AN ASSESSMENT OF THE SITE-SPECIFIC NUTRIENT MANAGEMENT (SSNM) FOR IRRIGATED RICE IN ASIA

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ABSTRACT

Site-specific nutrient management (SSNM) provides guidelines for effective nitrogen, phosphorus and potassium management to help farmers make better decisions on fertilizer input and output levels in rice production. I evaluated the assumptions underlying the SSNM strategy for rice in the top rice producing countries in the world: India, Indonesia, Philippines, Thailand and Vietnam. Using a generalized quadratic production function, I explored whether major nutrients are substitutes as inputs, and if there are complementarities between inorganic fertilizer and soil organic matter (SOM). I also used non-nested hypothesis framework to contrast the quadratic model against the linear von Liebig model. Results showed that the relationships among major nutrients vary across sites – *some inputs are complements, some are substitutes, and some are independent*. In addition, I found that the SOM significantly affects the economic returns to nitrogen fertilizer inputs. Accounting for these relationships in the fertilizer recommendation algorithm can make the SSNM strategy more adaptive to farmer's fields. In areas where soils have limiting organic matter content, fertilizer subsidy or distribution might not be appropriate means to support rice production. Increased rice productivity can be achieved through integrated soil fertility management and adoption of soil conservation technologies.

Keywords: rice, fertilizer recommendations, nitrogen, soil carbon content, organic matter

JEL codes: Q10, Q12, Q16

Introduction

Intensification of agriculture through the use of fertilizer remains one of the most likely options for increasing agricultural productivity in many parts of the world. Agricultural production must become more efficient in the use of fertilizer and essential plant nutrients. To ensure that nitrogen (N) and other essential plant nutrients are provided optimally and are readily available during crop growth periods, it is critical to define and establish an appropriate fertilization rate, which is the foundation to science-based nutrient management (Chuan et al., 2013). Fertilizer recommendation algorithms must adequately account for nutrient interactions as the driving force behind plant uptake.

To address this challenge, the International Rice Research Institute (IRRI) developed the site-specific nutrient management (SSNM) for rice in Asia. Unlike other fertilizer recommendation algorithms that are often derived from factorial fertilizer trials conducted across multiple locations, SSNM is an alternative approach for dynamic management of nutrients to optimize supply and demand of a nutrient within a specific field in a particular cropping season (Dobermann et al., 2004). SSNM defines the optimal amounts of N and other essential plant nutrients as the amounts that maximize yield. The underlying premise of SSNM is that if nutrients are applied to crops at appropriate times and rates, then the use of indigenous and applied nutrients will be optimized.[1] SSNM strategy, through the use of *Nutrient Manager for Rice*[2], is being practiced in Bangladesh, Guangdong, China, Tamil Nadu, India, Indonesia, Philippines, and West Africa (IRRI, 2012). Further work is being conducted to make this decision-tool available on mobile devices in other countries (e.g. Vietnam).

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[1] SSNM strategy offers proper timing and splitting patterns of fertilizer applications through the use of a location-specific nutrient splitting scheme or tools such as leaf color chart.

[2] *Nutrient manager for Rice* is a computer- and mobile phone-based application that provides farmers with fertilizer advice matching their particular farming conditions.

Like Stanford's 1.2 Rule[3], the SSNM fertilizer recommendations are based on the yield goal approach. Yield goal-based recommendations are N fertilizer recommendations that are based on the farmer's "target yield" or the yield that the farmer "hopes to achieve" on his field in a specific production unit, with additional adjustments in some areas for soil organic matter (SOM) or other soil characteristics (Vanotti and Bundy 1994). There are studies that assessed the impacts of SSNM strategy in rice (e.g. Dobermann et al. 2002, Pampolino et al., 2007; Rodriguez and Nga 2012). There are no studies that critically discuss and investigate some of the assumptions underlying the SSNM and its current N, phosphorus (P) and potassium (K) (or NPK) fertilizer recommendation algorithm, and assess its scope for improving irrigated rice management. The yield goal base approach only makes economic sense if the crop production satisfies two restrictions: (1) it is of the von Liebig functional form, i.e. there is a kink in the function, so that input and output prices do not affect the (interior) solution to the profit maximization problem; and (2) the kinks of the von Liebig response curves for different growing conditions lie on a ray out of the origin with a constant slope (Rodriguez and Bullock 2016).

The objective of this study is to discuss and evaluate the principles of SSNM research. I emphasized an underlying assumption about the relationship among the major soil nutrients and organic matter, and the assumption's implications for fertilizer recommendation. I explored whether major nutrients are technically substitutes or complements, and whether ex ante soil conditions matter to the return on investments in inorganic fertilizer, in particular N fertilizer. These issues are critical in the decision-making process of policymakers from the top rice producing countries in the world, and the path that these countries choose to take on fertilizer policy has significant implications for food security through the global market for rice.

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[3] The 1.2 Rule is that the corn producer should apply N fertilizer at a rate of 1.2 lb per acre for every per-acre bushel of a type of yield expected, with adjustments for previous crops grown and other factors.

The SSNM Strategy for Rice

The SSNM strategy for rice requires information on farmer's yield goal, indigenous supply of N, P, and K, and the crop nutrient requirements. Season-specific yield goals are set in the range of 70-80 percent of potential yield.[4] Crop nutrient requirements for a specific yield goal are quantified using the empirical modeling approach in Quantitative Evaluation of the Fertility Tropical Soils or QUEFTS (Jansen et al., 1990). The QUEFTS principles can be expressed in an equation as

$$F_X = \frac{U_X - U_{X_{0X}}}{E_{F_X}} \qquad (1)$$

where *X* is one of the three macronutrients N, P, or K, F_X (kg per ha) is the fertilizer nutrient requirement to achieve a specified yield target, U_X is the predicted optimal nutrient uptake requirement for the specified yield target (kg per ha), $U_{X_{0X}}$ is the indigenous nutrient supply, and E_{Fx} is the agronomic efficiency of fertilizer *X*. The indigenous nutrient supplies of N, P, and K are each defined as the total amount of that nutrient available to the crop from the soil during a cropping cycle, when other nutrients are non-limiting. It is estimated by measuring plant nutrient uptake in an omission plot. For example, the indigenous N supply can be measured as plant *N* uptake at harvest in a small 0-N plot located in a farm field, where P, K, and other nutrients are supplied in sufficient amounts so that plant growth is limited only by the indigenous N supply. This is one distinct characteristic of the SSNM approach, i.e. use of crop-based estimates of the indigenous nutrient supply instead of relying on soil tests. Hence equation (1) can be expressed using yield gain-based approach algorithm:

$$F_X = \frac{\left(Y_G - Y_{GX_{0X}}\right)U'_X}{E_{F_X}} \qquad (2)$$

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[4] Potential yield can be defined as grain yield limited by climate and genotype only, with all other factors not limiting crop growth.

where Y_G reflects the total amount of N, P, or K nutrient that must be taken up by the crop to achieve the yield goal or target yield (Y_G), $Y_{GX_{0X}}$ is X *nutrient*-limited yield or grain yields attainable from the indigenous supply of X nutrient, U_X' (a constant[5]) is the optimal plant nutrient uptake requirement of N, P, or to produce a ton of grain yield, and E_{F_X} is the agronomic efficiency of fertilizer X. Location-specific fertilizer requirements can be calculated for most irrigated rice areas based on the expected yield increase over the respective omission plot and using certain assumptions on plant nutrient requirements and fertilizer efficiency of applied fertilizer nutrients. The QUEFTS model predicts a linear increase in grain yield if nutrients are taken up in balanced amounts of 14.7 kg N, 2.6 kg P, and 14.5 kg K (U_X', equation 2) per one ton of grain yield produced, until the yield reaches about 70-80 percent of the potential yield (Witt et al., 1999). This algorithm is simple with minimal characterization or interviewing of farmers for each field, in order to ensure rapid, cost-effective delivery of field-specific guidelines to millions of small-scale farmers (Buresh et al., 2010).

By estimating a quadratic production function, I investigated two research questions:

(1) Is there evidence of complementary, von Liebig type relationships among N fertilizer, P fertilizer, and K fertilizer?

(2) Does yield response to N fertilizer application depend on the initial state of the soil?

A focus on agronomically optimal nutrient application rates can be misleading if it fails to note the importance of interaction between inputs, whether inputs are substitutes, complements, or independent. Understanding nutrient interactions may provide explanation as to why farmers over- or under-apply nutrients. While IRRI scientists acknowledge that deficiency of any one nutrient will impair the crop uptake and utilization of the other nutrients, there are no studies on

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[5] The nutrient requirement is only a constant if yield goals are chosen that are equal to or lower than 70 to 80 percent of the potential yield.

SSNM that have confirmed if there are indeed von Liebig type complementarities among the major soil nutrients: N, P and K. If nutrients exhibit a von Liebig type relationship, a given level of yield can only be attained by use of single combination of inputs. In this case allocations under profit maximization, which account for relative input and output prices, can be ignored in the fertilizer algorithm. Equation (2) suggests that input and output prices will not affect the amount of fertilizer recommendation. SSNM algorithm only makes economic sense if indeed the rice crop production function is linear von Liebig. The economically optimal fertilizer application rate is the minimum rate at which rice yield reaches its plateau. Any change in the ratios of input prices does not affect the fixed proportion in which inputs are optimally combined in the production process.

Input and output prices, however, affect production decisions of farmers. Dawe (1998) reports that the declining yield growth rates in double- and triple-crop rice monocropping systems were partly due to lower rice prices. When farmers are faced with cash constraints and if there are differences in availability and price of single fertilizer due to differential subsidy levels, they tend to buy and use mostly N fertilizers (Balasubramanian, 1999). If N fertilizer is applied alone, P becomes a limiting element after a few years of intensive cultivation with high doses of N and P application (Balasubramanian, 1999). If P becomes limiting in the soil and if indeed N and P are complements, adding more N fertilizer will not be beneficial for crops.

The existing SSNM algorithm does not also take into account the possible relationship of N fertilizer application and SOM, as reflected in soil carbon contents, C. A few studies show that increasing SOM makes fertilizer application of N more effective and can improve crop yields (e.g. Tiessen et al., 1994; Marenya and Barrett, 2009). Soil organic matter contributes to soil quality and ecosystem function through its influence on soil physical stability, soil microbial activity, nutrient storage and release, and environmental quality (Herrick and Wander, 1997).

Increasing organic C content in SOM reduces soil erosion and degradation, improves surface water quality, and increases soil productivity. Some studies also suggest that SOM content increases under inorganic fertilization, especially for inorganic N fertilizers (e.g. Majumder et al., 2008 and Reid, 2008). Lopez-Bellido et al. (2010) and Luo et al. (2010) suggest that soil organic content does not change, and others suggest that it decreases under inorganic fertilization (e.g. Manna et al., 2006, Khan et al., 2006; Li and Zhang, 2007). Moreover, previous studies show that indigenous N supply was quite variable among fields and not related to SOM content (Cassman, et al. 1996). Organic fertilizers in smallholder agriculture do not add nutrients to a cropping system as a whole, but rather are a means of nutrient transfer (Dobermann, 2004). The organic amendments when used as a complement to inorganic NPK increase yields but that increased yields are due to increased nutrient supply (N, P, K, or other nutrients under conditions of deficient soil nutrient supply) and not the "organic matter effect" (Dawe et al 2003).

I hypothesized that the marginal physical product (MPP), and hence the profitability, of N fertilizer application depends on soil C stocks which may vary systematically in farmers' fields. As an initial test, I used kernel-weighted local polynomial regression[6] to check if rice yields are strongly and directly associated with soil C stocks (Appendix Figures 1-8). With the exception of Suphan Buri, Thailand (SB_TH), there is clear evidence that grain yield increases as SOM increases. The marginal returns (MR) to fertilizer application may vary with SOM. For these reasons, there is a great need to quantify the role of SOM, particularly the soil C stocks, in relation to crop output response to N fertilizer in irrigated rice systems. The complementarity between SOM and N fertilizer application might mean that N fertilizer application becomes unprofitable on soils depleted of SOM (Marenya and Barrett, 2009). Poor soil fertility might

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[6] Weighted least squares regression is used to fit linear or quadratic functions of the predictors at the centers of neighborhoods (Cleveland, 1979). One chief attraction of this regression is that I do not need to specify a function of any form to fit a model to the data, only to fit segments of the data.

actually be a cause, not merely a consequence, of low rates of fertilizer use (Morris et al., 2007). If this is the case, then ex ante soil conditions matter a lot to the return on investments in fertilizer policies (Marenya and Barrett, 2009). In cases where soil degradation has become severe, provision of temporary fertilizer subsidies or cost-shares might not be an appropriate policy.

Literature Review

Most of the published studies on SSNM specifically examined its impact on fertilizer and/or paddy yields, primarily using field experiments. Dobermann et al. (2002) conducted on-farm experiments from 1997 to 1999 to develop and test a new SSNM approach for eight key irrigated rice production domains of Asia located in six countries. The average grain yield increased by 0.36 Mg per hectare with SSNM as compared to current farmers' fertilizer practice (FFP). SSNM also led to significant increases in nitrogen use efficiency. In terms of profitability, SSNM contributed to an increase in profitability of US$46 per hectare on average, across all sites. Son et al. (2004) particularly analyzed the SSNM in irrigated rice systems of the Red River Delta. A SSNM plot was established on each of the 24 farm fields as a comparison with the FFP. As compared to FFP, SSNM increased yield by 0.19 tons per hectare, decreased the total fertilizer cost by about $2 per hectare in 1998 and by $22 per hectare in 1999, and increased average farm profits by $41 per hectare in 1998 and $74 per hectare in 1999.

Pampolino et al. (2007) explored not only the economic benefits of SSNM but also its environmental impacts. SSNM led to higher efficiency of nitrogen use. SSNM decreased the percentage of total N losses from applied fertilizers, reducing the nitrous oxide emissions and global warming. Economic performance of SSNM adopters and non-adopters were also compared using economic data through focus group discussions. Gross revenue and gross return above fertilizer costs were higher for SSNM than non-SSNM farmers across three countries. In

China, Southern India, and the Philippines the profitability in SSNM ranged from $57 to $82 per hectare (Dawe et al 2003). In Vietnam (both southern and northern) intermediate levels of profitability was at $38-39 per hectare. The same was true for northwestern India (Khurana et al 2007) and China (Wang et al 2007). In 2009, Buresh et al. provided alternatives to factorial field trials and rigid nutrient balances for determining fertilizer K and P requirements in the SSNM strategy. However, their proposed framework did not specifically consider soil-plant-nutrient interactions and biological processes mediating nutrient availability.

Published reports on SSNM tend to be optimistic. There are no reports that critique the SSNM approach to fertilizer recommendation, and very few assess its scope for improving irrigated rice production. This paper contributes to the literature by providing a broader scope of analysis of SSNM in the irrigated rice systems by exploring whether there are indeed interactions among essential nutrients N, P, and K and whether complementarities between SOM and applied N fertilizer might mean that fertilizer application becomes unprofitable on soils with low SOM.

Data and Empirical Model

Data

The data on irrigated rice production and input use come from the IRRI project on *Reversing Trends of Declining Productivity in Intensive Irrigated Rice Systems* (RTDP) in five countries (India, Indonesia, Philippines, Vietnam, and Thailand) across tropical and subtropical environments in Asia (Table 1a). In each of the five countries, the data originated from both nutrient omission and fertilizer evaluation trials conducted in farmers' fields (Dobermann et al., 2002). The treatments used in the study are: (1) no fertilizer applied (0 N, 0 P, 0 K), (2) PK applied, 0 N applied, (3) SSNM, and (4) FFP with no interference by IRRI. All data were for irrigated rice, and water rarely limited plant growth. The 0-N plots received 30 kg P fertilizer and

50 kg K fertilizer per hectare. The 0-N, 0-P, and 0-K treatments were separated from the surrounding field by bunds and were moved to a different location after each crop grown, to avoid residual effects caused by nutrient depletion. Each experiment in the five countries was run for three to five years. I only used data for one year in some areas and two years in some areas because of data availability. Each treatment contained two to three replicate sampling plots per farm. Comparable methodologies for plant sampling, yield determination, and analysis for plant nutrients were used for collected data across countries and experiments (Witt et al., 1999). Soil data were collected at the single field/single treatment level, i.e., only for the field used for the agronomic research. Two 6x6 m plots were sampled for each treatment and the samples were processed separately. The total organic C of soil samples from 0-N plots was determined based on Walkley (1947).

The sample farmers at each site were selected based on the following criteria: (1) represent the most common soil types in the region, (2) represent the most typical cropping systems and farm management practices in the region, (3) represent a range of socioeconomic conditions (small to large farms, poor to rich farmers), (4) reasonable accessibility to allow frequent field visits, and (5) farmer interest in participating in the project over a longer term. Socio-economic data were collected at the whole-farm level, i.e. including the field used for the agronomic research as well as other fields belonging to the same farmer.

The Model

The rice production function for each experimental site can be defined by using a generalized quadratic specification (Chambers, 1988)[7]:

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[7] Berck and Helfand (1990) show that in the presence of heterogeneity, the polynomial and linear plus plateau approximations essentially converge, making the quadratic a viable alternative to the von Liebig and linear response

$$y = \beta_0 + \sum_{i=1}^{w} \beta_i x_i + \sum_{i=1}^{w} \sum_{j=1}^{w} \beta_{ij} x_i x_j + e \qquad (3).$$

Here *y* is grain yield, x_i is the vector of independent variables – N applied, P applied, K applied, and soil C stocks, age of farmers, farm area harvested, and dummy variable for high yielding season (HYS) – the β vector comprises the parameter estimates of interest and *e* is an iid N(0, σ^2) error term.[8] In order to explore the systematic relationship among fertilizer NPK application and *ex-ante* soil fertility in each experimental site, I tested the null hypothesis that N fertilizer, P fertilizer, and K fertilizer do not significantly interact with each other and soil C content has no indirect effects on yields through N fertilizer application:

$$\begin{aligned} &H_0: \beta_{ij} = 0 \\ &H_a: \beta_{ij} \neq 0 \end{aligned} \qquad (4).$$

A Wald test was performed to test the joint significance of parameters β_{ij} in equation (3) for each study site. If H_0 cannot be rejected, $\frac{\partial^2 y}{\partial x_i \partial x_j} \equiv \frac{\partial}{\partial x_i}\left(\frac{\partial y}{\partial x_j}\right) \equiv \beta_{ij} \equiv \beta_{ji} \equiv 0$, then it indicates independence of x_i and x_j. The marginal productivity of x_j is not affected by changes in the level of x_i. If H_0 is rejected, then nutrient interaction between x_i and x_j is present. If $\beta_{ij} \equiv \beta_{ji} > 0$, then x_i and x_j are technically complementary. The marginal product of x_i increases as x_j increases and vice versa. If $\beta_{ij} \equiv \beta_{ji} < 0$, then x_i and x_j are technically substitutes. Increasing x_i reduces the marginal productivity of x_j and vice versa. Tables 1b and 1c show the definition and summary of statistics, respectively, for the regression variables.

I used the non-nested hypothesis framework proposed by Davidson and MacKinnon (1983) to contrast the quadratic model (equation 3) against the linear von Liebig model,

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plateau models. Moreover, Berck et al. (2000) find that von Liebig models generally do not fit the data well and that actual estimation does not yield the right angle isoquants described in its derivation.

[8] The *N*, *P*, and *K* fertilizer application of farmers could be endogenous given by the unobserved factors that affect yields. There are no good instruments available to address endogeneity concerns in the production function estimation.

$$y = min\{\theta_0 + \theta_N N, \theta_1 + \theta_P P, \theta_2 + \theta_K K, L\} + e \qquad (5),$$

non-linear von Liebig model,

$$y = min\{\theta_0 + \theta_N N + \theta_{NN} N^2, \theta_1 + \theta_P P, \theta_2 + \theta_{PP} P^2 + \theta_K K + \theta_{KK} K^2, L\} + e \qquad (6),$$

and square-root model,

$$y = \beta_0 + \sum_{i=1}^{w} \beta_i x_i + \sum_{i=1}^{w} \sum_{j=1}^{w} \beta_{ij} \sqrt{x_i x_j} + e \qquad (7)$$

in all the study sites in the study.[9]

The *P* test may also be applied to the case of multivariate nonlinear regression models. The null hypothesis may be written as:

$$H_0: y_{it} = m_{it}(\theta) + u_{it}^0, \qquad u_t^0 \sim N(0, \Omega_0) \qquad (8),$$

and the alternative as:

$$H_1: y_{it} = g_{it}(\beta) + u_{it}^1, \qquad u_t^1 \sim N(0, \Omega_1) \qquad (9).$$

Here *i* indexes the *n* equations, *t* indexes the *T* observations, and Ω_j, *j*=1,2, is the *n*x*n* contemporaneous covariance matrix for the error terms corresponding to hypothesis H_j. The artificial compound model is

$$H_c: y_{it} = (1 - \alpha) m_{it}(\theta) + \alpha \hat{g}_{it} + u_{it} \qquad (10)$$

where, under H_0, the vector u_t should have covariance matrix Ω_0. Linearizing (10) around the point $\alpha = 0, \theta = \hat{\theta}$ yields the multivariate linear regression

$$y_{it} - \hat{m}_{it} = \hat{M}_{it}^T \theta + (\hat{g}_{it} - \hat{m}_{it}) + u_{it} \qquad (11)$$

where $\hat{m}_{it}$ and $\hat{g}_{it}$ denote $m_{it}(\hat{\theta})$ and $g_{it}(\hat{\beta})$, respectively while $\hat{M}_{it}$ denotes the vector of derivatives of $m_{it}(\theta)$ with respect to θ, evaluated at $\hat{\theta}$. This regression is to be estimated by generalized least squares, using $\hat{\Omega}$ as the assumed covariance matrix, and is referred to as the P_0 test. The test statistic is the *t* statistic on $\hat{\alpha}$.

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[9] *L* is the plateau yield.

Results and Discussion

Two variations of my basic model were estimated. In the first model, I only used the nutrients as controls in the production function while in the second model, I included a high-yielding season dummy (HYS) and farm area. I favored the second model over the first for all study sites and discussed only those results. The addition of controls, HYS and farm area in the second model proved to be statistically significant when included in the regression.[10]

Tables 2-4 report the OLS regression results from equation (3) by study site. Across all sites, there are significant coefficient estimates that do not have the expected signs in the first-order term. For example, the expected rice yield is decreasing in soil organic C content in Can Tho, Vietnam (CT_VN). It is possible that large amounts of organic materials repeatedly applied on soil with lower buffering capacity and high reducible iron content may cause acceleration in soil reduction and thereby potential iron toxicity in rice (Ponnamperuma, 1972). Literature suggests that plants suffering from iron toxicity may cover large contiguous areas such as in the Mekong Delta in Vietnam (Becker and Asch, 2005). Single parameter point estimates, however, are of limited usefulness here because it is impossible to vary only one term at a time in equation (3).

Marginal Physical Product and Output Elasticity

Using the regression results reported in Tables 2-4, I estimated the MPP and output elasticity at the mean for each variable on the entire sample plots in all locations (Tables 5-7). Except in Thanjavur (TJ_IN) and Uttar Pradesh (UP_IN) India and CT_VN, the MPP of N (MPP_N) fertilizer application is positive and the output elasticity is less than one, both significant

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[10] There is good reason to believe that some important variables in determining the yield are unobserved (e.g. skill level of farmers). I also ran a farmer fixed effects to correct for unaccounted farmer specific factors that may affect the level of fertilizer applied using the data only from farmers' field practice. I only have data on farmers' age and education. I also favored Model 2 over this model because of its greater precision.

at one percent level. The additional N fertilizer use[11] exerted a significant positive influence on the yield on most plots in the sample. Nitrogen fertilizer application increases the height of the leaves (Chaturvedi, 2005; Mandal et al. 1992), the number of tillers/m^2 (Chaturvedi, 2005; Rajput et al. 1988; Yoshida et al.,1978), and both the number and size of grain (Rupp and Hubner, 1995; Jamieson et al., 1995; Fisher et al., 1977).

The MPP_N is decreasing though in Aduthurai (AD_IN) (Figure 1), Sukamandi (SU_ID) (Figure 2), Nueva Ecija (NE_PH) (Figure 3), and Hanoi (HA) (Figure 4) but increasing in Suphan Buri, Thailand (SB_TH) at all N rates (Figure 5). The maximum yield will be achieved at N rate where the $MPP_N = 0$. These rates are 139 kg per ha in AD_IN, 135 kg per ha in SU_ID, 160 kg per ha in NJ_PH, and 100 kg per ha in HA_VN. In AD_IN, applying 139 kg per ha of N will result to almost 6 tons per ha of grain yield, given all the other factors constant at the mean level. If more than 139 kg per ha is applied, the MPP_N will be negative. The excessive N promotes lodging, and plants become more attractive to insects and diseases.

Meanwhile, the marginal contribution of a kilogram of P (MPP_P) is positive but the output elasticity is greater than one in UP_IN (Table 5). The MPP_P is positive and output elasticity is less than one in SU_ID (Table 6), CT_VN (Table 7) and HA_VN (Table 7) with 1 percent significance level. Phosphorus is a major component in ATP, the molecule that provides “energy” to the plant for such processes as photosynthesis, protein synthesis, nutrient uptake and nutrient translocation. The magnitude of the estimated coefficients of P reveals the significance of this nutrient in rice production, specifically in Vietnam. For example, a kilogram increase in P increases yield by 136 kg per ha in HA_VN. In contrast, NJ_PH and SB_TH have negative estimated MPP_P and output elasticity at the mean level (Table 6), which are both statistically

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[11] Henceforth in this section, the term “*N*” refers to “*N* fertilizer applied” and/or “*N* fertilizer.” Similar interpretations are used for “*P*” and “*K*.”

significant at one percent level. There is a possibility that most of the rice straws are retained in the field and hence those soils are often saturated with P due to continuous P fertilizer application. The extractable Olsen-P was relatively high on all farms in the sample (IRRI, 2012). No additional amount of P fertilizer is required to replenish P removed with grain and straw. The additional P fertilizer application might result to overapplication. The overapplication of P fertilizer does not necessarily lead to environmental damage, but the ability of soil to retain P is limited.

Like the P fertilizer, the marginal product of K fertilizer (MPP_K) varies across sites. The MPP_K is positive and output elasticity is less than one at the mean in SB_TH (Table 6). Potassium plays a key role in many metabolic processes in the plant. Proper K nutrition in rice promotes (1) tillering, (2) panicle development, (3) spikelet fertility, (4) nutrient uptake of nitrogen and phosphorus, (5) leaf area and leaf longevity, (6) disease resistance, (7) root elongation and thickness, (8) and culm (stem) thickness and strength (Aide and Picker, 1996). A negative MPP_K is observed in CT_VN (Table 7). The water from Mekong River Delta has high content of sediments which provides nutrients for crop. The additional K fertilizer application then would not be beneficial. If exchangeable K and K bearing minerals are high in soil, then soil will not be very responsive to K fertilizer addition. The K requirement of rice is sometimes supplied from plant residues turned under and from K in irrigation water (De Datta, 1981).

Evidence of complementarity among N-P-K fertilizers

The main interest of this paper is to explore the relationships among major nutrients and their relationships with inorganic fertilizer, particularly N fertilizer to soil fertility, as reflected in soil organic C content. Table 8 reports the results of the hypotheses testing of the nutrient interactions. The relationship of N, P and K varies across sites. This may be due to the plant's biological processes – *some inputs are complements, some are substitutes, and some are independent*.

The Wald test statistics for the interaction of N and P are not statistically significant in TJ_IN, UP_IN, NE_PH, and SB_TH. Given this, one cannot reject the null hypotheses that there is no interaction between N and P, $(\beta_{NP} = 0)$, in the model. The result can be interpreted such that N and P are independent from each other. If this is the case, the N and P requirements of crop can be estimated independently and can be applied without the other. However, previous studies report that N and P are complements (Sheriff, 2005). Nitrogen and P are found to be complements in SU_ID. Increasing application of P increases the marginal return of N.[12] Phosphorus enhances the root activities of rice crop and when N fertilizer is applied to a rice crop that has a healthy, active root system, the efficiency is high. This is because the N is absorbed before it can be transformed or lost. Moreover, the movement of N within the plant depends largely upon transport through cell membranes, which requires energy to oppose the forces of osmosis. Here, ATP and other high-energy P compounds provide the needed energy. In addition, when rice is grown with heavy N application, a decline in ratio of filled grains is frequently observed (Mae et al., 2006; Matsushima, 1993). The only way to further increase the yield is to improve the photosynthesis and biomass production of the rice (Makino, 2011), hence, through P fertilizer application.

In this regard, another interpretation of the relationship of N and P in TJ_IN, UP_IN, NE_PH, and SB_TH is that N might be already limiting in the soil and adding more P does not contribute to the crop growth, so $(\beta_{NP} = 0)$. Typically, the ratio of N to P is lower in manure than required by crops. If farm manure is used to satisfy the N requirements of crops,

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[12] The price of paddy rice is set at IDR 3,300 and *N* price is IDR 794.

overapplication of P might be possible. Given that N and P are complements, plants require these inputs in a fixed ratio. It is important that proper input ratio is accounted for in fertilizer recommendation algorithm.

There is also no significant interaction between P and K, $(\beta_{PK} = 0)$, in AD_IN, UP_IN, NE_PH, CT_VN, and HA_VN. Again, it is possible that one of the nutrients is already limiting. The marginal products of P and K are very low or even negative. If farmers practice selective fertilizer application, i.e. only applying P, application of K fertilizer to the soil will be limiting in the long run. Adding more K will have no indirect effect on yield. The Wald test also fails to reject the null hypothesis that there is no interaction between N and K fertilizer in AD_IN, TJ_IN, SU_ID, NE_PH, CT_VN, and HA_VN.

While the expectation is that N and P are complements, interestingly, my results provide clear evidence of substitution between these two nutrients in AD_IN and in both sites in Vietnam. Figures 6, 7 and 8 display the kernel-weighted local polynomial smoothing of the estimated marginal value product (MVP) of N against P, along with the cost of N and P fertilizer inputs (red horizontal line)[13]. If two nutrients are substitutes, increasing the application of one nutrient reduces the marginal returns of the other nutrient. The marginal returns of N are all higher than the cost of N at almost all levels of P in AD_IN and HA_VN. In CT_VN, beyond 20 kg/ha of P applied, the marginal returns to N are less than the price of N. This finding can also support the practice of farmers of selective application of nutrients. Compared to phosphate and potash fertilizer, N fertilizer is heavily subsidized in India. Hence, this adversely affects the consumption of P and K fertilizer. While the substitution of N and P maybe justified on economic

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[13] A kilo of rice is INR 24 in India and VND 8,000 in Vietnam. The input cost of *N* fertilizer INR 30 in India and VND 5,600 in Vietnam.

grounds, this relationship needs further research or studies that support it from a biological viewpoint.

On the other hand, N and K are found to be complements in UP_IN. Like phosphorus, K plays an important role in physiological process of rice, and contributes to greater canopy photosynthesis and crop growth. Potassium also increases the number of spikelets per panicle (flowers per grain bunch) and the percentage of filled grain. Individually, N and K significantly decrease yield, $\beta_N < 0$ and $\beta_K < 0$, while significantly increasing the marginal product of N, $(\beta_{NK} > 0)$ (Table 2). A positive relationship between yield and K can occur only if the positive effect of K on the marginal product of N is higher in absolute value than the direct effect of K on yield. Potassium must not be applied alone, but rather in combination with N. Given this, selective application of fertilizer, i.e. only applying N or K when farmers are faced with cash constraints, might bring more harm than good to the crop.

In Thailand, the resulting estimates are intuitive but quite inconsistent. Nitrogen fertilizer can be substituted for P $(\beta_{NP} < 0)$, and P can be substituted for K$(\beta_{PK} < 0)$. Hence, by transitivity, N and K are substitutes $(\beta_{NK} < 0)$ as well. Interestingly, results suggest otherwise. N and K are complements $(\beta_{NK} > 0)$ implying an increase yield due to the positive effect of K on the marginal product of N (Table 3). All else held constant, an extra kilogram of K is associated with an almost two-kilogram increase in yield to a kilogram of N. Given that K is not usually applied in Thailand, deficiency of K will not be a problem because nearly all rice straw (which is high in K) is left on the ground after harvest (Moya et al. 2004).

Is yield response to N fertilizer dependent on the ex-ante state of soil?

I also hypothesized that the yield response to N fertilizer is dependent on the ex-ante state of soil condition. At the ten percent significance level, the Wald test rejects the hypothesis that the interaction term of N and soil C content is jointly zero, $\left(\beta_{OrgCN} = 0\right)$, implying complementarity between soil fertility and N in Philippines and Hanoi, Vietnam (Table 8).

Figures 9 and 10 display the kernel-weighted local polynomial smoothing of the estimated MVP of N against the plots' soil organic C contents for NE_PH, and HA_VN, respectively. The figures clearly provide evidence that there exists a positive relationship between fertilizer yield response and soil C content. The marginal returns to N exceed the price of N fertilizer in both locations at all levels of a plot's soil organic content. The N fertilizer price is PHP 13.30 per kilogram and VND 5600 per kilogram in NJ_PH, and HA_VN, respectively. Figure 9 suggests that the MVP of N is rapidly increasing in all Philippine sample plots. Figure 10 shows that up to a C content level of approximately 17 g/kg, the marginal returns to N in Hanoi do not vary, then it increases at an increasing rate up to a C content level of approximately 22 g/kg, after which it increases at a decreasing rate. If further investments are devoted to increasing soil C content in Vietnam, N fertilizer application is expected to be profitable.

Although the Wald test failed to reject the hypothesis that the interaction term of N and soil carbon content C are jointly zero, $\left(\beta_{OrgCN} = 0\right)$, in all three sites in India, CT_VN and SB_TH, it is possible that soil C content in these areas is already limiting and adding more N does not contribute to the crop growth. For example, Figure 11 shows that at more than around 8 g/kg carbon content, the marginal returns of N fertilizer start to increase in AD. On average, the soil *C* content in AD is only 9 g/kg.

Non-nested Hypothesis Test Results

The results of the non-nested hypothesis tests rejected the linear von Liebig model specification, except in AD_IN (Table 9). The quadratic model outperformed all the rival specifications, both in a pairwise comparison as well as in a collective test against all the alternatives. The yield goal-based approach in SSNM strategy can be misleading. In the case of a quadratic functional form, profit maximization requires information on input and output prices and the marginal product of each increment of fertilizer. The economic optimal fertilizer rate is attained when the marginal product of fertilizer is equal to the ratio of input and output price. Given a non-zero price ratio, there is a difference between the yield maximizing and profit maximizing input levels. Rising fertilizer prices are a particular problem for poor farmers who could not afford sufficient fertilizers.

Conclusion and Policy Implications

In this study, I have reported clear evidence that interaction among major nutrients matters in making fertilizer recommendations to farmers. The relationships among *N*, *P*, and *K* vary across sites -- *some inputs are complements, some are substitutes, and some are independent*. I also found that SOM, manifested in soil C stocks, significantly affected the economic returns to N fertilizer inputs in some areas. The marginal product on N is low on soils with low C content. In other areas, SOM does not have an effect in N fertilizer application.

SSNM strategy should explicitly account for: (1) the nutrient interactions and (2) the relationship of N fertilizer and SOM. Accounting for these effects can make the SSNM strategy more adaptive to farmers' fields and will allow the integration of nutrient management techniques for maximum benefit to rice producers. The application of essential plant nutrients, particularly major nutrients and SOM, in optimal quantities and proportions is key to increased and sustained rice production. In addition, input and output prices should also not be ignored in SSNM algorithm. The quadratic model specification of the crop response outperformed linear von Liebig model. The major challenge for SSNM will be to retain the simplicity of the approach that is understandable to producers and extension agents while accounting for the relationship of NPK and soil organic matter.

The results of this study could stimulate not only IRRI scientists but also policymakers to review the existing fertilizer policies in the study countries. To ensure the effectiveness of fertilizer policies, they must be targeted not only to match the needs, preferences, and resources of farmers, but also to account for the interactions of production inputs. The substitutability, complementarity, or independence of major nutrients and SOM is also critical in the decision-making processes of policymakers from the study countries.

Government more often than not focuses on policies that are conducive to increased availability and consumption of fertilizers. If major nutrients, such as N and P, are substitutes, input and output prices are important in the determination of the economic optimal fertilizer rate. The decisions of farmers about what fertilizer to use depend upon which fertilizers are cheaper to obtain and apply. If major nutrients are complements, then direct subsidies for these nutrients must be considered. For example, if N and P are complements, low subsidized prices for N fertilizer matched by similar level for P fertilizer reduces the probability of farmers practicing selective application when they are faced with cash constraints. Fertilizer subsidy or distribution might not be appropriate means to support rice production, however, in areas where soils have limiting organic matter content. The yield response of rice to N depends on the initial state of the soil. Although IRRI scientists strongly encourage farmers to use organic fertilizer such as farmyard manure in their rice fields, this does not discount the need to explicitly incorporate the interaction of soil C content and N in the SSNM algorithm. In order for farmers to reap significant economic returns from N fertilizer application, soil scientists must ensure that there is adequate amount of SOM. In such a case, government intervention might consider putting greater emphasis on integrated soil fertility management and adoption of soil conservation technologies. Organic sources of nutrients (e.g. farmyard manure, crop residues carried over) can be promoted as a response to rising prices of commercial manufactured fertilizers and as a basis for increasing productivity. Extension agencies and others can potentially encourage further adoption of the use of organic fertilizers by emphasizing to farmers the benefit of organic materials on the physical properties of rice soils.

While the results of this paper suggest that nutrient interactions among major nutrients and soil organic matter tend to vary from site to site, there are two caveats to keep in mind when interpreting these results. First, while the economic analysis suggest that in some areas N and P are substitutes, this relationship needs further research or studies that support it from a biological viewpoint. Most of the previous studies suggest that N and P are complementary inputs. The second caveat is that results from this study only pertain to one to two years of experiment. If the crop response function to major nutrients and SOM varies from year to year, the results are only representative for a given state of nature observed at certain point in time (Anselin, Bongiovanni, and Lowenberg-DeBoer, 2004). A multi-year analysis would be an interesting extension of this study. This demonstrates a frontier where agricultural economists and agronomists can work together.

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Table 1a. Study area, RTDP, IRRI

COUNTRY	REGION/ PROVINCE	RICE DOMAIN	NO. OF FARMERS	CROPPING SYSTEM	CLIMATE	YEARS INCLUDED	CROPPING SEASON[a]
India	Tamil Nadu	Aduthurai	40	Rice-rice	Tropical	97	KR, TH
		Thanjavur	19	Rice-rice	Tropical	97,99	KR, TH
	Uttar Pradesh	Pantnagar	23	Rice-wheat	Sub-Tropical	97	KH
Indonesia	West Java	Sukamandi	30	Rice-rice	Tropical	96,98	DS, WS
Philippines	Nueva Ecija	Maligaya	50	Rice-rice	Tropical	95-96	DS, WS
Thailand	Central Plain	Suphan Buri	27	Rice-rice	Tropical	95-96	DS, WS
Vietnam	Mekong Delta	Can Tho	32	Rice-rice-rice	Tropical	96	DS, WS
	Red River Delta	Hanoi	24	Rice-rice-maize	Sub-Tropical	97	ER, LR

[a] *High yielding season: KR - Kuruvai, DS – Dry Season, ER – Early Rice; Low yielding season: TH – Thaladi, WS – Wet Season, LR – Late Rice.*

Table 1b. Description of variables

Variable	Description
Rice output (kg/ha)	Dependent variable (Y). Kilograms of rice harvested per hectare per season in a given year
Nitrogen applied (N/ha)	Kilogram of N per ha from fertilizers applied
Phosphorus applied (P/ha)	Kilogram of P per ha from fertilizers applied
Potassium (K/ha)	Kilogram of K per ha from fertilizers applied
Org C	Amount of carbon content in the soil (g/kg)
Age (year)	Age in years of the person responsible for production decisions on the plot
Educ (year)	Total years of schooling completed by the farmer
Farm area (ha)	Size of farm owned by the farmer
High yielding season (HYS)	Dummy variable. HYS=1; high yielding season HYS=0; low yielding season

Table 1c. Descriptive statistics

Site/Variable	Obs	Mean	Std. Dev.	Min	Max
INDIA					
Aduthurai					
Rice output (kg/ha)	1121	5 128.03	1 454.71	1 125.00	9 325.00
N applied (kg/ha)	1121	52.87	64.90	0.00	222.97
P applied (kg/ha)	1121	17.54	14.41	0.00	54.58
K applied (kg/ha)	1121	32.95	30.87	0.00	163.47
Org C (g/kg)	1121	9.04	1.25	4.50	14.90
Age (year)	867	47.31	11.74	26.00	70.00
Educ (year)	274	10.58	2.84	5.00	18.00
Farm area (ha)	1121	0.30	0.08	0.00	0.54
HYS	1121	0.37	0.48	0.00	1.00
Thanjavur					
Rice output (kg/ha)	77	4 632.96	1 281.16	1 710.00	7 629.00
N applied (kg/ha)	77	48.34	56.06	0.00	253.10
P applied (kg/ha)	77	10.60	15.31	0.00	72.47
K applied (kg/ha)	77	20.53	30.05	0.00	125.40
Org C (g/kg)	77	71.15	7.88	56.00	85.00
Age (year)	-	-	-	-	-
Educ (year)	-	-	-	-	-
Farm area (ha)	75	0.31	0.17	0.16	0.93
HYS	77	0.92	0.27	0.00	1.00
Uttar Pradesh					
Rice output (kg/ha)	84	5 068.41	1 190.91	2 361.00	7 648.00
N applied (kg/ha)	84	62.97	72.61	0.00	252.50
P applied (kg/ha)	84	24.64	8.44	3.18	51.35
K applied (kg/ha)	84	30.05	21.00	0.00	50.00
Org C (g/kg)	84	11.89	2.71	4.55	16.50
Age (year)	80	50.35	11.60	30.00	74.00
Educ (year)	40	11.10	3.37	5.00	16.00
Farm area (ha)	84	0.36	0.08	0.10	0.40
HYS	84	0.00	0.00	0.00	0.00

Table 1c. Continued…

Site/Variable	Obs	Mean	Std. Dev.	Min	Max
INDONESIA					
Sukamandi, West Java					
Rice output (kg/ha)	480	4 046.43	1 372.89	539.00	7 727.00
N applied (kg/ha)	480	55.36	66.03	0.00	253.97
P applied (kg/ha)	480	11.24	12.77	0.00	36.59
K applied (kg/ha)	480	17.37	23.83	0.00	102.12
Org C (g/kg)	480	15.70	4.97	7.93	24.90
Age (year)	435	43.30	13.81	24.00	82.00
Educ (year)	142	6.92	3.28	1.00	12.00
Farm area (ha)	480	0.99	1.18	0.10	5.33
HYS	480	0.78	0.42	0.00	1.00
PHILIPPINES					
Nueva Ecija, Philippines					
Rice output (kg/ha)	630	4 760.10	1 559.10	907.00	9 922.00
N applied (kg/ha)	630	41.96	63.98	0.00	266.15
P applied (kg/ha)	630	13.79	12.89	0.00	32.18
K applied (kg/ha)	630	22.83	22.11	0.00	61.80
Org C (g/kg)	630	10.39	2.78	4.02	16.50
Age (year)	558	51.02	13.60	24.00	84.00
Educ (year)	179	7.32	4.03	0.00	14.00
Farm area (ha)	630	1.73	0.96	0.40	5.00
HYS	630	1.00	0.00	1.00	1.00
THAILAND					
Suphan Buri, Thailand					
Rice output (kg/ha)	660	3 572.47	960.24	1 173.00	6 615.00
N applied (kg/ha)	660	34.61	52.66	0.00	191.99
P applied (kg/ha)	660	17.13	13.99	0.00	53.85
K applied (kg/ha)	660	16.69	23.52	0.00	50.00
Org C (g/kg)	660	10.49	6.67	0.78	25.14
Age (year)	651	46.91	8.84	28.00	70.00
Educ (year)	216	4.78	1.85	2.00	10.00
Farm area (ha)	660	1.55	0.96	0.16	3.52
HYS	660	0.65	0.48	0.00	1.00

Table 1c. Continued…

Site/Variable	Obs	Mean	Std. Dev.	Min	Max
VIETNAM					
Can Tho, Vietnam					
Rice output (kg/ha)	591	3 894.34	1 415.28	743.00	7 608.00
N applied (kg/ha)	591	32.22	54.18	0.00	182.21
P applied (kg/ha)	591	15.38	13.82	0.00	51.19
K applied (kg/ha)	591	19.20	22.38	0.00	50.00
Org C (g/kg)	591	18.54	4.11	10.80	31.70
Age (year)	591	47.80	11.00	30.00	67.00
Educ (year)	591	6.86	3.65	1.00	12.00
Farm area (ha)	591	0.81	0.67	0.00	3.60
HYS	591	0.65	0.48	0.00	1.00
Ha Noi, Vietnam					
Rice output (kg/ha)	96	5 627.50	1 389.42	2 840.00	9 975.00
N applied (kg/ha)	96	48.12	50.67	0.00	143.75
P applied (kg/ha)	96	24.25	8.10	6.01	36.42
K applied (kg/ha)	96	51.05	14.71	0.00	97.65
Org C (g/kg)	96	14.74	4.98	7.50	24.50
Age (year)	48	47.75	9.15	32.00	63.00
Educ (year)	24	7.08	2.65	2.00	10.00
Farm area (ha)	96	0.08	0.02	0.06	0.15
HYS	96	0.96	0.20	0.00	1.00

Table 2. Quadratic Rice Production Function Estimates, India

Variable	Aduthurai		Uttar Pradesh		Thankjavur	
	Model 1	Model 2	Model 1	Model 2	Model 1	Model 2
N	25.59***	25.30***	-128.7***	-107.2***	-9.845	-12.7
	-5.618	-5.634	-36.95	-35.31	-29.23	-30.46
Nsq	-0.107***	-0.107***	0.378**	0.366**	-0.00907	0.0372
	-0.0131	-0.0131	-0.156	-0.15	-0.108	-0.121
P	-19.97	-17.67	1024.5***	855.8**	24.54	84.46
	-15.7	-15.78	-345.6	-328.7	-99.92	-120.9
Psq	0.956***	0.870**	-20.86	-14.18	0.0359	0.353
	-0.362	-0.365	-14.61	-13.94	-0.653	-0.724
K	5.74	6.374	-1054.7**	-840.8**	53.90**	34.73
	-7.139	-7.175	-426.7	-406.5	-25.57	-32.41
Ksq	-0.114***	-0.111***	2.721	2.866	-0.122	-0.0315
	-0.0392	-0.0392	-2.452	-2.308	-0.159	-0.177
NP	-0.221*	-0.214*	-1.34	-1.914	-0.0488	-0.702
	-0.118	-0.118	-2.173	-2.085	-1.18	-1.381
PK	-0.0336	-0.0489	19.93	12.39	-1.109	-1.474*
	-0.149	-0.149	-17.24	-16.41	-0.735	-0.84
NK	0.0761	0.0727	4.566***	4.102***	-0.141	0.0711
	-0.0496	-0.05	-1.208	-1.147	-0.264	-0.349
OrgC	173.5	175.9	-149.3	-286.7	882.2***	785.4***
	-217.4	-218.4	-200.5	-209.5	-233.3	-261.8
OrgCsq	-7.558	-8.079	5.506	10.39	-5.941***	-5.296***
	-11.61	-11.67	-8.891	-9.667	-1.623	-1.809
OrgCN	0.618	0.629	0.537	0.485	0.283	0.24
	-0.463	-0.463	-0.633	-0.6	-0.291	-0.319
HYS		138.1*		-		326.2
		-71.63		-		-588.4
Farm area		2250.2		-21061.1**		448.5
		-2518.3		-8018.8		-2741.9
Farm area x farm area		-2860.5		40513.2***		359.8
		-4017.7		-13753.9		-2441.7
Constant	3.310.8***	2.879.2**	9.308.7***	11.624.0***	2.858.2***	2.550.6***
	-1013.8	-1120.1	-1756.9	-1900.3	-8317.3	-9128.2
No. of observations	1121	1121	84	84	77	75
Adjusted R-squared	0.408	0.409	0.51	0.567	0.642	0.629
Akaike Info Criteria	18934.8	18935.5	1380.163	1371.333	1253.152	1226.733
Bayesian Info Criteria	19000.09	19015.85	1411.763	1407.795	1283.622	1263.812

Standard errors in parentheses

* p<0.10, ** p<0.05, *** p<0.01

Table 3. Quadratic Rice Production Function Estimates, Indonesia, Philippines, and Thailand

Variable	West Java, Indonesia		Nueva Ecija, Phillippines		Suphan Buri, Thailand	
	Model 1	Model 2	Model 1	Model 2	Model 1	Model 2
N	21.32***	24.11***	17.43***	19.05***	-7.731	-4.565
	-3.732	-3.209	-6.287	-6.297	-5.871	-5.694
Nsq	-0.0881***	-0.0822***	-0.0662***	-0.0701***	0.0864**	0.0609
	-0.0141	-0.012	-0.0187	-0.0187	-0.042	-0.0412
P	-10.75	8.973	22.36	25.85	78.79***	74.12***
	-24.04	-20.54	-59.25	-59.16	-24.87	-24.06
Psq	0.448	-0.474	-1.052	-1.19	-0.476	-0.446
	-0.759	-0.65	-2.562	-2.554	-0.476	-0.464
K	-40.64***	-19.55	-9.655	-13.03	-	-14.42
	-14.04	-12.06	-29.42	-29.77	-	-13.62
Ksq	0.395***	0.198*	0.841*	0.851*	7.279	7.653*
	-0.127	-0.109	-0.456	-0.454	-4.674	-4.559
NP	0.255*	0.164	0.0975	0.0724	-0.381*	-0.334
	-0.13	-0.112	-0.332	-0.332	-0.229	-0.225
PK	0.844**	0.493*	-0.837	-0.727	-13.41*	-13.96*
	-0.327	-0.281	-1.405	-1.407	-7.782	-7.584
NK	0.0532	0.0229	-0.154	-0.159	1.787**	1.748**
	-0.0876	-0.0748	-0.19	-0.191	-0.893	-0.867
OrgC	91.64	73.59	74.54	137.9	-17.47	29.82
	-72.39	-63.72	-124.2	-126.3	-19.83	-28.79
OrgCsq	2.32	1.48	-3.101	-5.42	-0.0145	-1.71
	-2.208	-1.927	-5.713	-5.765	-0.983	-1.222
OrgCN	-0.102	-0.273**	0.684**	0.631*	0.0806	0.0412
	-0.157	-0.136	-0.339	-0.339	-0.0952	-0.0921
HYS		1402.6***		-		533.7***
		-109.3		-		-127.8
Farm area		620.2***		-474.5**		-8.541
		-129		-187.5		-202.3
Farm area x farm area		-122.3***		103.1**		-0.913
		-24.54		-43.77		-48.16
Constant	1.338.7**	449.1	3.719.0***	3.744.8***	3.471.4***	2.901.3***
	-562.7	-494.8	-660.1	-659.9	-96.53	-355.6
No. of observations	480	480	630	630	660	660
Adjusted R-squared	0.469	0.615	0.287	0.292	0.2	0.256
Akaike Info Criteria	8006.938	7855.506	10851.17	10848.61	10802.13	10757.67
Bayesian Info Criteria	8061.198	7922.286	10908.97	10915.29	10856.04	10825.05

Standard errors in parentheses

* p<0.10, ** p<0.05, *** p<0.01

Table 4. Quadratic Rice Production Function Estimates, Vietnam

Variable	Can Tho		Ha Noi	
	Model 1	Model 2	Model 1	Model 2
N	-8.633	16.94**	83.23	69.25
	-14.6	-8.549	-65.47	-63.38
Nsq	0.064	0.0341	-0.221	-0.256*
	-0.0948	-0.0557	-0.143	-0.139
P	235.8***	57.89	231.9	204.3
	-83.93	-49.16	-165.8	-164.4
Psq	-0.525	2.128**	1.464	2.622
	-1.514	-0.878	-2.66	-2.611
K	-38.39	-17.87	-53.79	-139.4
	-81.27	-47.03	-140.9	-139.4
Ksq	0.256	-1.329	0.376	0.743
	-1.673	-0.967	-0.577	-0.579
NP	-1.147	-1.209**	-2.550**	-2.741***
	-0.842	-0.491	-0.996	-0.997
PK	-3.409	0.581	-0.401	-0.178
	-3.233	-1.878	-1.505	-1.527
NK	0.861	0.233	0.175	0.639
	-0.538	-0.31	-0.879	-0.872
OrgC	-521.1***	-446.2***	-205.1	-265.4
	-109.3	-62.95	-156.5	-160.2
OrgCsq	12.61***	9.917***	11.01**	12.61**
	-2.761	-1.592	-4.798	-4.834
OrgCN	-0.205	-0.197	1.168**	1.224**
	-0.277	-0.159	-0.526	-0.514
HYS		2232.2***		1122.1*
		-68.55		-568.4
Farm area		507.6***		-73770.9**
		-141.2		-35356.7
Farm area x farm area		-103.3**		379887.0**
		-45.94		-178261.7
Constant	8.650.2***	6.384.1***	341.9	5167.6
	-1052.8	-616.5	-7097.7	-7221.5
No. of observations	591	591	96	96
Adjusted R-squared	0.142	0.718	0.498	0.536
Akaike Info Criteria	10175.29	9520.387	1607.71	1602.749
Bayesian Info Criteria	10232.26	9590.496	1641.047	1643.778

Standard errors in parentheses

* p<0.10, ** p<0.05, *** p<0.01

Table 5. Marginal physical product (MPP) and output elasticity at the mean, India

Variable	Aduthurai		Thanjavur		Uttar Pradesh	
	MPP	Output Elasticity	MPP	Output Elasticity	MPP	Output Elasticity
Total N (kg)	18.34 (1.36)***	0.19 (0.02)***	2.01 (12.85)	0.02 (0.13)	20.77 (22.67)	-0.09 (0.17)
Total P (kg)	-0.04 (6.59)	-0.01 (0.02)	27.77 (58.08)	0.06 (0.13)	408.94 (196.77)**	1.20 (0.87)**
Total K (Kg)	2.05 (3.97)	0.02 (0.02)	21.25 (16.9)	0.09 (0.07)	-104.99 (80.55)	-1.17 (0.49)**
Org C (g/kg)	63.06 (30.72)**	0.12 (0.05)**	43.32 (13.75)***	0.66 (0.21)***	-9.16 (47.81)	-0.02 (0.13)
Farm area	533.90 (472.02)	0.02 (0.03)	685.97 (1467.44)	0.04 (0.10)	918.68 (302.20)***	0.77 (0.25)***

Standard deviations in parenthesis

* p<0.10, ** p<0.05, *** p<0.01

Table 6. Marginal physical product (MPP) and output elasticity at the mean, Indonesia, Philippines, and Thailand

Variable	Sukamandi, West Java, Indonesia		Nueva Ecija, Philippines		Suphan Buri, Thailand	
	MPP	Output Elasticity	MPP	Output Elasticity	MPP	Output Elasticity
Total N (kg)	12.96 (1.04)***	0.18 (0.01)***	17.10 (2.43)***	0.15 (0.02)***	36.27 (8.27)***	0.32 (0.08)***
Total P (kg)	15.94 (7.68)**	0.04 (0.02)**	-20.53 (21.89)	-0.06 (0.06)	-270.83 (64.42)***	-0.70 (0.17)***
Total K (Kg)	-5.86 (5.06)	-0.02 (0.02)	9.15 (13.36)	0.04 (0.06)	230.31 (54.44)***	0.48 (0.12)***
Org C (g/kg)	104.96 (12.02)***	0.41 (0.05)***	51.82 (20.87)**	0.11 (0.05)**	-3.98 (8.17)	-0.01 (0.02)
Farm area	380.40 (94.06)***	0.09 (0.02)***	-123.87 (63.82)*	-0.04 (0.02)*	-11.78 (58.89)	-0.01 (0.03)

Standard deviations in parenthesis

* p<0.10, ** p<0.05, *** p<0.01

Table 7. Marginal physical product (MPP) and output elasticity at the mean, Vietnam

Variable	Can Tho		Ha Noi	
	MPP	Output Elasticity	MPP	Output Elasticity
Total N (kg)	1.36 (0.82)	0.01 (0.05)	28.81 (6.30)***	0.24 (0.05)***
Total P (kg)	95.54 (24.34)***	0.38 (0.10)***	190.42 (55.69)***	0.82 (0.24)***
Total K (Kg)	-52.44 (15.45)***	-0.26 (0.08)***	-37.11 (46.42)	-0.33 (0.42)
Org C (g/kg)	-84.76 (7.59)***	-0.40 (0.04)***	165.18 (32.24)***	0.43 (0.08)***
Farm area	340.30 (80.21)***	0.07 (0.02)***	-575.38 (244.84)**	-0.04 (0.03)*

Standard deviations in parenthesis

* p<0.10, ** p<0.05, *** p<0.01

Table 8. Results of Hypothesis Testing

Hypothesis: Parameter β_{ij}	Aduthurai, India		Thanjavur, India		Uttar Pradesh, India		Sukamandi, WJ, Indonesia	
	F value	*p-value*	*F value*	*p-value*	*F value*	*p-value*	*F value*	*p-value*
NP = 0	2.87	0.09	0.29	0.61	1.44	0.23	2.93	0.09
NP < 0		0.95		0.69		0.82		0.07
NP > 0		0.04		0.31		0.18		0.93
PK = 0	0.12	0.73	3.21	0.08	0.86	0.36	3.88	0.08
PK < 0		0.64		0.95		0.23		0.04
PK > 0		0.36		0.05		0.77		0.96
NK = 0	2.58	0.10	0.04	0.84	19.91	0.00	0.12	0.76
NK < 0		0.05		0.42		0.00		0.38
NK > 0		0.95		0.58		0.99		0.62
OrgCN = 0	1.78	0.18	0.74	0.45	0.69	0.42	4.76	0.04
OrgCN < 0		0.09		0.23		0.21		0.98
OrgCN > 0		0.91		0.77		0.79		0.02

Table 8. Continued….

Hypothesis: Parameter β_{ij}	Nueva Ecija, Philippines		Suphan Buri, Thailand		Can Tho, Vietnam		Hanoi, Vietnam	
	F value	*p-value*	*F value*	*p-value*	*F value*	*p-value*	*F value*	*p-value*
NP = 0	0.09	0.82	1.73	0.13	8.39	0.00	11.57	0.00
NP < 0		0.41		0.93		0.99		0.99
NP > 0		0.59		0.07		0.01		0.01
PK = 0	0.47	0.61	22.78	0.06	0.15	0.70	0.02	0.88
PK < 0		0.70		0.97		0.35		0.55
PK > 0		0.30		0.03		0.65		0.45
NK = 0	1.52	0.41	22.62	0.04	0.92	0.34	0.47	0.49
NK < 0		0.79		0.02		0.17		0.25
NK > 0		0.21		0.98		0.83		0.75
OrgCN = 0	3.97	0.06	0.22	0.65	2.09	0.15	3.05	0.08
OrgCN < 0		0.03		0.33		0.93		0.04
OrgCN > 0		0.97		0.67		0.07		0.96

Table 9. Nonnested hypothesis results based on P_0 test

SITE/ ALTERNATIVE HYPOTHESIS	NULL HYPOTHESIS			
	Linear von Liebig	Squared	Square-root	Non-linear von Liebig
India				
Aduthurai				
Linear von Liebig	-	12.41***	1.04	10.88**
Squared	1.12	-	0.03	1.66
Square-root	0.78	9.84***	-	1.7
Non-linear von Liebig	21.57***	13.74***	3.81*	-
ALL	3.10**	6.59***	2.91**	0.64
Thanjavur				
Linear von Liebig	-	1.81	1.83	2.09
Squared	5.11**	-	0.94	3.14*
Square-root	4.40**	0	-	3.70*
Non-linear von Liebig	69.16***	4.13**	7.48**	-
ALL	2.44*	1.34	2.04	1.33
Uttar Pradesh				
Linear von Liebig		0.15	1.87	0.8
Squared	3.84*		0.48	11.61***
Square-root	3.47*	0.12		12.50***
Non-linear von Liebig	6.94***	0.26	0.83	
ALL	1.54	0.12	1.09	4.35***
West Java, Indonesia				
Linear von Liebig	-	0.1	2.46	89.54***
Squared	53.74***	-	2.85*	268.64
Square-root	58.63***	3.47*	-	14.80***
Non-linear von Liebig	51.36***	0.68	0.06	260.41***
ALL	28.56***	1.94	2.58*	91.48***
Nueva Ecija, Philippines				
Linear von Liebig		0.05	0.69	3.22*
Squared	23.17***		2.86*	0.47
Square-root	25.66***	3.18*		0.7
Non-linear von Liebig	49.01***	2.01	2.49	
ALL	15.97***	7.04***	8.31***	0.67

Standard errors in parentheses

* p<0.10, ** p<0.05, *** p<0.01

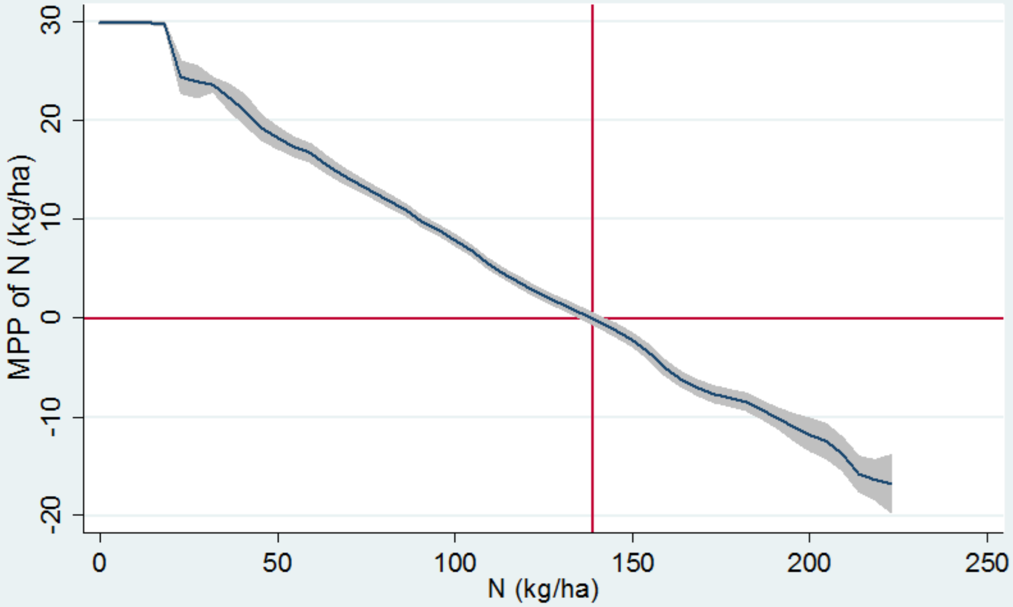
Table 9. Continued….

SITE/ ALTERNATIVE HYPOTHESIS	NULL HYPOTHESIS			
	Linear von Liebig	Squared	Square-root	Non-linear von Liebig
Suphan Buri, Thailand				
Linear von Liebig		0.01	22.57***	66.44***
Squared	24.70***		26.04***	17.24***
Square-root	28.87***	6.66**		17.81***
Non-linear von Liebig	10.21***	0.71	21.44***	
ALL		2.52*	18.31***	6.09***
Vietnam				
Can Tho				
Linear von Liebig	-	0.22	2	6.45*
Squared	21.48***	-	7.62***	7.91***
Square-root	15.49***	0.01	-	1.65
Non-linear von Liebig	27.05***	2.04	9.87***	-
ALL	10.31***	1.98	6.46***	4.55***
Hanoi				
Linear von Liebig	-	0.13	6.41**	0.16
Squared	6.20**	-	0.08	3.8*
Square-root	5.46**	6.37**	-	3.30*
Non-linear von Liebig	17.08***	0.67	5.21**	-
ALL	4.88***	1.45	2.35*	4.08***

Standard errors in parentheses

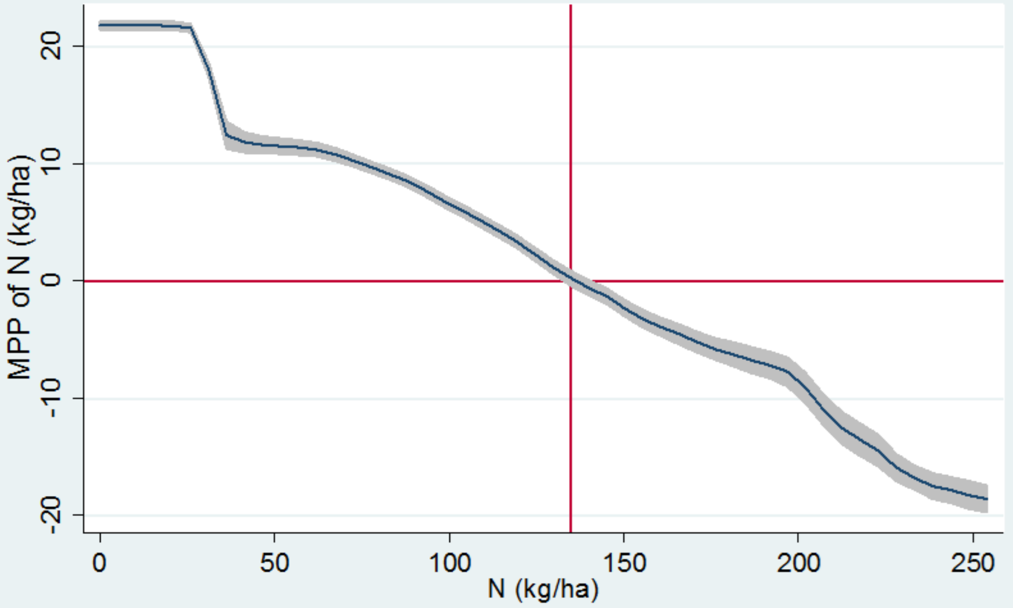
* p<0.10, ** p<0.05, *** p<0.01

Figure 1. Marginal Physical Product of N at the mean level
Aduthurai, India



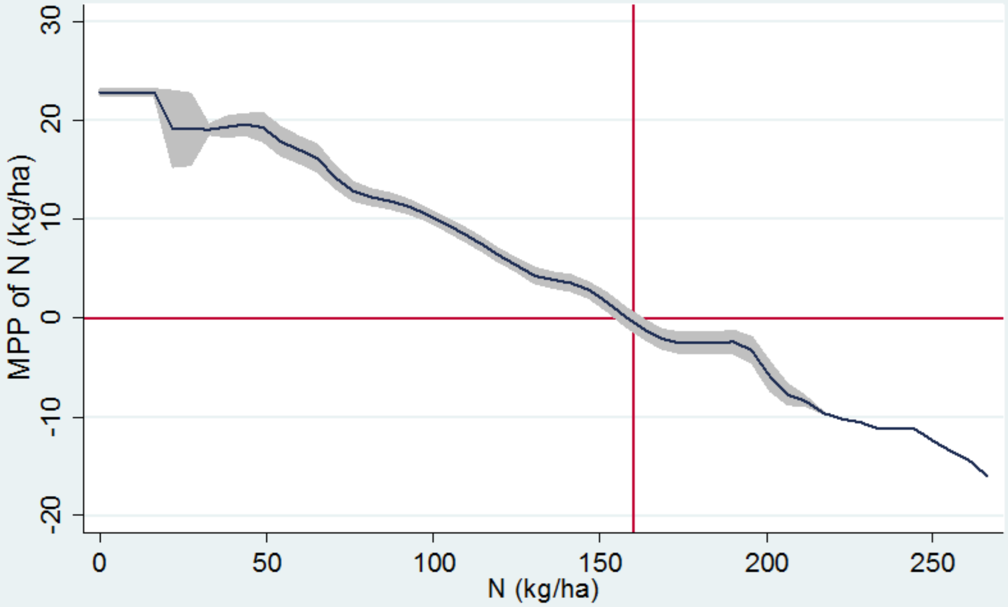
kernel = epanechnikov, degree = 0, bandwidth = 8.71, pwidth = 13.07

Figure 2. Marginal Physical Product of N at the mean level
Sukamandi, WJ, Indonesia



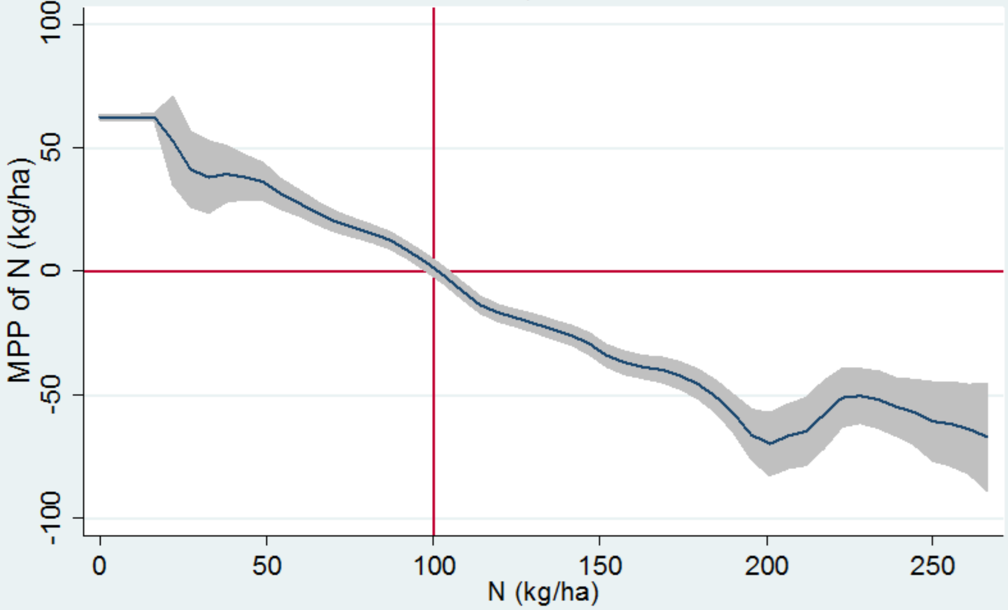
kernel = epanechnikov, degree = 0, bandwidth = 14.16, pwidth = 21.23

Figure 3. Marginal Physical Product of N at the mean level
Nueva Ecija, Philippines



kernel = epanechnikov, degree = 0, bandwidth = 8.95, pwidth = 13.42

Figure 4. Marginal Physical Product of N at the mean level
Ha Noi, Vietnam



kernel = epanechnikov, degree = 0, bandwidth = 8.32, pwidth = 12.48

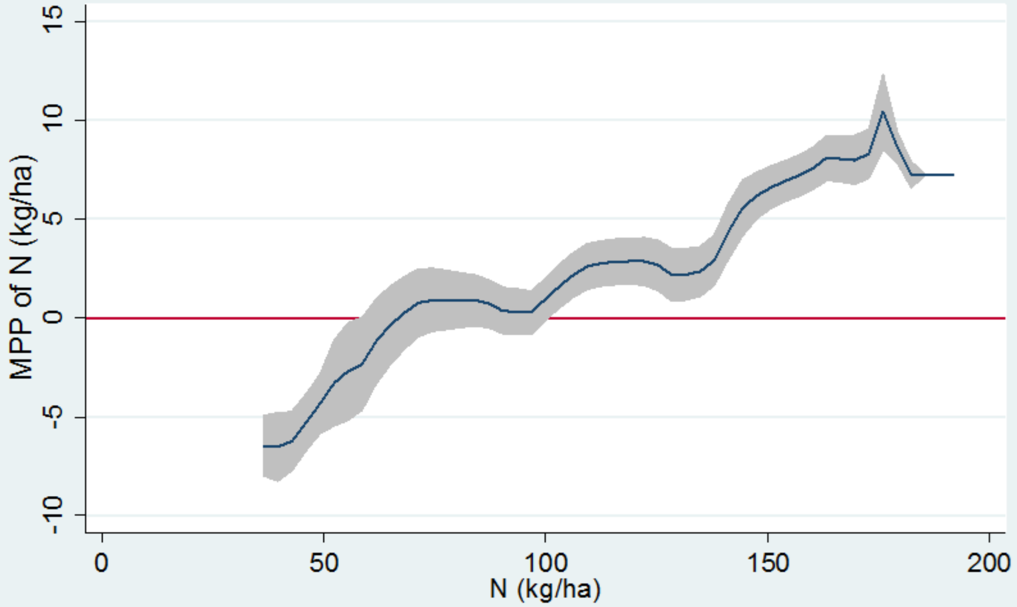


Figure 5. Marginal Physical Product of N at the mean level

Suphan Buri, Thailand

kernel = epanechnikov, degree = 0, bandwidth = 7.01, pwidth = 10.52

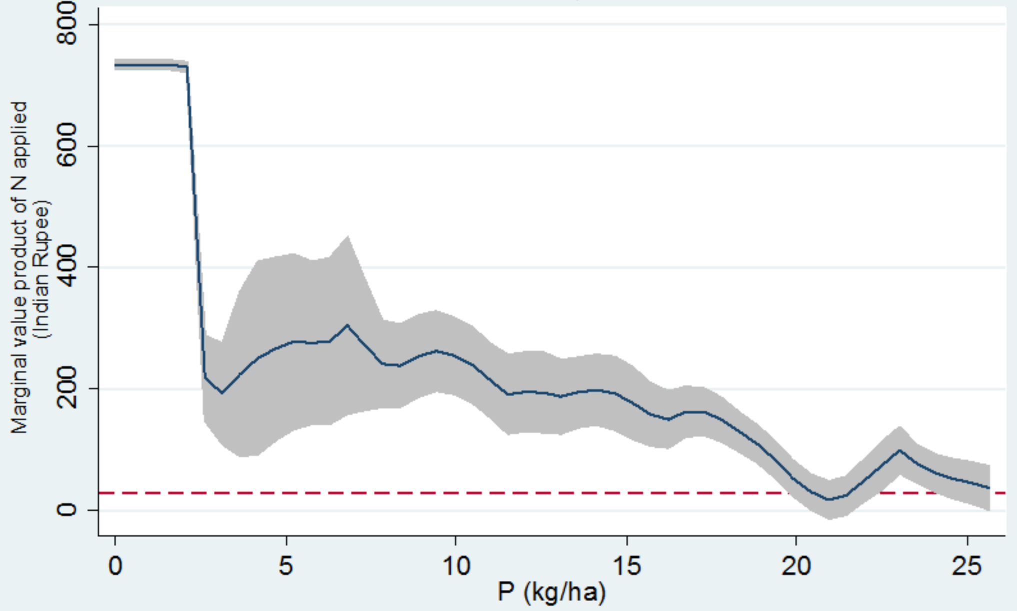


Figure 6. Marginal value product of N applied, by P applied

Aduthurai, India

kernel = epanechnikov, degree = 0, bandwidth = 1.04, pwidth = 1.56

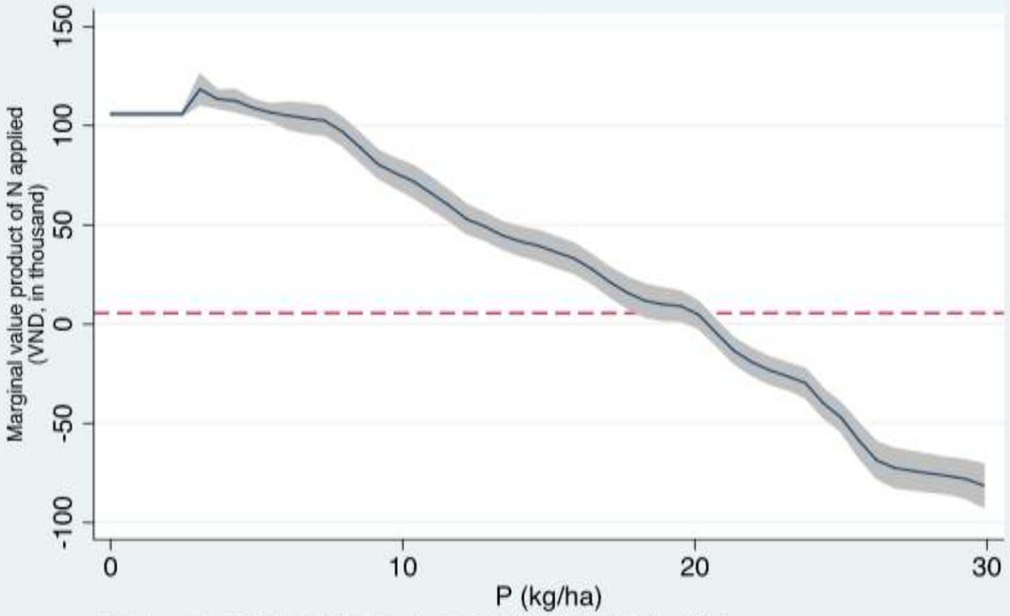


Figure 7. Marginal value product of N applied, by P applied
Can Tho, Vietnam

kernel = epanechnikov, degree = 0, bandwidth = 1.3, pwidth = 1.94

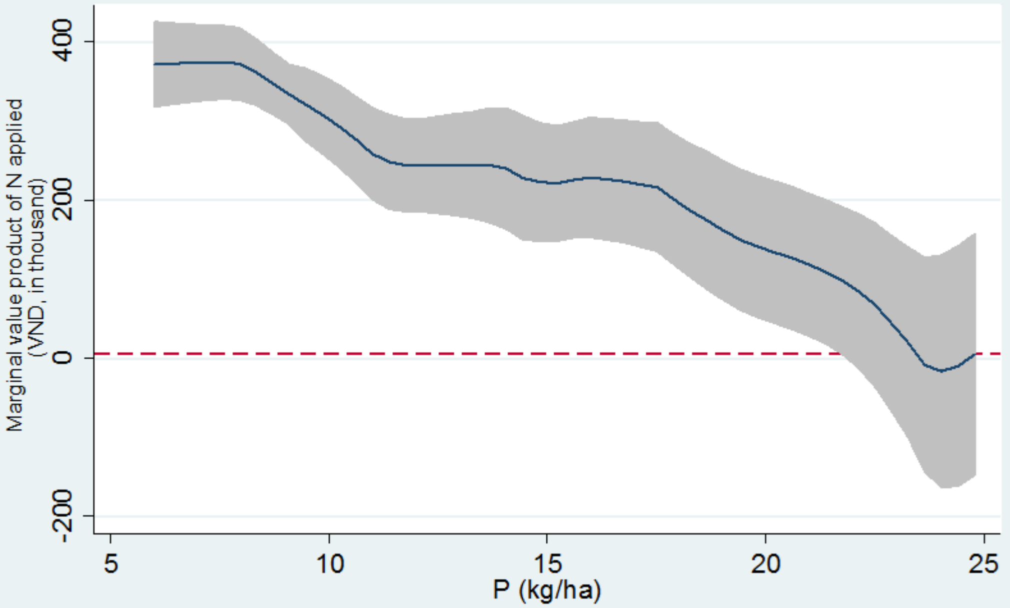
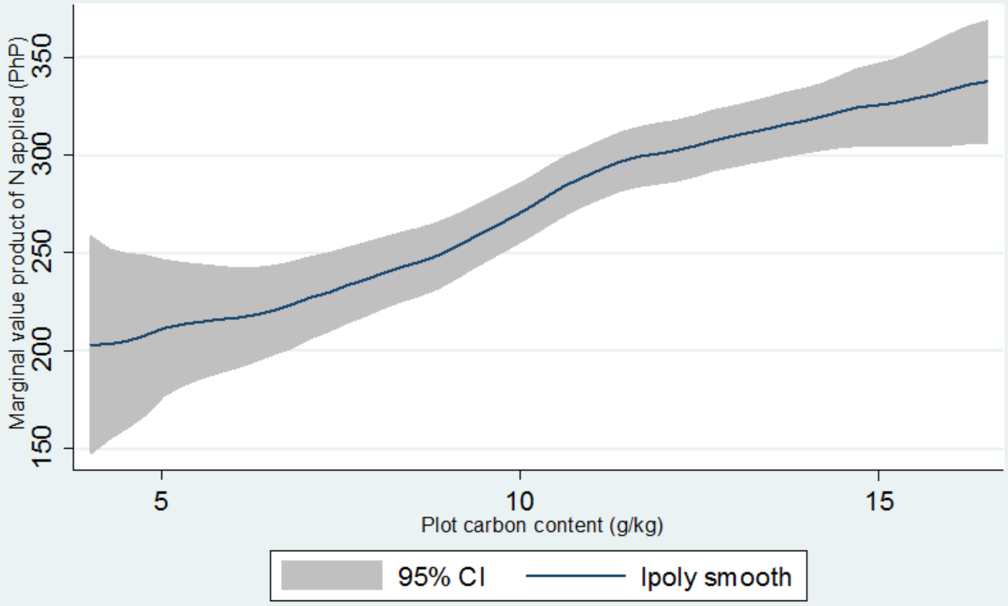


Figure 8. Marginal value product of N applied, by P applied
Hanoi, Vietnam

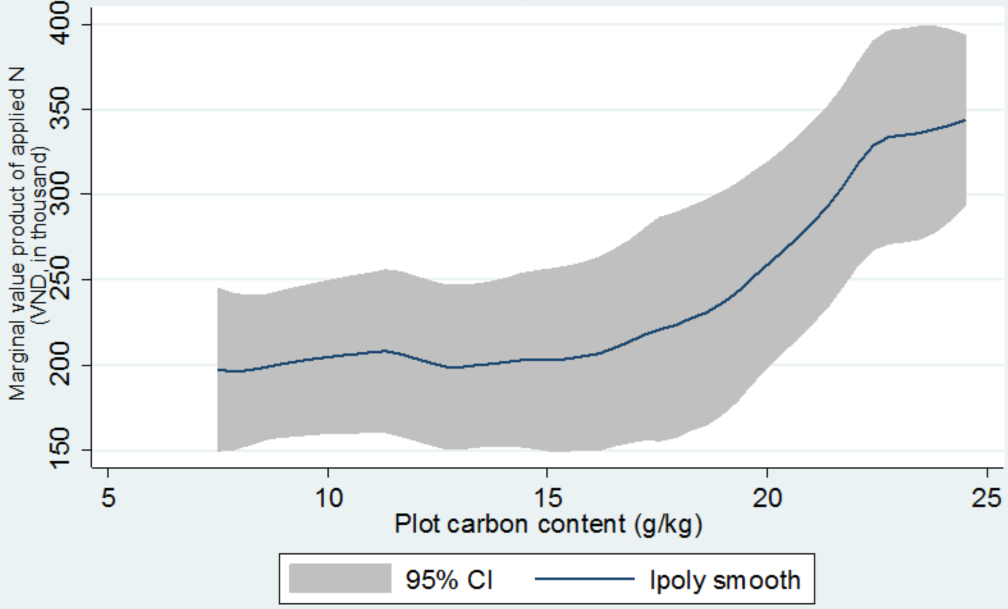
kernel = epanechnikov, degree = 0, bandwidth = 1.86, pwidth = 2.79

Figure 9. Marginal value product of N applied, by plot's carbon content
Nueva Ecija, Philippines



kernel = epanechnikov, degree = 0, bandwidth = 1.29, pwidth = 1.94

Figure 10. Marginal value product of N applied, by plot's carbon content
Hanoi, Vietnam



kernel = epanechnikov, degree = 0, bandwidth = 2.42, pwidth = 3.63

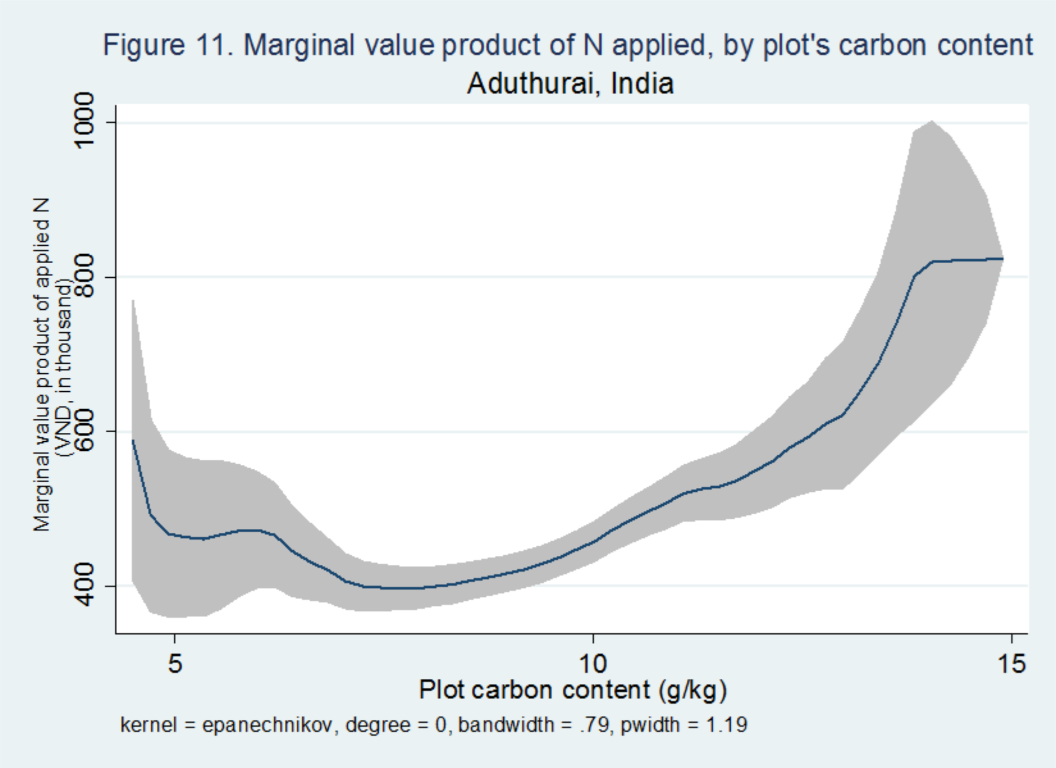
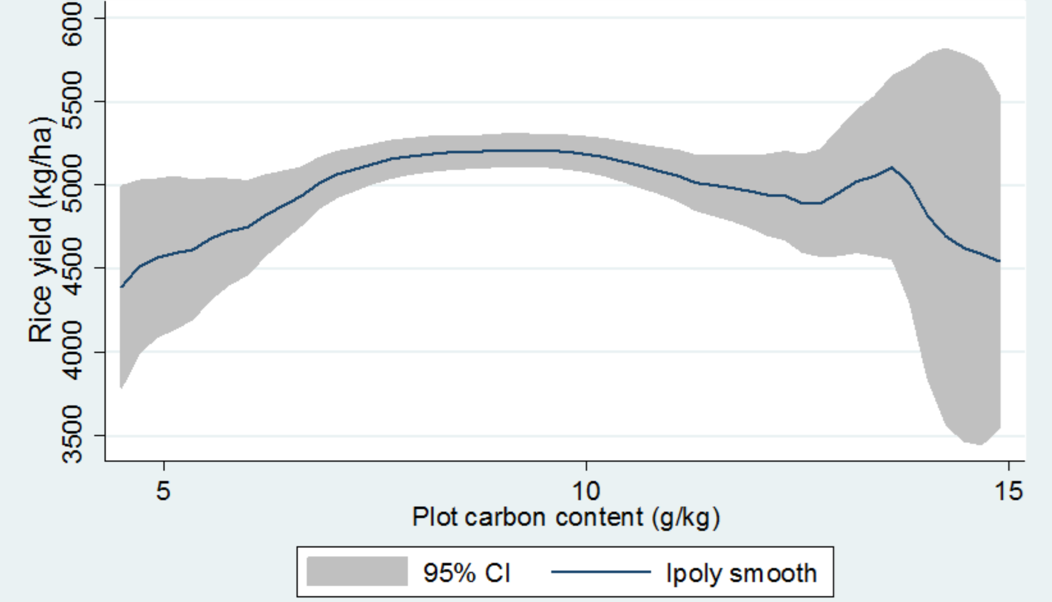


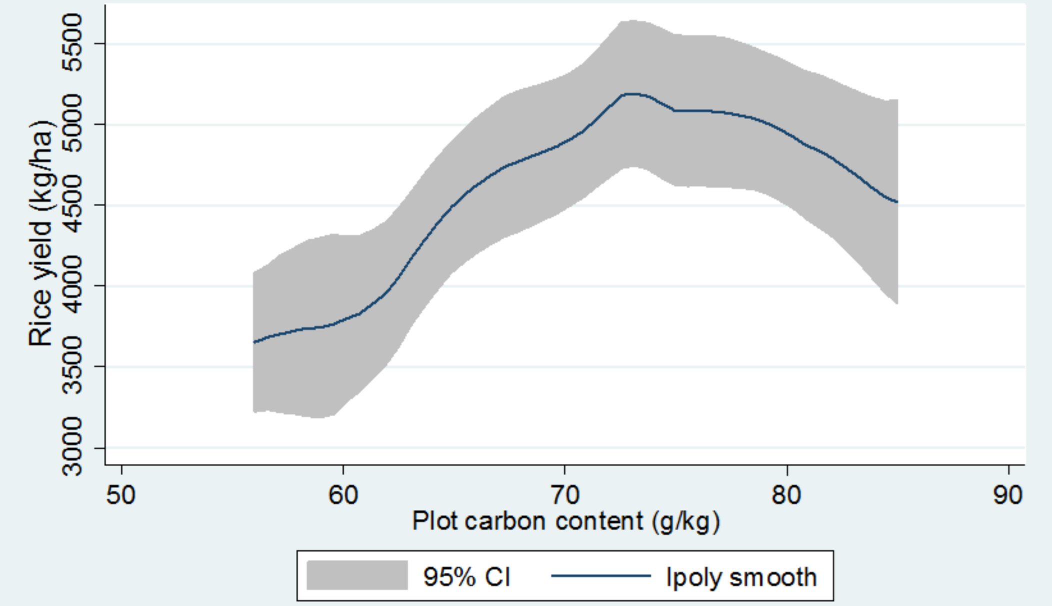
Figure 11. Marginal value product of N applied, by plot's carbon content
Aduthurai, India

kernel = epanechnikov, degree = 0, bandwidth = .79, pwidth = 1.19



Appendix Figure 1. Rice yield as a function of plot's carbon content
Aduthurai, India

kernel = epanechnikov, degree = 0, bandwidth = .88, pwidth = 1.32

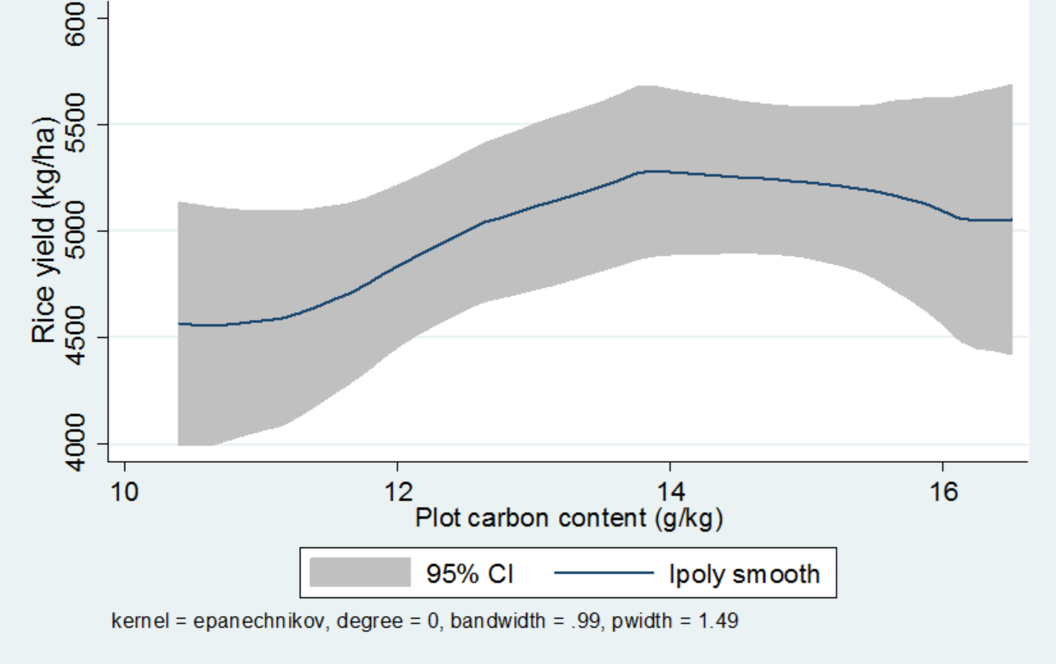


Appendix Figure 2. Rice yield as a function of plot's carbon content
Thanjavur, India

kernel = epanechnikov, degree = 0, bandwidth = 2.89, pwidth = 4.34

Appendix Figure 3. Rice yield as a function of plot's carbon content

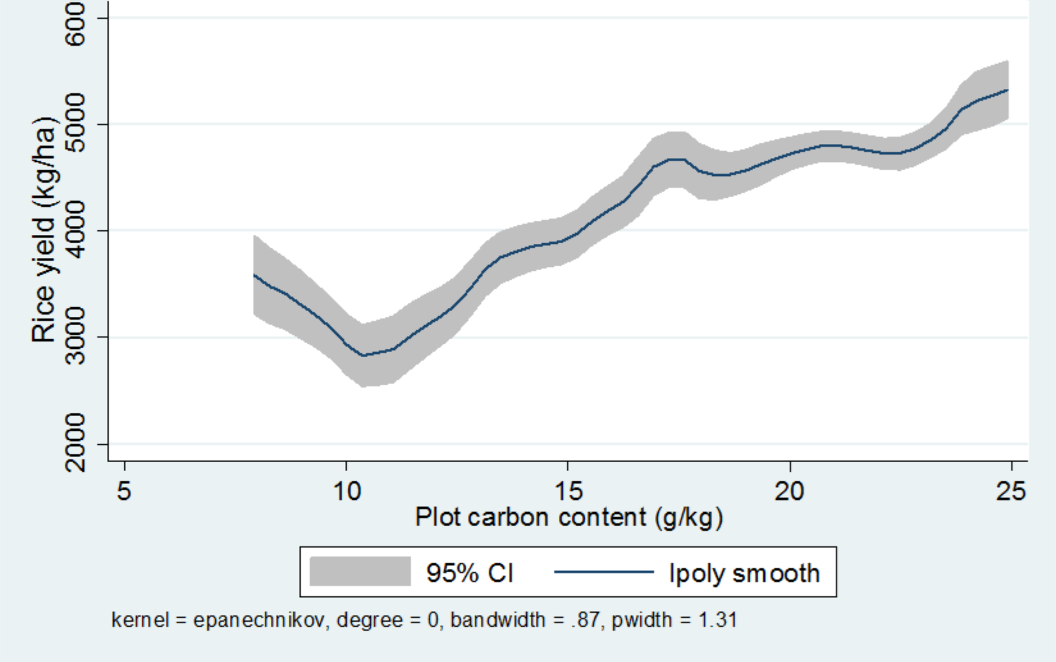
Uttar Pradesh, India



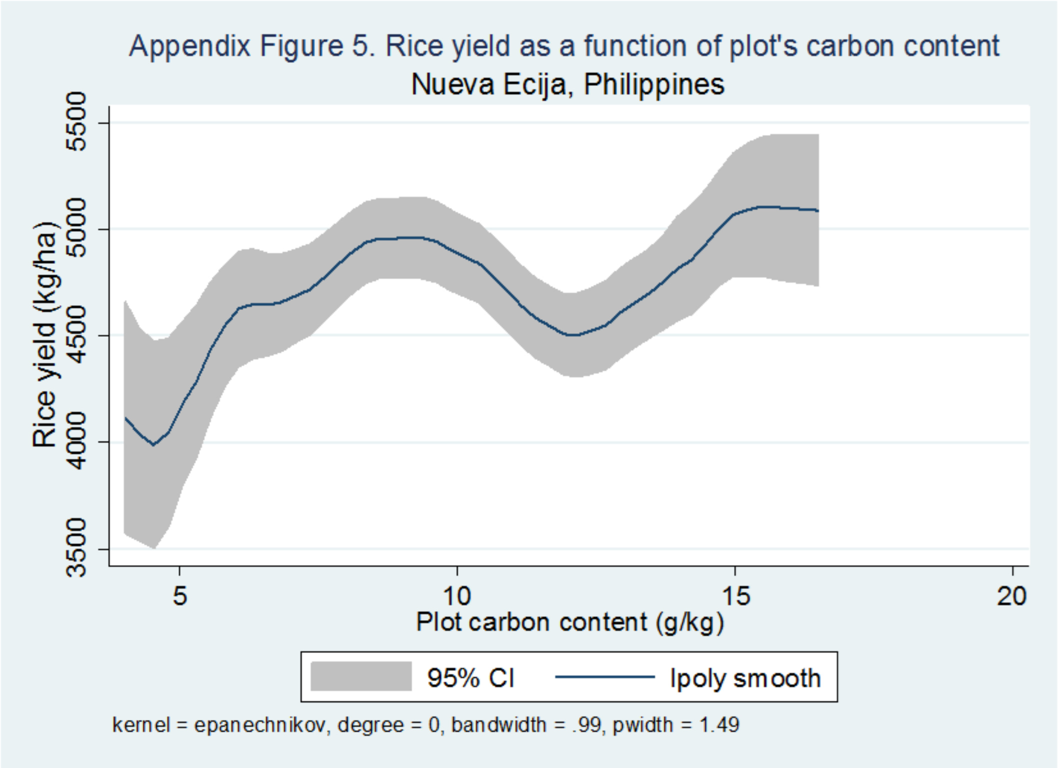
kernel = epanechnikov, degree = 0, bandwidth = .99, pwidth = 1.49

Appendix Figure 4. Rice yield as a function of plot's carbon content

West Java, Indonesia

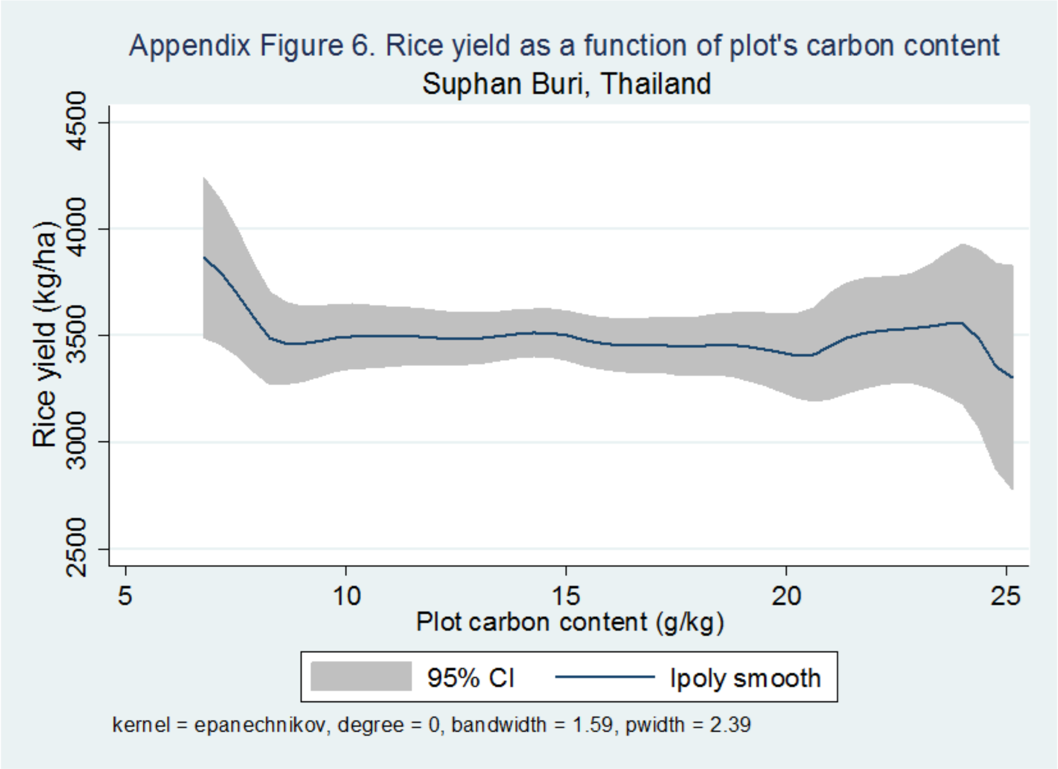


kernel = epanechnikov, degree = 0, bandwidth = .87, pwidth = 1.31



Appendix Figure 5. Rice yield as a function of plot's carbon content
Nueva Ecija, Philippines

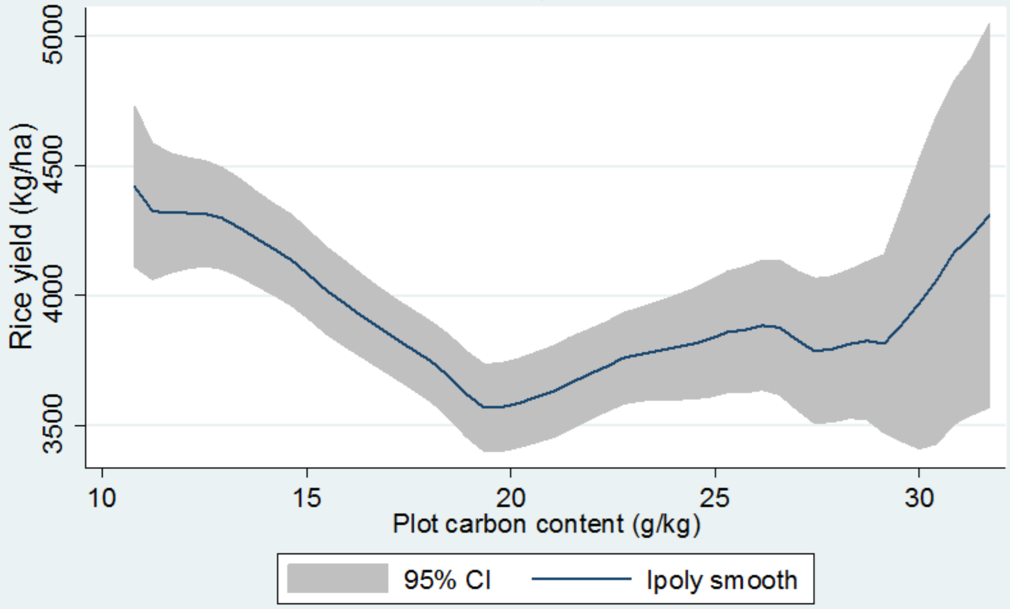
kernel = epanechnikov, degree = 0, bandwidth = .99, pwidth = 1.49



Appendix Figure 6. Rice yield as a function of plot's carbon content
Suphan Buri, Thailand

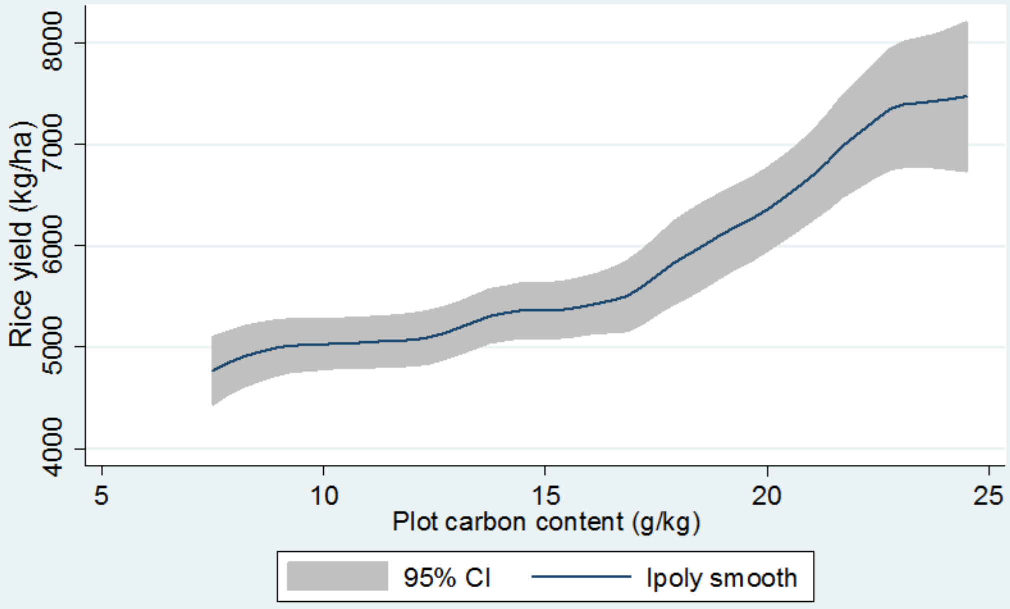
kernel = epanechnikov, degree = 0, bandwidth = 1.59, pwidth = 2.39

Appendix Figure 7. Rice yield as a function of plot's carbon content
Can Tho, Vietnam



kernel = epanechnikov, degree = 0, bandwidth = 1.81, pwidth = 2.71

Appendix Figure 8. Rice yield as a function of plot's carbon content
Ha Noi, Vietnam



kernel = epanechnikov, degree = 0, bandwidth = 2.08, pwidth = 3.12