

1 **Productivity and soil fertility relationships in rice production systems, Bangladesh**

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ABSTRACT

This paper presents an econometric analysis of the influence of soil fertility status on productivity and resource use in rice production utilizing survey data from 21 villages in three agro-ecological regions of Bangladesh. Detailed crop husbandry input-output data were collected from 380 paddy rice (*Oryza sativa*) farmers. Data collected included fertilizer, pesticide, labour, animal power services, irrigation, farm capital assets and rice yield. The soil fertility status in each region was determined by analysis of soil organic carbon, available nitrogen, phosphorus and potassium concentration. Analysis was based on a profit function, where the selected soil fertility parameters were incorporated as yield controlling variables. Results revealed that soil fertility has a significant influence on both productivity and farmers' resource allocation decisions. Output supply was significantly higher in fertile regions and input use was significantly lower. This observation indicates that in policy terms technological initiatives should be targeted at measures to identify areas of lower soil fertility so that inherent soil-based productivity restrictions can be minimized. In part this will be facilitated by the transfer of indigenous knowledge from farmers in higher productivity areas, thus increasing rice production and raising the competitiveness of Bangladeshi rice farmers.

Key words: Soil fertility, Rice production, Profit-function analysis, Bangladesh.

46 1. INTRODUCTION

47 Land is the most important natural resource that provides livelihood for the majority of
48 people in Bangladesh. Agriculture accounts for more than 50% of national income and employs
49 two-third of the labour force. The dominant sector is the field crop agriculture accounting for more
50 than 60% of agricultural value added. Among the field crops, rice is the major staple crop,
51 occupying 70% of the cropped area (BBS, 2001). Historically, being a food deficit country with an
52 extremely unfavourable land-person ratio of only 0.06 ha, Bangladesh has pursued a policy of
53 rapid technological progress in agriculture by promoting diffusion of a rice-based ‘Green
54 Revolution (GR)’ technology package. As a result, land-use intensity increased sharply to 175% in
55 1999 from its initial level of 146% in 1969 (Rahman and Thapa, 1999; and BBS, 2001) with
56 corresponding increase in input use. For example, use of chemical fertilizers increased six times
57 during 1968–94 and use of pesticides increased three-fold in just one decade during 1982–92
58 (Rahman and Thapa, 1999). Consequently, total rice output grew at an annual rate of 2.2 % during
59 1965-87 and then declined to half the previous rate at 1.1 % during 1988-97 (Otsuka, 2000). In
60 fact, the yield rate of modern rice steadily declined from 3.6 mt in 1969 to 2.4 mt in 1994 with an
61 estimated annual rate of decline of 1.2% (Rahman, 2002), thereby confirming that productivity
62 from GR technology is falling. It is believed that more than 65% of the total agricultural land is
63 suffering from declining soil fertility and about 85% of net area suitable for cultivation has an
64 organic matter below the minimum requirement (TFR, 1991). Soil analysis of 460 samples from
65 43 profiles from the same locations between 1967 and 1995 revealed a decline in fertility (Ali et
66 al., 1997) although this decline in soil fertility has not been explicitly linked to GR technology.
67 Baanante et al., (1993) noted that the present level of food crop production in Bangladesh takes up
68 an estimated 0.93 mt of nutrients (N, P, K and S) from the soil annually. Widespread adoption of

69 GR technology was identified as a cause of significant soil degradation and declining crop yields
70 in India (Singh, 2000; Yadav et al., 2000). Pimentel (1996) indicated that extensive use of
71 fertilizers and pesticides to support the GR has caused serious public health and environmental
72 damages worldwide, particularly in developing countries. Furthermore, it has been noted that
73 continued, intensive production of rice has lead to yield reductions in some countries in Asia,
74 explained in part by soil nutrient exhaustion (Doberman et al., 2002)

75 There is a large body of literature on GR covering several dimensions of this complex
76 technology package, such as productivity, growth, employment and equity (e.g., Das, 2002;
77 Rahman, 1999; Freebairn, 1995; Hazell and Ramasamy, 1991), but the interactions between soil
78 fertility status and farmers' indigenous knowledge have been less well studied. Payton et al.
79 (2003) identified that Bangladeshi farmers possess an intimate and sophisticated knowledge of soil
80 properties and management problems. Ali (2003) concluded that “despite their lack of knowledge
81 of soil genesis, soil morphology and soil chemistry, farmers were able to qualitatively identify
82 major typology, properties, and productivity constraints of topsoil” (pp. 333). This paper examines
83 resource allocation decisions made by the GR farmers of Bangladesh, a country that is particularly
84 vulnerable in terms of food security. The specific aim was to provide a measure of responsiveness
85 of selected soil fertility parameters with respect to the use of key production inputs and supply of
86 output (rice) which will be useful for policy makers.

87

88 **2. METHODOLOGY**

89 **2.1 Location and cropping in the study regions**

90 Three of the intensive rice producing areas of Bangladesh, Jamalpur, Jessore and Comilla,
91 were selected for this study. Jamalpur is located within Jamalpur Sadar Thana (central

92 administrative sub-district), in the south-eastern part of Jamalpur district. The study area is 180 km
93 northwest from Dhaka. Jessore is located in Manirampur Thana in the southern part of Jessore
94 district, 290 km southwest from Dhaka. Comilla is located in Matlab Thana in the south-eastern
95 part of Chandpur district, 120 km southeast from Dhaka.

96 An estimated 75% of the gross cropped area was under modern varieties of rice and wheat
97 and 62% was under irrigation in the study regions during the crop year 1996. The cropping
98 intensity (defined as the ratio of gross cropped area to net sown area multiplied by 100) of the
99 sample farms is estimated at 172.8 (183.3 in Jamalpur, 178.2 in Jessore and 148.2 in Comilla
100 region), which is very close to the national estimate of 173.2 for the year 1995/96 (BBS, 2001).

101

102 **2.2 Data and Variables**

103 The study is based on farm-level data for crop year 1996 collected from three agro-
104 ecological regions of Bangladesh. The survey was conducted from February to April 1997. The
105 specific selected regions were Jamalpur (representing wet agroecology), Jessore (representing dry
106 agroecology), and Comilla (representing both wet agroecology and an agriculturally developed
107 area). A multistage random sampling technique was employed to locate the districts, then the
108 *Thana* (sub districts), and then the villages in each of the three sub districts and finally the sample
109 households. A total of 380 households from 21 villages (174 households from eight villages of
110 Jamalpur Sadar *Thana*, 100 households from six villages of Manirampur *Thana* and 106
111 households from seven villages of Matlab *Thana*) form the sample for the study. Detailed input-
112 output data were collected for modern varieties of rice produced in a crop year. The dataset also
113 includes information on level of soil fertility determined from soil samples collected from
114 representative locations in the study villages.

115

116 **2.3 Soil sampling and analysis**

117 Data on physical and chemical properties of soils from the selected farmers' fields were
118 collected to evaluate the fertility status of the soil and to examine inter-regional differences
119 between the study areas. Soils were mapped in the three study areas at series level. Soil series
120 were distinguished following a process of detailed chemical and physical characterisation using
121 standard procedures (SRDI, 1991), based on assessment of inherent variability. SRDI (1991)
122 employed ranges and thresholds for key soil parameters (texture, colour, structure, pH, organic
123 carbon, available phosphorus, potassium and iron) to define and map separate soil series.
124 Therefore soil series as mapped were used to select five distinct sampling locations in each region,
125 giving a total of 15 composite soil samples in total, representing 15 different soil series. Soils were
126 collected from random locations within rice-plots within the survey households. Soil sub-samples
127 were collected from the 0 – 200 mm cultivated horizon at each of 3 – 5 random locations within a
128 selected plot, and were then thoroughly mixed to give a composite sample. Samples were air dried
129 prior to analysis.

130 As a part of a wider project (Rahman, 1998), soil samples were analyzed for (1) soil
131 organic carbon content, (2) available potassium, (3) available phosphorus, (4) available nitrogen,
132 (5) available sulphur, (6) available zinc, (7) soil texture, and (8) soil pH. In this paper, data are
133 presented for the key soil chemical parameters that are directly modified by routine fertilizer
134 practice and are less subject to inter-season and spatial variability, viz. soil organic carbon content,
135 available phosphorus, available potassium, and available nitrogen. Soil organic carbon (SOC)
136 content was measured using the Walkley-Black rapid titration method. Available phosphorus (P)
137 was extracted using Truog's extraction method and determined colorimetrically by

138 spectrophotometer. Available potassium (K) was extracted by neutral normal ammonium acetate
139 solution and determined by Gallenkamp flame photometer. Available (mineral) nitrogen (N) was
140 determined using the micro-Kjeldahl method. Full methodological details of all soil analyses are
141 given in PCARRD (1980). Soil organic carbon, available N, P and K concentrations were
142 converted into topsoil mass per unit area (kg ha^{-1}) assuming a soil bulk density of 1.0 Mg m^{-3} for
143 the cultivated soil horizon (0.00 – 0.20 m).

144

145 **2.4 Modelling influence of soil fertility status on farmers' resource allocation decisions**

146 A profit function approach is adopted to examine the effect of soil fertility status on
147 resource allocation decisions. The basic assumption is that farm management decisions can be
148 described as static profit maximization. Specifically, the farm household was assumed to maximize
149 'restricted' profits from growing modern rice, defined as the gross value of output less variable
150 costs, subject to a given technology and given fixed factor endowments. In this context, the
151 selected soil fertility parameters from the test results were treated as 'state-of-nature' variables and
152 added into the analysis following the approach adopted by Sidhu and Baanante (1981).

153

154 **2.4.1 Soil fertility variables**

155 In order to create these 'state-of-nature' variables for each of the sampled households, we
156 extrapolated our soil sample results taken from representative farm-plots to farm households
157 whose plots belong to the same village and fall within the same soil series. The justification for
158 adopting this approach is two-fold. First, in preparing the Land and Soil Resource Use Guideline
159 at *Thana* (sub-district) level, which includes a soil fertility map based on representative soil
160 sampling, the Soil Development Research Institute utilized the soil series classification system

161 (SRDI, 1991). They noted that a particular soil series is named/determined according to a number
162 of characteristics, e.g., texture, structure, colour, organic matter content, and soil pH. Also, in
163 general, chemical properties of soils within a given soil series were observed to be similar, as soils
164 mapped within each series was formed from the same parent material. Therefore it was assumed
165 that each soil series possessed similar properties. Hence, one can expect similar results from other
166 soil samples collected from the same soil series. Although it should be noted that there are obvious
167 limitations to this extrapolation, given that many soil properties are dynamic and depend not only
168 on parent material but also on recent management history, which was found to be similar across
169 surveyed farmers. As such, one can use replicate information on soil properties collected from one
170 location of a given soil series to other locations falling within the same soil series simply by
171 referring to the soil fertility map (SRDI, 1991). Second is the nature of the paddy fields from
172 where these samples were taken. We took soil samples from rice plots of surveyed households,
173 which were located within a large continuous block of land area designated as paddy fields where
174 most of the farmers of that village have rice plots. Furthermore, cross-referencing of these blocks
175 of paddy fields with the soil fertility map revealed that they all fell within the same soil series.
176 Therefore, extrapolation of soil fertility parameters to surveyed households with rice plots falling
177 within the same soil series was not expected to pose any significant limitation to the interpretation
178 of soil analysis data.

179

180 **2.4.2. The empirical model**

181 The general form of the translog profit function, dropping the subscript for the farm, is
182 defined as:

$$183 \ln \pi' = \alpha_0 + \sum_{i=1}^4 \alpha_i \ln P'_i + \frac{1}{2} \sum_{i=1}^4 \sum_{h=1}^4 \gamma_{ih} \ln P'_i \ln P'_h + \sum_{i=1}^4 \sum_{k=1}^7 \delta_{ik} \ln P'_i \ln Z_k$$

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$$+ \sum_{k=1}^7 \beta_k \ln Z_k + \frac{1}{2} \sum_{k=1}^7 \sum_{j=1}^7 \theta_{kj} \ln Z_k \ln Z_j + \varepsilon \quad (1)$$

185 where

186 π' = restricted profit (total revenue less total cost of variable inputs) normalized by price of
 187 output (P_y),

188 P'_i = price of the i th input (P_i) normalized by the output price (P_y),

189 i = 1, fertilizer price (taka kg^{-1})

190 = 2, labour wage (taka day^{-1})

191 = 3, animal power price (taka animal pair-days $^{-1}$)

192 = 4, pesticide price (taka 100 g^{-1} of active ingredients)

193 Z_k = quantity of fixed input,

194 k = 1, area under modern rice varieties (ha farm^{-1})

195 = 2, irrigation (taka farm^{-1})

196 = 3, farm capital (taka farm^{-1})

197 = 4, soil organic carbon content (kg ha^{-1})

198 = 5, soil available phosphorus (P), (kg ha^{-1})

199 = 6, soil available potassium (K), (kg ha^{-1})

200 = 7, soil available nitrogen (N), (kg ha^{-1})

201 ε = random error

202 \ln = natural logarithm

203 $\alpha_0, \alpha_i, \gamma_{ih}, \beta_k, \delta_{ik}$, and θ_{kj} , are the parameters to be estimated.

204 The corresponding factor share equations are expressed as,

205
$$S_i = -\frac{P_i X_i}{\pi'} = \frac{\partial \ln \pi'}{\partial \ln P'_i} = \alpha_i + \sum_{h=1}^4 \gamma_{ih} \ln P'_h + \sum_{k=1}^7 \delta_{ik} \ln Z_k \quad (2)$$

$$206 \quad S_y = \frac{P_y X_y}{\pi'} = 1 + \frac{\partial \ln \pi'}{\partial \ln P_y} = 1 + \sum_{i=1}^4 \alpha_i + \sum_{i=1}^4 \sum_{h=1}^4 \gamma_{ih} \ln P'_h + \sum_{i=1}^4 \sum_{k=1}^7 \delta_{ik} \ln Z_k \quad (3)$$

207 where S_i is the share of i th variable input, S_y is the share of output, X_i denotes the quantity of input i
 208 and Y is the level of rice output. Since the variable input and output shares form a singular system
 209 of equations (by definition $S_y - \sum S_i = 1$), one of the share equations, the output share, is dropped
 210 and the profit function and four variable input share equations are estimated jointly using
 211 Seemingly Unrelated Regression Estimation (SURE) procedure. The joint estimation of the profit
 212 function together with factor share equations ensures consistent parameter estimates (Sidhu and
 213 Baanante, 1981).

214 Among the regularity properties of the profit function specified in equation (3),
 215 homogeneity was automatically imposed because the normalized specification was used. The
 216 monotonicity property of a translog profit function model holds if the estimated output share is
 217 positive (Wall and Fisher, 1987 cited in Farooq et al., 2001) which was found in our case. The
 218 symmetry property was tested by imposing cross-equation restrictions of equality on the
 219 corresponding parameters between the profit function and the four factor demand equations. The
 220 test failed to reject the restrictions thereby confirming that the symmetry property also holds and
 221 the sample farms do maximize profit with respect to normalized prices of the variable inputs
 222 (Sidhu and Baanante, 1981). The convexity property was assumed to hold and was not tested.

223 Fertilizer, labour and animal power, are the three major inputs that are essential in
 224 producing any crop and contribute significantly to total cost of production (Rahman, 1999). Owing
 225 to diffusion of GR, pesticide also became an integral part of the system, although past studies
 226 consistently omitted this essential input, except for some in recent years, such as Tzouvelekas et al.
 227 (2001) and Wadud and White (2000). Total cultivated land devoted to modern rice is expected to
 228 have significant positive association with quantities of input demanded. Also, studies on

229 Bangladesh found land to be the most important input in crop production with a very high level of
230 output elasticity (Wadud and White, 2000). Lack of access to irrigation has been identified as one
231 of the principal reasons for stagnation in GR diffusion in Bangladesh (Rahman and Thapa, 1999).
232 Use of farm capital, other than land, is also important to a large extent in field crop production.

233 Inclusion of soil-related 'state-of-nature' variables is a rather uncommon practice in farm
234 economic analysis (Sidhu and Baanante, 1981). Moreover, given the emerging concerns regarding
235 sustainability of food production, declining soil fertility and other environmental problems arising
236 from GR adoption (e.g., Shiva, 1991; Pimentel, 1996; Rahman and Thapa, 1999; and Singh, 2000),
237 inclusion of these variables in economic decision making is becoming more and more important.
238 The key soil fertility variables used in this analysis were soil organic carbon and available N, P and
239 K, all of which are core components of soil fertility (Parkinson, 2003). Soil organic carbon (SOC)
240 is an important soil fertility indicator because it has a major influence on biophysical and
241 biochemical soil function. Soil pH was not included because the range of pH values observed was
242 restricted, and fell within the optimum range suitable for rice production environment (SRDI,
243 1991). Our *a priori* expectation was that input use levels of chemicals (i.e., fertilizers and
244 pesticides) would be lower in fertile regions due to a higher nutrient status of the soils.

245

246 **3. RESULTS**

247 Summary statistics of the variables used in the profit function model are presented in Table
248 1. Soil fertility variables included in the analysis were SOC, indicative of inherent soil physical,
249 chemical and biological fertility, and available soil N, P and K, the three macronutrients that are
250 yield limiting in rice production systems (Wijnhoud *et al.*, 2003). Table 2 presents the estimates of
251 the profit function estimated jointly with four variable input share equations. Thirty-one of the total

252 78 parameters are significantly different from zero at 10% level at least in the profit function.
253 Significance of the interaction terms indicates non-linearity in the production structure, which
254 justifies use of a flexible translog model instead of a more restrictive Cobb-Douglas model.

255 **[INSERT TABLES 1 AND 2 HERE]**

256 The parameter estimates of the profit function model are used to estimate the elasticities
257 with respect to variable input demand and output supply (Table 3). Most of the elasticity estimates
258 (43 out of 60) are significantly different from zero at 10% level at least indicating that modern rice
259 farmers are responsive to change in prices as well as fixed factor endowments including soil
260 fertility variables.

261 One of the key policy variables of interest is the output price. The supply response of
262 farmers to a rise in rice price is positive as expected but is low and inelastic. A one percent
263 increase in rice price will increase its supply by 0.27 percent. A positive but inelastic response of
264 output supply (rice or wheat) to its price has been common in Asia since 1970s. For example,
265 supply response of Basmati rice in Pakistan Punjab is estimated at 0.27 (Farooq *et al.*, 2001), rice
266 in Northern Thailand at 0.45 (Rahman and Sriboonchitta, 1995), and Mexican wheat in Indian
267 Punjab at 0.63 (Sidhu and Baanante, 1981). On the other hand, a rise in rice price will result in a
268 significant increase in demand for all inputs, the highest effect being on labour demand. A one
269 percent increase in rice price will increase labour demand by 0.94% and pesticide demand by
270 0.53%, respectively.

271 All own price elasticities are negative, consistent with theory although they lie in the
272 inelastic range. Price elasticity of demand for major inputs are closely similar ranging from -0.57
273 to -0.59 except fertilizers which is -0.25. A one percent reduction in input prices will increase its
274 use by 0.57 to 0.59 percent (0.25 percent for fertilizer input).

275

[INSERT TABLE 3 HERE]

276 Among the fixed factor endowments, supply response to an expansion in land area is high,
277 as expected. A one percent increase in land area will increase rice supply by 0.86 percent which is
278 comparable to those obtained by Farooq et al., (2001), Rahman and Sriboonchitta (1995) and
279 Sidhu and Baanante (1981). Among the inputs, response to an expansion in land area is also high.
280 A one percent increase in land area under modern rice varieties will increase fertilizer demand by
281 0.92 percent and pesticide demand by 0.41 percent thereby reinforcing the chemical intensity
282 argument of this GR technology. Irrigation and farm capital assets do not have significant
283 influence on output supply and input demand.

284

285 Table 3 also shows the influence of soil fertility on both output supply and input demand in
286 this cropping system. SOC is a commonly accepted indicator of soil fertility, there being a positive
287 relationship between organic carbon content and productivity in most cropping systems
288 (Parkinson, 2003). In this case, the influence of SOC is significantly positive on output (rice)
289 supply. This confirms that for these rice farmers, high inherent soil fertility leads to greater yields.
290 In addition, the analysis shows that farmers recognize that those soils with higher SOC, and hence
291 greater nutrient exchange capacities, were more fertile, and exploited the greater ability of the soil
292 to retain and supply fertilizer nutrients to the rice crop. These findings agree with the findings of
293 Payton et al. (2003), who noted that farmers can distinguish “soil fertility” based on feel and visual
294 observations, even in the absence of analytical data. The significant negative influence of SOC on
295 input demand shows that the higher inherent fertility (and hence higher yielding) production
296 systems required significantly less amount of inputs.

297 An increase in available N, P and K significantly increases rice supply, confirming well

298 known relationships between soil fertility and crop productivity (Yadav, 2003), although the
299 magnitude of influence is much higher for available K. Input demand declines significantly with
300 increase in available P and N, the magnitude of influence being much higher for available P. In
301 contrast, available K has significant positive influence on demand for all inputs. This observation
302 is counterintuitive, and needs further investigation.

303

304 **4. DISCUSSION AND POLICY IMPLICATIONS**

305 The inclusion of “state-of-nature” variables in economic analysis of farmers’ resource
306 allocation decision is uncommon, although in reality farmers’ production performance is highly
307 likely to be influenced by both economic as well as bio-physico-chemical factors. The present
308 study attempted to integrate these two strands of scientific enquiry into farmers’ decision making
309 processes. Therefore, we incorporated four key “state-of-nature” variables and examined their
310 influence on resource allocation decisions while explicitly controlling for farmers’ responses to
311 market indicators (i.e., the input and output prices) as well as other fixed resource endowments
312 (i.e., land, irrigation and farm capital assets).

313 On the whole, changes in market prices of inputs and outputs significantly influenced
314 farmers’ resource use and productivity (rice supply) as expected. A rise in rice price will increase
315 its supply as well as demand for all four inputs, with particularly high impact on labour use. Since
316 modern rice production technology utilises higher share of hired labour, the rise in labour demand
317 in response to rice price increase will lead to redistribution of gain accrued from modern
318 technology to landless labourers via wages, an argument in favour of widespread GR technology
319 diffusion in the first place. With respect to variable inputs, increases in their prices will depress
320 rice supply, although the magnitude of responsiveness is in the inelastic range. The responsiveness

321 to fertilizer price is lowest of all, implying that a rise in the price of fertilizer will have minimal
322 depressing effect on rice supply. This is perhaps because farmers growing modern varieties of rice
323 realises that fertilizer must be applied in order to obtain any decent amount of rice output
324 irrespective of its relative cost. Low elasticity of fertilizer input is one of the principle reasons
325 behind abolition of fertilizer subsidy and liberalisation of the fertilizer market in Bangladesh in
326 1992.

327 Among the conventional fixed factors, the role of paddy area in influencing productivity
328 and resource use is a dominant factor. This is expected in a land-scarce country like Bangladesh
329 where average farm size is only 0.60 ha (BBS, 2001). Therefore, an increase in the availability of
330 land will dramatically increase rice supply and will result in consequent increase in the use of
331 variable inputs. Once again, landless labourers will gain access to the profit generated by modern
332 technology adoption via higher demand for hired labour owing to increase in paddy area.
333 However, the influence of irrigation and farm capital asset on rice supply and input demand is
334 quite limited. This is probably because irrigation is largely applied at a fixed rate (mostly at a pre-
335 determined number of frequencies and hours in a season) and not very sensitive to farm size.
336 Similarly, farm capital assets possessed by most farmers are similar and largely composed of
337 traditional equipment and tools with little variation in value and quality.

338 All of the soil fertility variables had significant influence on rice output as expected,
339 thereby pointing towards their importance in raising farm productivity. The data analysis showed
340 that output increases significantly with higher concentration of SOC and available soil N, P and K.
341 Furthermore, there was a significant reduction in use of inputs in response to higher concentrations
342 of SOC and available soil P and N. The results presented in this paper demonstrate that the
343 disaggregation of soil fertility variables allows direct evaluation of the contribution that individual

344 components of soil fertility can make to rice yield. This observation emphasises the importance of
345 developing regional agricultural policy approaches that allow the transfer of indigenous
346 knowledge, as farmers do not carry out either detailed nutrient budgets or soil nutrient analysis on
347 a routine basis.

348 The overarching policy implication of this study is that enhancement of soil fertility exerts
349 a dual impact on the production process, leading to an increase in crop yield, and the reduced use
350 of variable inputs, thereby raising farmers' income and competitiveness in the market.
351 Enhancement of soil fertility status through more efficient nutrient utilisation will be beneficial on
352 both economic and bio-physico-chemical grounds. Therefore, government policies should be
353 geared towards devising an effective strategy that promotes soil conservation measures to ensure
354 and sustain future productivity potential of these soils. The farmers surveyed here, operating on a
355 range of soils of contrasting fertility status, were able to adjust input use effectively based on soil
356 observation and indigenous knowledge (Payton et al., 2003). However, there are other agro-
357 ecological zones in Bangladesh where lower natural soil fertility and lack of understanding of soil
358 fertility limits crop production severely. In these situations, the transfer of inherent soil fertility
359 knowledge acquisition skills is a necessary prerequisite for raising farm productivity in these less
360 fertile areas, and will result in a more efficient utilisation of nutrients, while maintaining a
361 relatively lower cost of input use. It is recommended that knowledge transfer of agro-economic
362 advice at village level, emphasising soil nutrient budgeting, be implemented in order to allow
363 increased nutrient utilisation efficiency in regions where soil fertility is depleted.

364

365 **5. CONCLUSIONS**

366 This research has demonstrated a clear relationship between soil fertility (a combined bio-
367 physico-chemical factor) and farmers' resource allocation decisions (an economic factor) in rice
368 production in the Jamalpur, Jessore and Comilla districts of Bangladesh. Results revealed that soil
369 fertility has a significant influence on farmers' resource allocation decisions. In this area of
370 Bangladesh, the supply of rice is significantly higher in fertile regions, as expected. We have
371 shown that there is a close relationship between rice yield and disaggregated indicators of soil
372 fertility. Our observation that the use of inputs is lower in more fertile regions reinforces the need
373 for a regular soil evaluation and analysis programme to inform resource allocation decisions and
374 hence increase competitiveness of these rice farmers by lowering the cost of inputs when soil
375 fertility status is enhanced. Challenges remain, as the transfer of technological and intuitive
376 knowledge is restricted by the lack of routine soil and crop monitoring procedures at farm level.
377 There is a requirement to focus agronomic advice and support at the local level, and hence
378 facilitate the transfer of indigenous knowledge from farmers in higher productivity areas.

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454 **Table 1. Description, measure and summary statistics of the variables**

Name	Description	Measurement	Mean	Standard deviation
<i>PR</i>	Profit from modern rice production	Taka ^a	10203.74	12345.33
<i>Y</i>	Quantity of modern rice output	Kg	2974.51	3153.39
<i>X_F</i>	Quantity of fertilizers	Kg	178.94	197.47
<i>X_W</i>	Quantity of labour	Person-days	63.11	57.21
<i>X_M</i>	Quantity of animal power services	Animal pair-days	19.40	20.97
<i>X_P</i>	Quantity of pesticides	100 g or ml of active ingredients	2.74	3.91
<i>Y_R</i>	Rice price	Taka kg ⁻¹	5.64	0.44
<i>F</i>	Fertilizer price	Taka kg ⁻¹	6.51	1.18
<i>W</i>	Labour wage	Taka person-day ⁻¹	45.56	8.25
<i>M</i>	Animal power price	Taka pair-day ⁻¹	84.71	17.72
<i>P</i>	Pesticide price	Taka per 100 g or ml of active ingredients	83.58	15.55
<i>L</i>	Land cultivated under modern varieties of rice	Hectare	0.73	0.79
<i>G</i>	Irrigation	Taka	1655.16	2471.83
<i>C</i>	Farm capital asset	Taka	12154.99	17183.39
<i>O</i>	Soil organic carbon	kg ha ⁻¹	40.28	31.34
<i>H</i>	Available soil phosphorus	kg ha ⁻¹	44.63	15.22
<i>K</i>	Available soil potassium	kg ha ⁻¹	68.58	31.63

<i>Q</i>	Available soil nitrogen	kg ha ⁻¹	38.11	11.98
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456 Note: ^a= Exchange rate of USD 1.00 = Taka 42.70 in 1996 (BBS, 2001)

457

458 **Table 2. Restricted parameter estimates of the translog profit function and factor share**
 459 **equations**

Variables	Parameters	Coefficients	t-ratio
Profit Function			
<i>Constant</i>	α_0	-325.8535	-0.97
$\ln P'_F$	α_F	-0.3255	-1.73*
$\ln P'_W$	α_W	-1.3284	-2.59***
$\ln P'_M$	α_M	-0.5583	-2.36**
$\ln P'_P$	α_P	-0.1085	-0.56
$\frac{1}{2}(\ln P'_F \times \ln P'_F)$	γ_{FF}	-0.1681	-9.37***
$\frac{1}{2}(\ln P'_W \times \ln P'_W)$	γ_{WW}	-0.4619	-8.23***
$\frac{1}{2}(\ln P'_M \times \ln P'_M)$	γ_{MM}	-0.1023	-5.45***
$\frac{1}{2}(\ln P'_P \times \ln P'_P)$	γ_{PP}	-0.0453	-2.68***
$\ln P'_F \times \ln P'_W$	γ_{FW}	-0.0309	-1.48
$\ln P'_F \times \ln P'_M$	γ_{FM}	-0.0045	-0.35
$\ln P'_F \times \ln P'_P$	γ_{FP}	-0.0369	-2.95***
$\ln P'_W \times \ln P'_M$	γ_{WM}	-0.1205	-4.84***
$\ln P'_W \times \ln P'_P$	γ_{WP}	-0.0326	-1.47
$\ln P'_M \times \ln P'_P$	γ_{MP}	-0.0012	-0.10
$\ln P'_F \times \ln Z_L$	δ_{FL}	0.0013	0.23
$\ln P'_F \times \ln Z_G$	δ_{FG}	0.0028	1.10
$\ln P'_F \times \ln Z_C$	δ_{FC}	0.0059	2.06**

Variables	Parameters	Coefficients	t-ratio
$\ln P'_F \times \ln Z_H$	δ_{FH}	0.0623	2.44**
$\ln P'_F \times \ln Z_O$	δ_{FO}	0.0307	3.04***
$\ln P'_F \times \ln Z_K$	δ_{FK}	0.0258	-1.57
$\ln P'_F \times \ln Z_Q$	δ_{FQ}	-0.0381	-2.02**
$\ln P'_W \times \ln Z_L$	δ_{WL}	0.0451	2.84***
$\ln P'_W \times \ln Z_G$	δ_{WG}	0.0280	3.99***
$\ln P'_W \times \ln Z_C$	δ_{WC}	0.0269	3.39***
$\ln P'_W \times \ln Z_H$	δ_{WH}	0.2918	4.24***
$\ln P'_W \times \ln Z_O$	δ_{WO}	0.1704	6.23***
$\ln P'_W \times \ln Z_K$	δ_{WK}	0.1089	2.42**
$\ln P'_W \times \ln Z_Q$	δ_{WQ}	-0.0559	-1.09
$\ln P'_M \times \ln Z_L$	δ_{ML}	-0.0037	-0.51
$\ln P'_M \times \ln Z_G$	δ_{MG}	0.0125	3.85***
$\ln P'_M \times \ln Z_C$	δ_{MC}	0.0119	3.25***
$\ln P'_M \times \ln Z_H$	δ_{MH}	0.1126	3.51***
$\ln P'_M \times \ln Z_O$	δ_{MO}	0.0661	5.15***
$\ln P'_M \times \ln Z_K$	δ_{MK}	0.0246	1.18
$\ln P'_M \times \ln Z_Q$	δ_{MQ}	-0.1012	-0.42
$\ln P'_P \times \ln Z_L$	δ_{PL}	0.0475	7.94***
$\ln P'_P \times \ln Z_G$	δ_{PG}	0.0042	1.62
$\ln P'_P \times \ln Z_C$	δ_{PC}	0.0031	1.05

Variables	Parameters	Coefficients	t-ratio
$\ln P'_P \times \ln Z_H$	δ_{PH}	0.0567	2.20**
$\ln P'_P \times \ln Z_O$	δ_{PO}	0.0349	3.38***
$\ln P'_P \times \ln Z_K$	δ_{PK}	0.0121	0.72
$\ln P'_P \times \ln Z_Q$	δ_{PQ}	-0.0468	-2.45**
$\ln Z_L$	β_L	1.8342	2.72***
$\ln Z_G$	β_G	-0.8041	-1.63
$\ln Z_C$	β_C	0.0362	0.12
$\ln Z_H$	β_H	12.0543	0.85
$\ln Z_O$	β_O	-15.0747	-0.84
$\ln Z_K$	β_K	71.1015	0.90
$\ln Z_Q$	β_Q	125.9763	1.05
$\frac{1}{2}(\ln Z_L \times \ln Z_L)$	θ_{LL}	-0.1670	-0.66
$\frac{1}{2}(\ln Z_G \times \ln Z_G)$	θ_{GG}	0.0205	2.51***
$\frac{1}{2}(\ln Z_C \times \ln Z_C)$	θ_{CC}	0.0065	0.71
$\frac{1}{2}(\ln Z_H \times \ln Z_H)$	θ_{HH}	10.7665	0.94
$\frac{1}{2}(\ln Z_O \times \ln Z_O)$	θ_{OO}	-6.7892	-1.09
$\frac{1}{2}(\ln Z_K \times \ln Z_K)$	θ_{KK}	3.0320	0.87
$\frac{1}{2}(\ln Z_Q \times \ln Z_Q)$	θ_{QQ}	-16.4661	-1.08
$\ln Z_L \times \ln Z_G$	θ_{LG}	-0.1459	-1.52
$\ln Z_L \times \ln Z_C$	θ_{LC}	-0.0223	-2.35**
$\ln Z_L \times \ln Z_H$	θ_{LH}	-0.1638	-1.74*

Variables	Parameters	Coefficients	t-ratio
$\ln Z_L \times \ln Z_O$	θ_{LO}	0.0087	0.25
$\ln Z_L \times \ln Z_K$	θ_{LK}	0.0186	0.28
$\ln Z_L \times \ln Z_Q$	θ_{LQ}	-0.0952	-1.41
$\ln Z_G \times \ln Z_C$	θ_{GC}	0.0027	0.81
$\ln Z_G \times \ln Z_H$	θ_{GH}	0.0763	1.21
$\ln Z_G \times \ln Z_O$	θ_{GO}	-0.0024	-0.09
$\ln Z_G \times \ln Z_K$	θ_{GK}	0.0219	0.37
$\ln Z_G \times \ln Z_Q$	θ_{GQ}	0.0730	1.61
$\ln Z_C \times \ln Z_H$	θ_{CH}	-0.0169	-0.41
$\ln Z_C \times \ln Z_E$	θ_{CE}	-0.0172	-1.15
$\ln Z_C \times \ln Z_K$	θ_{CK}	-0.0347	-1.18
$\ln Z_C \times \ln Z_Q$	θ_{CQ}	0.0230	0.77
$\ln Z_H \times \ln Z_O$	θ_{HO}	6.4610	0.96
$\ln Z_H \times \ln Z_K$	θ_{HK}	-8.1742	-0.83
$\ln Z_H \times \ln Z_Q$	θ_{HQ}	-10.0507	-1.08
$\ln Z_O \times \ln Z_K$	θ_{OK}	-1.7217	-0.73
$\ln Z_O \times \ln Z_Q$	θ_{OQ}	5.6452	0.99
$\ln Z_K \times \ln Z_Q$	θ_{KQ}	-12.1497	-0.97
Fertilizer share equation			
<i>Constant</i>	α_F	-0.3255	-1.73*
$\ln P'_F$	γ_{FF}	-0.1681	-9.37***

Variables	Parameters	Coefficients	t-ratio
$\ln P'_W$	γ_{FW}	-0.0309	-1.48
$\ln P'_M$	γ_{FM}	-0.0045	-0.35
$\ln P'_P$	γ_{FP}	-0.0369	-2.95***
$\ln Z_L$	δ_{FL}	0.0013	0.23
$\ln Z_G$	δ_{FG}	0.0028	1.10
$\ln Z_C$	δ_{FC}	0.0060	2.06**
$\ln Z_H$	δ_{FH}	0.0623	2.44**
$\ln Z_O$	δ_{FO}	0.0307	3.04***
$\ln Z_K$	δ_{FK}	0.0258	1.57
$\ln Z_Q$	δ_{FQ}	-0.0381	-2.02**

Labor share equation

<i>Constant</i>	α_W	-1.3284	-2.59***
$\ln P'_F$	γ_{FW}	-0.0309	-1.48
$\ln P'_W$	γ_{WW}	-0.4619	-8.23***
$\ln P'_M$	γ_{WM}	-0.1215	-4.84***
$\ln P'_P$	γ_{WP}	-0.0326	-1.47
$\ln Z_L$	δ_{WL}	0.0451	2.84***
$\ln Z_G$	δ_{WG}	0.0280	3.99***
$\ln Z_C$	δ_{WC}	0.0269	3.39***
$\ln Z_H$	δ_{WH}	0.2917	4.24***
$\ln Z_O$	δ_{WO}	0.1704	6.23***

Variables	Parameters	Coefficients	t-ratio
$\ln Z_K$	δ_{WK}	0.1089	2.42**
$\ln Z_Q$	δ_{WQ}	-0.0559	-1.09
Animal share equation			
<i>Constant</i>	α_M	-0.5582	-2.36**
$\ln P'_F$	γ_{FM}	-0.0045	-0.35
$\ln P'_W$	γ_{WM}	-0.1205	-4.84***
$\ln P'_M$	γ_{MM}	-0.1023	-5.45***
$\ln P'_P$	γ_{MP}	-0.0012	-0.10
$\ln Z_L$	δ_{ML}	-0.0037	-0.51
$\ln Z_G$	δ_{MG}	0.0125	3.85***
$\ln Z_C$	δ_{MC}	0.0119	3.25***
$\ln Z_H$	δ_{MH}	0.1126	3.51***
$\ln Z_O$	δ_{MO}	0.0661	5.15***
$\ln Z_K$	δ_{MK}	0.0246	1.18
$\ln Z_Q$	δ_{MQ}	-0.0101	-0.42
Pesticide share equation			
<i>Constant</i>	α_P	-0.1085	-0.56
$\ln P'_F$	γ_{FP}	-0.0369	-2.95**
$\ln P'_W$	γ_{WP}	-0.0326	-1.47
$\ln P'_M$	γ_{MP}	-0.0012	-0.10
$\ln P'_P$	γ_{PP}	-0.0453	-2.68***

Variables	Parameters	Coefficients	t-ratio
$\ln Z_L$	δ_{PL}	0.0475	7.94***
$\ln Z_G$	δ_{PG}	0.0042	1.62
$\ln Z_C$	δ_{PC}	0.0031	1.05
$\ln Z_H$	δ_{PH}	0.0567	2.20**
$\ln Z_O$	δ_{PO}	0.0649	3.38***
$\ln Z_K$	δ_{PK}	0.0121	0.72
$\ln Z_Q$	δ_{PQ}	-0.0468	-2.45**
Log likelihood		1420.28	
Observations		380	

460

461 Note: *** Significant at 1 percent level ($p < 0.01$)

462 ** Significant at 5 percent level ($p < 0.05$)

463 * Significant at 10 percent level ($p < 0.10$)

464 Variables P_i = normalised variable input prices, and Z_k = fixed inputs.

465 Subscripts F = fertilizer price, W = labour wage, M = animal power price, P = pesticide price, L = land

466 cultivated, G = irrigation, C = farm capital asset, H = available soil phosphorus, O = soil organic carbon

467 concentration, K = available soil potassium, and Q = available soil nitrogen.

468 Based on the estimation of the restricted translog profit function and four variable input share equations

469 with across-equation restrictions (symmetry) and linear homogeneity imposed.

470

471

Table 3. Estimated elasticities of translog profit function

	Rice price	Fertilizer price	Labour wage	Animal power price	Pesticide price	Land	Irrigation	Farm capital asset	Available soil phosphor	Available soil carbon	Available soil potassium	Available soil nitrogen
Rice	0.266	-0.011	-0.050	-0.065	-0.011	0.883	0.061	0.114	0.826	0.301	3.641	0.876
supply	(6.08)***	(-1.47)	(-2.18)**	(-3.73)***	(-1.35)	(16.87)***	(1.65)*	(0.50)	(2.51)***	(2.16)**	(2.90)***	(1.97)**
Fertilizer	0.164	-0.251	-0.159	-0.157	0.230	0.923	0.064	-0.011	-6.391	-0.714	3.523	-0.874
demand	(1.74)*	(-1.68)*	(-1.92)*	(-2.10)**	(1.73)*	(14.65)***	(1.60)	(-0.09)	(-2.55)***	(2.12)**	(2.83)***	(-2.03)**
Labour	0.944	-0.145	-0.571	0.324	0.063	0.739	-0.033	-0.077	-6.142	-0.590	3.628	-1.027
demand	(2.18)**	(-1.91)*	(-2.99)***	(1.07)	(0.53)	(12.95)***	(-0.06)	(-0.99)	(-2.50)***	(-1.77)*	(2.95)***	(-2.02)**
Animal	0.463	-0.120	0.308	-0.580	-0.070	0.956	0.012	0.002	-6.248	-0.643	3.583	-0.962
power demand	(3.73)***	(-2.10)**	(1.07)	(-7.17)***	(-1.38)	(15.99)***	(0.34)	(0.25)	(-2.52)***	(2.15)**	(2.87)***	(-2.00)**
Pesticide	0.534	0.261	-0.055	-0.182	-0.576	0.409	0.041	-0.259	-6.562	-0.798	3.452	-0.770
demand	(2.79)***	(0.72)	(-1.09)	(-1.51)	(-4.02)***	(5.75)***	(0.77)	(-1.79)*	(-2.54)***	(-2.12)**	(2.77)***	(-1.78)*

472

473 Note: Elasticity estimates computed at mean values.

474 Figures in parentheses are t-ratios.

475

*** Significant at 1 percent level ($p < 0.01$)

476

** Significant at 5 percent level ($p < 0.05$)

477

* Significant at 10 percent level ($p < 0.10$)