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Whether crop diversification is energy efficient: An empirical analysis from
Bangladesh

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WHETHER CROP DIVERSIFICATION IS ENERGY EFFICIENT: AN EMPIRICAL ANALYSIS FROM BANGLADESH

ABSTRACT

This study examines whether crop diversification provides economy in energy use and improves technical energy efficiency using a large survey data of 2,075 farms from 20 sub-districts of 17 districts in Bangladesh by applying a stochastic input-distance function approach. The results reveal that cereal production significantly increases energy use by 0.14% for every one percent increase in output. Renewable source of energy constitutes 59.6% of total inputs and labour energy alone constitutes 39%. Significant output complementarity exists between cereal and oilseed enterprises but competition exist between jute with pulse and/or oilseed enterprises. The mean technical energy efficiency is estimated at 68% implying that energy output can be increased by 32% by eliminating inefficiency. Diversification amongst enterprises is associated with energy inefficiency, implying that specialization into cereals improves efficiency. Large farms are inefficient whereas large family size improves efficiency. The key policy implication is that diversification of crop enterprises must maintain cereal (i.e., rice/wheat/maize) as the main base and then add non-cereal crops (e.g., oilseeds) in order to improve energy economy. Also, diversification within cereals from rice monoculture to wheat and/or maize will significantly improve technical energy efficiency.

JEL classification: O33; Q18; C21

Key words: Crop diversification, technical energy efficiency, scale economy of energy use, stochastic input distance function, Bangladesh.

1. Introduction

The renewed drive to increase agricultural production using modern technology to feed the growing population in the face of closing land frontier and falling yield levels has resulted in an unprecedented increase in the use of commercial energy in agriculture in developing

economies. The increase in energy use is particularly high in countries reliant on Green Revolution technology to promote agricultural growth which in turn is largely dependent on non-renewable fossil fuels, e.g., inorganic fertilizers, pesticides and mechanization (particularly for supplementary irrigation and land preparation) [1]. For example, commercial energy use in Bangladesh agriculture has been modest in the past but increased rapidly in recent years. The energy intensity (i.e., commercial energy/GDP ratio) in Bangladesh agriculture has increased from only 1.78 in 2000 to 11.31 in 2008 [2], implying that the sector is becoming energy intensive mainly due to the widespread diffusion of a rice-based Green Revolution initiated since the early 1960s, thereby, adding further a crisis to the existing problem of acute energy deficiency in the economy [1].

Bangladesh, dominated by rice culture accounting for 79.2% of the gross cropped area [3], is seeking to diversify its agricultural sector to other cereals (i.e., wheat and maize) as well as non-cereals (e.g., potatoes, vegetables, and spices, etc.). In fact, the Fifth Five Year Plan (1997–2002) set specific objectives to attain self-sufficiency in foodgrain production along with increased production of other nutritional crops, as well as to encourage export of vegetables and fruits, keeping in view domestic consumption demand and nutritional requirements [4]. The Plan also earmarked 8.9% of the total agricultural allocation to promote crop diversification. Subsequently, the Poverty Reduction Strategy Paper (2005) and the Sixth Five Year Plan (2011–2015) also emphasized crop diversification [5, 6] although no specific budget was earmarked in these plan documents.

Farmers in Bangladesh grow multiple crops with rice in order to meet subsistence as well as cash requirement [7]. However, expansion of non-cereals (e.g., potatoes, vegetables, onions and cotton), which are more profitable than rice cultivation, are slow because of the incompatibility of the existing irrigation system that is mainly suitable for rice production only [8]. But there is recognition that with better farming practices and varietal improvements,

the non-cereal crops will be more profitable and could lead to crop diversification as a successful strategy for future growth and sustainability of Bangladeshi agriculture [4, 6, 8, 9]. Recently, the National Food Policy Capacity Strengthening Program (NFPCSP) implemented by the Food and Agriculture Organization of the United Nations (FAO) and the Food Planning and Monitoring Unit (FPMU), Ministry of Food and Disaster Management, Bangladesh with the financial support of EU and USAID completed a large scale research on investigating financial and economic profitability of cereal and non-cereal crops (specifically, high yielding varieties of rice, aromatic rice, wheat, maize, lentil, mustard, and jute) in mid-2013 [10].

Therefore, given renewed drive by the Bangladeshi government to diversify its agricultural sector instead of intensifying existing rice-based Green Revolution technology, it is important to know whether such strategy of crop diversification is productive and efficient when evaluated in terms of energy use. This confirmation is important because not all crops that are deemed to be economically profitable are also efficient in terms of energy use. For example, the prawn-fish enterprise of the ‘gher farming system’¹ in Bangladesh, which is the most financially rewarding enterprise [11], is actually highly inefficient in terms of energy use [12].

Conclusions on the merit of crop diversification as a strategy for agricultural growth in the literature are mixed. Previous studies mainly focused on the impact of crop diversification either on income or overall production with favourable conclusions [13, 14, 15]. Only a few focused on its impact on technical efficiency where conclusions are mixed. For example,

¹ The term ‘gher’ refers to the modification of a paddy field to enable the operation of three enterprises: prawn (principal enterprise), fish, and high yielding varieties of rice. The middle of the ‘gher’ is surrounded by high and wide dikes with canals dug at the inner periphery of the dikes. The whole area of the ‘gher’ is filled with rain-water during the monsoon season, specifically from June to December, and closely resembles a typical pond. The ‘gher’ becomes dry naturally from January to April except the canals. This allows joint production of prawn, fish and rice in a single system known as ‘gher farming system’ [11].

while Coelli and Fleming [16] and Rahman [7, 17] concluded that crop diversification significantly improves technical efficiency on farms in Papua New Guinea and Bangladesh, but Llewelyn and Williams [18] and Haji [19] concluded otherwise for Indonesian and Ethiopian farms.

Given this backdrop, this study aims to examine: (a) the existence of energy economies of diversification amongst crop enterprises; and (b) the impact of diversification on technical energy efficiency in farming in Bangladesh. To our knowledge, such information is not available in the energy literature. Therefore, the present study will be a valuable contribution to the existing literature providing an evidence based conclusion on the merit of crop diversification as a strategy for agricultural growth when evaluated in terms of energy use. We do so by using a large scale sample survey of 2,075 farm households from 20 sub-districts of 17 districts of Bangladesh.

The paper is organised as follows. Section 2 presents the analytical framework, the model, and various performance measures developed to address the research objectives. Section 3 presents the results. The final section concludes and draws policy implications.

2. Research Methodology

2.1 *Analytical framework*

The importance of examining level of technical efficiency arises because gains in efficiency are derived from improvements in decision making, which in turn are assumed to be linked to a host of socio-economic conditions, e.g., education, experience, farm operation size, etc. that are largely under the control of the decision maker, i.e., farmer. In this study, we are examining whether diversification into various crop enterprises lead to gains in scale economy in energy use as well as gains in technical energy efficiency. In order to examine these two key objectives, we need to represent the multiple crop production system by specifying a multi-output, multi-input production technology. A distance function approach

(either output-orientated or input-orientated) is appropriate here, and can be analyzed using either parametric or non-parametric methods. We adopt an input oriented approach which is appropriate when inputs are endogenous (e.g., minimize energy use in our case) and output is exogenous [20]. We chose a stochastic distance function approach instead of a non-parametric deterministic approach (i.e., Data Envelopment Analysis) because of its ability to separate the random noise (e.g., weather variation, measurement errors, etc.) from technical inefficiency effects. For example, our data is spread over 17 districts (which enhances representativeness of the sample but potentially contains regional level variations) and covers a complete crop year cycle (which in turn is likely to be subject to weather variations) implying that the choice of a stochastic/parametric approach is more appropriate.

The production technology of the farm is defined using the input set, $L(y)$, representing the set of all input vectors, $x \in R_+^K$, which can produce the output vector $y \in R_+^M$. That is,

$$L(y) = \{x \in R_+^K : x \text{ can produce } y\} \quad (1)$$

The input-distance function is then defined on the input set, $L(y)$, as

$$D_I(x, y) = \max\{\rho : (x / \rho) \in L(y)\} \quad (2)$$

The properties of the distance function $D_I(x, y)$ are that it is non-decreasing, positive, linearly homogenous and concave in x , and increasing in y . The distance function, $D_I(x, y)$, takes a value ≥ 1 if the input vector, x , is an element of the feasible input set, i.e., $L(y)$ [$D_I(x, y) \geq 1$ if $x \in L(y)$]. The value of the distance function is equal to one if x is located on the inner boundary of the input set. And for this reason, the input oriented distance function can be interpreted as the multi-input input-requirement function which allows deviations (distance) from the frontier, and these deviations are interpreted in terms of technical efficiency [21].

2.2 The model

For empirical implementation of the distance function, we select the flexible translog (TL) functional form used by many [7, 12, 17, 21, 22, 23].

The translog input distance function with M outputs (Y_m) and K inputs (X_k) for the I farms (denoted i) is given as:

$$\begin{aligned} \ln D_i = & \alpha_0 + \sum_k \alpha_k \ln X_{ki} + \frac{1}{2} \sum_k \sum_l \alpha_{kl} \ln X_{ki} \ln X_{li} + \\ & \sum_m \beta_m \ln Y_{mi} + \frac{1}{2} \sum_m \sum_n \beta_{mn} \ln Y_{mi} \ln Y_{ni} + \sum_k \sum_m \tau_{km} \ln X_k \ln Y_m \end{aligned} \quad (3)$$

In order to satisfy the conditions of homogeneity of degree one in inputs and symmetry of the cross effects, the following constraints are imposed:

$$\sum_k \alpha_k = 1, \sum_{kl} \alpha_{kl} = 0, \sum_{km} \tau_{km} = 0 (k = 1, \dots, K), \text{ and}$$

$$\alpha_{kl} = \alpha_{lk} (k, l = 1, \dots, K), \text{ and} \quad (3a)$$

$$\beta_{mn} = \beta_{nm} (m, n = 1, \dots, M), \text{ respectively.} \quad (3b)$$

We impose these constraints by normalizing the input distance function by one of the inputs following Lovell et al. [24]. Thus equation (3) becomes

$$\begin{aligned} \ln D_i / X_{li} = & \alpha_0 + \sum_k \alpha_k \ln X_{ki}^* + \frac{1}{2} \sum_k \sum_l \alpha_{kl} \ln X_{ki}^* \ln X_{li}^* + \\ & \sum_m \beta_m \ln Y_{mi} + \frac{1}{2} \sum_m \sum_n \beta_{mn} \ln Y_{mi} \ln Y_{ni} + \sum_k \sum_m \tau_{km} \ln X_k^* \ln Y_m \\ = & TL(\mathbf{X}^*, \mathbf{Y}) \end{aligned} \quad (4)$$

We rewrite this function with $-\ln D_i = u_i$ as a one sided error term, and include the standard error term v_i to represent statistical noise, measurement error or unobserved inputs, which provides the following equation suitable for estimation:

$$-\ln X_{li} = TL(\mathbf{X}^*, \mathbf{Y}) - u_i + v_i \quad (5)$$

Following Morrison-Paul and Nehring [21] and Morrison-Paul et al. [22], we reverse the signs of Eq (5) in order to interpret various performance measures derived from Eq (5) that are similar to familiar functions, such as a production function:

$$\ln X_{1,i} = -TL(\mathbf{X}^*, \mathbf{Y}) - u_i + v_i \quad (6)$$

Equation (6) is now written in the same form as a standard stochastic production frontier seen in the literature. Equation (6) can be estimated econometrically using the maximum likelihood method, assuming that v_i are independently and identically distributed with zero mean and variance, σ_v^2 ; and the u_i are non-negative random variables which are independently distributed as truncations at zero of the normal distribution with unknown variance, σ_u^2 , and unknown mean, μ , defined by:

$$\mu_i = \delta_0 + \sum_z \delta_z Z_{zi} \quad (7)$$

The parameters of the equations (6) and (7) were estimated using maximum likelihood procedures in a single stage as following Coelli and Perelman [25].

2.3 *The performance measures*

We can derive various performance measures of the production process as elasticities from this estimated model. The sum of the first-order input elasticities represent scale economies, which provides information on the extent to which output increases with increase in input. The second-order elasticities reflect production complementarities which provide information on the economic impacts from output jointness [21].

The \mathbf{X} - \mathbf{Y} scale economy relationship of the input distance function can be represented by the sum of individual input elasticities which shows how much overall input use must increase in order to support a 1% increase in all outputs. At the same time, the individual input elasticity provides us with the information on how much input expansion is required for a 1% increase in output, i.e., Y_m : $-\varepsilon_{D,Y_m} = -\partial \ln D / \partial \ln Y_m = \partial \ln X_1 / \partial \ln Y_m = \varepsilon_{Y_m}$. This measure can be regarded as an ‘input share’ of Y_m (in relation to X_1). And the sum of these input elasticities

represents scale economies: $-\varepsilon_{D,Y} = -\sum_m \partial \ln D / \partial \ln Y_m = \sum_m \partial \ln X_1 / \partial \ln Y_m = \sum_m \varepsilon_{Y_m} = \varepsilon_Y$. A shortfall of ε_Y from 1 shows the extent of scale economies [21].

The first-order elasticities ε_{Y_m} and ε_Y can also be decomposed into second-order effects which reflect compositions of output in response to expansion of scale. This information shows how input elasticity of Y_m or output share (ε_{Y_m}) change in response to change in another output, which is a measure of output jointness of the production system. For example, $\varepsilon_{Y_m,Y_n} = \partial \varepsilon_{Y_m} / \partial \ln Y_n$ shows increase in the Y_m input share as Y_n increases. If $\varepsilon_{Y_m,Y_n} < 0$, then output jointness or complementarity is implied; i.e., the input use does not have to increase as much to expand Y_m if the Y_n level is greater. The cross-output coefficient estimate is the elasticity of this measure $\beta_{mn} : \varepsilon_{Y_m,Y_n} = \beta_{mn} = \varepsilon_{Y_n,Y_m}$ [21]). Finally, the one-sided error term, u_i provides information on the level of technical efficiency, $TE = \exp(u_i)$ [26].

2.4 Data and the study area

Data for this study was taken from a recently completed NFPCSP-FAO project. The data was collected during February–May 2012 through an extensive farm-survey in 17 districts covering 20 sub-districts (*upazillas*) of Bangladesh. A multistage stratified random sampling technique was employed. At the first stage, districts where the specified crops are dominant are selected. The selection of the districts also took into account specified characteristics, i.e., land elevation types of the region and type of technology. At the second stage, sub-districts were selected according to highest concentration of these specified crops in terms of area cultivated based on information from the district offices of the Directorate of Agricultural Extension (DAE). At the third stage, unions were selected using same criteria at the union/block level which was obtained from the sub-district offices of the DAE. Finally, the farmers were selected at random from the villages with the same criteria classified by three

standard farm size categories used in Bangladesh. These are: marginal farms (farm size 50–100 decimals), small farms (101–250 decimals), and medium/large farms (>250 decimals). To ensure equal representation of all farm size categories, a target of 105 farmers from each sub-district was set as follows: 35 marginal farms, 35 small farms, and 35 medium/large farms. However, actual sampled farms from two sub-districts deviated from the target. Boalmari sub-district of Faridpur was selected additionally to collect information on jute production and Birganj sub-district of Dinajpur was selected to include sufficient number of two of the main specified crops (i.e., irrigated wheat and maize) in the survey. This provided a total of 2,083 farm households (Table 1). However, due to some missing information, the final sample size stood at 2,075. The questionnaire used was pre-tested in Tangail district prior to finalization. The survey was carried out by trained enumerators who were graduate students of the Sher-e-Bangla Agricultural University, Dhaka and/or Bangladesh Agricultural University, Mymensingh.

[Insert Table 1 here]

2.5 Energy coefficients

We have applied an ex-post analysis to the level of energy inputs and outputs derived from crop diversification, because the data contains detailed information on all the quantities of inputs and outputs used in the production process. The standard energy coefficients from the existing published literature were used for conversion [27, 28, 29]. For some inputs and outputs, whose energy equivalents are not available, these were computed by using personal judgement and consultation with the academics from Bangladesh Agricultural University, Mymensingh.

Specifically, the production energy for power tiller, mechanical thresher and shallow tube wells were calculated as follows [27]:

$$M_{pe} = (GM_p) / (TW) \quad (8)$$

where M_{pe} is the energy of the machine per unit area, MJ ha⁻¹; G is the mass of machine, kg; M_p is the production energy of machine, MJ kg⁻¹; T is the economic life, h; and W is the effective field capacity, ha h⁻¹.

The diesel energy requirement was determined on the basis of fuel consumption, l h⁻¹. The data were converted into energy units and expressed in MJ ha⁻¹. The following equation was used in the calculation of fuel consumption [28]:

$$FC = P_m \cdot R \cdot SFC \quad (9)$$

where FC is the fuel consumption, l h⁻¹; P_m is the machine power, kW; R is the loading ratio, decimal; and SFC is the specific fuel consumption (0.25 l kWh⁻¹).

Table 2 presents the energy coefficients used in this study.

[Insert Table 2 here]

2.6 The empirical model

The production structure of crop farming in Bangladesh is specified using a multi-output multi-input stochastic input distance function. The general form of the flexible translog stochastic input distance function for the i^{th} farm is defined as:

$$\begin{aligned} \ln X_{1i} = & \alpha_0 + \sum_{k=2}^7 \alpha_k \ln X_{ki}^* + \frac{1}{2} \sum_{k=2}^7 \sum_{l=2}^7 \alpha_{kl} \ln X_{ki}^* \ln X_{li}^* + \sum_{m=1}^4 \beta_m \ln Y_{mi} + \frac{1}{2} \sum_{m=1}^4 \sum_{n=1}^4 \beta_{mn} \ln Y_{mi} \ln Y_{ni} \\ & + \sum_{k=2}^7 \sum_{m=1}^4 \tau_{km} \ln X_{ki}^* \ln Y_{mi} + \sum_{d=1}^{16} \kappa_d D_{di} + \sum_{c=1}^3 \omega_c C_{ci} - u_i + v_i \end{aligned} \quad (10)$$

and

$$u_i = \delta_0 + \sum_{z=1}^7 \delta_z Z_{zi} + \sum_{d=1}^{16} \kappa_d D_{di} + \zeta_i^* \quad (10a)$$

where the dependent variable X_I is the energy from machineries (i.e., power tiller for land preparation + mechanical thresher for threshing operations) used per ha for all crops; X^* are the other energy inputs normalized by the machinery energy variable (X_I); Y are the crop energy outputs; D are dummy variables to account for regional level fixed effects; and C are

dummy variables to account for zero values of crop enterprises (i.e., crop outputs containing zero values for some observations are specified as $\ln\{\max(Y_m, 1-C_c)\}$ following Battese and Coelli [30]; v is the two sided random error and u is the one sided error in eq. (10); \ln is the natural logarithm; Z in eq. (10a) are the variables representing farm specific characteristics to explain inefficiency; ζ is the truncated random variable; $\alpha_0, \alpha_{ks}, \alpha_{kl}, \beta_m, \beta_{mn}, \tau_{km}, \kappa_d, \omega_c, \delta_0$, and δ_z are the parameters to be estimated.

The model consists of seven production inputs (X); four outputs (Y); three dummy variables (C) to account for zero values of jute, pulse and oilseed enterprises; seven variables representing socio-economic characteristics of the farm (Z) included in the inefficiency effects model as predictors of technical inefficiency; and 16 dummy variables (D) to account for regional level fixed effects (in both functions). The seven inputs used in the analyses are: X_1 = machinery energy (MJ ha^{-1}), X_2 = total human labour (MJ ha^{-1}), X_3 = chemical fertilizers (MJ ha^{-1}); X_4 = organic manure (MJ ha^{-1}); X_5 = irrigation (MJ ha^{-1}); X_6 = seed (MJ ha^{-1}); X_7 = pesticides (taka). The four outputs are: Y_1 = cereals (includes High Yielding Varieties (HYV) and Hybrid rice in Boro (dry winter) season, HYV and Aromatic rice in Aman (monsoon) season, HYV wheat, and HYV maize) (MJ ha^{-1}); Y_2 = pulse (i.e., lentil) (MJ ha^{-1}); Y_3 = jute (MJ ha^{-1}); and Y_4 = oilseed (i.e., mustard) (MJ ha^{-1}). The seven variables representing socio-economic characteristics of the farm are: Z_1 = age of the farmer; Z_2 = family size; Z_3 = education of the farmer; Z_4 = dummy variable for involvement in NGO; Z_5 = land fragmentation (number of plots per farm); Z_6 = ogive index of output concentration (number); and Z_7 = farm operation size (ha). Table 3 presents the definitions, units of measurement, and summary statistics for all variables.

[Insert Table 3 here]

We have selected the Ogive (pointed arch) index, which provides a measure of concentration of output shares of the enterprises, to see whether diversification amongst

enterprises has an effect on technical energy efficiency, also applied by Rahman and Barmon [12] and Coelli and Fleming [16]. The Ogive index is defined as:

$$Ogive = \sum_{m=1}^M \frac{(Y_m - (1/M))^2}{1/M} \quad (11)$$

where M is the total number of production enterprises under consideration and Y is the share of the m th enterprise to total energy output. An Ogive value of 1/M indicates perfect diversification of output among enterprises. The justification for inclusion of other variables as determinants of inefficiency is from the existing literature.

3. Results

Maximum Likelihood Estimation (MLE) is used to estimate the parameters of the stochastic input distance function and the inefficiency effects model jointly in a single stage. Prior to discussing the results, we report the series of hypothesis tests conducted to determine functional form, input output separability and presence of inefficiency in the model (Table 4).

The first test was conducted to determine the appropriate functional form, i.e., the choice between a Cobb-Douglas or a translog functional form ($H_0: \alpha_{kl} = \beta_{mn} = \tau_{km} = 0$ for all k, l, m , and n). A generalised Likelihood Ratio (LR) test confirms that the choice of a translog production function is a better representation of the production technology.

Next, we tested for the separability of the inputs and outputs in the input distance function. This hypothesis is defined by equating all cross-terms between inputs and outputs to zero ($H_0: \text{all } \tau_{km} = 0 \text{ for all } k \text{ and } m$) [23]. The null hypothesis is strongly rejected, which implies that aggregation of all the inputs and outputs into a single index will be inconsistent.

Next, we tested for the presence of inefficiencies in the model. The parameter γ is the ratio of error variances from Eq. (10). Thus, γ is defined as being between zero and one, where if $\gamma = 0$, technical inefficiency is not present, and where $\gamma = 1$, there is no random noise. The value of γ is estimated at 0.90 (see lower panel of Appendix Table A1) which is significantly different from zero at 1% level, indicating that inefficiencies are present in the

model. Next we determine whether the variables introduced as inefficiency effects improve the explanatory power of the model. The null hypothesis ($H_0: \delta_z=0$ for all z) is rejected at the 1% level, implying that the distributions of inefficiencies are not identical across individual observations [23].

Finally, we also determine whether controlling for regional effects is worthwhile both in the production frontier as well as in the inefficiency effects function. The null hypothesis (H_0 : all $\kappa_k=0$ for all k) is strongly rejected at the 1% level, implying that there are significant variations across regions as we have expected (Table 4).

[Insert Table 4 here]

3.1 Energy productivity and scale economy in energy use

The parameter estimates of the stochastic input distance function and the inefficiency effects model for crop farming estimated jointly in a single stage is presented in Appendix Table A1. A large number of the coefficients in the input distance function are significantly different from zero at the 10% level at least. All the variables are mean-differenced prior to estimation so that the elasticities of the distance function with respect to input and output quantities at the sample mean correspond simply to the first order coefficients. All the signs on the first order coefficients of inputs and outputs are consistent with *a priori* expectations.

The overall measure representing incentive to increase the scale and diversity of farm enterprises is the scale elasticity ε_Y (Table 5). Although the estimate of $\varepsilon_Y=0.57$ suggests scale economies, ($\varepsilon_Y<1$ indicate scale economies), the formal test for constant returns to scale (i.e., $\varepsilon_Y=1$) cannot be rejected implying that constant returns to scale prevail in Bangladeshi farming. This finding is encouraging because the literature in this regard is mixed. For example, Asadullah and Rahman [31] report decreasing returns to scale in rice production

whereas Rahman [7, 17] noted increasing returns to scale for diversified crop production system in Bangladesh.

The individual output contribution to the scale elasticity is also presented in Table 5. Table 5 shows that only cereal output elasticity is significantly different from zero, implying that increasing the production of cereals will increase energy use substantially. The elasticity value is estimated at 0.14 implying that a 1% increase in cereal output will increase energy use by 0.14%.

The elasticities of the distance function with respect to input quantities are equal to the energy input shares and, therefore, reflect the relative importance of inputs in the production process. Table 5 reveals that all seven elasticities are negative, as expected, with only one input (pesticide energy) being not significantly different from zero. The elasticity with respect to labour is the largest with a value of -0.39, implying that labour represents 39% of the total energy use at the sample mean. Rahman and Barmon [12] reported even higher share of labour energy use (59%) for gher farming in Bangladesh.

The second order cross-effects represented by the cross-parameters of the estimated functions (β_{mn}) provides information on the output complementarities and their contribution to scale economies (mid-panel of Table 5). Four crop combinations are negative with cereal and oilseed enterprise combination being significantly different from zero at the 1% level, implying significant complementarity and/or output jointness [21]. This indicates that cereal and oilseed combination requires less energy inputs than it would otherwise require when produced independently. In contrast, combinations of jute with pulse and/or oilseed enterprises are positive and significantly different from zero at the 5% level at least, implying competition or output disjointness. This indicates that such combination of enterprises exert diseconomies in energy use instead. Overall, these results suggest that deriving scope

economies in Bangladeshi farming is not straightforward when evaluated in terms of energy use and is at contrast with those reported by Rahman and Barmon [12] and Rahman [7, 17].

[Insert Table 5 here]

3.2 Determinants of technical energy efficiency

Prior to the discussion of the determinants of technical inefficiency, we report summary statistics of technical energy efficiency scores. The mean technical energy efficiency is estimated at 68% implying that the average farm could increase energy output by 32% by eliminating inefficiency. Farmers exhibit a wide range of inefficiency ranging from 8% to 99% in multiple crop farming (Table 6). Nevertheless, 52.5% of the total farmers are operating at a technical energy efficiency level of 81% and above (Table 6). Observation of wide variation in technical efficiency is not surprising and is similar to the results of Rahman and Rahman [1], Rahman and Barmon [12], and Rahman [7, 17] for Bangladesh and Bravo-Ureta et al. [32] for developing economies worldwide covering a range of crops and systems, respectively.

[Insert Table 6 here]

The lower panel of Appendix Table A1 provides the results of the inefficiency effects model. The coefficients on these inefficiency predictors show only the direction of influence and do not provide information on the magnitude of influence. Therefore, we compute technical energy efficiency elasticities for these predictors presented in the lower panel of Table 5.

Family size significantly improves technical efficiency, perhaps through more timely supply of family labour, also reported by Rahman [17]. The elasticity estimate indicates that a 1% increase in family size will improve technical energy efficiency by 0.02%. Farm operation size is associated with energy inefficiency implying that large farms are relatively inefficient. The elasticity estimate indicates that a 1% increase in farm size will reduce efficiency by

0.005%. The conclusion regarding farm size and efficiency relationship is mixed in the literature. For example, while Rahman and Hasan [33] reported positive relationship in Bangladesh, Rahman et al. [11] and Aye and Mungatana [34] reported negative relationship for Bangladesh and Nigeria, respectively.

The negative coefficient on the Ogive index indicates that specialization significantly improves technical energy efficiency. The elasticity estimate indicates that a 1% increase in crop specialization will improve technical energy efficiency by 0.06%. This finding is supported by Rahman and Barmon [12] who evaluated Bangladeshi gher farming in terms of energy use. But when the merit of crop diversification is examined using conventional physical input-output framework, the evidence is in favor of diversification [7, 11, 17]. This is because specialization in Bangladesh is geared towards cereal production (i.e., mainly rice but area under wheat and maize are on the rise as well) all of which provides very high energy ratio (energy output/energy input) as compared to non-cereal crops. That is why production of cereals significantly improves technical energy efficiency, as output quantity is favoured by high energy content as compared to non-cereals which are low productive and contains low energy content.

4. Conclusions and policy implications

The aim of this study is to examine whether crop diversification is energy efficient. Specifically, we investigated whether crop diversification improves energy economy in input use and technical energy efficiency in crop farming in Bangladesh. The results are mixed and require cautious interpretation. Overall, constant returns to scale prevail in Bangladeshi farming. Production of cereals (rice/wheat/maize) increases energy inputs substantially. Among the inputs, labour alone accounts for 39% of total energy use. Also, 59.6% of total energy inputs are renewable, implying that the farming system in Bangladesh is not solely dependent on non-renewable sources of energy, which is encouraging. This trend is unlikely

to change substantially in the future because the main thrust of mechanization in agriculture was in land preparation which gradually replaced draft animal power services (because of its relative scarcity) by power tillers. Also, the use of organic manure in farming is increasing, particularly in wheat and maize production, thereby leading to a relative reduction in inorganic fertilizer use [1, 35, 37, 39]. However, with the rising cost of fossil fuels and imported machineries, farmers may revert to the use of draft animal power services for land preparation and farm gate transportation as well as increase application of organic manures provided that the livestock sector is developed subsequently to meet such increased demand.

We find that although cereal with other crop combinations has the expected negative sign of output jointness or complementarity, significant evidence of energy economy exists only in cereal and oilseed enterprise combination. On the other hand, combination of non-cereal enterprises, such as jute with pulses or oilseeds provides diseconomies in the use of energy input. Crop diversification is associated with inefficiency, implying that specialization into cereals improves technical energy efficiency. Large farms are inefficient while family size improves efficiency perhaps through timely use of family supplied labour.

The main policy implication of this study is that Bangladesh should pursue crop diversification but needs to choose enterprise combinations strategically. Most importantly any diversification strategy must maintain cereal production as the main base and then add non-cereal crops in order to reap the benefit of energy economy in input use, e.g., cereal and oilseed combination. Next, within cereal enterprise itself, farmers could diversify from rice monoculture to wheat or maize enterprises in order to improve technical energy efficiency. It is important to improve technical energy efficiency in agriculture as it implies potential to produce more output without exerting additional pressure on already deficient commercial energy resources. Also, crop enterprises which create large energy balance are sustainable in the long run in terms of energy use [1, 12]. In fact, recent studies demonstrated that technical

energy efficiency of wheat and maize production are much higher than rice. For example, the technical energy efficiency of wheat and maize production is estimated at 88% [35] and 93% [1] as compared with rice at 77% [36]. The area under wheat and maize is on the rise in Bangladesh with the latter increasing at a faster rate. For example, wheat area in Bangladesh has increased from 125.6 thousand ha in 1972 to 479.1 thousand ha in 2006 [37] whereas maize area increased from only 2.7 thousand ha in 1972 to 128.3 thousand ha in 2009 [38], indicating that farmers are already seeking diversification within cereals, apparently to benefit from productivity and financial gains, if not to save energy explicitly. This is because maize ranks first in terms of yield and financial benefit with Benefit Cost Ratio (BCR) estimated at 1.63 as compared with wheat (BCR 1.40) and rice (BCR 1.14) [39].

Achievement of these policies is challenging. Nevertheless, diversification from rice monoculture to other cereals (i.e., wheat and maize) and adding non-cereal enterprises while keeping cereals as the main base will significantly improve both energy economy and energy efficiency in Bangladesh agriculture, which is a goal worth pursuing.

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APPENDIX

[Insert Appendix Table A1 here]