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Sustainable Environmental Economics in Farmers' Production Factors via Irrigation Resources Utilization Using Technical Efficiency and Allocative Efficiency

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Abstract: This study reports the results of farmers' production via irrigation resources utilization and efficiency parameters of technical efficiency and allocative efficiency by way of sustainable environmental economics. The hypothesis is that factors of farmers' production affect technical efficiency and allocative efficiency in the irrigation scheme as sustainable environmental economics. Data from cross section and panel data were used and then the productivity parameters measurement of the production function are outlined in two scenarios: first, the data report that the parameters such as output elasticity determine factors of inefficiency and technical efficiency. Second, it presents the scores for the allocative efficiency to explain whether production factors (resources) are optimally, under- or over-allocated by farmers in the irrigation systems under environmental sustainability. This paper presents the productivity and efficiency parameters estimated using stochastic frontier analysis for the translog production function, which was estimated by the MLE method, and the allocative efficiency for the factor inputs allocation in the irrigation systems estimated by ordinary least square for the Cobb-Douglas production function. This study concludes that collective farmers lead into technical inefficiency and over use of factors of production.

Keywords: sustainable environment; irrigation; allocative efficient; technical efficient; elasticities

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1. Introduction

This study was based a on cross-sectional data set aimed at sustainable environmental economics in farmers' production factors via irrigation resource utilization on the supply technologies use/adoption. It is theoretically and empirically accepted that individuals will join the group for collective farming if the private benefits exceed the cost of cooperation [1], and that individuals not only consider private material benefits, but also non-tangible benefits offered by the farming collective [2]. There is a collective management for necessary maintenance of the system and process of infrastructures, water allocation, distribution and control to ensure efficient performance of the system that generates benefits intended for the users [3,4]. Thus, the performance of an irrigation system as a production unit is usually indicated or explained in terms of productivity and efficiency measurement [5]. Productivity is defined as the ratio of outputs of the production process to its inputs, while efficiency refers to the comparison between observed outputs and optimal outputs, and observed inputs and optimal inputs. Productivity is a residual due to variations either across producing units or through time. The scale of operation, operating efficiency, or environment in which production occurs can be the residual attributed to differences in production technologies. Efficiency is a residual too, but it also requires the existence of a benchmark or comparison to the best practice. In the efficiency measurement, a production possibility or behavioral goal of the producer is defined as optimum. In these events, efficiency in the former is technical, and in the later, efficiency is measured by comparing observed and optimum costs, revenue, profit (allocative), or whatever goal the producer is assumed to pursue. Thus, efficiency and productivity are success indicators, which are performance metrics by which producers or producing units are evaluated [5,6].

1.1. Theoretical Review

Worldwide, natural resources management, particularly common natural resources (common pool resources) such as irrigation systems management is studied based on collective action theory [7,8]. This theory states that an irrigation system is sustainable and in a functional and predictable physical state, and there is congruence between the rules linking social structure, ecology and technology and collective decision making [9,10]. These institutional designs are useful in explaining factors which may influence collective action, but have overlooked the important characteristics underlying the interactions, and how an actor can efficiently coordinate their undertaking (transaction) without friction [11]. On the other hand, the neo-classical economics theories tend to focus resource management around market mechanism [12], stating that the price responds to factor scarcity resulting into factor substitutions, and ultimately resource management efficiency is achieved because scarcity will lead to a higher price; hence, stimulate investment and adjust to reach equilibrium. These assertions are right, but cannot solve the problem of the common, especially on issues related to equity allocation (pro-poor inclusion), because individual interest is profit maximization rather than efficiency [13,14]. As such, excluded individuals may devise mechanisms including opportunism or free-riding on resource utilization, and so inefficiency outcome remain unsolved. None of the previous theories succinctly reviewed have incorporated a mixture of theoretical perspective—a novelty in studying sustainable environmental problem in this study. Therefore, focusing on a single theory does not improve efficiency gain in this context. Farmers' production factors theoretical component is thus considered in understanding the economic organization and institutional aspects related to human behavior and identify factors, which predict successfulness in the technical and allocative efficiency to enhance irrigation systems performance [15].

1.2. Empirical Review

According to [16] transaction cost economics theory concentrates on the relative efficiency of different exchange processes. Transaction cost analysis can be applied to issues of irrigation systems management, because in many common resources, efficient management of common property rights that are granted collectively are often challenged by various sources of uncertainty that result in high transaction costs in its management [17]. In general, technical and allocative efficiency is considered a tool that translates into efficient performance of irrigation systems. Yet, most studies have ignored transaction cost analysis, which are important elements in the technical and allocative efficiency successfulness [17,18], and it also embodies non-tangible values [19,20]. The transaction costs emerge as a linkage within the institutions and others between social, economic, and environmental/ecological interactions with resource users. An economic theory of production based on technical efficiency and allocative efficiency, combined with transaction cost economics and social capital theories, were used to architecture the interactions which were designed in terms of clustered factors: external factors determining use and accessibility conditions of irrigation services as a proxy for technical and allocative management efficiency, technology characteristics, and users behavior, motivation and perceptions on the technologies used, such as output price incentives and risk perception, to understand the technical and allocative efficiency successfulness [21].

2. Materials and Methods

The study was conducted at Lake Mugesera in 2020, covering five irrigation schemes. These areas have different agro-ecological systems defined by different farming system zonation that is characterized by the interactions of cultural, agro-biological aspects such as dominant soil types, rainfall distribution and socio economic factors such as input-output markets, own farmers' priority on crops cultivated and resources capabilities [22]. Selected areas have also more or less homogeneous characteristics on other aspects related to culture, particularly crops grown in the irrigation schemes and the characteristic of input-output market. In terms of irrigation scheme characteristics they are traditional improved schemes, that depend on temporary rivers for their water source, but sometimes with reservoir/dams constructed to collect rainwater during the season. Occasionally, an electrical pump for water abstraction from the main source of water, Lake Mugesera, is used.

The research design included a comprehensive field survey that combined two types of data collection methods: The first data collection involved cross-sectional design that was engaged to study the individual farmers and group aspects at the household level, or "primary cross sectional data set, obtained at household level". The study relied on primary information collected to cover mainly the governance, transaction costs, technology characteristics and the social capital variables in the form of their various proxies. A farm household was used as a unit of observation for the analysis. To identify the causality, the design compared farmers participating in irrigation farming by creating clusters during analysis: those engaged in irrigation and that value collective action, and those engaged in both irrigation and rainfed in each of the scheme surveyed. The second data approach involved the use of longitudinal (panel data design) survey at irrigation group level, relying on secondary information recorded by the irrigation group's organization (management) over time, "longitudinal/panel data set (repeated observations over the same unit of analysis), which is secondary data set obtained at group level records in each irrigation scheme". The data set covered a period of 10 years (from 2009–2018) to compare group dynamics and individual effects (heterogeneity) on institution quality across the schemes over the time period. In the first approach to sampling, purposive sampling was used to obtain a total of 5 irrigation schemes; and in the second approach to sampling, survey respondents' selection targeted farmers involved in the irrigation farming. The survey employed a multi-stage sampling procedure based on the two stages approach. First, purposive sampling was used to obtain a total of 5 irrigations schemes, both traditional and modern, which are distributed along the Lake Mugesera water basin. The selection criteria for the irrigation schemes were based on the potential function (operational) of the irrigation facilities, and the age of the scheme (that is, has been working/operational for the past 5–10 years or so) in order to capture the dynamic conditions.

The second stage involved survey respondents' selection: targeting farmers involved in the irrigation farming. From each scheme, one farmer irrigation group/water users' association for group level analysis, and 30 farm households participants in the irrigation farming only, and those engaged in both irrigation and rainfed farming, in addition to off–farm activities, engagement for individual household-level analysis were randomly sampled. In total 5 irrigation groups (100% response rate) and initially 345 households were collected; however, 312 households, about a 90.43% response rate, was reached after data cleaning. For technical and allocative efficiency, data were constructed and grouped into external and internal efficiency conditions in resource utilization. The external efficiency conditions encompassed aspects, which reflect the congruency conditions of resource utilization efficiency. They included external efficiency, technology characteristics, and user behavior motivation. These were then linked to data measuring internal efficiency (input–output relations) in a production frontier context that capture technical efficiency and allocative efficiency.

The external efficiency data were measured by constructing cropping intensity (CI) index (area sown over total area cultivated-ratio), management and leadership aspects in irrigation services provision (e.g., group leadership-dummy, good, or otherwise) as a proxy indicator on use and access for irrigation facilities. Technology characteristics data were irrigation soil fertility status (dummy, good/fertile, or otherwise), proximity/distance from homestead to the irrigation scheme (km), and land owned in the irrigation command area (acres). Resource users' behavior motivation data included risk perception on the use of an irrigation scheme (dummy, risk averse, or otherwise prefer). Other variables were constructed based on interactions between age and capital, and non-tangible benefits such as use of collective farming as a bridge for external service support and income earning from irrigation farming. Other data included output and inputs (fertilizers) prices, and percent of time allocated for irrigation faming management (%). Transaction costs related data were grouped into information and knowledge (contact) such as number of meetings (frequency/number), irrigation training attendance (dummy, yes or otherwise), and communication/travel cost in regard to irrigation issues (Rwanda). Demographic data such as age (years), sex (dummy, male, or otherwise), and education level (category) were also captured.

The internal efficiency data were constructed based on input-output relations in a production function context to measure technical efficiency and allocative efficiency scores. Data set type required for technical efficiency and allocative efficiency included harvested output/yield (kg), and inputs used such as fertilizers, labor all measured in quantities (kg or number), water allocation/distribution into plots/field (dummy, good or otherwise not). The analysis of this study involved two estimation techniques. First, technical efficiency was estimated using stochastic frontier analysis (SFA) technique, which estimated the production function and TE inefficiency model in a single stage using Frontier 4.1. The production function also produced the output elasticities, and the technical inefficiency effects (determinants of technical inefficiency). Second, allocative efficiency of factor inputs were computed based on coefficients generated by OLS estimation of the Cobb-Douglas production function. The two estimation techniques are mathematically formalized separately as follow:

2.1. Allocative Efficiency (AE)

The technical efficiency modelling follows [23]; using the Cobb-Douglas production functional form and is specified by:

$$y = AX_i^{\beta i} - X_n^{\beta n} \tag{1}$$

where;

y = pineapple yield output (pieces)

$X_i \ldots\ldots X_n$ = Inputs used (quantities measured in their respective units)

A = Constant

$\beta_i \ldots\ldots \beta_n$ = Parameters to be estimated.

Equation (1) can be written in its linear form for OLS estimation to compute the marginal value product (*VMP*) for each factor of production as in Equation (2). The Cobb-Douglas production function linear form is given by:

$$\ln y = \ln A + \sum_{i=1}^{n} \beta \ln X_i + \varepsilon_i \tag{2}$$

where;

y = Output,

X_i = Inputs,

ε = Error term,

$A,\ \beta$ = Parameters to be estimated.

The *VMP* is defined from Equation (2) above, using the coefficient estimates to generate marginal physical product (MPP) of the i-th factor, which is written as:

$$MP_i = \frac{\partial y}{\partial X_i} = \beta_i \frac{y}{X_i} \tag{3}$$

where;

y = Geometric mean (mean of natural logarithm) of the output,

X_i = Geometric mean (mean of natural log) of inputs,

β_i = Estimated coefficients of inputs.

Thus, the *VMP* of input is obtained by multiplying the *MP* by the output price, P_y.

$$VMP_i = MP \times P_y \tag{4}$$

$$\text{The allocative efficiency } (AE) = \frac{VMP_{xi}}{MFC_{xi}} \tag{5}$$

However, farmers under imperfect markets are price takers; hence, the marginal cost of inputs (*MFC*) approximates the price of the factor P_{xi}. The allocative efficiency is therefore given by:

$$AE = \frac{VMP_{xi}}{P_{xi}} \tag{6}$$

Three scenarios can be observed for decisions of resource allocation as follows:
If $\frac{VMP_{xi}}{MFC_{xi}} > 1$ the input is under used
If $\frac{VMP_{xi}}{MFC_{xi}} < 1$ the input is over used and
If $\frac{VMP_{xi}}{MFC_{xi}} = 1$ the input is efficiently allocated in the system

2.2. Technical Efficiency (TE)

To model *TE* the standard stochastic production frontier model is used. It is given by:

$$Y_i = f\left(X_i \beta_{(k)}\right) e^{v_i - U_k} \tag{7}$$

where;
Y_i = Output of *i*-th farm,
X_i = Denotes a row vector of inputs used by the *i*-th farm,
$\beta_{(k)}$ = Vector of unknown parameters to be estimated,
v_i = Symmetric random error identically distributed as $N\left(0, \sigma^2_{vk}\right)$.
U_k = A non-negative random variable assumed to account for technical inefficiency and assumed to be independently and identically distributed, and truncations at zero of the normal distribution with mean $\mu_{i(k)}$ and variance $\sigma^2_{u(k)}$.

The *TE* of *i*-th farm is then obtained by:

$$TE_i = \frac{Y_i}{e^{x_i \beta^k + v_i}} = e^{-u_{ii}} \tag{8}$$

The Cobb-Douglas production functional form using MLE method was employed to estimate technical efficiency using Frontier 4.1.

3. Results Analysis

3.1. Descriptive Statistics Used for the Production Function

Table 1 provides definitions and summary statistics for the variables used for the stochastic frontier analysis of the production function and technical efficiency estimations. Variables were selected to outlines the productivity parameters measurement of the production function in two scenarios: first, reports the parameters such as output elasticity, technical efficiency and determinants of inefficiency. Second, presents the scores for the allocative efficiency to explain whether production factors (resources) are optimally under- or over-allocated by farmers in the irrigation systems under collective farmers management.

The table indicates that the average yield produced by farmers was 48.87 tons per hectare. The average plant seed amount used in the production of pineapple was 41,693.91 kg per ha, with big variations ranging from 500 kg to 48,000 kg. The average amount for the fertilizers normally used by farmers was 226.60 kg per ha, also far below recommendations (ibid), and average number of days used to work on irrigation farming were 181 person days, with a wide variation ranging from 2 to 505 person days per ha. The working days include a full range of activities from farming to pre- and post-harvest management such as harvesting, transportation, threshing, drying, packaging, etc. Other inputs used were capital investment, which were directly used in irrigation farming such as labor costs with an average amounting to RWF 4,454,920, though there were a wide variation ranging from RWF 3500 to 4,800,000. The strategy for water distribution in the plots/field was rated for satisfaction (good, fair, or unfair) as inputs to satisfy the crop-water requirement for the cropping period, which averaged to 1.33. Other variables included in the model of technical inefficiency effects are shown in Table 1 along with their summary statistics.

Table 1. Definition of variables used in the SFA for the production function and technical inefficiency Model.

Variable	Description	Measure	Mean	Std. Dev.	Min	Max
Output						
Yield	Pineapple yield harvested per ha	Tonne	48.87	16.39	1	56
Inputs:						
InputsInpu~t	Plant amount used per ha	Kg	41,693.91	10,254.17	500	48,000
Inputfert	Fertilizer amount used per ha	Kg	226.60	85.99	20	600
Labor	Number of days worked per ha	Person/day	181.06	65.52	2	505
Capitalinv	Cash investment cost	RWF	4,454,920	831,728.3	3500	4,800,000
WateriDistr	Satisfaction of water distribution in plots as inputs	Category	1.33	0.47	1	2
Variables affecting deviation of output from frontier:						
Gender_Sex	Sex of farmer decision maker in farming	Dummy	1.42	0.49	1	2
Age	Age of farmers	Years	44.61	8.69	18	75
Education_~u	Education level of farmer	Category	2.96	0.86	1	6
Irrgland	Irrigation land owned in the scheme	Acres	2.32	1.88	.2	14
Irrigdist	Distance from home to the irrigation scheme	Km	2.64	5.32	.1	27
Irrgtrain	Acquisition of irrigation technology training	Dummy	0.59	0.49	0	1
Gpleader	CA group leadership style in the scheme	Dummy	0.81	0.39	0	1
Nofmeeting	Frequency of meetings related to irrigation issues per cropping period	Number	13.10	3.92	0	30
Expirrig	Experience in irrigation farming	Years	7.51	3.07	1	21
Soilirrgat	Soil status/fertility in the scheme	Dummy	0.74	0.44	0	1
Riskpercept	Risk perception on the irrigation technology/resource use	Dummy	0.22	0.43	0	2
Price	Output price per unit kg	Kg	445.19	306.69	0	2000
AverageArea	Average area under irrigation farming (acres)		380	0	380	380
LNNTB	Interaction effect between non-tangible benefits such as use of CF for external support access and income	Number	2,615,462	3,492,629	0	1.6×10^7
LNcontactc~t	Contact/communication cost such as phones and travel cost	RWF	6358.97	1529.93	0	7600
LNCI	Index of cropping intensity as a proxy of good governance in the irrigation system	Index number	1.47	0.49	1	2
Prcfym	Cost of manure input (FYM)	RWF	601.15	447.80	0	6000
Prcnpk	Cost of fertilizer input (NPK)	RWF	463.59	354.09	0	4700
Prcurea	Cost of fertilizer (UREA)	RWF	797.82	820.42	0	7200
Prcmcn	Cost of fertilizer (Micronutrients)	RWF	2000.64	2333.89	0	20,000
Percentage	Percent total time devoted for irrigation farm management	Percent	68.24	13.31	0	130

3.2. Production Function Estimation Results for the Production Frontier

Technical efficiency, output elasticity and technical inefficiency effects: the maximum likelihood estimates (MLE) of the parameters of the stochastic frontier production function and the technical inefficiency model were simultaneously estimated in a single stage using Frontier 4.1 statistical package [24]. Table 2 reports the statistical tests to confirm the appropriateness of SFA in the frontier production function. Ref. [25] explain the variation of outputs from the frontier attributed by the technical inefficiency that it ranges between

0 and 1. If gamma, $\gamma \rightarrow 0$ implies that there is no inefficiency in the model and the traditional average response function can be estimated by OLS method. The results in Table 2 for this study indicate that the variance parameter gamma is close to one (γ = 0.960589) and significant at a 1% level, implying that the inefficiency effects are likely to be significantly high in the analysis of the output (yields) for the sampled farmers in the irrigation system. In other words, 96.1% of the inefficiency is due to technical inefficiency and only 0.4% due to random error. The generalized likelihood ratio test is significant at a 1% level, rejecting the null hypothesis that inefficiency effects are absent and farmers production factors do not affect sustainable environmental economics, or that they have simpler distributions.

Table 2. MLE estimates for the production function frontier and technical inefficiency model.

Output Yield	Coef.	Std. Err.	z	$p > \|z\|$
Production frontier				
InputsInputpl~t	0.0006	0.0001	6.35 *	0.000
Inputfert	0.0707	0.0163	4.35 *	0.000
Labor	−0.0192	0.0089	−2.15 **	0.032
Capitalinv	-1.30×10^{-6}	1.00×10^{-6}	−1.44	0.149
WateriDistr	4.3619	2.3193	1.88 ***	0.060
Technical inefficieny model				
Gender_Sex	0.0018	1.1540	0.00	0.999
Age	−0.0344	0.1192	−0.29	0.772
Education_Edu	0.4858	0.9585	0.51	0.613
Irrgland	0.9243	0.7548	1.22	0.228
Irrigdist	0.0075	0.2163	0.03	0.972
Irrgtrain	5.6425	2.0481	2.75 *	0.006
Gpleader	4.4696	2.2405	1.98 **	0.048
Nofmeeting	−0.3225	0.1554	−2.08 **	0.037
Expirrig	2.7772	0.3066	9.06 *	0.000
Soilirrgat	3.6679	1.7232	2.13 **	0.033
Riskpercept	−1.9209	1.5803	−1.22	0.229
Price	0.0079	0.0022	3.55 *	0.000
LNNTB	-2.42×10^{-7}	1.56×10^{-7}	−1.54	0.123
LNcontactcost	−0.0020	0.0004	−5.03 *	0.000
LNCI	8.8809	1.5803	5.62 *	0.000
Prcfym	−0.0007	0.0009	−0.72	0.427
Prcnpk	−0.0025	0.0013	−1.84 ***	0.066
Prcurea	−0.0028	0.0007	−4.05 *	0.000
Prcmcn	−0.0003	0.0006	−0.60	0.549
Percentage	0.0601	0.1069	0.56	0.574
_cons	−3.9024	15.1857	−0.26	0.797
Variance parameters				
sigma2	364.7588	36.4879		
Gamma	0.9606			
/mu	9.62×10^{-8}			
Log likelihood function = −1198.9776				
LR 270.10 *** = 0.0000				

Note: significance levels: * $p < 0.01$, ** $p < 0.05$, *** $p < 0.1$.

Based on the variance parameters estimates (gamma and sigma–square) in Table 2 regarding the technical inefficiency structure, five factors were identified to have positive effects on reducing the technical inefficiency of farmers in the surveyed irrigation schemes. The coefficient for the variable ownership of irrigation land (irrgland) was positive and not significant, which indicates that farmers with ownership of land within the irrigation scheme command area tend to be more inefficient. This is perhaps because the land owned can be improved with certainty, rather than fear of eviction if the land is rented out. These results are supported by the findings from [26] which confirmed that land ownership has a greater impact on productivity through greater land investment for improvement, and also credit access in places where the land is regularized with title deeds. The governance-related variable, group leadership style and discretion (Gpleader), had a positive coefficient and significance at a 5% level, implying that increasing the good governance of the group leadership increases farmers' technical inefficiency in the irrigation scheme. This is unexpected because good leadership encourages others to work, but also good leadership is a key to improvement of performance [27].

The output price coefficient (price) is positive and significant at 1%, indicating that increasing output price increases inefficiency in irrigated pineapple production. The plausible explanation is obvious that price is an incentive for supply response accounting for farm management that is motivated by encouragement of the best combination of inputs use and substitution of income earning to leisure. These results point to the need for strengthening market incentives through effective policies that will improve farm output profitable market access [28]. The coefficient for the variable regarding interaction effects between non-tangible benefits and income (LNNTB*income) was negative and not significant. This implies that as the non-tangible benefits increase the effect of income on reducing technical inefficiency decreases [29]. In other words, non-tangible benefits (use of collective farmers as a network for external service support access) have a positive relationship with income earning, hence, efficiency would be increased by the interaction of these variables.

Other variables grouped into information and knowledge such as frequency of meetings (nofmeeting) and irrigation training (irrgtrain) had coefficients with negative and positive signs and significance at 5% and 1% level, respectively, indicating that the increase in technical inefficiency is positively influenced with the decrease in the frequency of meetings convened, and perhaps the frequency of meetings reduces farm working time. The results also indicate that an increase in irrigation training increases technical inefficiency. This is contrary to the assumption that training (non-formal continued education of farmers) enhances efficiency and productivity [30]. The increase in technical inefficiency is perhaps due to farmers failing to take advantage of opportunities in the irrigation system to move up the factors of production along the expansion path [31]. This could be a result of risk-aversion behavior farmers have or due to bad collective farmers organization and management experience, rather than a lack of information synthesis. However, the coefficient for the variable related to risk perception (riskpercept) was negative and insignificant and, hence, did matter in influencing technical inefficiency.

The fertilizer inputs prices of (prcfym and prcmcn) had coefficients with negative sign coefficients and were not significant, while fertilizer inputs prices of (prcnpk, prcurea) had a negative sign and significance at 10% and 1% level, respectively. The results imply a decreased technical inefficiency with the use of such inputs, perhaps because they are used in the best combination to balance the nutrients required, which shows the quality of sustainable environmental practices. Demographic variables, such as sex and formal education level (educ), were positive and insignificant, while age was negative and insignificant. Though age was insignificant, it indicated that it had a positive influence in reducing technical inefficiency, which conformed to other studies related to the importance of education in improving efficiency and productivity [32].

3.3. Output Elasticities and Return to Scale

The results of the production function estimates to measure output elasticities and technical efficiency (TE) were obtained for the major common inputs used by farmers in pineapple production under irrigation farming in the study area. The major inputs used were plants, fertilizer, labor, capital, and water allocation (distribution) strategy based on calendar of water distribution in the plots/fields (Table 2). Coefficients results for the estimated output elasticities for all inputs were as expected, with exception of negative signs for labor and capital investment inputs. The coefficient for labor was negative and significant while capital investment was negative and not statistical significant perhaps unqualified farmers at un-recommended rate. Similarly, on capital investment probably were invested under poor farming conditions such as drought or flood, or else were applied at un-recommended rates, which lowered the yields. The output elasticities with respect to inputs were: seed plant (0.0006) and fertilizer (0.0707) were positive and significance indicating positive relationship on proportion of seed plant and fertilizer and the output produced though very smaller.

Nevertheless, all inputs elasticities were inelastic. Water distribution was positive and significant, implying that it was important in influencing the yields produced, and the capital that most employed included implements such as ox ploughs usually owned by many households, and little or non-cash use in their farming activities; hence, capital did not matter, resulting in an under-capacity utilization of the irrigation scheme (resource). Additionally, it might be because an irrigation scheme depends on rainfall availability to keep functional. Though significant, as expected, water distribution/allocation into plots/field was found to have the highest elasticity (4.36), confirming the positive relationship with output production (yield). The return to scale computed as the sum of output elasticities of all inputs is estimated to be 4.41, implying that on average pineapple production farmers in irrigation exhibit an increasing return to scale. Farmers are still operating at region one of the classical production function, which starts with zero inputs use, an irrational behavior, and choosing their goal inconsistently with maximization of returns. However, if all factors were increased by 1%, pineapple production (yields) would increase by 4.41% (Table 3).

Table 3. Output elasticities for all inputs used.

Inputs Variables	Elasticities
InputsInputpl~t	0.0005924 *
Inputfert	0.0707742 *
Labor	−0.0192243
Capitalinv	-1.30×10^{-6}
WateriDistr	4.361809 ***
Total return to scale	4.41395

* Significance level when $p < 0.01$, while *** significance level when $p < 0.1$.

3.4. Allocative Efficiency of Factor Inputs in the Irrigated Pineapple Production

The Cobb-Douglas production function linear form was obtained by estimating OLS regression for the major inputs used in pineapple production (plant seed, fertilizer, labor, capital, water distribution timing strategy, and satisfaction of crop water requirement in the plots), which was imputed on a cost/price basis to compute marginal physical product (MPP) and the value of marginal product (VMP) for each input to ascertain the allocative efficiency. The prices for plant seed, fertilizer and labor inputs were based on the average market prices, while average capital invested was used as the price for capital. The price for water distribution satisfaction was imputed based on the cost or contributions payable by a farmer per cropping season as water right charges in the scheme, where farmers normally paid 50 kg of fresh pineapple, which was converted to the equivalent sales market price of RWF 25,000. Ref. [32] estimated the irrigation water price in the production of pineapple Mugesera and Rukira water basin authorities to be RWF 22,250 per ha.

The results of the marginal physical product (MPP), the value of marginal product (VMP), marginal factor cost (MFC) and allocative efficiency (AE) of each input used for pineapple production in this study are summarized in Table 4: the MPP for water distribution was the highest, which indicated that additional water can increase pineapple yield by 463.598, equivalent to 4223.1 kg per ha. On the other hand, inputs of labor and capital investment were negatively correlated with the pineapple yield output. An increase of one labor (one person's work day) is expected to decrease the pineapple yield by 0.33, equivalent to 3.02 kg per ha, perhaps because most farmers do not have enough skills since no training is given, but also to avoid risks due to rainfall/water uncertainty. Similarly, increase in capital value is expected to decrease the yield by 0.0002 (0.00138 kg), meaning that the additional value of capital use does not reflect pineapple output returns in the irrigation systems. An increase of 1 kg of fertilizer is also expected to increase pineapple yield by 2.5, equivalent to 22.78 kg. The increase in yield is probably due to rich nutrient balance applied for the fertilizers input used, because most farmers use a variety of fertilizer. An increase in 1 kg of plant seed is also expected to increase pineapple yield by 0.115, equivalent to 0.104 kg.

Table 4. MPP, VMP, MFC and AE Estimates.

Inputs	MPP	MVP (Rwf)	MFC (Rwf)	AE (MVP/MFC)
InputsInputpl~t	0.011499	2.874884	4400	0.000653383
Inputfert	2.5007357	625.1839	400	−0.01382726
Labor	−0.331854	−82.9635	6000	−0.01382726
Capitalinv	−0.000151	−0.03788	7200	-5.2605×10^{-6}
WateriDistr	463.59867	115,899.7	25,000	4.635986767

In the allocative efficiency (AE) shown in Table 4, three inputs (plant seed, labor and capital investment) are less than 1, indicating that they are over used, while two inputs (fertilizers and water distribution) are greater than 1, indicating that they are less used. The results that are over used confirm that farmers do not optimally allocate resources into the irrigation systems, despite several technical trainings related to irrigation technologies and good agricultural practices directed towards irrigation schemes. Farmers can optimally increase outputs by best combining inputs for nutrient balances and improvement of access to profitable output markets. This can be enhanced through comprehensive farmer field schools in a value chain development framework in the irrigation schemes. Collective farmers have to be trained on business planning and management, and also to participate in project monitoring and evaluation under the new input indicators production factors executed by the authors, which will contribute at-large in the project's sustainability.

4. Discussion

The study shows the results of farmers' production via irrigation resources utilization and efficiency parameters of technical efficiency and allocative efficiency by way of sustainable environmental economics. Two types of data collection methods were used: the first data collection involved cross-sectional design which was engaged to study the individual farmers and group aspects at household level. The second data approach involved the use of longitudinal (panel data design) survey at irrigation group level, "longitudinal/panel data set (repeated observations over the same unit of analysis), which is secondary data set obtained at group level records in each irrigation scheme". The analysis of this study involved two estimation techniques. First, technical efficiency was estimated using the stochastic frontier analysis (SFA) technique using Frontier 4.1. The production function also produced the output elasticities, and the technical inefficiency effects. Second, allocative efficiency of factor inputs were computed based on coefficients generated by OLS estimation of the Cobb-Douglas production function.

The results in Table 2 for this study indicate that the variance parameter gamma is close to one (γ = 0.960589) and significant at 1% level, implying that the inefficiency effects are likely to be significantly high in the analysis of the output (yields) for the sampled farmers in the irrigation system. In other words, 96.1% of the inefficiency is due to technical inefficiency and only 0.4% due to random error. The generalized likelihood ratio test is significant at a 1% level, rejecting the null hypothesis that inefficiency effects are absent and farmers production factors do not affect sustainable environmental economics, or that they have simpler distributions.

5. Conclusions

Coefficients results for the estimated output elasticities for all inputs were as expected, with exception of negative signs for labor and capital investment inputs. The coefficient for labor was negative and significant while capital investment was negative and not statistically significant. The output elasticities with respect to inputs were seed plant (0.0006) and fertilizer (0.0707), which were positive and significant indicating positive a relationship on proportion of seed plant and fertilizer and the output produced, though it was very small. The allocative efficiency shown in Table 4, three inputs (plant seed, labor and capital investment) are less than 1, indicating that they are over used. While two inputs (fertilizers and water distribution) are greater than 1, indicating that they are less used, the results that are over used confirm that farmers do not optimally allocate resources into irrigation systems, despite several technical trainings related to irrigation technologies and good agricultural practices directed towards irrigation schemes. Farmers can optimally increase outputs by best combining inputs for nutrient balances and improving access to profitable output markets. This can be enhanced through comprehensive farmer field schools in a value chain development framework in the irrigation schemes, as a recommendation. The paper also recommend four indicators: economic, which is in terms of productivity as influenced by water resource use; social, in terms of equity in resource allocation; environmental, as related to sustainability which is reflected on the upgrading, maintaining and degradation of the environment; and management, in terms of reliability, adequacy, efficiency and flexibility in water distribution.

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