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Resource Use Efficiency and Cleaner Agricultural Production: An Application of Technical Inefficiency Effects Model for Paddy Producing Zones of West Bengal

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Abstract

It is possible to enhancement of agricultural productivity with environmental sustainability through efficient utilization of resources. This hypothesis is examined by the efficiency and the responsible factors for controlling inefficiency of the farms. The empirical analyses are conducted based on the secondary data of 14 960 farms scattered into five different paddy producing zones of West Bengal, India. The Efficiency estimates disclose that clayey soil texture zone is the most efficient and sandy and gravelly soil texture zone is the least efficient concerning paddy production. The study concludes with appropriate policy implications that the inefficiency on the part of the farms is caused by inefficient utilization of the chemical fertilizers, viz., nitrogen and potassium and insecticides and by the efficient utilization of this the farm can increase its productivity with environmental sustainability.

Keywords

Paddy production, zonal efficiency, stochastic production frontier, technical inefficiency effects model, environmental sustainability.

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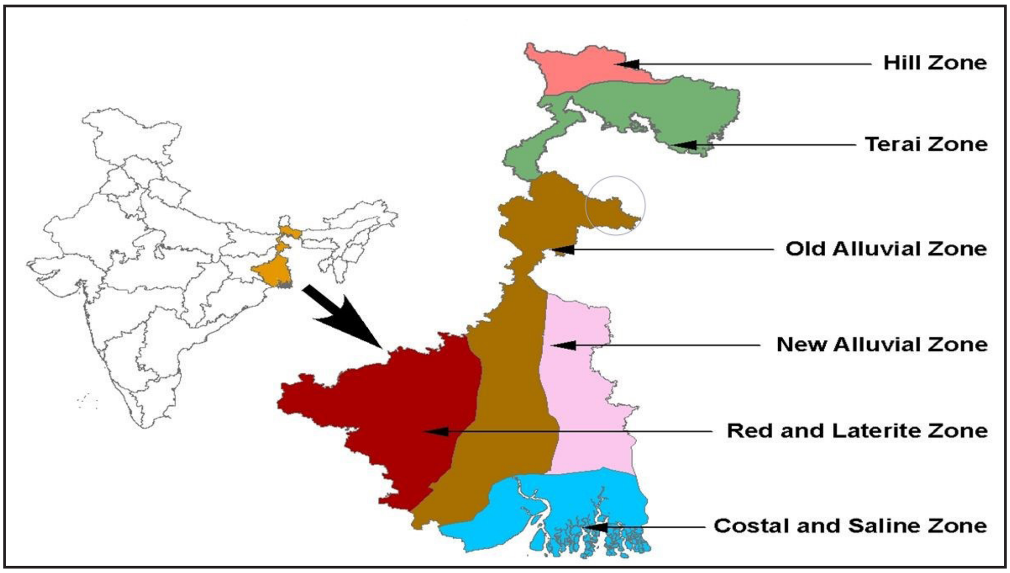
Introduction

India is the second-largest paddy producer (with a production of 109.7 million tons in 2017) after China in the World (Kumari et al., 2018). According to the FAO report, rice production in India accounted for 178.3 million metric tons in 2020 and Indian rice exports touched 14.46 million tons in 2020, including 11.56 million ton of non-Basmati rice. India is the world's largest rice exporting country. West African country Benin is one of the major importers of non-basmati rice from India. Other destination countries are Nepal, Bangladesh, China, Cote D' Ivoire, Togo, Senegal, Guinea, Vietnam, Djibouti, Madagascar, Cameroon, Somalia, Malaysia, Liberia U.A.E. etc. In 2020-21, India increases export non-basmati rice to Timor-Leste, Puerto Rico, Brazil, Papua New Guinea, Zimbabwe, Burundi, Eswatini, Myanmar and Nicaragua. Basmati rice major destination countries are Saudi Arab, Iran, Iraq, Kuwait, UK, USA, Oman, Canada etc. West Bengal is the highest non-basmati rice producing state in India.

Globally main inputs for high-yielding paddy cultivation are chemical fertilizers and nitrogen (N), phosphorus (P), and potassium (K) are the most applied nutrient for paddy production. One-ton rough paddy production requires about 15-20 kg of mineral N, 11 kg P_2O_5, and 30 kg K_2O (Roy et al., 2006). Since N use efficiency is very poor in paddy (Zhang et al., 2015), about 50%-70% of added N is lost as N_2O, NO_3, and NH_3 to air and water and contributes to environmental degradation. Freshwaters receive around 39-95 Tg N/year from agricultural soils (Voss et al., 2011). The impact of the application of synthetic fertilizers on increasing crop productivity and ensuring food surplus has been broadly accepted in the past (McArthur and McCord, 2017). However, excessive application of synthetic fertilizers to support increased productivity in certain regions around the globe is alarming for environmental sustainability (Cheng et al., 2019; Ren et al., 2021). Reactive nitrogen is a highly volatile element, and it diffuses through air and water (Erisman et al., 2013). The problems of nitrate leaching and runoff to water bodies can cause environmental degradation (Vitousek et al., 2009). Many past studies have documented incontestable environmental costs (Norse and Ju, 2015) and human health-related economic costs (Gourevitch et al., 2018; Wang and Lu, 2020) because of nitrogen application in crop production. Appropriate input use in crop production is one of the pillars of agricultural sustainability (Zhang et al., 2015). Thus, a cleaner production helps in achieving the balance between the goals of crop productivity and long-term environmental sustainability is required while applying chemical fertilizer. The combination of manure and optimal chemical fertilizer application has positive impacts on soil health through changes in soil organic carbon content and microbial and enzyme activities (Ozlu et al., 2019). In our study, we consider the single Indian state, West Bengal as it is the highest paddy producing state in India (Maps of India, 2016). The West Bengal is divided into six paddy producing zones (see Figure 1 for details). This paddy producing zones are traditionally made by cross-comparing elements such as air temperature, rainfall, water deficit and soil texture. The main soil texture of Terai, Old Alluvial, New Alluvial, Red & Laterite and costal Saline paddy producing zones are sandy & gravelly, sandy loam, clayey, red & laterite and clayey loams respectively. These six zones divide West Bengal **six agro-climatic zones**.

It is important to examine whether the farm is operating efficiently or not. As efficient utilisation of the scarcer resources will result larger output with same inputs or same out with lower inputs. In both cases the farm will enjoy higher profit. This environment persuades us to reconnoitre the research question: does efficient utilisation of the scarce and costly resources enable the farm to achieve the goal of clean production, which guarantees increasing productivity with environmental sustainability? This question has twin research objectives. Initially, the efficiency of the different paddy producing zones is compared in this study and then explains the major causes of inefficiency of the paddy producing farms in West Bengal. This analysis explores whether farms are utilising chemical fertilizers and insecticides efficiently or not. As inefficient utilisation of chemical fertilizers and insecticides, not only reduces the productivity of the concerned farm also responsible for environmental degradation, means dirty production scenario. The novelty of the study lies in the fact that where resource use efficiency is investigated to manage the balance between farm productivity and environmental sustainability. Thus the uniqueness of the study is in terms of specified objectives, methodology and the choice of the study area.

The present paper is structured in an aforesaid way: after the introduction section, in Section 2, we have discussed the materials and methods utilised to explore the mentioned objectives. The empirical results are presented in Section 3. The section 4 is followed by the discussion which presents possible reasons for such empirical results. Finally, the conclusion and policies for clear production are presented in Section 5.



Source: Google map

Figure 1: Agro climatic zone of West Bengal.

Materials and methods

The data sources to explore the said objectives empirically and the theoretical underpinning are discussed in this section. The econometric model for investigating the objectives is also presented in this section.

Econometric model

The stochastic production function for the panel data is presented as follows:

$$y_{it} = \exp(x_{it}\beta + \varepsilon_{it}) \quad (1)$$

Where y_{it} denotes the production of the i^{th} ($i = 1,2,\ldots., N$) farm at t^{th} ($t = 1,2,\ldots, T$) time period.

x_{it} is the ($1Xk$) vector of quantities of inputs for the i^{th} ($i = 1,2,\ldots., N$) farm at t^{th} ($t = 1,2,\ldots, T$) time period. β is the ($kX1$) vectors of unknown parameters which are to be estimated. ε_{it} is the random disturbances of the i^{th} ($i = 1,2,\ldots., N$) farm at t^{th} ($t = 1,2,\ldots, T$) time period.

Following Aigner et al. (1977), Meeusen and van den Broeck (1977), the disturbances are assumed as follows:

$$\varepsilon_{it} = V_{it} - U_{it} \quad (2)$$

The are assumed to be distributed as iid $N(0, \sigma^2_V)$. It captures random variation in output due to some uncontrolled, suchlike weather, etc. On the contrary, U_{it} s are non-negative disturbances reflecting *technical inefficiency* in production. It is assumed to be independently distributed. In the present study it is assumed to follow truncated normal distribution with mean $z_{it}\delta$ and variance σ^2_U (Battese and Coelli, 1995). Here z_{it} is a vector of ($1Xm$) vectors of independent variables. These explanatory variables represent the factors responsible for farm's controllable technical inefficiency. δ is the ($mX1$) vector of unknown parameters. V_{it} and U_{it} individually as well as mutually independent.

Consequently, the stochastic frontier production function can be written as:

$$y_{it} = \exp(x_{it}\beta + V_{it} - U_{it}) \quad (3)$$

Equation 3 represents the production function depicting the relationship between output and inputs. On the contrary, the U_i, the technical inefficiency effects are presented here as the function of several explanatory variables z_{it} along with the unknown vector coefficients δ. The variables included z_{it} in may be recognized as inputs but they cannot be identified as inputs in the traditional sense, rather these inputs are used for obtaining better and greater quantity of output. Following Battese and Coelli (1995), corresponding to Equation 8, the technical inefficiency effects is specified as follows:

$$U_{it} = z_{it}\delta + \omega_{it} \quad (4)$$

The random variable, ω_{it} *Truncated normal* $(0, \sigma^2_U)$ such that the point of truncation is $-z_i\delta$, that is, $\omega_{it} \geq -z_{it}\delta$. Thus U_{it} follow a non-negative truncation of the $N(z_i\delta, \sigma^2_U)$ distribution. The technical efficiency of the production of i^{th} ($i = 1,2,\ldots., N$) farm at t^{th} ($t = 1,2,\ldots,T$) time period is defined as:

$$TR_{it} = \exp(-U_{it}) = \exp(-z_i\delta - \omega_{it}) \quad (5)$$

For estimating simultaneously, the parameters of Equation 3 and 5, the most appropriate method is maximum likelihood estimation technique. The corresponding variance parameters are defined as:

$\sigma^2 = \sigma^2_V + \sigma^2_U$ and $\gamma = \frac{\sigma^2_U}{\sigma^2}$, where γ lies between 0 and 1 depending on the dominance of σ and σ_U respectively (Battese and Coelli, 1995). All these parameters are estimated by using FRONTIER-4.1 programme (Coelli, 1996).

Pesaran's test for cross sectional independence

Earlier studies based on panel data conclude that panel data models probably "exhibit substantial cross-sectional dependence in the errors" (Baltagi, 2005; and Pesaran, 2006). Such interdependencies will not only make the estimators biased but also inconsistent. Accordingly, it is always recommended before applying the panel data model one should test the independence of the cross-sectional error. In this regard, Pesaran, (2006), test is widely recommended. The null and alternative hypotheses are specified as follows:

H_0: The error term (u_{it}) is assumed to be independent and identically distributed across the cross-sectional unit and over-time.

H_1: The error term may be correlated across the cross-section.

The rejection of the null hypothesis or conversely the acceptance of the alternative hypothesis indicates serial correlation.

Data

The study is entirely based on secondary data. The principal data source is "the Directorate of Economics and Statistics, the Department of Agriculture and Farmers Welfare, the Ministry of Agriculture and Farmers Welfare, the Government of India". The data includes 14 960 numbers of farm-level information including five different agro-climatic zones. The information concerning the relevant variables is in the monetary (US $) form of current prices for uniformity of our study.

Variables

To facilitate the empirical analysis, we need three types of variables. Firstly, we need a pertinent output variable. Secondly, we need an explicit set of inputs which have a strong footprint on the production. Finally, we need a specific set of inputs which have a strong influence on output however, not implicitly recognised as necessary and sufficient for production. These variables are categorized as exogenous variables.

Output variable

West Bengal is recognized as the largest producer and consumer of paddy in India. More than 13% in 2016-17 of total paddy production in India is contributed by West Bengal (Maps of India, 2016). Accordingly, we consider paddy production as our output indicator. The inter-zonal comparison of efficiency in producing paddy is only possible if we could identify the proper output indicator. Based on earlier literature on agricultural efficiency (Battese and Coelli, 1995; Ahmed et al., 2018) we consider "Paddy production in Quantile per hectare", that is, paddy productivity as the output variable. Besides that, we can consider the total value of produced paddy or total quantity of paddy production by the farm as an output variable. In both cases there are problems. If we consider the total value of paddy as output, then zonal price variation may affect the output variable. Moreover, transportation costs from farm to market may cause a difference in the prices. On the contrary, if we consider total quantity as output we may end up with larger output that may be a result-end of a large operational landholding. Accordingly, we consider paddy productivity as the output variable for the present study.

Input variables

To specify the production frontier after identification of the output variable we need to specify an appropriate set of inputs. Traditionally, labour and capital are considered as the two important inputs and following that traditional concept here also we have considered, any kind of labour and machineries utilized for production as inputs. Concerning inputs, we have two alternatives; either we can use the monetary expenditures on inputs or the physical inputs. It is noteworthy that the prices of the enlisted inputs are determined centrally and consequently if the monetary expenditures on the inputs are available it is always preferable to use them as inputs (Tiedemann and Latacz-Lohmann, 2013). Moreover, as the study is based on panel data the amount of physical inputs may be non-available for one or two periods. Such incidences may compel us to drop that period. The availability of the balance sheets enables us to collect all input related statistics in monetary terms. Accordingly, we consider all input variables in value terms (monetary value) in current prices for uniformity of our study. The list of the input variables along with their definition is furnished in Table 1.

We have considered Seed Value (US$), to address the quality of the paddy seeds. Here, seed value is in direct relation with the quality of the seed.

Variables	Definition	Category
Product (Qtls.)(y)	Paddy production in Quantile per hectare.	---
ln(y)	Natural logarithm form of rice production per hectare.	Output
Family Labour (US$) (*FL*) ($x_1$)	A system in which several members of the household including children are involves in agricultural activities and they are not financially sound to hire labour.	Input
Attached Labour (US$) (*AL*)($x_2$)	These type labourers are attached to some cultivator household on the basis of a written or oral agreement. Their employment is permanent and regular.	Input
Casual Labour (US $) (*CL*) ($x_3$)	This type of labourers are free to work on the farm of any farmer and payment is generally made to them on a daily basis.	Input
Hired Animal Labour (*HAL*) (US $) ($x_4$)	The farmers are hired animal for agricultural activity and paid hired charger.	Input

Source: Authors' own specification based on data from the Directorate of Economics and Statistics, the Department of Agriculture and Farmers Welfare, the Ministry of Agriculture and Farmers Welfare, the Government of India.

Table 1: Descriptions of the variables. (To be continued).

Variables	Definition	Category
Owned Animal Labour (US $) (*OAL*) ($x_5$)	The farmers are used their own animal for agricultural activities.	Input
Hired Machine (US $) (*HM*)($x_6$)	The farmers are hired machine for agricultural activity like combine harvester, rotary tiller, plough, tractor trailer, power harrow, leveler, ripper machine and dice harrow etc. and paid hired charges.	Input
Own Machine (US $) (*OM*)($x_7$)	The farmers are used their own machine for agricultural activities.	Input
Own Irrigation Machine (US $) (*OIM*)($x_8$)	The farmers are used their own irrigation machine for agricultural activities.	Input
Hired Irrigation Machine (US $) (HIM) ($x_9$)	The farmers are hired irrigation machine for agricultural activities and paid hired charges.	Input
Canal and Other Irrigation Charges (US $) (*OIC*) ($x_{10}$)	The farmers are paid charges for use of others people's source of water for agricultural activity.	Input
Seed Value (US $) (SV) ($x_{11}$)	Cost of high yielding seeds which in agriculture by the farmer.	Input
Fertiliser (N) (US $) (*N*) ($z_1$)	Nitrogen based fertilizer. It plays an important role in crop plant. It is involved in various critical process, such as growth, leaf area-expansion and biomass-yield production.	Exogenous
Fertiliser (P) (US $) (*P*) ($z_2$)	Phosphorus based fertilizer. It plays a role in plant development and, subsequently flower development.	Exogenous
Fertiliser (K) (US $) (*K*) (($z_3$)	Potassium based fertilizer. It is used in agriculture land to increase crop yield as proper amount of potassium in soil can enhance root growth, improve drought resistance, active many enzyme systems.	Exogenous
Other Fertiliser (US $) (*OF*) ($z_4$)	Other fertilizer except NPK	Exogenous
Manure (US $)($z_5$)	Waste matter from animals that is mixed with soil to improve the soil health and help plants grow.	Exogenous
Insecticides (US $) ($z_6$)	Insecticides are substances used to kill insects. They are used primarily in agriculture to control pests that infest crop.	Exogenous

Source: Authors' own specification based on data from the Directorate of Economics and Statistics, the Department of Agriculture and Farmers Welfare, the Ministry of Agriculture and Farmers Welfare, the Government of India.

Table 1: Descriptions of the variables. (Continuation).

Exogenous variables

It is a well-established fact that having all necessary inputs in sufficient quantities does not ensure that we end up with an efficient amount of output (Battese and Coelli, 1995). Other than acts of God sometimes farms make inefficient utilization of some scarce and expensive resources resulting in inefficiency in the production process and the farm ends up with an output level lower than the desirable or frontier output level. Such inefficiencies on the part of the farm are controllable and efficient utilization of such resources not only escalates the farm's production (or technical) efficiency but reduce costs of production also enables the farm to operate on the cost frontier and makes it cost-efficient. These variables by no means are necessary for production and thus cannot be included in the traditional inputs set. We termed them exogenous variables. We have included these variables to facilitate the inefficiency effects analysis.

As the primal concern of the present paper is to detect the consequences of the uses of chemical fertilisers and insecticides in the agricultural production of West Bengal on the environment, we have considered expenditures on three major chemical fertilizers, viz., nitrogen, phosphorus, and potassium (NKP) uses in the main agricultural product (paddy) in West Bengal separately as three inefficiency effects variables. Along with this, we also consider expenditures on chemical insecticides as an added inefficiency effects variable. The rest two inefficiency effects variables are expenditures on manure and other fertilizers.

The complete lists of exogenous variables along with their detailed descriptions are presented in the Table 1.

After recognizing the output, inputs and exogenous variables for the present study the equations of the model are presented as follows:

$$\begin{aligned}\ln(y_{it}) = \alpha_0 + \alpha_{FL}\ln(\mathrm{FL}_{it}) + \alpha_{AL}\ln(\mathrm{AL}_{it}) + \alpha_{CL}\ln(\mathrm{CL}_{it}) + \\ + \alpha_{HAL}\ln(\mathrm{HAL}_{it}) + \alpha_{OAL}\ln(\mathrm{OAL}_{it}) + \\ + \alpha_{HM}\ln(\mathrm{HM}_{it}) + \alpha_{OM}\ln(\mathrm{OM}_{it}) + \alpha_{OIM}\ln(\mathrm{OIM}_{it}) + \\ + \alpha_{HIM}\ln(\mathrm{HIM}_{it}) + \alpha_{OIC}\ln(\mathrm{OIC}_{it}) + \alpha_{SV}\ln(\mathrm{SV}_{it}) \quad (6)\end{aligned}$$

Where, ln is the natural logarithm (i.e., to the base e).

The technical inefficiency effects equation is presented as follows:

$$U_{it} = \delta_N \ln(N_{it}) + \delta_K \ln(K_{it}) + \delta_P \ln(P_{it}) + \delta_{OF} \ln(OF_{it}) + + \delta_{Manure} \ln(Manure_{it}) + \delta_{Insecticides} \ln(Insecticides_{it}) \quad (7)$$

Both the equations are estimated by using FRONTIER 4.1, developed by Coelli, (1996).

Results and discussion

The empirical findings are analyzed in this section.

Pesaran's test for cross sectional independence

The test result is presented in the Table 2 and it is obtained by using the STATA-12.

The table discloses that the value of Pesaran's test of cross-sectional independence is -1.404 and the corresponding probability is 0.1602. The value of the "Average absolute value of the off-diagonal elements" is 0.448. The test result empowers us not to reject the null hypothesis, which implies no cross-sectional dependence. Accordingly, we proceed to the empirical exploration of our said objectives.

Technical Efficiency estimates of different zones of West Bengal producing paddy

Our empirical analysis is concentrated only in five agro-climatic zones of West Bengal. Based on the availability of the data we have measured the technical efficiency of the paddy producing farms over the period 2013-14 to 2017-18. The Table 3 presents the results of technical efficiency across agro-climatic zones over the study period.

The panel mean efficiency scores, as well as the overall mean efficiency scores, are also mentioned in the table. The ranking of the different paddy producing agro-climatic zones is done based on the panel mean efficiency scores. The comparisons across paddy producing agro-climatic zones are performed considering overall mean efficiency as the benchmark (Maity, 2017; Maity and Singh, 2021). Accordingly, a paddy producing agro-climatic zone is recognized as relatively technically efficient if the efficiency score of the concerned paddy producing agro-climatic zone exceeds the "overall mean efficiency" and vice-versa. This benchmark results in three zones out of five zones being technically efficient. Accordingly, sixty per cent of the paddy producing agro-climatic zones is technically efficient. In the initial period, 2013-2014 the Old Alluvial zone was the most efficient (0.991). On the contrary, in the concerned period, Coastal Saline (0.856) was the least efficient zone. It is noteworthy that the Old Alluvial zone remains the most efficient paddy producing zone for the entire study period. Concerning the least

Pesaran's test of cross sectional independence	Average absolute value of the off-diagonal elements	Probability
-1.404	0.448	0.1602*

Note: *Evidence shows data are cross-sectionally independent

Source: Authors' own calculation based on data from the Directorate of Economics and Statistics, the Department of Agriculture and Farmers Welfare, the Ministry of Agriculture and Farmers Welfare, the Government of Indiaand Farmers Welfare, the Ministry of Agriculture and Farmers Welfare, the Government of India

Table 2: Pesaran's test of cross sectional independence.

Year → / Zone ↓	2013-2014	2014-2015	2015-2016	2016-2017	2017-2018	PME*	Ranking
II-Terai	0.867	0.974	0.980	0.945	0.862	0.926	5
III-New Alluvial	0.979	0.972	0.980	0.926	0.963	0.964	3
IV-Old Alluvial	0.991	0.996	0.996	0.995	0.993	0.994	1
V- Red & Latterite	0.907	0.978	0.988	0.989	0.986	0.970	2
VI- Coastal Saline	0.856	0.891	0.990	0.948	0.983	0.934	4
Mean Efficiency (Yearly)	0.920	0.962	0.987	0.961	0.957	---	---
Mean Efficiency (Overall)							

Note: *Panel Mean Efficiency of the zones

Source: Authors' own calculation based on data from the Directorate of Economics and Statistics, the Department of Agriculture and Farmers Welfare, the Ministry of Agriculture and Farmers Welfare, the Government of Indiaand Farmers Welfare, the Ministry of Agriculture and Farmers Welfare, the Government of India

Table 3: Technical Efficiency estimates of different zones of West Bengal producing paddy.

efficient region, our observation is that during 2013-14 and 2014-15, the Coastal Saline zone was the least efficient on the list. For the next two time periods (2015-16 and 2016-17) New Alluvial zone became the least efficient paddy producing zone of West Bengal. However, during 2017-18, the Terai region becomes the least efficient on the list. Based on the panel mean efficiency (PME) scores we conclude that the Old Alluvial zone is the most efficient paddy producing zone of West Bengal while Terai is the least efficient.

However, it is noteworthy that the ranking of the paddy producing zones of West Bengal based on efficiency score only shows the relative performance of the concerned zone and does not designate any hierarchy concerning production. For instance, the relative "panel mean efficiency" score for the New Alluvial zone is 0.964 and the zone was recognised as the least efficient during 2015-16 and 2016-17. The Gangetic alluvial region especially the New Alluvial zone consists of Nadia, East-Bardhaman, Howrah and Hooghly and thus the third and fourth topper paddy producing districts are located here. In fact, the individual performances of these districts considering paddy production are really appreciating. The efficiency score of the paddy production system stipulates that if the New Alluvial zone could operate its paddy production system as efficiently as the Old Alluvial zone, the zone could have escalated its production as much as the current total production of the Old Alluvial zone.

Paddy in West Bengal is cultivated in 18 different districts of West Bengal. Among these 18 districts 4 districts, viz., Burdwan, Birbhum, Nadia and Hoogly belong to the high productivity group. Accordingly, two districts viz., Burdwan and Birbhum are in the Old Alluvial zone while two other districts, viz., Nadia and Hoogly are in the New Alluvial zone. Even after this New Alluvial zone is not ranked second in the list considering overall panel mean efficiency. Therefore, there must be some inefficiency lies in the execution of the existing technology which aggravates the differences in the technical efficiency of paddy production. The absence of such a study makes it impossible to cross-check the result with earlier studies. The Old Alluvial zone includes Siliguri Subdivision (Darjeeling), Dakshin Dinajpur, Malda, Murshidabad, Nadia, North 24-Parganas, Hooghly, Burdwan, Bankura, Birbhum, Paschim Medinipur. These districts are recognised as the paddy producing hub for West Bengal. In fact, the top two paddy producing districts of West Bengal are Burdwan and Birbhum (West Bengal, 2001). These two districts are in the Old Alluvial zone. On the contrary, the political constitution of the Terai and Dooars region includes different parts of three different districts of West Bengal, viz., the plains of Darjeeling District, the whole of Jalpaiguri and Alipurduar district and the upper region of Cooch Behar District. These districts are considered less fertile concerning paddy. Accordingly, our efficiency results are confirmed with reality.

Stochastic Frontier Model: factors affecting efficiency

The stochastic frontier production function as presented by equation (6) can be viewed as the log-linearised version of the Cobb-Douglas production function. The maximum-likelihood estimators along with the estimated standard errors of equations are presented in the Table 4.

The absence of multicollinearity is confirmed by the Table A.1 in Appendix. The empirical estimates concerning stochastic production function reveal that the estimated coefficient of the inputs Attached Labour (US $), Owned Animal Labour (US $), Hired Machine (US $), Own Machine (US $), Own Irrigation Machine (US $) are statistically meaningful with expected sign. The estimated coefficients of the above-mentioned input variables indicate that an escalation of the expenditures on these inputs helps in the expansion of paddy productivity. The estimated coefficient Attached Labour (US$) is statistically significant with a positive sign. The Attached Labour (US$) is a replica of hired labour and consequently hired labour has a positive influence on productivity. Even after the modernization of the technology in agriculture, in West Bengal use of bullock labour in agriculture is still significant. Accordingly, we find the estimated coefficient of expenditure on the purchase of animal labour is in positive relation to output and the result is also statistically meaningful. In fact, ownership of animal labour has a beneficial effect on the paddy productivity across different zones of West Bengal (Shanmugam and Sundararajan, 2008). It is interesting to note that machineries have a strong influence on the paddy productivity across zones of West Bengal. As such both the estimated coefficients on the expenditures of machineries (own and hired) help in escalating the paddy productivity across zones. Moreover, we are 99% confident about the effectiveness of these results. These estimated coefficients

	Variables	Coefficients		S.E	t-ratio
	Constant	β_0	0.389	1.211	0.321
Family Labour (US \$) (*FL*) (x_1)	ln(x_1)	β_1	0.003	0.049	0.053
Attached Labour (US \$) (*AL*)(x_2)	ln(x_2)	β_2	0.013*	0.007	1.939
Casual Labour (US \$) (*CL*) (x_3)	ln(xx_3)	β_3	0.099	0.139	0.707
Hired Animal Labour (*HAL*) (US \$) (x_4)	ln(x_4)	β_4	0.009	0.011	0.824
Owned Animal Labour (US \$) (*OAL*) (x_5)	ln(x_5)	β_5	0.012*	0.007	1.662
Hired Machine (US\$) (*HM*)(x_6)	ln(x_6)	β_6	0.259***	0.107	2.424
Own Machine (US\$) (*OM*)(x_7)	ln(x_7)	β_7	0.021***	0.007	2.848
Own Irrigation Machine (US \$) (*OIM*) (x_8)	ln(x_8)	β_8	0.016***	0.003	5.544
Hired Irrigation Machine (US \$) (*HIM*) (x_9)	ln(x_9)	β_9	0.004	0.01	0.355
Canal and Other Irrigation Charges (US \$) (*OIC*) (x_{10})	ln(x_{10})	β_{10}	0.014	0.013	1.073
Seed Value (US \$) (*SV*) (x_{11})	ln(x_{11})	β_{11}	-0.212***	0.082	-2.597
Fertiliser (N) (US \$) (*N*) (z_1)	ln(z_1)	δ_1	2.02E-04*	1.08E-04	1.876
Fertiliser (P) (US \$) (*P*) (z_2)	ln(z_2)	δ_2	9.87E-05**	4.96E-05	1.99
Fertiliser (K) (US \$) (*K*) (z_3)	ln(z_3)	δ_3	2.21E-04	1.28E-04	0.947
Other Fertiliser (US \$) (*OF*) (z_4)	ln(z_4)	δ_4	-8.09E-04***	3.76E-04	-2.154
Manure (US \$)(z_5)	ln(z_5)	δ_5	-9.25E-07	2.95E-05	-0.031
Insecticides (US \$) (z_6)	ln(z_6)	δ_6	1.61E-04***	5.38E-05	2.997
	$\hat{\sigma}_s^2$		0.002***	0.001	2.421
	γ		0.472***	0.157	2.999
	μ		0.306***	0.112	2.74
	Log(likelihood)		-49.538		
	LR test		14.166		

Note: ***, **, * are significant at 1%, 5% and 10% level

Source: Authors' own calculation based on data from the Directorate of Economics and Statistics, the Department of Agriculture and Farmers Welfare, the Ministry of Agriculture and Farmers Welfare, the Government of Indiaand Farmers Welfare, the Ministry of Agriculture and Farmers Welfare, the Government of India

Table 4: Maximum likelihood estimates of the stochastic production frontier function of different zones of West Bengal producing paddy.

concerning machineries reveal that escalations in the expenditures on the agricultural machineries help in enhancing paddy productivity across zones. We observe that the expenditures for purchasing the irrigation machineries have a positive influence on the paddy productivity. It is interesting to note that irrigation is important as disclosed by the value of the corresponding t-coefficient of "Own Irrigation Machine (US\$)" and "Canal and Other Irrigation Charges (US\$)". In both cases the corresponding t-statistics exceed unity. The ownership of irrigation machineries is also important as revealed by the fact that the estimated coefficient of "Hired Irrigation Machine (US\$)" is not only low in value but also the corresponding t-statistics is very low. Another input variable "Seed value" is in negative relation with the paddy productivity. The estimated coefficient stipulates that a 1% increase in the expenditures for seed reduces paddy productivity by 0.212% and we are 99% confident about the effectiveness of the result.

We next consider the particular interest of this study, that is, the estimated coefficients of the inefficiency effects model. Altogether we have considered six inefficiency effects variables. As our objective is to explore the consequences of the use of chemical fertilizers on agriculture as well as the environment, we have considered the expenditures on three major chemical fertilizers used in the paddy production in West Bengal as inefficiency effects variables. Among these three variables the estimated coefficients of the expenditures on nitrogen, and potassium are statistically meaningful. However, all these three variables are in positive relationships with the controllable inefficiency of the farm. This implies that the excessive expenditures on these chemical fertilisers result in a reduction of the paddy producing efficiency of the farm. Thus reducing the utilisation of these chemical fertilizers, particularly, nitrogen, and potassium will make the farm more production (technical) efficient. A similar result we obtain for the inefficiency effect variable, insecticides. An increase in the expenditures on insecticides reduces the production (technical) efficiency of the farm. The corresponding estimated coefficient is significant at the 1% level. The negative sign of the expenditures on other fertilizers motivates us to encourage the farmers to use more of these types of fertilizers for paddy production. The estimated coefficient reveals that an escalation of the expenditures on other fertilizers helps the farm to approach the frontier by controlling the farm level inefficiency in paddy production. This result is supported by another estimated coefficient expenditure on manure, although the estimated coefficient is statistically insignificant.

The authors next consider the possible reason behind these empirical results.

Discussion

The stochastic production frontier depicts the traditional input-output relationship and our finding is that expenditures on Attached Labour (US $) are in a positive relationship with the total paddy productivity. Here Attached Labour (US $) is a replica of the hired labour. This result supports the view of Bharadwaj (1974), and Rudra and Mukhopadhya (1976). Accordingly, we conclude that Attached Labour (US$) (hired labour) is more efficacious for escalating the agricultural productivity than family labour as hired labour diminishes the likelihood of disguised unemployment in the agricultural sector which is supposed to be the dominant characteristic of Indian agriculture. Cultivation practices in India, particularly in West Bengal are dominated by the use of bullock labour. Consequently, our empirical results evidence that ownership of animal labour (Owned Animal Labour (US $) is one of the primary determinants of the paddy productivity across zones of West Bengal (Shanmugam and Sundararajan, 2008). Our input based findings reveal that machineries in any form are the preeminent factor for enhancing paddy productivity across paddy producing zones of West Bengal. Accordingly, both Hired Machine (US $) and Own Machine (US $) are in positive relationships with the paddy productivity. The estimated coefficients for these two machineries related variables disclose that there is an urgent need to introduce as well as encourage the adoption of modern techniques in agricultural practices (Feder et al., 1985). Although agriculture in India mainly relies on the monsoon, however, Green Revolution establishes the importance of irrigation. Our study also finds ownership of irrigation machineries as an important factor in enhancing paddy productivity in West Bengal. The expenditures on irrigation machineries are always positivity relation to paddy productivity however, only the expenditures on Own Irrigation Machine (US $) become statistically meaningful. The obvious reason is that the appropriate and proper utilization of the irrigation machineries only be ensured by the ownership. Sometimes farmer finds the hired irrigation machineries are not in proper order and thus fails to fulfil the purpose. This may be the reason for the statistical insignificance of the estimated coefficient. Regarding the statistic insignificance of the Canal and Other Irrigation Charges (US $), we presume that in West Bengal major irrigation types are- Surface, Drip, sprinkler, Center pivot, Lateral move, Sub-irrigation and Manual irrigation, (Geography booster, 2015) and consequently Canal irrigation is rarely used. As such the corresponding estimated coefficient becomes statistically insignificant. Seed is the raw materials for agricultural production. After the introduction of the HYV seeds in paddy from 1968 onwards, it gains popularity. The government of India provides seed subsidies. Only certified seeds are qualified for such subsidy. For the certified hybrid rice seeds the farmer receives subsidy of "Rs. 2000 per quintal or 50% of the total costs" (Agri farming, 2020). Even such, the poor farmers of West Bengal find difficulties in purchasing HYV paddy seeds. An increase in the price of the seeds aggravates their difficulties. In such circumstances, the farmers prefer to use the traditional seed. The HYV seeds are more productive in comparison to the traditional seeds. Accordingly, an increase in the seed values results in lower paddy productivity, as this increase in the seed values forces the poor small and marginal farmers to switch to traditional seeds (Mondal, 2010), which results in lower productivity.

The analysis of the results related to the inefficiency effects model is of our interest. Here the negative sign of the estimated coefficient means the concerned variable affects the efficiency of the farm positively and vice-versa. Accordingly, the positive and significant effects of the variables Fertiliser (N) (US $), Fertiliser (P) (US $) and Insecticides (US$) indicate an increase in the expenditures for purchasing nitrogen, potassium and insecticides will reduce the paddy producing efficiency of the farm. The modernization in Indian agriculture started its journey in 1960 with the introduction of the Green revolution. The farmers apply nitrogen and potassium to enhance productivity and insecticides to protect the plant. However, excessive utilization of chemical fertilizers as well as insecticides not only increases the cost of production but also increases the subsidy burden of the India government (Gupta, et al., 2020). Moreover, our estimated results reveal that the increase in the use of nitrogen, potassium and insecticides actually reduces the technical efficiency of the farm. Both these chemical fertilizers and insecticides have a strong impact on environmental degradation. The excessive use of these chemical fertilizers and insecticides mixes with the soil and causes water as well as soil pollution. As these chemical fertilizers are made available to the farmers at a subsidized rate an excessive utilization of these puts a subsidy burden on the society. The improper utilization of these expensive chemical fertilizers also increases the per-unit cost of production on the farm. Accordingly, the inefficient use of these fertilizers and insecticides not only reduces the efficiency of the paddy producing farm but also puts a social and economic burden on society. Farmers argue that concerning the climate condition of India the amount of insecticides they are using are indeed the requirements for the survivorship of the plants. However, our estimated result is opposing the farmers' argument concerning the utilization of insecticides. The positive sign of the estimated coefficient related to insecticides reveals that there is inefficiency in the application of insecticides. The reduced expenditures on insecticides will increase the efficiency of the farm. As the applied insecticides remain in grains as well as in leaves it has serious health implications also. Moreover, the applied insecticides mix with rainwater and then pollute both the surface as well as groundwater. Consequently, the over-application of insecticides contributes to environmental degradation. The positive sign of the estimated coefficient may be the outcome of all these reasons. If the farms could utilize nitrogen, potassium and insecticides in appropriate doses it will escalate the efficiency of the farm with environmental and economic sustainability (Bora, 2022). Under "Other Fertiliser (US $)" we have included the expenditures incurred by the farm to purchase organic fertilizers. The negative sign of the estimated coefficient ensures that an increase in the use of these fertilizers will help in increasing the efficiency of the farm (Chivenge et al., 2021). The utilization of such fertilizers, as well as insecticides, is environmental friendly and economic also. Thus use of such fertilizers and insecticides help to enhance farms' production efficiency without compromising environmental sustainability (Chivenge et al., 2021; Bora, 2022).

Conclusion

The development of the agricultural sector is necessary not only for ensuring food security but also for the sustainable supply of raw materials. India is the world's biggest rice exporter. India exported 21.42 million tonnes of rice in 2020 and in 2021 its export increased by 21%. The main paddy producing state of India is West Bengal. Accordingly, the present study concentrates on examining the paddy producing efficiency of different paddy producing zones of West Bengal. Based on our empirical results we have suggested the following mitigation policies:

Firstly, agriculture in West Bengal requires commercialization by emphasizing hiring trained labour. The family labour if adequately trained and in demand then only he or she should be employed, otherwise it is better to keep the family labour aside. Secondly, the farmers should be provided with enough funds for purchasing their own agricultural and irrigation machineries. To ensure this an expansion of the institutional credit is highly recommended, particularly for the marginal and small farmers. Thirdly, the government has to restrict the seed value by fixing an upper ceiling. Under such circumstances, the government also needs to take appropriate steps to control black marketing.

To ensure clean agricultural production following policies are suggested:

Firstly, we observe that the inefficiency of the farms is caused by improper utilization of chemical fertilizers, nitrogen and potassium. The proper utilization of nitrogen, potassium and insecticides will escalate the efficiency of the farm. Accordingly, it is highly recommended that soil testing is a must for all farms. The efficient utilization of nitrogen and potassium will increase the efficiency of the paddy producing farm with environmental and economic sustainability. Secondly, the estimated coefficient of the inefficiency effect variable, insecticides is in positive relation to inefficiency and the result is statistically meaningful. As discussed earlier this means reduced expenditures on insecticides will not only increase the efficiency of the farm but also ensure economic and environmental sustainability. If the farmers face difficulties with limited applications of the insecticides, they are recommended to switch to organic insecticides. The application of Neem (margo), and Haldi (turmeric) based insecticides will be agro as well as environmental friendly. Thirdly, we observe the increased expenditures on other fertilizers help in increasing the production efficiency of the farm. These fertilizers include mainly organic fertilizers, viz., vermicompost, natural nitrogen, etc. These fertilizers achieve the goal of increasing productivity with environmental sustainability.

By adopting these steps the West Bengal government will help the farmers to increase their income with environmental sustainability.

Concerning the limitations of the study, we must say microbes in flooded paddy, produce methane, some of which is emitted into the atmosphere. Considering the quantity of production around the world and methane is such a powerful greenhouse gas, experts say reducing those emissions is important. In fact, paddy cultivation is liable for 10% of global greenhouse gas emissions from agriculture and shifting paddy production to a set of practices that cut methane could have significant impacts. However, the non-availability of data restricts us to extend the present empirical analysis including methane emission results from paddy production. Moreover, the choice of the variables for the empirical analysis is dictated by data availability. Thus depending on the availability of data the paper can be extended by considering other dimensions of the environmental consequences of paddy production. Furthermore, the efficiency of the different paddy producing zones of West Bengal is estimated by using the FRONTIER-4.1 programme. Thus the ranking of the zones becomes time-invariant. This can also be considered a limitation of the model.

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References

[1] Agri Farming (2020) "Seed subsidy schemes (Government) for farmers in India". [Online]. Available: https://www.agrifarming.in/seed-subsidy-schemes-government-for-farmers-in-india [Accessed: 5 Nov., 2021].

[2] Ahmed, K. D., Burhan, O., Amanuel, A., Diriba, I. and Ahmed, A. (2018) "Technical efficiency and profitability of potato production by smallholder farmers: The case of Dinsho District, Bale Zone of Ethiopia", *Journal of Development and Agricultural Economics*, Vol. 10, No. 7, pp. 225-235. ISSN 2006-9774. DOI 10.5897/JDAE2017.0890.

[3] Aigner, D., Lovell, C. K. and Schmidt, P. (1977) "Formulation and estimation of stochastic frontier production function models", *Journal of Econometrics*, Vol. 6, No. 1, pp. 21-37. E-ISSN 1872-6895, ISSN 0304-4076. DOI 10.1016/0304-4076(77)90052-5.

[4] Baltagi, B. H. (2005) "*Econometric Analysis of Panel Data*", John Wiley & Sons Ltd., West Sussex, England. ISBN-13 978-0-470-01456-1.

[5] Battese, G. E. and Coelli, T. J. (1995) "A model for technical inefficiency effects in a stochastic frontier production function for panel data", *Empirical Economics*, Vol. 20, No. 2, pp. 325-332. E-ISSN 1435-8921. ISSN 377-7332. DOI 10.1007/BF01205442.

[6] Bharadwaj, K. (1974) "Notes on farm size and productivity", *Economic and Political Weekly*, Vol. 9, No. 13, pp. A11-24. ISSN 0012-9976. E-ISSN 2349-8846.

[7] Bora, K. (2022) "Spatial patterns of fertilizer use and imbalances: Evidence from rice cultivation in India", *Environmental Challenges*, Vol. 7, No. 100452, pp. 1-10. ISSN 2667-0100. DOI 10.1016/j.envc.2022.100452.

[8] Coelli, T. J. (1996) "A guide to FRONTIER version 4.1: a computer program for stochastic frontier production and cost function estimation", CEPA Working papers, Vol. 7, pp. 1-33.

[9] Erisman, J. W., Galloway, J. N., Seitzinger, S., Bleeker, A., Dise, N. B., Petrescu, A. R. and de Vries, W. (2013) "Consequences of human modification of the global nitrogen cycle", *Philosophical Transactions of the Royal Society B: Biological Sciences*, Vol. 368, No. 1621, p. 20130116. DOI 10.1098/rstb.2013.0116.

[10] Fageria, N. K. and Baligar, V. C. (2005) "Enhancing nitrogen use efficiency in crop plants", *Advances in Agronomy*, Vol. 88, pp. 97-185. DOI 10.1016/S0065-2113(05)88004-6.

[11] Feder, G., Just, R. E. and Zilberman, D. (1985) "Adoption of agricultural innovations in developing countries: A survey", *Economic development and cultural change*", Vol. 33, No. 2, pp. 255-298. E-ISSN 1539-2988, ISSN 0013-0079. DOI 10.1086/451461.

[12] Gaddi, G. M., Mundinasmani, S. M. and Hiremath, G. K. (2002) "Resource use efficiency in groundnut production in Karnataka - an economic analysis", *Agricultural Situation in India*, Vol. 58, No. 11, pp. 517-522. ISSN 0002-1679.

[13] Geography booster (2015) "*Different types of irrigation and irrigation systems*". [Online]. Available: http://westbengal.pscnotes.com/geography-booster/different-types-of-irrigation-and-irrigation-systems/ [Accessed: Nov. 5, 2021].

[14] Gourevitch, J. D., Keeler, B. L. and Ricketts, T. H. (2018) "Determining socially optimal rates of nitrogen fertilizer application", *Agriculture, Ecosystems & Environment*, Vol. 254, pp. 292-299. ISSN 0167-8809. DOI 10.1016/j.agee.2017.12.002.

[15] Gupta, N., Tripathi, S. and Dholakia, H. H. (2020) "*Can Zero Budget Natural Farming Save Input Costs and Fertiliser Subsidies?, Evidence from Andhra Pradesh*". New Delhi: Council on Energy, Environment and Water. [Online]. Available: https://www.ceew.in/publications/can-zero-budget-natural-farming-save-input-costs-and-fertiliser-subsidies-evidence [Accessed: Nov. 10, 2021].

[16] Cheng, S., Zheng, Z. and Henneberry, S. (2019) "Farm size and use of inputs: explanations for the inverse productivity relationship", *China Agricultural Economic Review*, Vol. 11, No. 2, pp. 336-354. ISSN 1756-137X . DOI 10.1108/CAER-09-2018-0192.

[17] Chivenge, P., Saito, K., Bunquin, M. A., Sharma, S. and Dobermann, A. (2021) "Co-benefits of nutrient management tailored to smallholder agriculture", *Global Food Security*, Vol. 30, p. 100570, pp. 1-8. ISSN 2211-9124. DOI 10.1016/j.gfs.2021.100570.

[18] Kumari, B., Chandel, B. S. and Lal, P. (2018) "An econometric analysis of optimality for sustainable paddy production in India", A*gricultural Economics Research Review*, Vol. 31, pp.139-145. E-ISSN 0974-0279, ISSN 0971-3441. DOI 10.5958/0974-0279.2018.00029.0.

[19] Maity, S. (2017) "Reform Raises Efficiency of Tea Estates in India", *AGRIS on-line Papers in Economics and Informatics*, Vol. 9, No. 2, pp. 101-116. ISSN 1804-1930. DOI 10.7160/aol.2017.090209.

[20] Maity, S. and Singh, K. (2021) "Frontier production functions, technical efficiency and panel data: with application to tea gardens in India", *International Journal of Business and Globalisation*, Vol. 27, No. 4, pp. 571-591. E-ISSN 1753-363. ISSN 1753-3627. DOI 10.1504/IJBG.2021.113797.

[21] Maps of India (2016) "Top 10 Rice Producing States of India". [Online]. Available: https://www.mapsofindia.com/top-ten/india-crops/rice.html [Accessed: Nov. 15, 2021].

[22] McArthur, J. W. and McCord, G. C. (2017) "Fertilizing growth: Agricultural inputs and their effects in economic development", *Journal of Development Economics*, Vol. 127, pp.133-152. ISSN 0304-3878. DOI 10.1016/j.jdeveco.2017.02.007.

[23] Meeusen, W. and van Den Broeck, J. (1977) "Efficiency estimation from Cobb-Douglas production functions with composed error", *International Economic Review*, Vol. 18, No. 2, pp. 435-444. ISSN 0020-6598. DOI 10.2307/2525757.

[24] Mondal, M. H. (2010) "Crop Agriculture of Bangladesh: Challenges and Opportunities", *Bangladesh Journal of Agricultural Research*, Vol. 35, No. 2, pp. 235-245. E-ISSN 2408-8293, ISSN 0258-7122. DOI 10.3329/bjar.v35i2.5886.

[25] Norse, D. and Ju, X. (2015) "Environmental costs of China's food security", *Agriculture, Ecosystems & Environment*, Vol. 209, pp. 5-14. ISSN 0167-8809. DOI 10.1016/j.agee.2015.02.014.

[26] Ozlu, E., Sandhu, S. S., Kumar, S. and Arriaga, F. J. (2019) "Soil health indicators impacted by long-term cattle manure and inorganic fertilizer application in a corn-soybean rotation of South Dakota", *Scientific Reports*, Vol. 9, p. 11776, pp.1-11. ISSN 2045-2322. DOI 10.1038/s41598-019-48207-z.

[27] Pesaran, M. H. (2006) "Estimation and inference in large heterogeneous panels with a multifactor error structure", *Econometrica*, Vol. 74, No. 4, pp. 967-1012. E-ISSN 1468-0262. DOI 10.1111/j.1468-0262.2006.00692.x.

[28] Reddy, D. N., Reddy, A. A. and Bantilan, M. C. S. (2014) "The impact of Mahatma Gandhi National Rural Employment Guarantee Act (MGNREGA) on rural labor markets and agriculture", *India Review*, Vol. 13, No. 3, pp. 251-273. ISSN 1473-6489. DOI 10.1080/14736489.2014.937271.

[29] Ren, C., Jin, S., Wu, Y., Zhang, B., Kanter, D., Wu, B., Xi, X., Zhang, X., Chen, D., Xu, J. and Gu, B. (2021) "Fertilizer overuse in Chinese smallholders due to lack of fixed inputs", *Journal of Environmental Management*, Vol. 293, p. 112913. ISSN 0301-4797. DOI 10.1016/j.jenvman.2021.112913.

[30] Roy, R. N., Finck, A., Blair, G. J. and Tandon, H. L. S. (2006) "Plant nutrition for food security. A guide for integrated nutrient management", *FAO Fertilizer and Plant Nutrition Bulletin*, Vol. 16, pp. 368. ISBN 92-5-105490-8. ISSN 0259-2495.

[31] Rudra, A. and Mukhopadhya, M. M. (1976) "Hiring of labour by poor peasants", *Economic and Political Weekly*, Vol. 11, No. 1/ 2, pp. 33-36. E-ISSN 2349-8846, ISSN 0012-9976.

[32] Sarker, M. N. I. (2016) "Role of banks on agricultural development in Bangladesh", *International Journal of Ecology and Development Research*, Vol. 1, No. 1, pp. 10-15. ISSN 2167-0449.

[33] Shanmugam, K. R. and Soundararajan, V. (2008) "Sources of output growth in Indian agriculture during the post-reform period", Working Paper 26, pp. 1-15, Madras School of Economics, Chennai, India.

[34] Tiedemann, T. and Latacz-Lohmann, U. (2013) "Production Risk and Technical Efficiency in Organic and Conventional Agriculture – The Case of Arable Farms in Germany", *Journal of Agricultural Economics*, Vol. 64, No. 1, pp. 73-96. E- ISSN 1477-9552. DOI 10.1111/j.1477-9552.2012.00364.x.

[35] Vitousek, P. M., Naylor, R., Crews, T., David, M. B., Drinkwater, L. E., Holland, E., Johnes, P. J., Katzenberger, J., Martinelli, L. A., Matson, P. A. and Nziguheba, G. (2009) "Nutrient imbalances in agricultural development", *Science*, Vol. 324, No. 5934, pp. 1519-1520. E-ISSN 1095-9203, ISSN 0036-8075. DOI 10.1126/science.1170261.

[36] Voss, M., Baker, A., Bange, H. W., Conley, D., Deutsch, B., Engel, A., Heiskanen, A. S., Jickells, T., Lancelot, C., McQuatters-Gollop, A. and Middelburg, J. (2011) "Nitrogen processes in coastal and marine ecosystems", In: *The European Nitrogen Assessment*: *Sources, Effects and Policy Perspectives*, pp. 147-176, Cambridge University Press. DOI 10.1017/CBO9780511976988.011.

[37] Wang, Y. and Lu, Y. (2020) "Evaluating the potential health and economic effects of nitrogen fertilizer application in grain production systems of China", *Journal of Cleaner Production*, Vol. 264, p. 121635. ISSN 0959-6526. DOI 10.1016/j.jclepro.2020.121635.

[38] Zhang, X., Davidson, E. A., Mauzerall, D. L., Searchinger, T. D., Dumas, P. and Shen, Y. (2015) "Managing nitrogen for sustainable development", *Nature*, Vol. 528, pp. 51-59. E-ISSN 1476-4687, ISSN 0028-0836. DOI 10.1038/nature15743.

Appendix

Variables	ln(x_1)	ln(x_2)	ln(x_3)	ln(x_4)	ln(x_5)	ln(x_6)	ln(x_7)	ln(x_8)	ln(x_9)	ln(x_{10})	ln(x_{11})	ln(z_1)	ln(z_2)	ln(z_3)	ln(z_4)	ln(z_5)	ln(z_6)
ln(x_1)	1																
ln(x_1)	-0.40	1															
ln(x_3)	-0.19	0.33	1														
ln(x_4)	-0.18	0.19	0.28	1													
ln(x_5)	-0.29	-0.04	-0.07	0.43	1												
ln(x_6)	0.16	0.19	0.44	0.43	-0.08	1											
ln(x_7)	-0.07	-0.19	0.10	0.29	0.05	0.23	1										
ln(x_8)	-0.13	0.34	0.24	0.68	0.14	0.36	0.31	1									
ln(x_9)	-0.40	0.35	0.30	-0.07	0.36	-0.01	-0.32	-0.04	1								
ln(x_{10})	-0.37	0.20	0.47	-0.24	-0.07	-0.11	-0.03	-0.22	0.19	1							
ln(x_{11})	0.31	0.09	0.04	0.02	-0.34	0.29	0.06	0.25	-0.48	-0.13	1						
ln(z_1)	-0.21	0.39	0.48	0.50	0.31	0.43	0.15	0.62	0.09	0.35	0.10	1					
ln(z_2)	-0.06	0.27	0.41	0.39	0.22	0.57	0.37	0.60	-0.27	0.06	0.25	0.83	1				
ln(z_3)	0.23	-0.03	0.36	0.46	-0.11	0.39	0.45	0.45	-0.35	0.04	0.51	0.63	0.75	1			
ln(z_4)	0.26	0.15	0.21	0.02	-0.32	0.37	0.14	0.21	-0.15	0.01	0.65	0.23	0.31	0.55	1		
ln(z_5)	0.20	-0.36	-0.41	0.11	0.16	0.14	-0.06	-0.23	-0.31	-0.34	-0.05	-0.29	-0.01	-0.15	-0.10	1	
ln(z_6)	0.21	-0.15	0.24	-0.11	-0.37	0.45	0.46	-0.02	-0.38	0.19	0.51	0.16	0.46	0.64	0.60	0.14	1

Source: Authors' own calculation based on secondary data

Table A.1: Correlation diagnostics.