantly different (p=0.25) (Figure 3.1b). This difference between treatments was more pronounced when comparing end of season yield. Farmers that used simple mechanization had a smaller, more "stable" distribution of yield ($p<0.05$). Farms where simple mechanization was used had an inter-quartile range for yield 511 compared to 1,293 kg ha^{-1} under hand distributed inputs (Figure 3.1c).

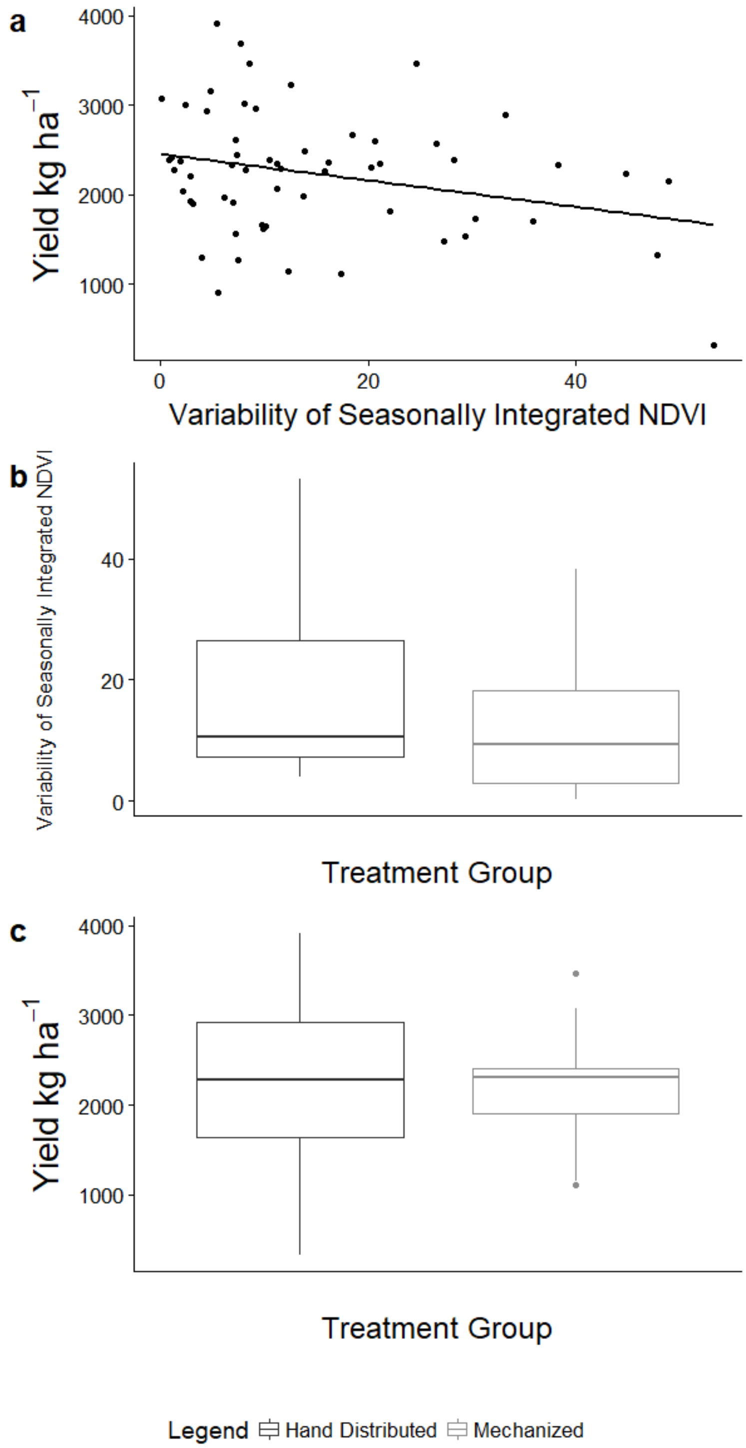

Figure 3.1. a) An increase in variability of seasonally integrated NDVI within a farmer's field is associated with a decrease in yield, b) The variability of seasonally integrated NDVI was smaller when simple mechanization was used compared to hand distributed fertilizer, c) Farms where simple mechanization was used were found to have more stable yields than those who applied inputs by hand.

3.3.2 Yield Response to Nitrogen and Phosphate Rates

We found a significant main effect of treatment on the efficiency of N and P fertilizers and end of season yield ($p<0.01$ & $p<0.01$, respectively). When simple mechanization was used, farmers were able to achieve a significant, positive relationship between their N (b_1= 7.3, $p<0.01$) and P (b_1=16.7, $p<0.01$) fertilizer rates and yield (Figure 3.2a & 3.2b). In the farmer practice of hand distributed fertilizer application, yield did not respond to increasing N and P rates (b_1=-1.6, p=0.21 & b_1=-12.6, $p<0.05$, respectively), indicating an inherent inefficiency. Similar relationships between treatment fertilizer efficiency were also observed on seasonally integrated NDVI. There was a strong slope interaction effect between treatments with simple mechanization providing a significant, positive relationship to both N (b_1= 0.05, $p<0.05$) and P (b_1= 0.18, $p<0.01$) rates. This relationship was non-significant under hand distributed fertilizer treatment.

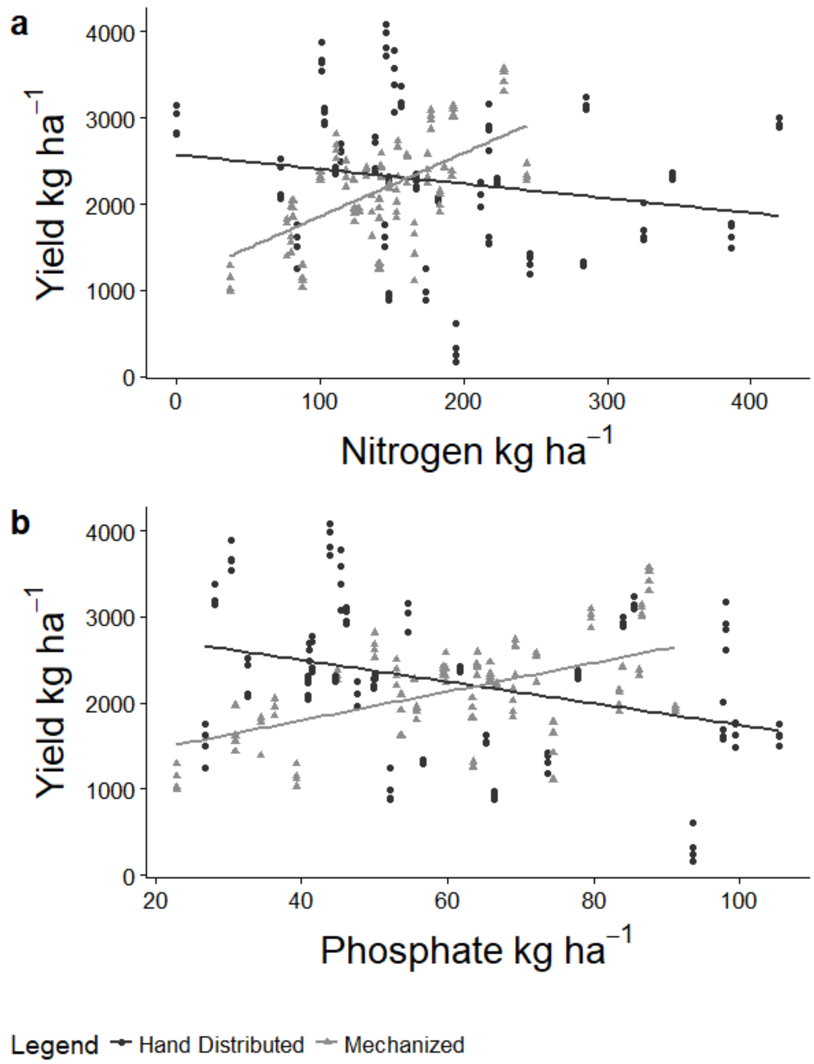

Figure 3.2. Yield response to fertilizer under two different treatments. a) yield response to N under different treatments indicated that farmers that used simple mechanization had a positive, significant efficiency as opposed to hand distributed fertilizers, b) yield response to P was similar to the response to N in efficiency between the two treatments. Sub-sample estimates of yield per field show variability per field under different treatments.

3.3.3 Seedling Density and Yield Response to Seed Rates

A significant main effect indicated there was a difference in the response of seedling density establishment to seed rates under different treatments ($p<0.01$). Seedling density increased with an increase in seed rate when simple mechanization was used ($b_1= 0.74$, $p<0.01$), while the opposite was true under hand distributed ($b_1= -0.31$, $p<0.05$). Additionally, a main effect was observed between treatments for the relationship between yield and seed rate ($p=0.05$). Under simple mechanization, yield was found to increase as seed rates increased ($b_1= 4.4$, $p=0.06$). As we observed in the relationship between N and P rates and yield under hand distributed inputs, there was a non-significant relationship or negative between seed rates and seedling density establishment and yield ($b_1= -0.31$, $p<0.05$ & $b_1= -1.9$, $p=0.21$, respectively). The variability of seedling germination was found to be different between treatments when controlling for seed rate ($p<0.05$). The response of the variability of seedling germination changed with differing seed rates between the two treatments. At the first quartile and median seed rates, farmers had smaller variability of seedling germination under simple mechanization compared to hand distributed (Figure 3.3). At higher seeding rates (third quartile), hand distributed seed had less variability in seedling emergence.

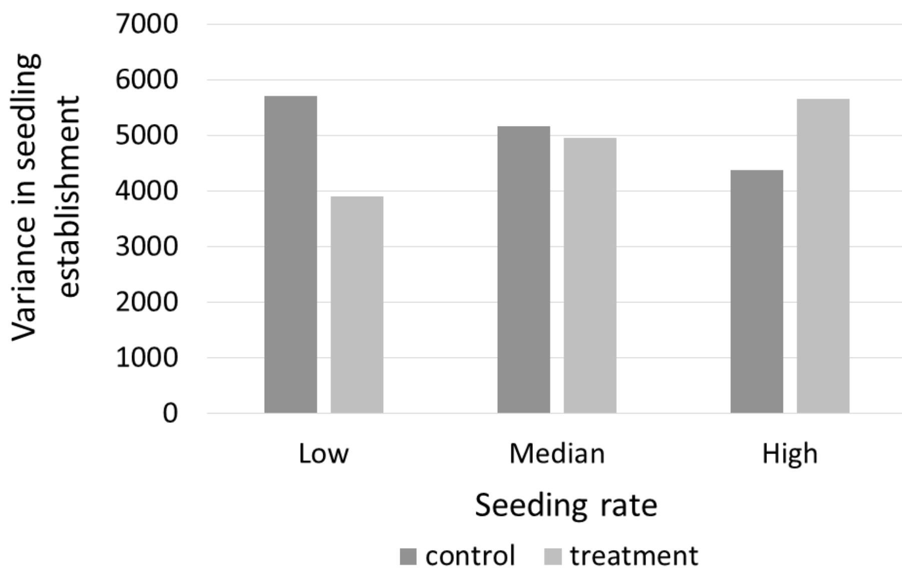

Figure 3.3. Variation in seedling germination in farmer's fields at different seeding rates between the two treatments.

3.3.4 Mechanistic Responses to a More Precise Input Application

To better understand why input efficiencies were improved under simple mechanization, we quantified how multiple relationships between agronomic factors changed between treatments. We examined partial correlations of two variables while controlling for a third to better understand the relationships between factors to see if measureable change in their effect on each other was different between treatments. While controlling for the third variable, we determined the correlation coefficient between the controlled variable and the independent variable predicting on the dependent variable. We used yield and seasonally integrated NDVI as our dependent variables. For example, Model 1 in Table 2.1 describes the relationship of yield (dependent variable) to N rate and seasonally integrated NDVI (independent variables), with estimates shown indicating each independent variable controlling for each other. The covariation between the two independent variables is also provided. A visual representation of these models are shown in Figure 3.4. Models 1 through 5 were ordered logically because each subsequent model, i.e. model 2 following model 1 retains at least one independent or covarying factor from the previous model to better explain its results.

Model 1 establishes the large influence that seasonally integrated NDVI has on yield based on the positive, significant estimates within both treatments. The difference between treatments occurs when we look at the covariance between N rate and seasonally integrated NDVI, whereby they strongly covaried with each other under simple mechanization and do not under hand distributed.

Treatment	Model #	Variable 1	Variable 2	Variable 3	$r_{12,3}$	$r_{13,2}$	$r_{2,3}$ (covariance)
Hand distributed	1	Yield	N rate	SINDVI	-0.36†	**0.66***	0.08
	2	Yield	Density	SINDVI	0.39†	**0.41***	**0.6*****
	3	SINDVI	N rate	Density	0.18	**0.61*****	-0.09
	4	SINDVI	Density	Seed rate	**0.62*****	0.22	-0.31†
Mechanization	1	Yield	N rate	SINDVI	0.33†	**0.76*****	**0.54*****
	2	Yield	Density	SINDVI	-0.01	**0.74*****	-0.03
	3	SINDVI	N rate	Density	**0.48****	0.19	0.35†
	4	SINDVI	Density	Seed rate	0.03	**0.42***	**0.61*****

Table 3.1. The partial correlations between Variable 1 and Variable 2 controlling for Variable 3 are provided in column $r_{1,2\sim3}$. The partial correlations between Variable 1 and Variable 3 controlling for Variable 2 are shown in column $r_{1,2\sim3}$. Column $r_{2,3\ (covariance)}$ is the correlation coefficient between variables 2 and 3. Explanation of acronyms: Seasonally Integrated Normalized Difference Vegetation Index, SINDVI. †<0.1, *p < 0.05, **p < 0.01, and ***p < 0.001.

Model 1 indicated that seasonally integrated NDVI strongly predicts end of season yield shown by positive, significant estimates for both mechanized and hand distributed treatments (b1=0.76, p<0.001 & b1=0.066, p<0.001, respectively). However, under mechanization N rate and seasonally integrated NDVI also covaried (b1=0.54, p<0.001) whereas this was not the case when hand distribution was used (b1=0.08, $p>0.1$). Model 2 provided evidence that plant density effectively traded roles with N rate from model 1 between treatments, and that plant density strongly covaried with seasonally integrated NDVI under hand distributed rather than the mechanized treatment (b1=0. 6, $p<0.001$ & b1=0.-03, $p>0.001$, respectively). Model 3 provided validation of the results from models 1 and 2, indicating that N rate was a strong predictor of seasonally integrated NDVI under simple mechanization (b1=0.61, $p<0.001$), and conversely that plant density fulfilled this role under hand distributed (b1=0.48, $p<0.05$). Model 4 indicated that when hand distributed, seed rate became disconnected from seedling density by the lack of a significant covariance (-0.31, $p>0.10$). Seedling density and seed rate covaried when simple mechanization is used (0.61, $p<0.001$).

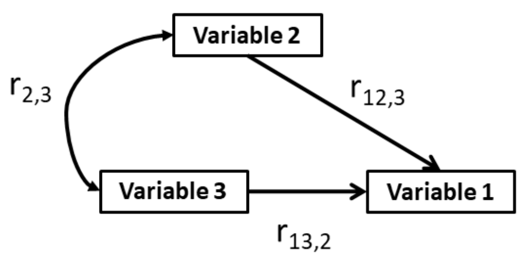

Figure 3.4. A conceptual framework for models displayed in Table 1.

3.3.5 Labor Efficiency

Simple mechanization was 52% faster at applying the same rate of seed compared to applying it by hand ($F_{1,38}=76.8$, $p<0.01$). Farmers that distributed fertilizer by hand took an average of 2.1 hours to complete sowing a hectare, while this value was 1 hour using simple mechanization.

3.3.6 Profit Stability and Return on Investments

Farmers that used simple mechanization had more predictable profits than those applying inputs by hand as indicated by a smaller inter-quartile range of \$140 USD compared to \$318 ($p<0.05$) (Figure 3.5a). Even though farmers that applied inputs by hand used more fertilizer compared to simple mechanization, profits were equivalent between the treatments (\$530 compared to \$509) ($F_{1,56}=0.17$, $p=0.68$). Similar to the relationship between N, P and yield, we found that there was a significant interaction effect among treatments between fertilizer rates and farmer profits ($F_{1,56}=8.2$, $p<0.01$ & $F_{1,56}=13.1$, $p<0.01$, respectively). We found that when simple mechanization was used, profits increased with rate increases of N ($b_1= 2.8$, $F_{1,28}=9.1$, $p<0.01$) and P ($b_1= 3.7$, $F_{1,28}=8.3$, $p<0.01$). When fertilizer was applied by hand, increasing N rates ($b_1= -1.7$, $F_{1,28}=3.9$, $p=0.05$) or P ($b_1= -0.9$, $F_{1,28}=3.5$, $p=0.06$) did not increase partial-profit. There was no significant interaction effect among seed rates and profits between the treatments ($F_{1,56}=3.5$, $p=0.07$).

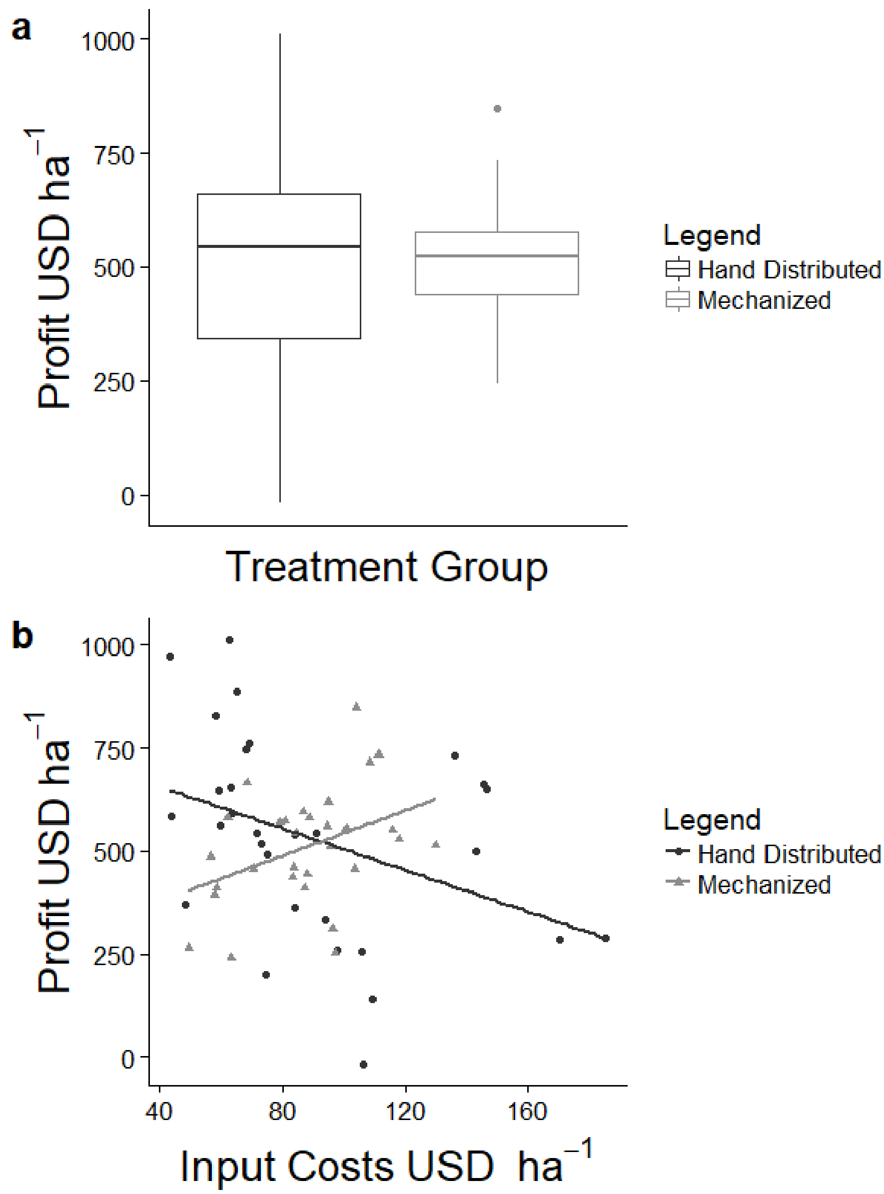

Figure 3.5. a) distribution of profits between two the two treatments indicate that simple mechanization provided more predictable profits, b) response of profit to increasing input costs was positive with simple mechanization, but negative when inputs were distributed by hand.

With more predictable profits, and a greater return on investment from fertilizer with simple mechanization, we found that there was a significant difference among treatment groups between cost of inputs (N, P, and seed) and profits ($F_{1,56}=7.2$, $p<0.01$). Farmers in the simple mechanization treatment group had a positive relationship between the costs associated with inputs and profit (b_1= 2.8, $F_{1,28}$=5.2, $p<0.05$), while the opposite was true for the treatment group using hand distributed inputs (b_1= -2.5, $F_{1,28}$=4.9, $p<0.05$) (Figure 3.5b).

3.3.7 Growing Conditions Section

Yield was affected by different environmental conditions found across the 60 farms in the study, but the influence of these factors on yield were not found to have significant interaction effects between treatment groups. Soil texture classifications ranged between clayey to silty loam soils, with both the percentages of clay and silt found to affect yield ($F_{1,56}$=5, $p>0.05$ & $F_{1,56}$=3.8, p=0.055, respectively) while indicating no interaction between the mechanization and hand distributed treatments ($F_{1,56}$=0.2, p=0.65 & $F_{1,56}$=0.35, p=0.57, respectively). The effect of seasonal abstraction of water through the soil profile did not have an effect on yield, nor was there an interaction effect among treatments ($F_{1,56}$=0.165, p=0.67 & $F_{1,56}$=0.46, p=0.5, respectively). The slope of the Crop Water Stress Index was found to not impact end of season yield, nor was there a treatment interaction effect ($F_{1,56}$=3.5, p=0.07 & $F_{1,56}$=0.72, p=4, respectively). Atmospheric temperatures above 31°C constituting terminal heat stress (Al-Khatib and Paulsen, 1984) did not occur around the time of anthesis within our study.

3.4 Discussion

3.4.1 The Benefits of Precision, Cost of Imprecision

The use of simple mechanization provided farmers with multiple advantages over the traditional practice of applying inputs by hand. Foremost of these benefits was the reduction of variability of yield, offering farmers more predictable, stable yields. Although the difference between treatments with respect to the variability of seasonally integrated NDVI was not statistically significant, the significant improvement in yield stability and improved relationships within covariance model 1 demonstrated that the difference between treatments was biologically significant. As we saw in the response of yield to N and P rates under the two treatments, using simple mechanization led to a more homogenous spatial distribution of inputs across the field and therefore increased the likelihood that each wheat plant had access to these fertilizers during the growing season. Conversely, our data suggests that applying fertilizer by hand introduced a measure of spatial unpredictability and local aggregation in fertilizer distribution throughout farmer fields. Uneven distribution of fertilizer across the field led to unequal nutrient availability to individual plants, thereby limiting healthy growth, and ultimately yield.

Our results indicated that the higher yield stability found under simple mechanization was a response to increasing the strength of the relationship between fertilizer and yield. Figure 3.2a & 2b show the positive, predictable yield response for fertilizer rates when they applied with added precision. This was also observed in model 1 where there was a strong relationship between seasonally integrated NDVI and yield that was mediated by N rate when simple mechanization was used. This observed relationship between yield and seasonally integrated NDVI mediated by N rate is what would be expected in a farming system with uniform plant access to fertilizer (Labus et al., 2002; Teal et al., 2006). The relationship between fertilizer, yield and seasonally integrated NDVI was weakened when inputs were applied by hand, with model 2 indicating that seedling density became the main predictor of seasonally integrated NDVI rather than N rate when inputs were hand distributed.

The disassociation of yield to increasing rates of N in the hand distributed treatment was particularly surprising because this group of farmers applied 18% more N ($F_{1,56}$=3.6, p=0.06) than farmers using simple mechanization. This challenged our expectation that the impacts to yield from a non-uniform application of fertilizer could be overcome by increasing fertilizer rates, and points to the decrease in efficiency that occurs when inputs are traditionally applied. Additionally, lower intercepts for both N and P on farms using simple mechanization (Figure 3.2a & 2b) provided evidence that this treatment group may have been on poorer quality land, and that simple mechanization may have helped overcome even this limiting factor of the production system.

A more consistent response to fertilizer was achieved using simple mechanization even though farmers that distributed inputs by hand used greater rates for two of the three macronutrients. This includes not only more N, but 11 of the 30 farmers in the group applied an average of 24 kg ha^{-1} of K while farmers in simple mechanization treatment applied none. Potassium has been found in multiple studies to be an underused, but critical farm input towards improved wheat productivity in South Asia (Ladha et al., 2003; Park et al., 2018). Even with more inputs used in the hand distributed treatment, there was no statistical difference in the magnitude of yield between simple mechanization and hand distributed treatments (2,168 compared to 2,255 kg ha^{-1}) ($F_{1,56}$=0.22, p=0.64).

The covariance models provide added context for efficiency gains we saw in Figure 3.2a (these relationships held with P rates as well). Because NDVI is strongly associated with fertilizer uptake and crop vigor (Hansen and Schjoerring, 2003), the absence of a significant influence of N rate on seasonally integrated NDVI under hand distributed treatment was troubling. This suggested that when fertilizer is applied by hand, the relationship between N rate and seasonally integrated NDVI became weak enough that stand density became the de facto agronomic factor which best predicted seasonally integrated NDVI. These results underscored the reality that farmers using traditional hand distributed methods were forfeiting yield to inefficiency caused by non-uniform application of fertilizers. In covariance models 1 and 3, simple mechanization showed evidence of improving the relationship of fertilizer to yield and seasonally integrated NDVI.

The benefits observed from using simple mechanization with respect to seedling density establishment, reduction of seedling density variability under low and median seed rates, and improving the relationship between seed rate and yield paralleled those found with fertilizer efficiencies. Similar benefits of precision agriculture have been observed in the rice-wheat cropping systems of the Indian states of Uttar Pradesh and Bihar adjacent to the study site, where zero-till has increasingly replaced hand distributed practice (Erenstein and Laxmi, 2008; Keil et al., 2015). Seed rates in our study were high relative to averages in Bihar, India which shared similar environments and cropping system (Pathak et al., 2003), with farmers across both treatments in our study applying 37% more seed per hectare compared to farmers in in Bihar (184 compared to 116 kg ha^{-1}) (Park et al., 2018). The higher rates of seed used in Nepal may reflect a risk reduction strategy by farmers to try and overcome the poor relationship we observed between seed rates, seedling establishment, and yield when applied by hand.

Unfortunately, the apparent assumption made by farmers that adding more seed leads to greater seedling establishment and yield does not appear to be a good risk management strategy when not paired with precise sowing. This is because, as we observed in covariance model 4, seedling density and seed rate covaried when simple mechanization was used, which was not the case when seed was hand distributed. Higher adoption of zero-tillage in Bihar may be a partially responsible for lower seed rates, in part because direct seeding adds a measure of precision to sowing thereby reducing the need for more seed, but rather relying on mechanization to improve the efficacy of a lesser rate (Erenstein and Laxmi, 2008; Keil et al., 2015).

We believe the simple mechanization we implemented in our study could provide a pragmatic, lower-cost intermediate practice between the low precision conventional practice of hand distributed seed and fertilizer paired with incorporation by cultivation and/or rotovation, and the higher precision direct seeding and fertilizing of zero tillage. This widespread use of zero tillage in Bihar, and across other Indian states was a decades long product of both an active government and non-governmental organizations presence in the agricultural sector, and also the development a strong private network of service providers that offer zero tillage service (Keil et al., 2015, 2016). As with fertilizer and labor availability, it is therefore unlikely a change from rotovation and cultivation to zero tillage, and the precision it brings to the farmer's production system, will occur in the near future in Nepal. Simple mechanization offered multiple production advantages over traditional practices through improved input efficiencies, all the while fitting within the traditional semi-mechanized system necessary towards scaling up potential adoption (George, 2014).

3.4.2 Assessing Unexplained Variation in Study

Within hand distributed treatment the negative response of density to seed rate, and a changing response in the changing variability of seedling germination under different seed rates, and the negative or non-significant responses of N and P to yield was puzzling. Some farmers applying inputs by hand had excellent yields, while others had poor yields. While our hypothesis was that a more uniform application of inputs would reduce intra-field variability, we suspected that the poor efficiencies we observed under hand distributed inputs were interacting with unknown sources of variability associated with environmental heterogeneity within a farmer's field. The clearest evidence of this sources of stress are the varying levels of germination variability with different seed rates (Figure 3.3), and covariance model 4. We suspect that farmers applying seed by hand at the third quartile seed rate achieved a lower variability of seedling germination in part because they were applying variable seed rates to areas prone to higher seedling stress, thereby helping to offset expected seedling die off with higher seed rates. The absence of covariation between seed rate and seedling density in covariance model 4 within the hand distributed treatment is perhaps indicative of this environmental variability as well. This source of variation when combined with the lack of uniformity of seed application may have led to higher die off of seedlings because of the higher risk of aggregation into parts of field with higher risk of stress during germination. Conversely, it appeared that precision application of inputs minimized the influence of this unexplained variability to the point at which positive efficiencies could be achieved. This can be observed in the positive relationship between seedling establishment and seed rate when simple mechanization was used under similar growing conditions as the hand distributed treatment.

The source or sources of variation that mitigated the relationships between yield, seasonally integrated NDVI, and N and the other relationships in Table 1 were most likely associated with soil-water-plant interactions. Differences in fertilizer availability to plants has been attributed to the pH of the soil (Sanyal and Datta, 1991) and variable fertilizer sorption rates due to differences in the drying of soil profiles (Sah and Mikkelsen, 1986). Waterlogging stress is associated with poorly drained soils can also prevent uptake nutrients and water in wheat (Luxmoore and Stolzy, 1969) which can reduce end of season yield (Trought and Drew, 1980). Landscape position can influence these relationships as well (McDonald et al., 2006). Stresses within soil-water-plant interactions may also help explain the disassociation between seed rate and seedling density (Grable, 1966). Further investigation into this source of variability would provide better context as to why precision agriculture appears to alleviate it, as well as identify practices to solve it directly.

3.4.3 Addressing a Declining Labor Pool with Higher Labor Efficiency

Our results demonstrated that simple mechanization was a labor saving technology that doubled the labor efficiency of the input of application process when compared to traditional hand distributed practices. An improvement in labor efficiency could help alleviate bottleneck and labor problems of a shrinking agricultural workforce and associated knowledge base that is not being replaced with supplemental labor or mechanization in an environment that penalizes yield if key farming operations are delayed. This can also facilitate more timely farm operations during labor bottlenecks such as early sowing and top dressing of N.

The mechanized treatment also demonstrated that the agricultural knowledge and skillsets of laborers can also be effectively mechanized. Farmers that distributed inputs by hand had on average 22 years of experience honing this skill. Prior to implementation of this study, our researchers had no previous experience using the simple mechanization tool in order to best simulate a new user. The gains in seed, fertilizer and labor efficiency we observed under the simple mechanization treatment with no previous experience demonstrates that precision agriculture via mechanization effectively replaced skilled agricultural labor during the input application stage of farming operations.

3.4.4 Increasing the Predictability of Profit for Smallholders

Introducing simple mechanization provided farmers not only with more predictable profit, but also greater stability of return on investment of their inputs. We believe that from a farmer's perspective, these results can be interpreted to represent less risk to their bottom line when considering the scarcity of access to inputs (Gollin, 2006). Farmers that hand applied their inputs faced higher risk in their wheat production, as we saw no evidence that adding more inputs benefited their end of season yield and profit. Our results highlight that low fertilizer application rates in Nepal may not only be a byproduct of poor government policy and limited private sector development, but likely hesitation on farmer's part because they historically have seen little profit response to higher rates of inputs under the widely adopted hand distributed technique. This could also help explain why farmers do not reinvest remittance dollars into more farming inputs (Maharjan et al., 2013). Introducing technologies like the spreader evaluated in this study that improves the relationship between inputs and profit can increase farmer confidence in investing in their farms, which in the long-term could help improve productivity and profitability of Nepali agriculture.

3.5 Conclusion

Adding precision to fertility and seed placement by simple mechanization was an improvement over traditional practices in four distinct ways: 1) increased input efficiency with respect to yield and seedling density, 2) doubled labor efficiency during the input application process, 3) reduced variability of yield within and between fields, and 4) assured farmers returns on investment from their inputs. Our analysis indicated that many of the variability and human error problems associated with traditional hand distributed practices can be overcome with the addition of relatively simple mechanization, while still fitting within semi-mechanized tillage system. Solutions like the chest-mounted spreader can offer a low-cost precision agriculture stopgap between traditional practices and larger mechanization like zero tillage while still offering more timely farming operations and better labor and input efficiencies. Increasing the return of investment to farmers may help reverse the chronic underinvestment in farm operations observed in Nepal. Countries like Bangladesh, Sri Lanka, Thailand, Vietnam, and Uganda still use hand distribution of farm inputs small grains cropping systems and likely suffer inefficiencies as a result. Simple mechanical solutions like our intervention may provide similar benefits in these countries, and we recommend that they be tested in production environments with similar labor and efficiency problems.

3.6 Funding

This work was supported by the Bill & Melinda Gates Foundation, Seattle, WA [grant number OPP1052535]; the United States Agency for International Development, Washington D.C. [grant number BFS-G-11-00002]; and the United States Borlaug Fellows in Global Food Security Awarded to Purdue University, Washington D.C. [grant number A11023.2].

3.7 Acknowledgements

We acknowledge the Bill and Melinda Gates Foundation, the United States Agency for International Development, and the United States Agency for International Development's Borlaug Fellowship program administered through Purdue University for funding this study. We thank Shalin Acharaya, Sailesh Sigdel, and Anurag Pandey for their help in collecting data and managing a challenging field campaign. Mention of trade names or commercial products in this publication is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.

3.8 Literature Cited

1. ATTRA, (2018) Sustainable Agriculture, in: National Center for Appropriate Technology (Ed.), Master Publication List.
2. Central Bureau of Statistics, (2009) Nepal Labour Force Survey, in: Secretariat, N.P.C. (Ed.), Kathmandu, Nepal.
3. Donald J. Garrot, J., Ottman, M.J., Fangmeier, D.D., Husman, S.H. (1994) Quantifying Wheat Water Stress with the Crop Water Stress Index to Schedule Irrigations. Agronomy Journal 86.
4. Erenstein, O., Laxmi, V. (2008) Zero tillage impacts in India's rice–wheat systems: A review. Soil & Tillage Research 100, 1-14.
5. George, T. (2014) Why crop yields in developing countries have not kept pace with advances in agronomy. Global Food Security 3, 49-58.
6. Gollin, D., (2006) Impacts of International Research on Intertemporal Yield Stability in Wheat and Maize: An Economic Assessment, in: CIMMYT (Ed.), Mexico, D.F.
7. Grable, A.R. (1966) Soil Aeration and Plant Growth. Advances in Agronomy 18, 57-106.
8. Hansen, P.M., Schjoerring, J.K. (2003) Reflectance measurement of canopy biomass and nitrogen status in wheat crops using normalized difference vegetation indices and partial least squares regression. Remote Sensing of the Environment 86, 542-553.
9. Joshi, K.D., Conroy, C., Witcombe, J.R., (2012) Agriculture, seed, and innovation in Nepal: Industry and policy issues for the future. International Food Policy Research Institute, Washington, D.C., pp. 1-60.
10. Kaphle, A., (2014) Nepal, once known for farming, now exports people; migrants earn big but face risks, The Washington Post, Washington, D.C.
11. Karan, P.P., Ishii, H., Kobayashi, M., Chrestha, M., Vajracharya, C., Zurick, D., Paure, G. (1994) Nepal: Development and Change in a Landlocked Himalayan Kingdom. Tokyo: Institute for the Study of Language and Cultures of Asia and Africa.
12. Keil, A., D'souza, A., McDonald, A. (2015) Zero-tillage as a pathway for sustainable wheat intensification in the Eastern Indo-Gangetic Plains: does it work in farmers' fields? Food Security 7, 983-1001.
13. Keil, A., D'Souza, A., McDonald, A. (2016) Growing the service economy for sustainable wheat intensification in the Eastern Indo-Gangetic Plains: lessons from custom hiring services for zero-tillage. Food Security 8, 1011-1028.
14. Kim, S. (2015) ppcor: An R Package for a Fast Calculation to Semi-partial Correlation Coefficients. Communications for Statistical Applications and Methods 22, 665-674.
15. Krishnamoorthy, K., Lee, M. (2014) Improved tests for the equality of normal coefficients of variation. Computer Statistics 29, 215-232.
16. Labus, M.P., Nielsen, G.A., Lawrence, R.L. (2002) Wheat yield estimates using multi-temporal NDVI satellite imagery. International Journal of Remote Sensing 23, 4169-4180.
17. Ladha, J.K., Dawe, D., Pathak, H., Padre, A.T., Yadav, R.L., Singh, B., Singh, Y., Singh, Y., Singh, P., Kundu, A.L., Sakal, R., Ram, N., Regmi, A.P., Gami, S.K., Bhandari, A.L., Amin, R., Yadav, C.R., Bhattarai, E.M., Das, S., Aggarwal, H.P., Gupta, R.K., Hobbs, P.R. (2003) How extensive are yield declines in long-term rice-wheat experiments in Asia? Field Crops Research 2003, 159-180.

18. Luxmoore, R.J., Stolzy, L.H. (1969) Root Porosity and Growth Responses of Rice and Maize to Oxygen Supply. Agronomy Journal 61, 202-204.
19. Mahajan, A., Gupta, R.D., (2009) The Rice–Wheat Cropping System, in: A., M., R.D., G. (Eds.), Integrated Nutrient Management (INM) in a Sustainable Rice—Wheat Cropping System, Springer, Dordrecht.
20. Maharjan, A., Bauer, S., Knerr, B. (2013) International Migration, Remittances and Subsistence Farming: Evidence from Nepal. International Migration 51.
21. McDonald, A.J., Riha, S.J., Duxbury, J.M., Steenhuis, T.S., Lauren, J.G. (2006) Water balance and rice growth responses to direct seeding, deep tillage, and landscape placement: Findings from a valley terrace in Nepal. Field Crops Research 95, 367-382.
22. Metz, J. (1995) Development in Nepal: Investment in the Status Quo. GeoJournal 35, 175-184.
23. NIDS, (2018) Migration Data, in: Studies, N.I.o.D. (Ed.), Katmandu, Nepal.
24. Ortiz-Monasterio, J.I., Dhillon, S.S., Fischer, R.A. (1994) Date of sowing effects on grain yield and yield components of irrigated spring wheat cultivars and relationships with radiation and temperature in Ludhiana, India. Field Crops Research 37, 169-184.
25. Pandey, S.P. (2014) The role of fertilizer in transforming the agricultural economy of Nepal. ReSAKSS Asia 9.
26. Park, A.G., Davis, A.S., McDonald, A.J. (2018) Priorities for Wheat Intensification in the Eastern Indo-Gangetic Plains. Global Food Security 17, 1-8.
27. Pathak, H., Ladha, J.K., Aggarwal, P.K., Peng, S., Das, S., Singh, Y., Singh, B., Kamra, S.K., Mishra, B., Sastri, A.S.R.A.S., Aggarwal, H.P., Das, D.K., Guptaj, R.K. (2003) Trends of climatic potential and on-farm yields of rice and wheat in the Indo-Gangetic Plains. Field Crops Research 80, 223-234.
28. Pingali, P., (2007) Agricultural Mechanization: Adoption Patterns and Economic Impact, in: Evenson, R., Pingali, P. (Eds.), Handbook of Agricultural Economics, Oxford, pp. 2779-2805.
29. Pingali, P., (2010) Agriculture Renaissance: Making "Agriculture for Development" Work in the 21st Century, in: Pingali, P., Evenson, R. (Eds.), Handbook of Agricultural Economics. Elsevier, Oxford, pp. 3867-3894.
30. Pinheiro, J., Bates, D., DebRoy, S., Sarkar, D., Team, R.C., (2017) {nlme}: Linear and Nonlinear Mixed Effects Models.
31. R Core Team, (2017) R: A language and environment for statistical computing, R Foundation for Statistical Computing. ISBN 3-900051-07-0, Vienna, Austria.
32. Sah, R.N., Mikkelsen, D.S. (1986) Transformations of Inorganic Phosphorus During the Flooding and Draining Cycles of Soil. Soil Sci. Soc. Am. J 50, 62-67.
33. Sanyal, S.K., Datta, S.K.D. (1991) Chemistry of Phosphorus Transformations in Soil.
34. Seddon, D., Adhikari, J., Gurung, G. (2002) Foreign Labor Migration and the Remittance Economy of Nepal. Critical Asian Studies 34, 19-40.
35. Sharma, K. (2006) Development Policy, Inequity and Civil War in Nepal. Journal of International Development 18, 553-569.
36. Teal, R.K., Tubana, B., Girma, K., Freeman, K.W., Arnall, D.B., Walsh, O., Raun, W.R. (2006) In-Season Prediction of Corn Grain Yield Potential Using Normalized Difference Vegetation Index. Agronomy Journal 98, 1488-1494.
37. Trought, M.C.T., Drew, M.C. (1980) The Development of Waterlogging Damage in Wheat Seedlings (Triticum Aestivum L.) I. Shoot and Root Growth in Relation to

Changes in the Concentration of Dissolved Gases and Solutes in the Soil Solution. Plant and Soil 54, 77-94.
38. WFP, (2010) The Food Security Atlas of Nepal. World Food Program. Government of Nepal, World Food Program.
39. Wiegand, C.L., Richardson, A.J. (1990) Use of Spectral Vegetation Indices to Infer Leaf Area, Evapotranspiration and Yield: I. Rationale. Agronomy Journal 82, 623-629.
40. Wolf, D.D., Smith, E.S. (1979) Uniformity of Seed and Fertilizer Distribution with A Hand-Operated Spinning Spreader. Transactions of the ASAE 22, 0761-0762.

CHAPTER 4: MITIGATING WATERLOGGING STRESS IN NEPALI WHEAT PRODUCTION THROUGH PRECISION AGRICULTURE AND IRRIGATION SCHEDULING INVERVENTIONS

4.1 Introduction

Yields of cereal grains in Nepal are the lowest among neighboring countries in south Asia. At a more local scale, wheat yields in the flat, arable Terai of Nepal were 47% lower than those of the adjacent Indian state of Bihar even though they share the same yield potential, indicating a large opportunity to increase yields through better management (Aggarwal et al., 2000; Park et al., 2018). Increasing the productivity of agriculture is a practical strategy towards improving per capita income at the household level because 33% of Nepal's population relies on farming for their livelihood (World Bank, 2018). While long-term solutions must address the socioeconomic and political roots of crop productivity and investment in agriculture, short-term solutions using simple technologies or changes to existing agronomic practices which improve yield outcomes can offer immediate progress towards improving farmer livelihoods. In this research, we demonstrate that yield reductions from water-related stresses associated with flood irrigation can be mitigated by more appropriate irrigation timing and introduction of precision agriculture.

Low investment in agricultural infrastructure has made environmental stresses more difficult to manage in Nepa; because farmers have less access to the tools necessary to address them. Limited access to capital (Sharma, 2006), fertilizer and seed (Bista et al., 2013), and labor (Maharjan et al., 2013) have weakened the capacity of farmers to use adaptive management in the face of different environmental stresses (Gulati et al., 2010; Sharma, 2006). The effect of this low investment in agricultural infrastructure can be observed in irrigation management when comparing Nepal to the bordering Indian state of Bihar, which shares a similar agroecology and climate, but different policy and socioeconomic conditions (Aggarwal et al., 2000; Pathak et al., 2003). Farmers in Bihar on average use two irrigations throughout a growing season compared to the single irrigation event observed in Nepal (Park et al., 2018). Lower flexibility in irrigation management in Nepal may be symptom of socioeconomic conditions, but has important ramifications for crop productivity.

Irrigation decisions in Nepal, particularly for farmers that use a single irrigation, must balance the risk between two different types of stresses: drought and waterlogging stress. Deciding when to apply irrigation can either minimize or exacerbate the influence of either stress (Chakwizira et al., 2014; Watson et al., 1976). Irrigating wheat at least once is considered a critical agronomic practice in the Eastern Indo Gangetic Plains - where the Terai of Nepal is located – because rainfall is an unreliable source of water during the wheat season (Chatrath et al., 2007). Drought stress has been shown to have increasingly detrimental effects to yield when it occurs in the mid to late-season wheat season (Chakwizira et al., 2014). Farmers increase the risk of drought stress if they irrigate too early in the crop’s development. However, waterlogging stress is more harmful to yield when it occurs earlier in crop development. It is a substantial stress to seedlings because it depletes the dissolved oxygen from the soil, which negatively affects respiration by both plant roots and soil micro-organisms (Grable, 1966). Depleting roots of oxygen adversely affects the permeability of roots to water, alters hormone balance of the shoot, and reduces the accumulation of nutrients (Burrows and Carr, 1969; Hopkins et al., 1950; Reid et al., 1969). This limits root and shoot growth, biomass accumulation and final crop yield (Bourget et al., 1966). Waterlogging stress of wheat in the Eastern Indo Gangetic Plains is most often attributed to ponding that occurs after flood irrigation

(Gupta and Seth, 2007; Melhuish et al., 1991). Farmers in Nepal apply irrigation into fields that are surrounded by bunds, which are small earthen walls to contain water, and continue to apply water until it has reached the highest point within the field (WFP, 2010). During the course of the irrigation, the soil reaches full saturation and begins to pond. The longer the duration of ponding on wheat crops, the greater the losses to end of season yield (Melhuish et al., 1991; Olgun et al., 2008). Balancing the influence of these stresses with proper irrigation management is a challenge that farmers confront every wheat season.

The impact on crop productivity from waterlogging and drought stresses often varies within fields because of heterogeneous soils conditions (Adamchuk et al., 2010). The effect of heterogeneous soil conditions on yield can be exacerbated by the imprecise practice of applying seed and fertilizer by hand (Maheswari et al., 2008). The application of inputs by hand, followed (or sometimes proceeded to prepare the field) by cultivation or rotovation is the most typical seed bed and tillage preparation method in Nepal (Manandhar et al., 2009). This semi-mechanized seed bed and tillage preparation method is being fully mechanized across the Eastern Indo Gangetic Plains in countries like India by using zero-tillage technology which provide greater precision of input application (Erenstein and Laxmi, 2008). Zero-tillage replaces the imprecise hand application of inputs by drilling them directly into the soil at a specified rate (Keil et al., 2015). Greater precision of inputs has been associated with better yield and grain quality within heterogeneous field conditions because individual plants have greater access to nutrients, which provide some resilience to stress (Hopkins et al., 1950; Mulla et al., 1992). Unfortunately, widespread adoption of zero-till in Nepal has been limited (3% of farmers in Nepal compared to 87% in Bihar, India) (Park et al., 2018). Limited adoption of zero-till has been attributed to difficult to overcome cultural, socioeconomic and agribusiness constraints

(Joshi et al., 2012; Metz, 1995; Sharma, 2006). Technological solutions that provide greater uniformity of inputs, but that also fit within the dominant semi-mechanized seed bed and tillage preparation system may have a higher likelihood of adoption because barriers to adoption are smaller. The concept of using “appropriate technologies” – those that fit within an existing agricultural framework – has been argued to provide greater success of adoption to new technologies (ATTRA, 2018). Introducing appropriate technology interventions that offer some degree of precision, but are also cheaper and simpler than zero-till, may provide a near-term path to more efficient fertilizer use and greater resilience to stresses for smallholder farmers in Nepal.

Both waterlogging and drought stress arise from suboptimal irrigation scheduling and implementation. In Nepal, the diesel pump is the sole means of water conveyance from either aboveground or groundwater sources (Shah et al., 2006). Access to diesel pumps is an important factor influencing when farmers will irrigate their land. Although there are an estimated 100,000-120,000 diesel pumps in use on the Terai (Biggs et al., 2011; Joshi et al., 2012), owners of those pumps on average only rent 29.3% of their total pumping hours to other farmers (Shah et al., 2006). Pump owners are typically smallholders themselves, and prioritize irrigating their crops before providing rental services to other farmers. Farmers who rent pumps therefore compete not just against pump owners to irrigate at a specific time, but other renters as well. Applying a single irrigation therefore not only reduces rental costs, but diesel fuel costs as well. Diesel fuel is one of the most expensive inputs in the Nepali agricultural system (Joshi et al., 2012), and has been defined as ‘the most critical problem’ facing irrigation management by farmers there (Shah et al., 2006). Despite high diesel prices and upfront costs, the demand for diesel pumps appears to be strong (Biggs et al., 2011). Purchases of diesel pumps are growing rapidly, compared to purchases of other forms of mechanized equipment in Nepali agriculture

(Joshi et al., 2012). This growth is evidence of farmer need for greater irrigation flexibility, and the overall demand for mechanization on the landscape.

Understanding the influence of water-related stresses, and finding solutions that reduce their impact to yield will be imperative to gradually increasingly the productivity of wheat in Nepal. Targeted interventions to reduce the impact of these stresses must therefore quantity their impact on yield, as well as the effect that the different interventions had on reducing these stresses, if any. We believe that in lieu of the success of expensive, more complicated equipment like zero-till, the introduction of appropriate technology that provides a greater measure of precision and uniformity may facilitate greater plant access to nutrients thereby improving resilience to stress. Additionally, investigation into the scheduling of irrigation across a large number of farmers may provide insight into whether a change in timing may increase or decrease the effect of a given water-related stress to yield. The insight that comes from an assessment of both the nature of dominant stresses in an agricultural system, and the effect that targeted interventions have on that stress with respect to yield, may also help inform broader policy solutions that have can further improve the productivity of the farming system in Nepal.

In this research, we sought to identify whether waterlogging, drought stress, or both had a significant impact on the yield within our experiment. We then detail the crop response from the selected water-related stress under two different treatments, one where farmers applied inputs by hand and another in which they were applied from a chest-mounted mechanized spreader. We hypothesized that the introduction of a chest-mounted spreader that improved within-field uniformity of inputs would reduce the impact that this stress had on wheat productivity by making nutrient access more homogenous to individual plants. We also assessed the impacts to yield from different timing of irrigations in relation to the phenology of the wheat crop, with the hypothesis that the inappropriate timing of irrigation is associated with a decrease in productivity by the increase of either stresses or both. Using information on irrigation management from other south Asian countries like India, we provide policy makers in Nepal additional context on the relationship between diesel pump access, the number of irrigation events, crop productivity, and abiotic stress management.

4.2 Methods

4.2.1 Study Location and Timing

The study area was located in the district of Rupandehi in the Terai region of Nepal near the town of Siddharthanagar (27.51268° N, 83.4814° E) within a dominant rice-wheat rotation annual cropping pattern (Mahajan and Gupta, 2009). Trials were sown on farmer fields within a 5 km^2 area in November of 2016 and harvested in April of 2017. The study area climate is sub-tropical, with an average annual rainfall of approximately 1,400 to 2,000 mm of which 85% typically falls during monsoon and a mean annual temperature between 20 and 25 °C (WFP, 2010).

4.2.2 Experimental Design and Input Rates

Sixty farmers were selected at random within a two-level Completely Randomized Design trial, with 30 then randomly assigned into each treatment. One treatment ('mechanized application') received an application of farm inputs using a chest-mounted spreader, while the other treatment ('hand application') applied these inputs by hand, following local farmer practice. A researcher using the chest-mounted spreader applied farm inputs within the mechanized treatment, while farmers in the hand distributed treatment applied inputs individually to their own fields. Field sizes in the study were between 0.014 ha to 0.11 ha with an average of 0.04 ha. To capture a representative sample of response variables across each farmer's field, four 1 m^2 subsamples were randomly established where seasonal measurements were taken.

In this on-farm study, we controlled only for different application techniques of fertilizer and seed, noting carefully other sources of variation among farms. We determined that a number of the randomly selected farmers would not have access to fertilizer whatsoever because of inadequate access or funding. Therefore, we provided a flat rate of 4 kg of urea and 3.75 kg of diammonium phosphate to all farmers regardless of field size to ensure that farmers could participate in the trials. Farmers in the hand application treatment group on average applied 109, 59.4, and 23.9 kg ha^{-1} of nitrogen (N), phosphate (P) and potassium (K), respectively. In the mechanized application group, farmers on average applied 89.9, 62.2 and 0 kg of N, P, and K, respectively. Farmers provided their own seed, planting at 185 kg seed ha^{-1} using either the hand applied or mechanized application method they were assigned to. Farmers in the hand application treatment applied significantly more K ($F_{1,58}$=12.3, p<0.001) and while there was no significant difference between N, P, and seed rates ($F_{1,58}$=3.6, p=0.06, $F_{1,58}$=0.28, p=0.59, $F_{1,58}$=0.001, p=0.99, respectively). Different inputs rates occurred for two reasons, 1) when farmers provided their own fertilizer, they usually added it to the flat rate that we provided, thereby increasing their overall application rates (information that we recorded, along with field area, to calculate fertilizer application rates in kg ha^{-1}), and 2) varying sizes of farmers' fields meant that rates changed accordingly, though there was no difference in field size between treatments ($F_{1,58}$=1.9, p=0.18). In each of the treatment groups, the same twelve wheat varieties were represented among the farmer fields.

4.2.3 Technological Intervention and Traditional Practices

Here we describe in greater detail the two different application methods for farm inputs in the trials. The mechanized, precision agriculture technology we introduced was a chest-mounted spreader (*Model 2750, Manufacturer-EarthWay)*. These spreaders are commonly used to broadcast fertilizer and grass seed for lawn establishment and maintenance in many parts of the world. The chest-mounted spreader has an agitator that feeds granular inputs from a mounted nylon hopper bag to a distribution plate which spreads the inputs in a 45° fanning action in front of the user. The user controls rate of application through a flow control mechanism and the rate of cranking speed. Farm inputs were applied by moving along the edge of the field with the left of fan of inputs meeting with the right side of the preceding pass (Wolf and Smith, 1979). The price of an *EarthWay* spreader at the time of publication is $35 USD. We compared the mechanized chest-mounted spreader with the traditional practice of applying farm inputs by hand. In the hand application treatment, farmers applied inputs by hand as uniformly as possible from a container held on their person as they walked up and down the field. In both treatments, inputs were incorporated either by rotovation or cultivation. The effect of rotovation and cultivation on yield was not significantly different across treatment groups ($F_{3,56}$=2.3, p=0.93 & $F_{3,56}$=0.28, p=0.56, respectively).

4.2.4 Irrigation Practices

Fifty-five farmers in our study applied a single irrigation, and five applied two irrigations. Two of the farmers that applied twice scheduled one irrigation prior to sowing. All other irrigations, including all farmers that used a single irrigation, applied water after seedlings were established. Water was applied to fields using flood irrigation, with plastic piping attached to diesel pumps drawing water from canals, ponds or from tubewells. Farmers would generally apply irrigation water until their fields were completely flooded to ensure all portions of the field received at least some water. Uneven fields led to some portions of the fields being ponded for longer than others.

4.2.5 Waterlogging Stress and Drought Stress

To identify waterlogged conditions, volumetric soil moisture values at 0-10 cm depth were taken with a volumetric soil moisture meter approximately every two weeks at all sub-samples across all the farms throughout the growing season. The area under the curve of the seasonal volumetric values at 0-10 cm were then integrated by subsample and averaged per field to estimate a representative total volumetric water content at the soil surface over the course of the growing season (R Core Team: splinefun, 2018). Higher values of volumetric water at the soil surface represented a soil surface that was wetter over the course of the season. Soil texture was also determined for each field to determine if it influenced drainage.

Drought stress of the wheat crop was estimated by measuring the Crop Water Stress Index (CWSI) every two weeks at each subsample for all farms from canopy closure until the onset of senescence (Donald J. Garrot et al., 1994). The CWSI quantifies plant water stress canopy temperatures and meteorological conditions, and is commonly used to schedule irrigations. Plant temperatures indicate water stress because stomata close in reaction to depletion of water in the soil, resulting in a decrease in water uptake and an increase in the temperature of the leaf. We fit a simple linear model for seasonal CWSI at each sub-sample through time, which was then averaged across each farm to create a representative measure of drought stress. We chose to use the seasonal slope of CWSI to represent drought stress because we did not begin to measure

CWSI till canopy closure (~zadoks 30, stem elongation), after which all irrigations were complete. We assumed that with no more irrigation, and very little seasonal precipitation, the slope of CWSI through the season would be a good approximation for the level of stress experienced within the subsamples. Higher slope estimates of CWSI through time were interpreted as indicating greater drought stress on the crop over the course of the season, with lower slopes representing less change in drought stress, indicating smaller drought stress. To determine total rainfall for the season, a single weather station was installed near the centroid of the field sites.

4.2.6 Normalized Difference Vegetation Index, End of Season Yield Estimates

A dual crop-cut and yield modelling approach was used to estimate wheat yields at all four subsamples. This was necessary because the harvest time of wheat by farmers was unpredictable, which required us to have all crop-cuts complete in a timely manner which only allowed for a single crop-cut at each field. First, we recorded measurements of Normalized Difference Vegetation Index (NDVI) throughout the season using a *GreenSeeker* approximately every two weeks from sowing to harvest. Measurements were collected at every subsample within each field at approximately 0.5 m above the top of the wheat stand. Second, a single crop cut was taken at one of the subsamples in all fields to have a direct measure of yield. Third, a quadratic model was fit to the seasonal NDVI curves, with the random effects for the linear and intercept term for every farm, and a random effect for the intercept for every subsample (Model 1). Fourth, we estimated the maximum seasonal NDVI for each subsample using the fitted curves at each subsample. Finally, we fit a simple linear model between crop-cut yield values and maximum NDVI, stratified by wheat cultivar. We then used these predictions of final yield as our values for yield across all sub-samples within each field of the study. This modelling approach was possible because of the strong relationship between NDVI and end of season biomass and yield (Wiegand and Richardson, 1990).

Model 1: $y_{ijk} = \beta_1 + \beta_2 d_{ik} + \beta_3 d^2_{ik} + b_{i,1} + b_{i,2} d_{ik} + b_{ij} + \varepsilon_{ijk}$,

$i = 1,\ldots,60$, $j = 1,\ldots,4$, $k = 1,\ldots,n_{ij}$

4.2.7 Seasonally Integrated Normalized Difference Vegetation Index

To have a better understanding of the mechanisms by which a more or less uniform application of fertilizer under different treatments may have on fertilizer uptake and resilience to stress, we needed to determine a measurement that could account for both of these factors. In addition to being strongly related to yield outcomes, NDVI is also a valuable tool for estimating plant stress and fertilizer uptake (Jackson et al., 1986; Malingreau, 1989). The seasonal integration of NDVI measurements throughout a season has been found to be a strong proxy for crop growth that we needed to estimate in order to detect treatment effects on fertilizer uptake and yield (Labus et al., 2002). To create this measure, we used the NDVI measurements we recorded every two weeks and integrated the seasonal values through time to have an approximation of crop vigor over the course of the season, or “seasonal area under the curve” of NDVI values (R Core Team: splinefun, 2018). We used these seasonally integrated NDVI estimations as a reasonable intermediary between yield, fertilizer uptake and stress so that we could better understand the mechanisms by which a more uniform application of fertilizer affected their interactions.

4.2.8 Statistical Analysis

To determine the effect that drought and waterlogging stress had on yield, we used R (R Core Team, 2018) to perform general linear mixed effects models analysis of the relationship between yield and total volumetric water at the soil surface over the course of the growing season, and yield and seasonal CWSI slopes. As independent variables, we entered total volumetric water at the soil surface over the course of the growing season and seasonal CWSI slopes, with the response variable being yield. To determine if waterlogging stress was more influential in affecting yield earlier in the wheat's phenology, we stratified the dataset into two groups using the zadoks scale (Zadoks et al., 1974). In the first group, we stratified the dataset so that it only contained the integrated volumetric water at the soil surface prior to zadoks stage 32, the last recorded stage during which there was an irrigation. We then used in the aforementioned general linear mixed effects model to test the effect of integrated soil moisture at the soil surface on yield. The second group was stratified to account for the integrated volumetric water at the soil surface after zadoks stage 32, with the same general linear mixed effects model used. Visual inspection of residuals did not indicate any deviations from normality or heteroscedasticity. A Pearson product-moment correlation coefficient was computed to assess the relationship between total volumetric water at the soil surface prior to zadoks stage 32 and percent clay content, as well as between the total volumetric water at the soil surface and CWSI seasonal slopes.

To test whether the relationship between timing of irrigation with respect to crop phenology and yield was linear, quadratic or polynomial, we conducted model selection based on maximum likelihoods (R Core Team, 2018). The most model which most parsimoniously fit the data was selected as the optimal model (Burnham and Anderson, 2002). This model was fit using the 55 farmers who only used a single irrigation to have specific inference relating to this common practice in Nepal.

Structural equation models were used to visually conceptualize and quantify the causal relationships and partial-correlations among four interacting variables: Nitrogen rate, total volumetric water content at the soil surface over the course of the growing season, seasonally integrated NDVI, and yield (Grace, 2006; Williams et al., 2016). The objective was to determine if there were significant changes to the way these four variables interacted under the mechanized and hand application treatments with respect to the influence that stress (total volumetric water content at the soil surface) and fertilizers (N rate) had on crop growth (seasonally integrated NDVI) and yield. We used this method because the flexibility of structural equation models allowed us to decompose the nature of the interactions between the four variables including, direction (positive or negatively influencing each other), strength (the size of the coefficient), and significance in a way that models such as unstructured multiple regression cannot provide (O'Rourke and Hatcher, 2013; Smith et al., 2014). We scaled and centered each of the four continuous variables so that they were within the same data range to provide standardized regression coefficients and covariances (R Core Team, 2018). We then used the *lavaan* package (Rosseel, 2012) in R to structure the model using a maximum likelihood estimator such that N rate and total volumetric water content at the soil surface covaried with each other, while both regressed to predict seasonally integrated NDVI. Seasonally integrated NDVI was then regressed on yield. Models were fitted using the Comparative Fit Index to indicate good fit but prevent model saturation (approximately between 0.85 and 0.95), Aikake Information Criterion (AIC), and χ^2-values.

Multiple regression analysis was used to better understand the decision making behind the first irrigation scheduled by farmers. Using data of the 58 farmers who applied their first irrigation after establishing their seedlings, we treated the day of year of the first irrigation as the response variable, while the predictor variables were the phenology of the wheat crops in Zadoks growth score and the minimum volumetric soil moisture prior to irrigation. We structured the model this way to determine if farmers were deciding to irrigate their crop based on the phenology of their plant, their perceived dryness of the soil, both or neither. Using this method, we sought to reveal the rationale behind farmer decisions that have important ramifications for water-related stress.

4.3 Results and Discussion

4.3.1 Waterlogging and Drought Stress Impacts

Understanding the impact of different abiotic stresses on crop productivity can help guide the selection of agronomic practices that can mitigate their effects on yield. Among the 60 farmers within our study, waterlogging stress as represented by greater amounts of soil moisture at the soil surface (0-10 cm depth) throughout the course of the growing season, had a negative impact on final yield (b_1=-0.6, $F_{1,58}$=5.6, $p<0.05$) (Figure 4.1a). In contrast, the level of drought stress observed in this study as represented by the seasonal slope of CWSI did not affect crop yield (b_1= 77235, $F_{1,58}$=3.5, p=0.07) (Figure 4.1b). As would be expected, there was a moderately negative correlation between drought and waterlogging stresses (r = -0.41, df = 58, $p < 0.01$), indicating that as the amount of water at the soil surface increased, seasonal CWSI slope decreased. Because one of the two stresses reduced yield, and the stresses are negatively related, farmers may have the capacity to “balance” the stresses such that the impact of both is insignificant. We believe this information highlights the importance of decision making by farmers in managing both stresses. Striking a balance between too much and too little water is a challenging risk management problem faced by the farmers in our study, but not unique to Nepal. Farmers who are more risk averse tend to apply more water per unit of land than those that are not (English and Orlob, 1978; English et al., 2002).

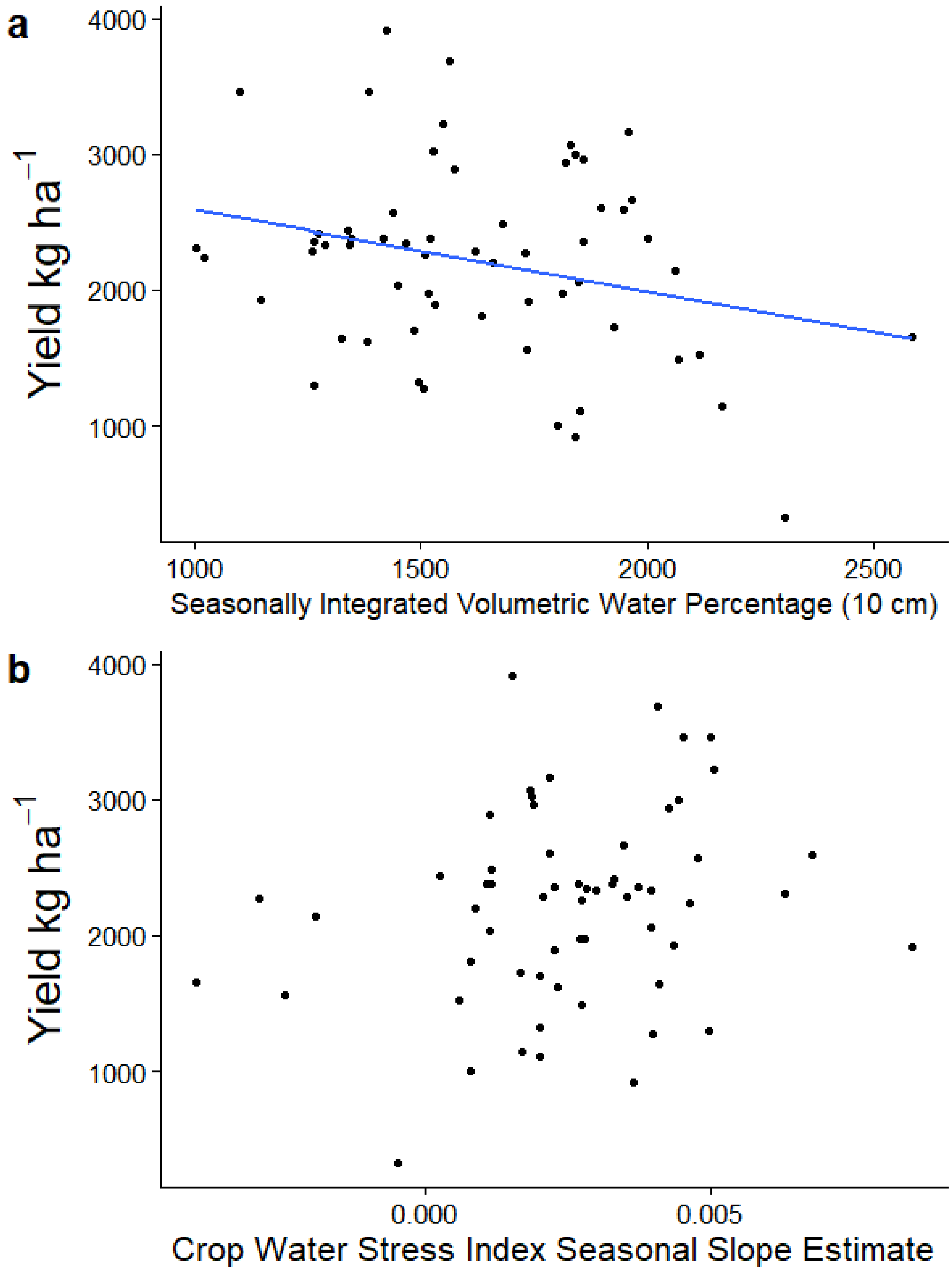

Figure 4.1. Relationship between total seasonal volumetric water at the soil surface (at 0-10 cm) and seasonal Crop Water Stress Index slopes estimates in relation to yield; a) A significant, negative relationship between total seasonal volumetric water at the soil surface and yield (b_1=-0.6, $F_{1,58}$=5.6, p<0.05) indicates that increases in conditions associated with waterlogging stress reduced yield; b) Crop Water Stress Index slopes estimates did not have a significant association with yield (b_1= 77235, $F_{1,58}$=3.5, p=0.07).

4.3.2 Timing of Waterlogging Stress

The impact of waterlogging stress on crop yield varies with the development stage at which it occurs. We interpreted the negative effects on yield from total seasonal volumetric water at the soil surface to be associated with waterlogging stress from flood irrigation in the early stages of crop development because of two reasons: 1) greater amounts of volumetric water at the soil surface prior to zadoks stage 32 (initiation of stem elongation and most mature stage to be irrigated) were associated with a decrease in final yield (b_1= -1.1, $F_{1,58}$=12, p<0.01) (Figure 4.2a), while this was not the case with more mature plants after zadoks stage 32 (b_1= 0.61, $F_{1,58}$=1.77, p=0.19) (Figure 4.2b), and 2) only 54 mm of rain fell during the wheat season, indicating that any impact of total seasonal volumetric water at the soil surface to yield was the product of the early irrigation events observed in this study. Additionally, there was a moderately strong, positive relationship between the total integrated seasonal volumetric water early in crop development (prior to zadoks 32) and the clay content of the soil ($r = 0.41$, df = 58, $p < 0.01$), indicating that poor drainage due to high clay content may have played a role in restricting the movement of water through the soil profile and contributing to waterlogging stress. We interpreted these three pieces of evidence to mean that as flood irrigation water rapidly ponded on the soil surface (due to excessive irrigation on heavy soils), waterlogging stress began to impact the crop in its early stages of development. In conclusion, waterlogging at the soil surface early in the wheat crop's development was a significant stress that negatively impacted yields. In the next section, we will examine the potential for increased precision of input application to reduce the risk from waterlogging stress, regardless of irrigation timing.

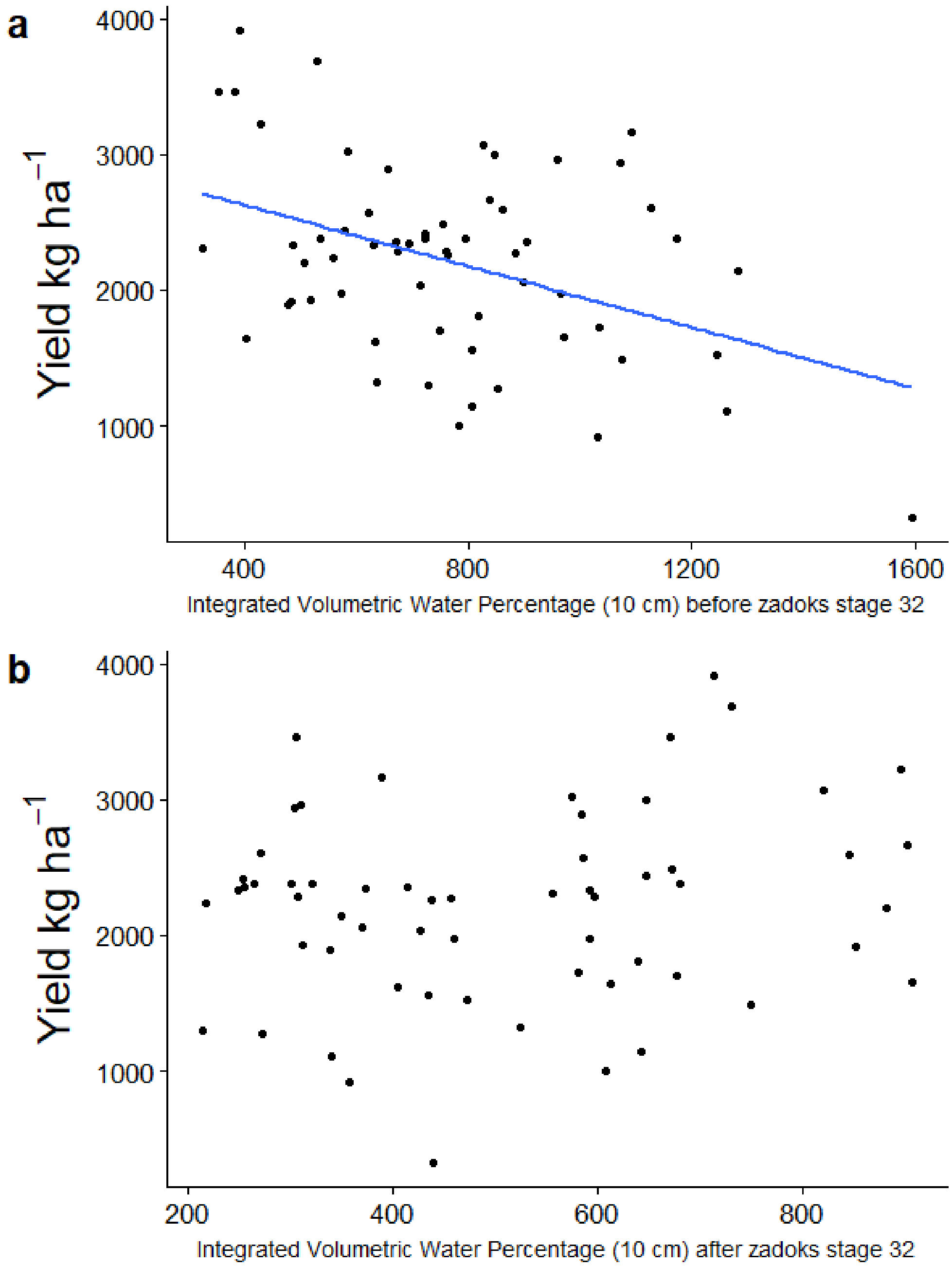

Figure 4.2. The effect of waterlogging stress as represented by integrated volumetric water percentage at the soil surface before and after zadoks stage 32 on final yield; a) integrated volumetric water percentage at the soil surface was found to have a significant, negative effect on yield prior to zadoks development stage 32 (b_1= -1.1, $F_{1,58}$=12, p<0.01), b) volumetric water after zadoks stage 32 did not have a significant effect on yield (b_1= 0.61, $F_{1,58}$=1.77, p=0.19).

4.3.3 Precision Input Application Mitigated Waterlogging Stress

Field scale stresses that affect crop productivity are often associated with soil heterogeneity caused by both management-induced and natural processes. If farm inputs are applied more uniformly, and with less within-field aggregation, individual wheat plants are more likely to have access to nutrients necessary for growth thereby providing greater resilience to stress (Maheswari et al., 2008). Farms where simple mechanization was used saw a positive, significant relationship ($b_1 = 0.74$, $p<0.001$) between their N rate and seasonally integrated NDVI, the intermediary between N and yield which is a strong proxy for the health of a crop throughout the growing season (Figure 4a). N rate did not covary with the total seasonal volumetric water at the soil surface, nor did total volumetric water at the soil surface have a significant effect on seasonally integrated NDVI ($b_1 = -0.11$, $p= 0.51$). Nitrogen rate explained a third ($R^2 = 0.3$) of the variability of seasonally integrated NDVI, which had a strong, positive association with final yield ($b_1 = 0.64$, $p<0.001$). Seasonally integrated NDVI explained 57% of the variability associated with yield.

The structural equation model for hand distributed inputs (Figure 4b) contrasts markedly with the previous model. Rather than N rate having a significant influence over seasonally integrated NDVI ($b_1 = 0.15$, $p = 0.32$), the total seasonal volumetric water at the soil surface replaced N to have a significant, negative influence on seasonally integrated NDVI ($b_1 = -0.39$, $p < 0.05$). This reduced the explained variability of seasonally integrated NDVI to 16%. While seasonally integrated NDVI was still a positive predictor of yield ($b_1 = 0.69$, $p<0.001$), the overall variability of yield explained by seasonally integrated NDVI decreased ($R^2 = 0.39$).

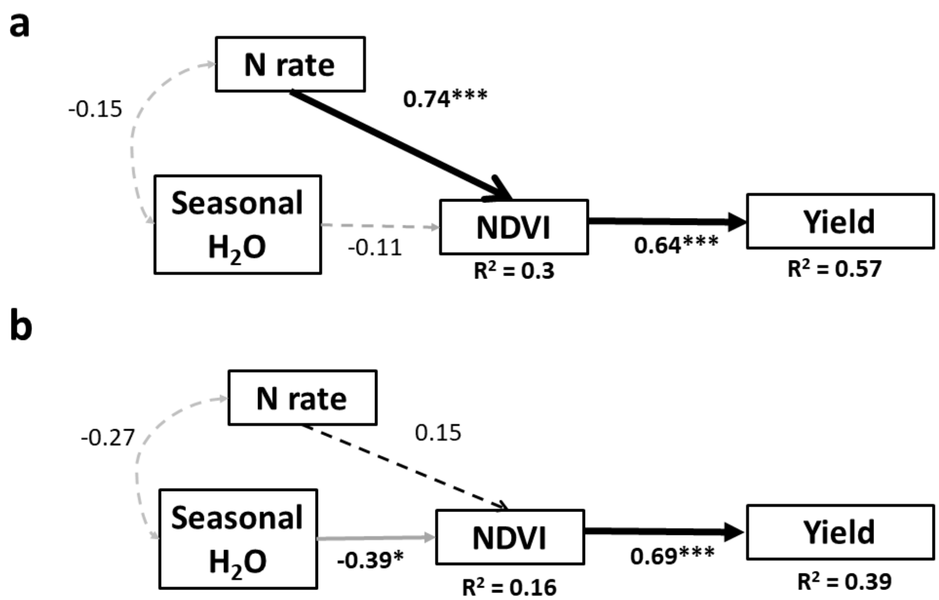

Figure 4.3. Structural equation models showing effects of total volumetric water at the soil surface (Seasonal H_2O) and N rate (N rate) on seasonally integrated NDVI (NDVI) and yield (Yield) in mechanized and hand distributed treatments; a) chest-mounted, mechanized treatment ($\chi2$ = 3.5, df = 2, P = 0.17, AIC = 253, CFI=0.96); b) hand distributed ($\chi2$ = 4.2, df = 2, P = 0.12, AIC = 366, CFI=0.88); model fits for the treatment models indicate good support for each. Single-headed arrows denote standardized regression coefficients, while double-headed arrows denote covariances between variables. Grey arrows indicate negative relations, and black arrows denote positive relationships. $P < 0.05$ (*), $P < 0.01$ (**), $P < 0.001$ (***).

Farmers who applied inputs with higher precision using mechanized application incurred a smaller impact from the total seasonal volumetric water at the soil surface when compared to farmers who applied inputs by hand (Figure 4.3a & 3.3b). The effect of precision input application in this farming system was to improve the linkages between fertilizer (N rate) and crop growth (seasonally integrated NDVI), and weaken the linkages between waterlogging stress (total volumetric water at the soil surface) and crop growth. This appears to be a byproduct of a more uniform application of fertilizer, as plants with greater access to essential nutrients overcame waterlogging stress (Cakmak, 2005). The opposite appears to have occurred when fertilizers were applied by hand, as the waterlogging stress became the driving force determining crop growth rather than N rate. The heterogeneous application of inputs by hand appears to have reduced plant access to nutrients to a large enough extent that fertilizer became less effective, which we believe was observed in the equivalent yield between the mechanized and hand application treatments (2,168 compared to 2,255 kg ha^{-1}, respectively) ($F_{1,58}$=0.22, p=0.64). These similar yields occurred even though the hand application treatment used 18% more N ($F_{1,58}$=3.6, p=0.06) and was the only treatment group to apply any K ($F_{1,58}$=0.001, p=0.99). We have greater confidence that a more homogenous application of inputs contributed to improved linkages between fertilizer, crop growth and yield, because we found that there was no significant difference treatment interaction effect with respect to the total volumetric water at the soil surface and yield for the seasonal total ($F_{3,56}$= 1.8, p=0.63), before zadoks stage 32 ($F_{3,56}$=4.5, p=0.47), or after zadoks stage 32 ($F_{3,56}$= 1.2, p=0.2). This can be interpreted as meaning that the waterlogging stress we observed was equally distributed across both treatments, adding validity their effects. These results highlight the value that precision application of farm inputs can have in heterogeneous field conditions, and offer a partial solution to reducing the impact of waterlogging stress.

4.3.4 Changing Time of Irrigation to Reduce Waterlogging Stress

Timing of irrigation with respect to the phenology of wheat has been shown to be an important factor in determining water related stresses. A shift in the phenology at which a wheat crop is irrigated could potentially result in improved yield outcomes by reducing waterlogging stress. Of the 55 farmers in our study who applied a single irrigation, farmers that waited for greater development of their wheat crop to apply irrigation had higher yields. Every Zadoks growth stage that a farmer delayed in irrigating was associated with an increase in yields by 65.9 kg ha^{-1} (b_1=65.9, $F_{1,53}$=14.7, $p<0.05$) (Figure 4.4). Farmers that irrigated before the initiation of tillering, yielded 29% less than those who irrigated after tillering began (1,891 compared to 2,651 kg ha^{-1}) ($p<0.05$). More developed plants have been found have greater resilience to waterlogging stress because they produce greater amounts of adventitious roots which have a higher porosity than primary roots, allowing greater uptake of water and nutrients even in waterlogged conditions (Luxmoore and Stolzy, 1969). This mechanism weakens the effect of waterlogging on more developed plants, and although root and shoot development may still be reduced, the effect on vegetative growth is not as great and therefore impact to yield is reduced (Watson et al., 1976). Although the fit of this relationship was linear rather than quadratic ($F_{1,51}$, $p<0.05$) (Figure 4.4), we caution that delaying irrigation too late into the season will cause yield to decline as drought stress increases (Chakwizira et al., 2014). It is important to note that the inference of these results are on heavier soils where drainage at the soil surface is a problem, and where a single irrigation was used. Based on these results, we conclude that farmers who rely on a single irrigation for seasonal plant available moisture should delay this irrigation towards the end of leaf development and beginning of tillering stages.

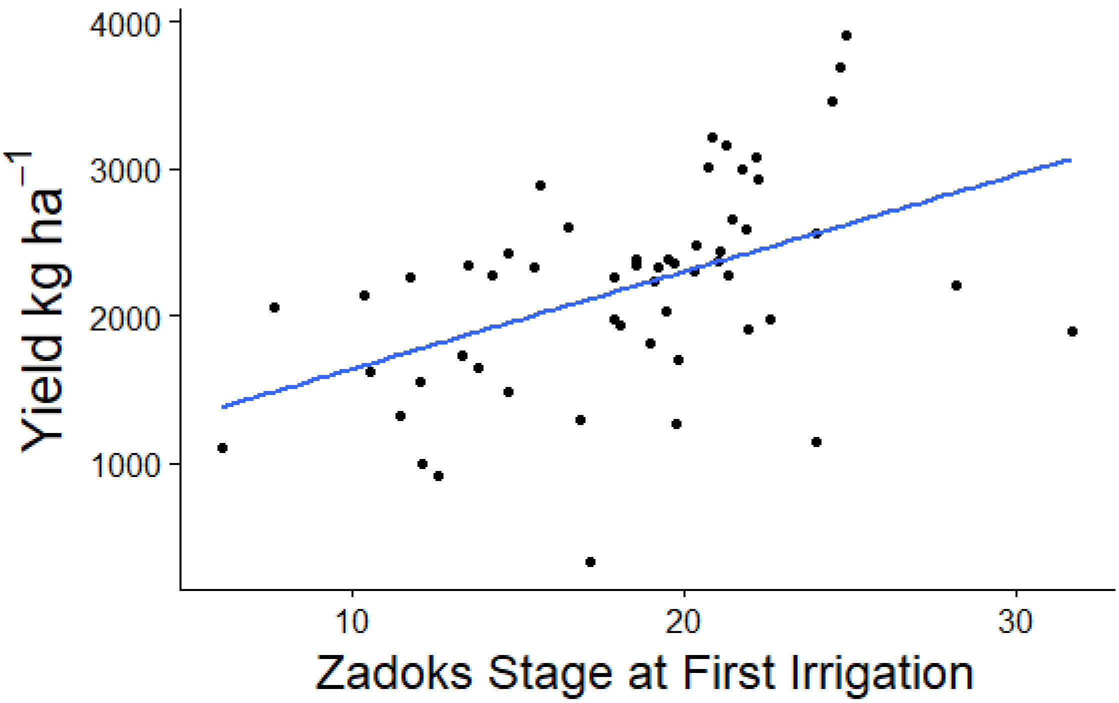

Figure 4.4. The linear relationship between yield and the zadoks stage of wheat when the first irrigation was applied to the field (b1=65.9, F1,53=14.7, p<0.05). Delaying irrigation timing so that the crop was more developed improved yield.

4.3.5 Farmer Decision of Irrigation Scheduling

The decision to irrigate is often determined by a farmer's assessment of soil moisture, plant development, and access to diesel pumps. If farmers are more influenced by their determination that soil moisture is deficient, convincing them to delay irrigation based on the phenology of the crop will be more challenging. We used a multiple regression model to reveal the behavioral decision of when farmers irrigated. Farmers appeared to have chosen the date of their irrigation based on the development stage of the plant, rather than the soil moisture at 0-10 cm. In a multiple regression, the day of irrigation was best predicted by the stage of the crop at the day of irrigation (b_1=0.4, $F_{2,52}$=4.6, $p<0.05$) rather than the soil moisture at the top ten centimeters right before the irrigation event (b_1=-0.05, $F_{2,52}$=4.6, p=0.82). These results suggest that between soil moisture and the development of the wheat crop, farmers made the decision to irrigate based on the phenology of the crop. In addition to the development stage of the crop, we recognize that the decision of time to irrigate was likely associated with the availability of access to a diesel pump. In an agricultural system with freedom of choice of when to irrigate, our results suggest that the foundation of an effective extension message already exists. This is because delaying irrigation to a later development stage is an adjustment of an existing cultural practice (as opposed to convincing farmers that soil moisture is the appropriate method of timing an irrigation). With a strong extension message, risk from waterlogging stress could be reduced and overall yield could be improved with an adjustment in timing of irrigation to reflect appropriate stage of wheat. In a system where there are constraints on availability of diesel pumps, solutions to overcoming waterlogging stress would need to account for both a shift in timing of irrigation and also address the scarcity of diesel pumps.

4.3.6 Diesel Pump Accessibility

The timing of irrigation with respect to the phenology of the wheat crop relies on access to diesel pumps in a timely manner. Access to pumps at a specific crop stage is a challenge to the majority of farmers because they are reliant on the diesel pump rental system. Increasing the overall number of pumps on the Nepali landscape could help improve the flexibility of timing of irrigations during critical periods of crop development. Identifying solutions towards increasing the accessibility to irrigation in Nepal has been a contested topic as to whether it should be farmer and private sector based, or regulated through government incentives (Biggs et al., 2011). A dual farmer-private and government approach that address the underlying mechanisms of inaccessibility to irrigation will likely be the most effective approach (Lam, 1996).

4.3.7 Split Irrigation

Ninety-two percent of the farmers in our study applied irrigation water in a single event. We observed that when farmers applied a single irrigation, they flooded their fields to the point of ponding. Unfortunately, the strategy of ponding a field with flood irrigation in wheat has been found to reduce yield outcomes with every added hour of waterlogged conditions (Melhuish et al., 1991). Farmers in our study who split their irrigations (a total of five farmers) had 9% higher yields relative to those that applied a single irrigation (2,399 compared to 2,195 kg ha^{-1}). Splitting irrigations did not double the total volumetric water at the soil surface which we associated with waterlogging stress; with soils under split irrigations having 20% higher seasonal volumetric water. We speculate that farmers used a single irrigation as both a cost and risk mitigation strategy. By applying a single irrigation, farmers do not have to pay another rental fee to the pump owners, which reduces their production costs for that season. Additionally, irrigating to the point of ponding reflects farmers' knowledge that sufficient moisture must be in the soil profile for the entire growing season because of the little expected precipitation in the Terai (Chatrath et al., 2007). While we observed benefits to splitting irrigation in our study, the low number of farmers who used two irrigations in our study does not allow for significant inference. As we will see, we can investigate regions bordering the Terai of Nepal with similar agroecologies but with different levels of agricultural investment - like Bihar, India - to observe irrigation management in a country where investment in agriculture is higher yet still share similar climates (Aggarwal et al., 2000; Ladha et al., 2003).

The purpose of managing farm risk is to control possible adverse consequences of uncertainty that arise from production decisions (Moschini and Hennessy, 2001), and in our study we believe we observed most of the farmers choosing to mitigate the agronomic and financial risks associated with additional rental fees, diesel fuel, potential unavailability of pump access, and drought stress by applying a single irrigation with excessive amounts of water rather than appropriately managing waterlogging stress. The rationale for farmers to do so is clear: the uncertainty associated with reducing the amount of water applied in a single irrigation is considered a risk in case there is little seasonal precipitation, thereby exposing them to greater drought stress later in the season. If farmers were to apply two irrigations, their costs would also increase thereby reducing profits in addition to the added labor of finding and negotiating the rental of a diesel pump. By choosing to mitigate these particular costs and risks, farmers in our study have instead burdened themselves with waterlogging stress. This type of risk selection has been observed in global irrigation management, where deficit irrigation has been argued as a solution towards reducing agricultural water use (Fereres and Soriano, 2007).

Constrained by limited capital, applying a single irrigation with heavy ponding may be the best option farmers in Nepal have when managing different risks. The effect of different irrigation management can be observed in bordering Bihar, India which shares similar agroecologies with the Terai of Nepal, yet are influenced by starkly different government policy supports and socioeconomics (Biggs et al., 2011; Pathak et al., 2003). Farmers in Bihar apply on average two irrigations a season, which was part of an overall management package that resulted in higher wheat yields relative to Nepal (Park et al., 2018). Continuing and expanding existing policies that support access to diesel fuel for the rural poor on the Terai (Joshi et al., 2012) may be an reasonable means of encouraging a split irrigations, thereby reducing waterlogging stress. Additionally, identifying the appropriate amount of irrigation water for soils with different drainage would contribute to a better understanding of how to reduce waterlogging stress.

4.4 Conclusion

Our results suggest that farmers in the Terai of Nepal reduced their yields by introducing stresses from waterlogged conditions by applying irrigation too early in the phenology of the wheat crop. To reduce this stress, they can alter two practices within the current agronomic system, 1) use precision application of inputs to promote greater resilience to stress that results from more uniform plant access to nutrients, and 2) when using a single irrigation where ponding occurs in the field, delay irrigation till the crop is more robust to stress around the tillering development stage. At the policy level, better defining the need for diesel pumps on the landscape can help shape policy that facilitates timely access to pumps at critical times in crop development. Continuing existing diesel subsidies and reprioritizing them to the agricultural regions could reduce costs for farmers so that they may be more inclined to split their irrigations, thereby reducing the time the crop is waterlogged. Introducing appropriate technologies like the chest-mounted spreader and adjusting the timing of irrigation offer solutions to farmers without requiring substantial shifts to their existing practices. These simple solutions likely have scope in similar agroecologies in developing countries where agricultural investment is low, and the number of irrigations is limited.

4.5 Literature Cited

1. Adamchuk, V.I., Ferguson, R.B., Hergert, G.W., (2010) Soil Heterogeneity and Crop Growth, in: Oerke, E.-C., Gerhards, R., Menz, G., Sikora, R.A. (Eds.), Precision Crop Protection - the Challenge and Use of Heterogeneity. Springer, New York, pp. 3-16.
2. Aggarwal, P.K., Talukdar, K.K., Mall, R.K., (2000) Potential Yields of Rice-Wheat System in the Indo-Gangetic Plains of India. Rice-Wheat Consortium Series 10, New Delhi, India, pp. 1-16.
3. ATTRA, (2018) Sustainable Agriculture, in: National Center for Appropriate Technology (Ed.), Master Publication List.

4. Biggs, S., Justice, S., Lewis, D. (2011) Patterns of Rural Mechanisation, Energy and Employment in South Asia: Reopening the Debate. Economic and Political Weekly 46, 78-82.
5. Bista, D., Amgain, L., Shrestha, S. (2013) Food security scenario, challenges, and agronomic research directions of Nepal. Agronomy Journal of Nepal 3, 41-52.
6. Bourget, S.J., Finn, B.J., Dow, B.K. (1966) Effects of different soil moisture tensions on flax and cereals. Canadian Journal of Soil Science 46, 213-216.
7. Burrows, W.J., Carr, D.J. (1969) Effects of Flooding the Root System of Sunflower Plants on the Cytokin in Content in the Xylem Sap. Physiologia Plantarum 22, 1105-1112.
8. Cakmak, I. (2005) The role of potassium in alleviating detrimental effects of abiotic stresses in plants. Journal of Plant Nutrition and Soil Science 168, 521-530.
9. Chakwizira, E., Brown, H.E., Meenken, E.D., Gillespie, R.N., Maley, S., George, M.J., Michel, A.J., Dellow, S.J. (2014) Effects of timing of drought stress on grain yield of feed wheat. Agronomy New Zealand 44.
10. Chatrath, R., Mishra, B., Ferrara, G.O., Singh, S.K., Joshi, A.K. (2007) Challenges to wheat production in South Asia. Euphytica 157, 447–456
11. Donald J. Garrot, J., Ottman, M.J., Fangmeier, D.D., Husman, S.H. (1994) Quantifying Wheat Water Stress with the Crop Water Stress Index to Schedule Irrigations. Agronomy Journal 86.
12. English, M.J., Orlob, G.T., (1978) Decision theory applications and irrigation optimization, in: Center, C.W.R. (Ed.).
13. English, M.J., Solomon, K.H., Hoffman, G.J. (2002) A Paradigm Shift in Irrigation Management. Journal of Irrigation & Drainage Engineering 128, 11.
14. Erenstein, O., Laxmi, V. (2008) Zero tillage impacts in India's rice–wheat systems: A review. Soil & Tillage Research 100, 1-14.
15. Fereres, E., Soriano, M.A. (2007) Deficit irrigation for reducing agricultural water use. Journal of Experimental Botany 58, 147–159.
16. Grable, A.R. (1966) Soil Aeration and Plant Growth. Advances in Agronomy 18, 57-106.
17. Grace, J.B. (2006) Stuctural Equation Modeling and Natural Systems. Cambridge University Press, Cambridge.
18. Gulati, A., Ganesh-Kumar, A., Shreedhar, G., Pullabholta, H., Zhang, X., Sainju, M.M., Pant, B.D., (2010) Ensuring Food and Nutritional Security in Nepal, in: Nepal, U.S.A.f.I.D.-v.U. (Ed.). New Delhi: International Food Policy Research Institute, Kathmandu, Nepal.
19. Gupta, R., Seth, A. (2007) A review of resource conserving technologies for sustainable management of the rice–wheat cropping systems of the Indo-Gangetic plains (IGP). Crop Protection 26, 436-447.
20. Hopkins, H.T., Specht, A.W., Hendricks, S.B. (1950) Growth and nutrient accumulation as controlled by oxygen supplied to plant roots. Plant Physiology 25, 193-204.
21. Jackson, R.D., Pinter, P.J., Reginato, R.J., Idso, S.B. (1986) Detection and Evaluation of Plant Stresses for Crop Management Decisions. IEEE Transactions on Geoscience and Remote Sensing 24, 99-106.
22. Joshi, K.D., Conroy, C., Witcombe, J.R., (2012) Agriculture, seed, and innovation in Nepal: Industry and policy issues for the future. International Food Policy Research Institute, Washington, D.C., pp. 1-60.

23. Keil, A., D’souza, A., McDonald, A. (2015) Zero-tillage as a pathway for sustainable wheat intensification in the Eastern Indo-Gangetic Plains: does it work in farmers’ fields? Food Security 7, 983-1001.
24. Labus, M.P., Nielsen, G.A., Lawrence, R.L. (2002) Wheat yield estimates using multi-temporal NDVI satellite imagery. International Journal of Remote Sensing 23, 4169-4180.
25. Ladha, J.K., Dawe, D., Pathak, H., Padre, A.T., Yadav, R.L., Singh, B., Singh, Y., Singh, Y., Singh, P., Kundu, A.L., Sakal, R., Ram, N., Regmi, A.P., Gami, S.K., Bhandari, A.L., Amin, R., Yadav, C.R., Bhattarai, E.M., Das, S., Aggarwal, H.P., Gupta, R.K., Hobbs, P.R. (2003) How extensive are yield declines in long-term rice-wheat experiments in Asia? Field Crops Research 2003, 159-180.
26. Lam, W.F. (1996) Improving the Performance of Small-Scale Irrigation Systems: The Effects of Technological Investments and Governance Structure on Irrigation Performance in Nepal World Development 24, 1301-1315.
27. Luxmoore, R.J., Stolzy, L.H. (1969) Root Porosity and Growth Responses of Rice and Maize to Oxygen Supply. Agronomy Journal 61, 202-204.
28. Mahajan, A., Gupta, R.D., (2009) The Rice–Wheat Cropping System, in: A., M., R.D., G. (Eds.), Integrated Nutrient Management (INM) in a Sustainable Rice—Wheat Cropping System, Springer, Dordrecht.
29. Maharjan, A., Bauer, S., Knerr, B. (2013) International Migration, Remittances and Subsistence Farming: Evidence from Nepal. International Migration 51.
30. Maheswari, R., Ashok, K.R., Prahadeeswaran, M. (2008) Precision Farming Technology, Adoption Decisions and Productivity of Vegetables in Resource-Poor Environments. Agricultural Economics Research Review 21, 415-424.
31. Malingreau, J.P. (1989) The Vegetation Index and the Study of Vegetation Dynamics. Springer, Dordrecht.
32. Manandhar, G.B., Adhikary, S.K., Sah, G. (2009) Sustainable Agricultural Practices and Technologies in Nepal. Tech. Monitor.
33. Melhuish, F., Humphreys, E., Muirhead, W., White, R. (1991) Flood irrigation of wheat on a transitional red-brown earth. I. Effect of duration of ponding on soil water, plant growth, yield and N uptake. Australian Journal of Agricultural Research 42, 1023-1035.
34. Metz, J. (1995) Development in Nepal: Investment in the Status Quo. GeoJournal 35, 175-184.
35. Moschini, G., Hennessy, D.A., (2001) Uncertainty, risk aversion, and risk management for agricultural producers, in: Gardner, B.L., Rausser, G.C. (Eds.), Handbook of Agricultural Economics, Oxford, pp. 87-153.
36. Mulla, D.J., Bhatti, A.U., Hammond, M.W., Benson, J.A. (1992) A comparison of winter wheat yield and quality under uniform versus spatially variable fertilizer management. Agriculture, Ecosystems and Environment 38, 301-311.
37. O'Rourke, N., Hatcher, L. (2013) A step-by-step approach to using SAS for factor analysis and structural equation modeling, 2nd ed. SAS Institute, Cary, NC.
38. Olgun, M., Kumlay, A.M., Adiguzel, M.C., Caglar, A. (2008) The effect of waterlogging in wheat (T. aestivum L.). Acta Agriculturae Scandinavica Section B - Soil and Plant Science 58, 193-198.
39. Park, A.G., Davis, A.S., McDonald, A.J. (2018) Priorities for Wheat Intensification in the Eastern Indo-Gangetic Plains. Global Food Security 17, 1-8.

40. Pathak, H., Ladha, J.K., Aggarwal, P.K., Peng, S., Das, S., Singh, Y., Singh, B., Kamra, S.K., Mishra, B., Sastri, A.S.R.A.S., Aggarwal, H.P., Das, D.K., Guptaj, R.K. (2003) Trends of climatic potential and on-farm yields of rice and wheat in the Indo-Gangetic Plains. Field Crops Research 80, 223-234.
41. R Core Team, (2018) R: A language and environment for statistical computing, in: Computing, R.F.f.S. (Ed.), Vienna, Austria.
42. R Core Team: splinefun, (2018) R: A language and environment for statistical computing, in: Computing, R.F.f.S. (Ed.), Vienna, Austria.
43. Reid, D.M., Crozier, A., Harvey, B.M.R. (1969) Effects of flooding on the export of gibberellins from the root to the shoot. Planta 89, 376-379.
44. Rosseel, Y. (2012) lavaan: An R Package for Structural Equation Modeling. Journal of Statistical Software 48, 1-36.
45. Shah, T., Singh, O.P., Mukherji, A. (2006) Some aspects of South Asia’s groundwater irrigation economy: analyses from a survey in India, Pakistan, Nepal Terai and Bangladesh. Hydrogeology Journal 14, 286-309.
46. Sharma, K. (2006) Development Policy, Inequity and Civil War in Nepal. Journal of International Development 18, 553-569.
47. Smith, R.G., Davis, A.S., Jordan, N.R., Atwood, L.W., Daly, A.B., Grandy, A.S., Hunter, M.C., Koide, R.T., Mortensen, D.A., Ewing, P., Kane, D., Li, M., Lou, Y., Snapp, S.S., Spokas, K.A., Yannarell, A.C. (2014) Structural Equation Modeling Facilitates Transdisciplinary Research on Agriculture and Climate Change. Crop Science 54, 475-483.
48. Watson, E.R., Lapins, P., Barron, R.J.W. (1976) Effect of waterlogging on the growth, grain and straw yield of wheat, barley and oats Australian Journal of Experimental Agriculture and Animal Husbandry 16, 114-122.
49. WFP, (2010) The Food Security Atlas of Nepal. World Food Program. Government of Nepal, World Food Program.
50. Wiegand, C.L., Richardson, A.J. (1990) Use of Spectral Vegetation Indices to Infer Leaf Area, Evapotranspiration and Yield: I. Rationale. Agronomy Journal 82, 623-629.
51. Williams, A., Hunter, M.C., Kammerer, M., Kane, D.A., Jordan, N.R., Mortensen, D.A., Smith, R.G., Snapp, S., Davis, A.S. (2016) Soil Water Holding Capacity Mitigates Downside Risk and Volatility in US Rainfed Maize: Time to Invest in Soil Organic Matter? PLOS ONE 11.
52. Wolf, D.D., Smith, E.S. (1979) Uniformity of Seed and Fertilizer Distribution with A Hand-Operated Spinning Spreader. Transactions of the ASAE 22, 0761-0762.
53. World Bank, (2018) Rural Population Growth, 2018 ed. World Bank, https://data.worldbank.org/indicator/SP.RUR.TOTL.ZS.
54. Zadoks, J.C., Chang, T.T., Konzak, C.F. (1974) A decimal code for the growth stages of cereals. Weed Research 14, 415-421.

CHAPTER 5: CONCLUSIONS

In the Eastern Indo Gangetic Plains, implementation of better agronomic management and technologies can meaningfully improve yields and the livelihoods of farmers. In our research, we observed that adoption of particular practices benefited crop productivity across different socioeconomic and government policy environments. For example, in both Nepal and Bihar, India the earlier sowing of wheat was associated with lower yield gaps likely from reduced impact from terminal heat stress. Yet while some agronomic practices improved yield across both Bihar and Nepal, some interventions were more suited to production environments where investment in agriculture was lower. That was the case in Nepal, where we investigated how introduction of appropriate technologies could help alleviate fertilizer inefficiencies and improve return on investment for farmers.

The introduction of a technology like the chest-mounted spreader in Nepal represented a stop-gap between the current state of agriculture, and a more efficient, more mechanized system that relies less on human labor (such as wider adoption of zero-till observed in Bihar). We recognized that long-term solutions to food security in the Eastern Indo Gangetic Plains would need to address the root problems of access to capital, land fragmentation, land ownership rights, and lack of reinvestment in farms which limit farmer productivity. However, using management practices and technologies that we found in our research to improve yield outcomes can offer shorter-term solutions that can help bridge the gap to these long-term goals.

In our first manuscript, we used an extensive on-farm production practice and crop yield surveys across both Nepal and Bihar, India, we identified four agronomic practices that reduced yield gaps without the introduction of new technologies. These four management practices involved sowing time, varietal selection, fertility, precision agriculture and irrigation management. The first agronomic practice that reduced yield gaps was sowing earlier while using long maturing varieties. The benefits of this combined practice was likely a result of reducing the risk from terminal heat stress while also accumulating more growing degree days across a season. Greater accumulation of growing degree days across the season led to a greater crop development by delaying the onset of an early reproductive phase. The second practice was to increase the input rates of N and P, and particularly K. Potassium emerged as an important input for all farmers in study because it is systematically under-applied in the Eastern Indo Gangetic Plains, and also because it is stored in the wheat stalk which is commonly removed from the field after harvest, preventing potassium cycling from crop residue. Overall, farmers in Nepal applied less fertilizer than farmers in Bihar did. This was the result of an underdeveloped private fertilizer market in Nepal that forces many farmers to purchase fertilizer on the gray-market. Lower fertilizer efficiencies in Nepal may have also indicated that fertilizer quality may be sub-optimal, and that other farmer practices limited the effectiveness of fertilizer relative to farmers in Bihar.

The third practice that reduced yield gaps was the use of zero-till for input application. While we did not find that zero-tillage was associated with earlier sowing in our study, we believe the yield gains we observed from using zero tillage were from the added measure of precision in the application of fertilizer and seed relative to these inputs being applied by hand when incorporated by conventional tillage. Rather than applying them by hand, zero-till drills inputs directly in the soil. We speculated that the higher precision of application may be a contributing factor as to why fertilizer efficiencies were greater in Bihar, India than Nepal. We believe zero-till is a potential intervention that not only improves the efficacy of fertilizer through greater precision of application, but also saves time in labor costs. Lastly, we found that more irrigations led to smaller yield gaps. Farmers in Bihar were applying on average two irrigations compared to the single irrigation used in Nepal. We suspected that the extra irrigation in Bihar was part of adaptive management to hotter, drier climate, and also a better capacity for cash investment compared to Nepal.

The dissimilarities of agronomic practices and yield gaps we observed between Nepal and Bihar were related to socioeconomics and government policies of each region. Even though farmers in Bihar faced some similar constraints to farmers in Nepal, better financial and policy support for infrastructure and agricultural inputs, extension, research at the federal level and development of private service networks in Bihar made a marked improvement in yield outcomes. One major difference agricultural practices we observed in our study was the significant adoption of zero-till in Bihar and poor adoption in Nepal. We considered zero-till to be a method by which farmers could achieve higher input and labor efficiencies. While greater rates of adoption of zero-till in Nepal should be an agricultural development goal for the future, the current state of farmer socioeconomics and agribusiness has led to low adoption rates. The recognition of these socioeconomic constraints toward larger, more expensive precision agriculture options was the motivating factor to introduce the chest-mounted spreader. The spreader was affordable, easy to maintain, yet still provided a measure of agricultural precision. We considered the chest-mounted spreader to be a technology that was capable of reducing within field variability of wheat yield by introducing more uniformity to the application of farm inputs. This research question drove our investigation of the impacts of using the chest-mounted spreader in Nepal.

The introduction of the chest-mounted spreader was found to have agronomic benefits when compared to the traditional practice of applying inputs by hand. Using the chest-mounted spreader, farmers were able to increase their input and labor efficiencies, and reduce the variability of yield within their farms. Increased input efficiencies and more stable yields led to consistent return on investments for farmers, which was not the case when inputs were applied by hand. We also observed that the influence of waterlogging stress – a stress identified to be associated with waterlogged conditions early in the plant development – was reduced when a more uniform application of inputs was applied. We believed both the increase in efficiency of both seed and fertilizer, and the reduction of the influence of waterlogging stress was the result of plants having more uniform access to nutrients. By reducing the within-field aggregation of nutrients, individual plants were able to have a higher likelihood of utilizing these resources which improved fertilizer efficiency. We also contend that this mechanism was associated with greater resilience to waterlogging stress by providing nutrients during critical growth periods when stress was abundant, effectively allowing well-nourished crops grow through the stress.

The utility of the chest-mounted spreader lies within its ability to increase labor and fertilizer efficiencies when compared to applying inputs by hand. Increasing efficiencies will be part of a holistic solution towards the problem of under investment in farms in the Eastern Indo Gangetic Plains. This is particularly true for fertilizer and seed inputs, because farmers who have applied inputs by hand demonstrated no relationship between the amount of fertilizer or seed they applied and their final yield. We believed this lack of relationship led to farmers having no guarantee of return on investment to increased input rates, creating a dubious reason to buy more fertilizer and likely contributed towards lack of investment in farms. Solving this problem of input inefficiency, and subsequently convincing farmers that precision agriculture can be part of a successful farming operation, may be a good start for more mechanization in the Nepali landscape as farmers see the benefits. The benefits we saw to labor efficiency also showed promise towards helping improve the productivity in the Nepali farming system. With agricultural labor diminishing, and larger mechanization like zero-till inaccessible for most farmers, the chest-mounted spreader is a useful tool towards reducing labor constraints. With no previous experience, researchers were able to achieve the same yields as farmers who had on average 22 years experience and at double the speed per hectare. Instead of needing specialized labor trained in input application, farmers can own chest-mounted spreaders or hire service providers with this equipment to complete the operation in more timely fashion. This is critical with respect to labor bottlenecks, in particular early sowing of wheat in an effort to reduce the impact of terminal heat stress.

We also observed that farmers reduced their yields by applying flood irrigation too early in the development of their wheat crop, causing waterlogging stress. In addition to using the chest-mounted spreader to reduce the impact of waterlogging stress, we found that when using a single irrigation, delaying irrigation until the crop was more robust to stress around the tillering development stage improved yields. This problem reflected the larger context of unavailability of diesel pumps on the landscape, competition among farmers for the best times to irrigate, and perhaps a lack of knowledge about the susceptibility of younger wheat plants to waterlogging stress.

Our research identified multiple agronomic practices and technologies that helped improve farmers' yields. We believed the greatest tools for improvement within the Eastern Indo Gangetic Plains using agronomic were those that increased the efficiency of inputs, because farmers in Bihar and Nepal are both constrained by their costs. We also found that waterlogging stress had a real impact to wheat yields, and that changes to irrigation scheduling could reduce its impact. We believe incorporating these findings into future policy can help improve outcomes for farmers in our study area.

APPENDIX A: ADDITIONAL TABLES AND FIGURE FOR PRIORITIES FOR WHEAT INTENSIFICATION IN THE EASTERN INDO-GANGETIC PLAINS

Table A.1a – parameter estimates for Bihar, India

	Coefficient	SE	DF	t-value	p-value	Random effects	SD
dtm	75.1998	8.9671	326	8.38616	0	Env. Cluster	211.09
sdoy	-28.217	4.8757	326	-5.7872	0	Village	644.1
PCI	-0.1594	0.3686	25	-0.4325	0.6691	Residual	654.2
n.kgha	25.6721	10.6903	326	2.40145	0.0169		
$n.kgha^2$	-0.0746	0.0408	326	-1.83	0.0682		
p.kgha	11.1646	3.5971	326	3.1038	0.0021		
k.kgha	0.677	1.997	326	0.33903	0.7348		
sd.kgha	-9.0489	2.9214	326	-3.0975	0.0021		
irrig	-926.7	352.809	326	-2.6266	0.009		
$irrig^2$	222.721	71.7899	326	3.1024	0.0021		
zt	374.902	131.469	326	2.85164	0.0046		

[a]Explanation of fixed effects parameters: dtm, days to maturity; sdoy, sowing day of year; PCI, Per Capita Income; n.kgha, N kg ha^{-1}; $n.kgha^2$, quadratic term of N kg ha^{-1}; p.kgha, P kg ha^{-1}; k.kgha, K kg ha^{-1}; sd.kgha, Seed kg ha^{-1}; irrig, number of irrigations; $irrig^2$, quadratic term of irrigation number; zt, zero till.

Table A.1b - parameter estimates the Terai of Nepal

	Coefficient	SE	DF	t-value	p-value	Random effects	SD
sdoy	-8.796	2.1561	730	-4.0796	0.0001	Village	501.9
PCI	0.2696	0.6703	730	0.40219	0.6877	Residual	616.01
n.kgha	4.2552	1.0869	730	3.91498	0.0001		
p.kgha	-4.7578	1.8193	730	-2.6151	0.0091		
k.kgha	9.091	2.6094	730	3.48395	0.0005		
irrig	128.278	50.2208	730	2.55427	0.0108		

[a]Explanation of fixed effects parameters: sowing day of year; PCI, Per Capita Income; n.kgha, N kg ha^{-1}; p.kgha, P kg ha^{-1}; irrig, number of irrigations; $irrig^2$.

Table A.1c - parameter estimates
Environmental cluster 1

	Coefficient	SE	DF	t-value	p-value	Random effects	SD
sdoy	-4.516	2.6665	509	-1.6936	0.0909	Village	514.1
PCI	3.1679	2.5867	509	1.22471	0.2213	Residual	608.4
n.kgha	4.5752	1.2783	509	3.5791	0.0004		
p.kgha	-4.4148	2.1321	509	-2.0707	0.0389		
k.kgha	10.0509	3.8386	509	2.61836	0.0091		

[a]Explanation of fixed effects parameters: sdoy, sowing day of year; PCI, Per Capita Income; n.kgha, N kg ha^{-1}; p.kgha, P kg ha^{-1}; k.kgha, K kg ha^{-1}.

Table A.1d - parameter estimates
Environmental cluster 2

	Coefficient	SE	DF	t-value	p-value	Random effects	SD
sdoy	28.663	19.813	83	1.44666	0.1518	Village	243.7
dtm	243.421	39.9228	83	6.0973	0	Residual	702.1
PCI	-0.184	0.6111	6	-0.3015	0.7732		
n.kgha	4.848	3.7219	83	1.30254	0.1963		
p.kgha	11.886	7.5983	83	1.56435	0.1215		
k.kgha	14.662	7.2019	83	2.03592	0.0449		
sdoy*dtm	-4.476	1.2763	83	-3.5074	0.0007		

[a]Explanation of fixed effects parameterssdoy, sowing day of year; : dtm, days to maturity; PCI, Per Capita Income; n.kgha, N kg ha^{-1}; p.kgha, P kg ha^{-1}; k.kgha, K kg ha^{-1}; dtm*sdoy, interaction effect between cultivar maturity and sowing day of year.

Table A.1e - parameter estimates
Environmental cluster 3

	Coefficient	SE	DF	t-value	p-value	Random effects	SD
dtm	-4.583	13.442	192	-0.3409	0.7335	Village	562.5
sdoy	-18.278	4.4258	192	-4.1298	0.0001	Residual	626.3
PCI	1.46	0.6005	192	2.43169	0.0159		
n.kgha	7.081	2.0764	192	3.41032	0.0008		
p.kgha	-4.23	3.9644	192	-1.0669	0.2873		
irrig	199.823	77.1338	192	2.5906	0.0103		

[a]Explanation of fixed effects parameters: dtm, days to maturity; sdoy, sowing day of year; PCI, Per Capita Income; n.kgha, N kg ha^{-1}; p.kgha, P kg ha^{-1}; k.kgha; irrig, number of irrigations.

Table A.1f - parameter estimates
Environmental cluster 4

	Coefficient	SE	DF	t-value	p-value	Random effects	SD
sdoy	-11.243	6.7777	60	-1.6589	0.1024	Village	218.3
PCI	6.3448	2.8304	11	2.24169	0.0466	Residual	733.1
k.kgha	15.7782	7.0995	60	2.22244	0.03		

[a]Explanation of fixed effects parameters: sowing day of year; PCI, Per Capita Income; k.kgha, K kg ha^{-1}.

Table A. 1g - parameter estimates
Environmental cluster 5

	Coefficient	SE	DF	t-value	p-value	Random effects	SD
sdoy	-25.185	5.4629	181	-4.6103	0	Village	588.4
dtm	55.6	12.1916	181	4.56055	0	Residual	671.2
PCI	-0.322	0.4119	16	-0.7819	0.4457		
n.kgha	38.268	14.8367	181	2.57929	0.0107		
$n.kgha^2$	-0.12	0.0577	181	-2.0792	0.039		
p.kgha	12.641	4.2259	181	2.99122	0.0032		
sd.kgha	-4.79	3.5255	181	-1.3587	0.1759		
zt	697.001	173.264	181	4.02277	0.0001		

[a]Explanation of fixed effects parameters: sdoy, sowing day of year; dtm, days to maturity; PCI, Per Capita Income; n.kgha, N kg ha^{-1}; $n.kgha^2$, quadratic term of N kg ha^{-1}; p.kgha, P kg ha^{-1}; sd.kgha, Seed kg ha^{-1}; zt, zero till.

Table A.2a Nepal varietal information

ID	Variety	Frequency	% adoption	Yield (kg ha^{-1})	Yield std. dev.
1	Aaditya	26	0.03	2153	522
2	ANL	10	0.01	1927	552
3	Bhrikuti	213	0.26	2062	605
4	Bijay	69	0.08	2116	588
5	BL 3629	1	0.00	1500	NA
6	Gautam	89	0.11	2330	715
7	Janaki	1	0.00	5362	NA
8	krishna	1	0.00	2062	NA
9	Kundan	5	0.01	2564	729
10	Local	89	0.11	2289	681
11	Naini	2	0.00	1717	839
12	Nepal 297	13	0.02	2183	712
13	Nepal 502	1	0.00	2550	NA
14	Ni 343	4	0.00	1883	198
15	NL	76	0.09	2176	685
16	NL 251	1	0.00	1800	NA
17	NL 297	96	0.12	2402	703
18	NL 971	8	0.01	2254	657
19	NN296	1	0.00	1200	NA
20	Others	22	0.03	2241	709
21	PBW 232	1	0.00	2250	NA
22	PBW 333	1	0.00	1500	NA
23	PBW 342	1	0.00	2250	NA
24	PBW 343	54	0.07	2351	665
25	PBW 345	1	0.00	1500	NA
26	PBW 363	1	0.00	2294	NA
27	PBW 502	15	0.02	2183	756
28	PBW 503	1	0.00	2178	NA
29	PBW 505	2	0.00	1688	265
30	PBW 543	1	0.00	1750	NA
31	PBW 573	1	0.00	1200	NA
32	Rajdevi	1	0.00	2786	NA
33	Rohenee	1	0.00	2700	NA
34	Rohit	1	0.00	3135	NA
35	RR 21	3	0.00	2147	373
36	Sarvottam	1	0.00	2250	NA
37	Suji	1	0.00	2475	NA
38	UP	1	0.00	2438	NA

Table A.2b Bihar, Indian Varietal Information

ID	Variety	Frequency	% adoption	Yield (kg ha^{-1})	Yield std. dev.
1	Baaz	19	0.05	3987	819
2	CBW 39	5	0.01	5120	1000
3	CSW 16	2	0.01	5075	601
4	CSW 18	1	0.00	3500	NA
5	HD 2733	44	0.12	4762	772
6	HD 2824	7	0.02	4557	828
7	HD 2967	8	0.02	5266	693
8	HD 2985	3	0.01	2713	690
9	HUW 234	12	0.03	2402	437
10	Kedar	1	0.00	2850	NA
11	KRL 210	1	0.00	2860	NA
12	Lok1	23	0.06	2700	689
13	PBW 154	13	0.04	2350	376
14	PBW 343	112	0.31	4543	979
15	PBW 373	26	0.07	3186	1238
16	PBW 502	77	0.21	4435	979
17	PBW 550	1	0.00	4570	NA
18	Raj 4120	4	0.01	4380	1006
19	Ufan	1	0.00	2340	NA
20	UP 262	4	0.01	2375	490
21	WH 711	1	0.00	3320	NA

Table A.3a – Eastern Indo-Gangetic Plains summary statistics for elite, low-performing, and average yielding farmers.

Eastern Indo-Gangetic Plains													
Units	Days	kg ha-1	kg ha-1	kg ha-1	kg ha-1	Julian Days	# of events	% adoption	% adoption	% adoption	$USD	kg ha-1	kg ha-1
Elite													
Mean	Cultivar Maturity	Nitrogen	Phosphate	Potassium	Seed	Sowing Date	Irrigations	zero till	rotovation	cultivation	Per Capita Income	YGF	Yield
	122.98	93.98	50.86	14.67	143.15	328.62	1.82	0.23	0.41	0.37	611.00	0.00	3693.92
SD	Cultivar Maturity	Nitrogen	Phosphate	Potassium	Seed	Sowing Date	Irrigations	zero till	rotovation	cultivation	Per Capita Income	YGF	Yield
	4.80	41.61	20.83	19.30	32.27	10.92	0.86	0.42	0.49	0.48	208.05	0.00	1176.19
Low-performing													
Mean	Cultivar Maturity	Nitrogen	Phosphate	Potassium	Seed	Sowing Date	Irrigations	zero till	rotovation	cultivation	Per Capita Income	YGF	Yield
	121.90	95.09	52.55	8.81	131.68	333.92	1.78	0.47	0.28	0.25	640.81	-3106.81	2217.17
SD	Cultivar Maturity	Nitrogen	Phosphate	Potassium	Seed	Sowing Date	Irrigations	zero till	rotovation	cultivation	Per Capita Income	YGF	Yield
	5.46	34.03	17.28	15.35	24.54	10.42	0.78	0.50	0.45	0.44	315.43	418.67	908.79
Farmer Averages													
Mean	Cultivar Maturity	Nitrogen	Phosphate	Potassium	Seed	Sowing Date	Irrigations	zero till	rotovation	cultivation	Per Capita Income	YGF	Yield
	122.06	95.04	53.47	12.09	141.86	329.93	1.64	0.29	0.35	0.36	619.18	-1252.44	2799.23
SD	Cultivar Maturity	Nitrogen	Phosphate	Potassium	Seed	Sowing Date	Irrigations	zero till	rotovation	cultivation	Per Capita Income	YGF	Yield
	5.27	38.56	18.82	20.03	29.34	12.07	0.77	0.45	0.48	0.48	252.13	927.64	1238.13

Table A.3b – Bihar, India, summary statistics for elite, low-performing, and average yielding farmers.

Bihar, India													
Units	Days	kg ha-1	kg ha-1	kg ha-1	kg ha-1	Julian Days	# of events	% adoption	% adoption	% adoption	$USD	kg ha-1	kg ha-1
Elite													
Mean	Cultivar Maturity	Nitrogen	Phosphate	Potassium	Seed	Sowing Date	Irrigations	zero till	rotovation	cultivation	Per Capita Income	YGF	Yield
	126.38	147.08	70.47	23.51	113.41	327.03	2.57	0.86	0.00	0.14	462.68	-18.38	5228.92
SD	Cultivar Maturity	Nitrogen	Phosphate	Potassium	Seed	Sowing Date	Irrigations	zero till	rotovation	cultivation	Per Capita Income	YGF	Yield
	3.94	26.18	13.38	27.57	14.63	13.67	0.83	0.35	0.00	0.35	391.88	37.53	1099.65
Low-performing													
Mean	Cultivar Maturity	Nitrogen	Phosphate	Potassium	Seed	Sowing Date	Irrigations	zero till	rotovation	cultivation	Per Capita Income	YGF	Yield
	118.97	118.19	56.89	10.62	116.84	338.30	2.24	0.84	0.00	0.16	755.86	-3572.43	2477.84
SD	Cultivar Maturity	Nitrogen	Phosphate	Potassium	Seed	Sowing Date	Irrigations	zero till	rotovation	cultivation	Per Capita Income	YGF	Yield
	5.07	25.30	12.32	18.54	11.33	9.18	0.64	0.37	0.00	0.37	407.52	302.69	659.39
Farmer Averages													
Mean	Cultivar Maturity	Nitrogen	Phosphate	Potassium	Seed	Sowing Date	Irrigations	zero till	rotovation	cultivation	Per Capita Income	YGF	Yield
	125.58	132.13	66.52	23.35	116.61	329.87	2.38	0.87	0.00	0.13	483.56	-1458.86	4121.36
SD	Cultivar Maturity	Nitrogen	Phosphate	Potassium	Seed	Sowing Date	Irrigations	zero till	rotovation	cultivation	Per Capita Income	YGF	Yield
	5.01	30.82	13.84	28.80	15.38	12.98	0.65	0.34	0.00	0.34	408.64	1071.80	1197.60

Table A.3c – Terai of Nepal, summary statistics for elite, low-performing, and average yielding farmers.

Terai of Nepal													
Units	Days	kg ha-1	kg ha-1	kg ha-1	kg ha-1	Julian Days	# of events	% adoption	% adoption	% adoption	$USD	kg ha-1	kg ha-1
Elite													
Mean	Cultivar Maturity	Nitrogen	Phosphate	Potassium	Seed	Sowing Date	Irrigations	zero till	rotovation	cultivation	Per Capita Income	YGF	Yield
	121.82	77.89	44.29	11.00	152.11	329.74	1.56	0.04	0.53	0.43	661.97	0.00	3193.39
SD	Cultivar Maturity	Nitrogen	Phosphate	Potassium	Seed	Sowing Date	Irrigations	zero till	rotovation	cultivation	Per Capita Income	YGF	Yield
	4.52	29.72	17.85	13.21	30.55	10.22	0.70	0.20	0.50	0.50	81.33	0.00	635.36
Low-performing													
Mean	Cultivar Maturity	Nitrogen	Phosphate	Potassium	Seed	Sowing Date	Irrigations	zero till	rotovation	cultivation	Per Capita Income	YGF	Yield
	122.95	76.17	48.25	3.67	149.16	331.10	1.18	0.05	0.60	0.35	678.01	-2764.22	1509.30
SD	Cultivar Maturity	Nitrogen	Phosphate	Potassium	Seed	Sowing Date	Irrigations	zero till	rotovation	cultivation	Per Capita Income	YGF	Yield
	5.11	29.19	17.89	6.70	25.04	9.20	0.52	0.22	0.49	0.48	56.76	336.19	415.54
Farmer Averages													
Mean	Cultivar Maturity	Nitrogen	Phosphate	Potassium	Seed	Sowing Date	Irrigations	zero till	rotovation	cultivation	Per Capita Income	YGF	Yield
	121.99	78.45	47.64	7.05	153.15	329.96	1.30	0.03	0.51	0.46	679.84	-1160.10	2207.83
SD	Cultivar Maturity	Nitrogen	Phosphate	Potassium	Seed	Sowing Date	Irrigations	zero till	rotovation	cultivation	Per Capita Income	YGF	Yield
	4.69	28.92	17.80	11.32	26.97	11.65	0.55	0.18	0.50	0.50	74.39	839.76	667.75

Table A.3d – Environmental Cluster 1, summary statistics for elite, low-performing, and average yielding farmers.

Environmental Cluster 1													
Units	Days	kg ha-1	kg ha-1	kg ha-1	kg ha-1	Julian Days	# of events	% adoption	% adoption	% adoption	$USD	kg ha-1	kg ha-1
Elite													
Mean	Cultivar Maturity	Nitrogen	Phosphate	Potassium	Seed	Sowing Date	Irrigations	zero till	rotovation	cultivation	Per Capita Income	YGF	Yield
	122.67	89.88	50.41	6.86	153.38	329.66	1.40	0.07	0.55	0.38	696.95	-3.67	3106.79
SD	Cultivar Maturity	Nitrogen	Phosphate	Potassium	Seed	Sowing Date	Irrigations	zero till	rotovation	cultivation	Per Capita Income	YGF	Yield
	4.80	26.99	16.01	11.31	27.91	9.32	0.62	0.26	0.50	0.49	27.18	11.96	544.31
Low-performing													
Mean	Cultivar Maturity	Nitrogen	Phosphate	Potassium	Seed	Sowing Date	Irrigations	zero till	rotovation	cultivation	Per Capita Income	YGF	Yield
	124.17	78.52	49.07	2.33	150.29	329.73	1.14	0.06	0.65	0.29	698.84	-2767.37	1461.48
SD	Cultivar Maturity	Nitrogen	Phosphate	Potassium	Seed	Sowing Date	Irrigations	zero till	rotovation	cultivation	Per Capita Income	YGF	Yield
	5.01	26.79	16.62	5.45	25.10	8.62	0.40	0.25	0.48	0.46	14.00	353.63	408.49
Farmer Averages													
Mean	Cultivar Maturity	Nitrogen	Phosphate	Potassium	Seed	Sowing Date	Irrigations	zero till	rotovation	cultivation	Per Capita Income	YGF	Yield
	121.87	82.27	50.10	4.06	153.59	329.17	1.17	0.04	0.54	0.42	701.47	-1229.69	2126.15
SD	Cultivar Maturity	Nitrogen	Phosphate	Potassium	Seed	Sowing Date	Irrigations	zero till	rotovation	cultivation	Per Capita Income	YGF	Yield
	4.73	27.77	16.89	8.47	24.02	11.48	0.44	0.21	0.50	0.49	22.29	831.15	631.46

Table A.3e – Environmental Cluster 2, summary statistics for elite, low-performing, and average yielding farmers.

Environmental Cluster 2													
Units	Days	kg ha-1	kg ha-1	kg ha-1	kg ha-1	Julian Days	# of events	% adoption	% adoption	% adoption	$USD	kg ha-1	kg ha-1
Elite													
Mean	Cultivar Maturity	Nitrogen	Phosphate	Potassium	Seed	Sowing Date	Irrigations	zero till	rotovation	cultivation	Per Capita Income	YGF	Yield
	128.40	149.90	71.76	22.20	118.60	323.10	3.40	1.00	0.00	0.00	395.00	-28.00	5622.00
SD	Cultivar Maturity	Nitrogen	Phosphate	Potassium	Seed	Sowing Date	Irrigations	zero till	rotovation	cultivation	Per Capita Income	YGF	Yield
	0.84	14.82	8.47	12.02	13.38	7.77	0.52	0.00	0.00	0.00	198.80	61.97	400.08
Low-performing													
Mean	Cultivar Maturity	Nitrogen	Phosphate	Potassium	Seed	Sowing Date	Irrigations	zero till	rotovation	cultivation	Per Capita Income	YGF	Yield
	118.55	113.09	56.61	2.18	120.45	339.55	2.27	0.82	0.00	0.18	682.00	-3814.55	2035.46
SD	Cultivar Maturity	Nitrogen	Phosphate	Potassium	Seed	Sowing Date	Irrigations	zero till	rotovation	cultivation	Per Capita Income	YGF	Yield
	3.24	21.79	13.95	7.24	6.07	5.20	0.90	0.40	0.00	0.40	0.00	101.13	101.13
Farmer Averages													
Mean	Cultivar Maturity	Nitrogen	Phosphate	Potassium	Seed	Sowing Date	Irrigations	zero till	rotovation	cultivation	Per Capita Income	YGF	Yield
	122.00	130.63	64.87	10.29	119.89	334.40	2.71	0.97	0.00	0.03	486.74	-1751.38	3797.18
SD	Cultivar Maturity	Nitrogen	Phosphate	Potassium	Seed	Sowing Date	Irrigations	zero till	rotovation	cultivation	Per Capita Income	YGF	Yield
	7.58	25.23	12.58	12.47	11.72	11.43	0.68	0.17	0.00	0.17	207.19	1331.17	1335.24

Table A.3f – Environmental cluster 3, summary statistics for elite, low-performing, and average yielding farmers.

Environmental Cluster 3													
Units	Days	kg ha-1	kg ha-1	kg ha-1	kg ha-1	Julian Days	# of events	% adoption	% adoption	% adoption	$USD	kg ha-1	kg ha-1
Elite													
Mean	Cultivar Maturity	Nitrogen	Phosphate	Potassium	Seed	Sowing Date	Irrigations	zero till	rotovation	cultivation	Per Capita Income	YGF	Yield
	120.83	73.42	39.93	18.94	148.89	328.75	1.72	0.06	0.47	0.47	586.97	0.00	3408.50
SD	Cultivar Maturity	Nitrogen	Phosphate	Potassium	Seed	Sowing Date	Irrigations	zero till	rotovation	cultivation	Per Capita Income	YGF	Yield
	3.92	40.72	19.28	15.64	33.57	12.45	0.78	0.23	0.51	0.51	162.22	0.00	1181.86
Low-performing													
Mean	Cultivar Maturity	Nitrogen	Phosphate	Potassium	Seed	Sowing Date	Irrigations	zero till	rotovation	cultivation	Per Capita Income	YGF	Yield
	121.79	83.21	48.82	24.67	133.08	327.13	1.58	0.33	0.29	0.38	426.17	-2930.71	2909.25
SD	Cultivar Maturity	Nitrogen	Phosphate	Potassium	Seed	Sowing Date	Irrigations	zero till	rotovation	cultivation	Per Capita Income	YGF	Yield
	4.73	37.16	19.92	21.15	26.98	7.46	0.72	0.48	0.46	0.49	225.71	412.97	1241.26
Farmer Averages													
Mean	Cultivar Maturity	Nitrogen	Phosphate	Potassium	Seed	Sowing Date	Irrigations	zero till	rotovation	cultivation	Per Capita Income	YGF	Yield
	121.04	86.64	48.82	25.67	142.53	328.75	1.74	0.22	0.36	0.42	527.60	-1071.46	3018.17
SD	Cultivar Maturity	Nitrogen	Phosphate	Potassium	Seed	Sowing Date	Irrigations	zero till	rotovation	cultivation	Per Capita Income	YGF	Yield
	4.54	44.09	21.83	24.98	32.68	11.54	0.70	0.42	0.48	0.50	233.46	904.87	1335.25

Table A.3g – Environmental cluster 4, summary statistics for elite, low-performing, and average yielding farmers.

Environmental Cluster 4													
Units	Days	kg ha-1	kg ha-1	kg ha-1	kg ha-1	Julian Days	# of events	% adoption	% adoption	% adoption	$USD	kg ha-1	kg ha-1
Elite													
Mean	Cultivar Maturity	Nitrogen	Phosphate	Potassium	Seed	Sowing Date	Irrigations	zero till	rotovation	cultivation	Per Capita Income	YGF	Yield
	121.50	62.50	35.42	18.90	140.90	329.30	2.00	0.00	0.30	0.70	599.10	0.00	3698.70
SD	Cultivar Maturity	Nitrogen	Phosphate	Potassium	Seed	Sowing Date	Irrigations	zero till	rotovation	cultivation	Per Capita Income	YGF	Yield
	4.53	17.47	21.50	16.12	39.57	7.60	0.82	0.00	0.48	0.48	56.20	0.00	486.12
Low-performing													
Mean	Cultivar Maturity	Nitrogen	Phosphate	Potassium	Seed	Sowing Date	Irrigations	zero till	rotovation	cultivation	Per Capita Income	YGF	Yield
	119.63	67.75	46.27	8.63	153.75	343.00	1.88	0.00	0.38	0.63	581.88	-2658.75	1400.25
SD	Cultivar Maturity	Nitrogen	Phosphate	Potassium	Seed	Sowing Date	Irrigations	zero till	rotovation	cultivation	Per Capita Income	YGF	Yield
	3.50	15.99	16.53	8.31	40.69	19.20	1.13	0.00	0.52	0.52	1.55	332.42	210.85
Farmer Averages													
Mean	Cultivar Maturity	Nitrogen	Phosphate	Potassium	Seed	Sowing Date	Irrigations	zero till	rotovation	cultivation	Per Capita Income	YGF	Yield
	119.43	70.24	43.26	12.36	150.57	331.32	1.71	0.00	0.36	0.64	588.52	-1220.16	2504.11
SD	Cultivar Maturity	Nitrogen	Phosphate	Potassium	Seed	Sowing Date	Irrigations	zero till	rotovation	cultivation	Per Capita Income	YGF	Yield
	3.87	21.05	16.48	12.73	36.84	13.25	0.75	0.00	0.48	0.48	35.06	839.54	774.80

Table A.3h – Environmental cluster 5, summary statistics for elite, low-performing, and average yielding farmers.

Environmental Cluster 5													
Units	Days	kg ha-1	kg ha-1	kg ha-1	kg ha-1	Julian Days	# of events	% adoption	% adoption	% adoption	$USD	kg ha-1	kg ha-1
Elite													
Mean	Cultivar Maturity	Nitrogen	Phosphate	Potassium	Seed	Sowing Date	Irrigations	zero till	rotovation	cultivation	Per Capita Income	YGF	Yield
	124.95	146.95	69.62	25.14	112.10	331.05	2.24	0.90	0.00	0.10	506.48	-7.62	4870.95
SD	Cultivar Maturity	Nitrogen	Phosphate	Potassium	Seed	Sowing Date	Irrigations	zero till	rotovation	cultivation	Per Capita Income	YGF	Yield
	4.76	29.25	14.56	32.70	14.72	16.01	0.70	0.30	0.00	0.30	442.72	17.00	1265.77
Low-performing													
Mean	Cultivar Maturity	Nitrogen	Phosphate	Potassium	Seed	Sowing Date	Irrigations	zero till	rotovation	cultivation	Per Capita Income	YGF	Yield
	122.00	117.43	58.41	7.90	113.10	335.00	2.14	0.71	0.00	0.29	952.71	-3161.91	2929.05
SD	Cultivar Maturity	Nitrogen	Phosphate	Potassium	Seed	Sowing Date	Irrigations	zero till	rotovation	cultivation	Per Capita Income	YGF	Yield
	6.32	26.76	12.75	17.26	14.00	11.05	0.48	0.46	0.00	0.46	571.51	469.78	609.88
Farmer Averages													
Mean	Cultivar Maturity	Nitrogen	Phosphate	Potassium	Seed	Sowing Date	Irrigations	zero till	rotovation	cultivation	Per Capita Income	YGF	Yield
	124.74	132.09	66.46	19.36	115.99	330.75	2.27	0.84	0.00	0.16	571.10	-1299.18	4038.54
SD	Cultivar Maturity	Nitrogen	Phosphate	Potassium	Seed	Sowing Date	Irrigations	zero till	rotovation	cultivation	Per Capita Income	YGF	Yield
	5.59	31.69	14.42	28.62	16.56	13.54	0.57	0.37	0.00	0.37	492.09	929.26	1128.19

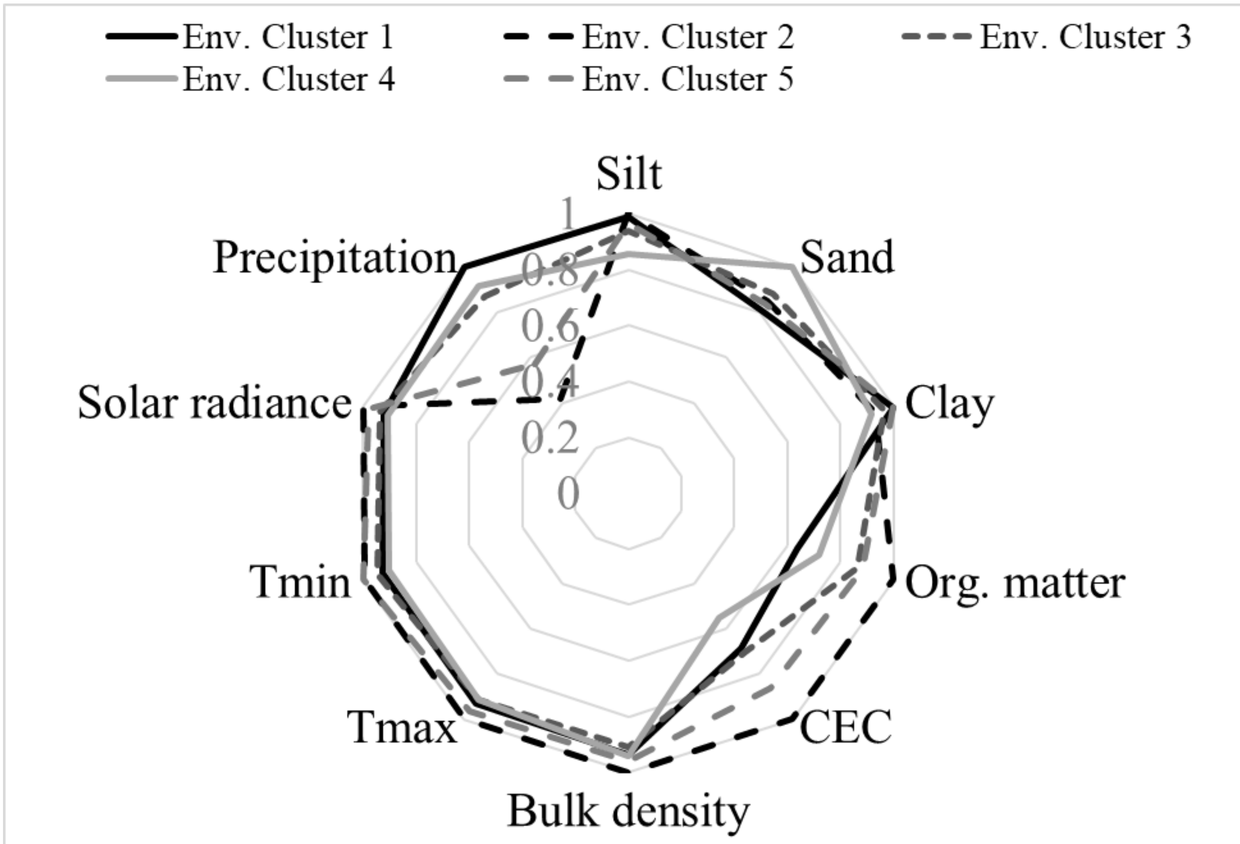

Figure A.1 Radar plot of the percent difference among environmental factors in different environmental clusters. All values were scaled relative to the maximum value of different environmental factors for a relative comparison among factors measured in different values.