

Article

An Economic Comparison between Alternative Rice Farming Systems in Tanzania Using a Monte Carlo Simulation Approach

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Abstract: Tanzania is the second-largest producer of rice (*Oryza sativa*) in Eastern, Central, and Southern Africa after Madagascar. Unfortunately, the sector has been performing poorly due to many constraints, including poor agricultural practices and climate variability. In addressing the challenge, the government is making substantial investments to speed the agriculture transformation into a more modernized, commercial, and highly productive and profitable sector. Our objective was to apply a Monte Carlo simulation approach to assess the economic feasibility of alternative rice farming systems operating in Tanzania while considering risk analysis for decision-makers with different risk preferences to make better management decisions. The rice farming systems in this study comprise rice farms using traditional practices and those using some or all of the recommended system of rice intensification (SRI) practices. The overall results show 2% and zero probability of net cash income (NCI) being negative for partial and full SRI adopters, respectively. Meanwhile, farmers using local and improved seeds have 66% and 60% probability of NCI being negative, correspondingly. Rice farms which applied fertilizers in addition to improved seeds have a 21% probability of negative returns. Additionally, net income for rice farms using local seeds was slightly worthwhile when the transaction made during the harvesting period compared to farms applied improved varieties due to a relatively high price for local seeds. These results help to inform policymakers and agencies promoting food security and eradication of poverty on the benefits of encouraging improved rice farming practices in the country. Despite climate variability, in Tanzania, it is still possible for rice farmers to increase food production and income through the application of improved technologies, particularly SRI management practices, which have shown a promising future.

Keywords: rice; management practices; risk; Monte Carlo simulation; stochastic variables; Tanzania

1. Introduction

The population of developing countries is increasing rapidly. Many of these countries rely on rice (*Oryza sativa*) as a staple food, and it is estimated that the demand will increase by up to 70% over the next three decades [1,2]. However, the area of land suitable for agriculture, the length of growing seasons and yield potential for cereals including rice are expected to shrink, particularly along semi-arid margins, affecting food availability and exacerbating malnutrition [3]. It is also estimated that 15–20 Mha of the world's 79 Mha of irrigated rice lowlands, which provide three-quarters of the world's rice supply, will suffer some degree of water scarcity [4]. These concerns can only be countered by applying improved agricultural practices, including rice irrigation schemes and hybrid rice varieties [5]. Other scholars [6–14] have argued that low rice productivity could be addressed through judicious use of agronomic inputs like transplanting young single seedlings with wider spacing, alternating wetting and drying fields, and use of fertilizers.

In Tanzania, rice is the second most important staple food and commercial crop after maize (*Zea mays*) and a significant source of employment, income and food security for farming households [15–17]. Tanzania is the second-largest producer of rice in Eastern, Central, and Southern Africa after Madagascar [18]; about 71% is produced under rain-fed conditions and 29% under irrigation [19]. The demand for rice in Tanzania is projected to triple by 2025. The yield is still relatively low (1.6 t/ha) due to increases in temperature and decreases in annual rainfall [20,21]. Even with the weak performance of the sector inconsistently, Tanzania exports to neighboring countries like Burundi, Kenya, Rwanda, and Uganda. Additionally, rice demand is likely to continue rising due to the COVID-19 pandemic's impact, which may have had a substantial effect on rice production due to the lockdown and movement restriction measures to limit the spread of the virus [22,23]. Additionally, the sector's lower performance is linked to predominantly rain-fed production, the limited adoption and availability of improved cultivars, moderate application of fertilizers, and intensive use of traditional planting techniques with small-sized areas for cultivation [24]. Kahimba et al. [25] argued that if limited agricultural interventions were to be applied, yields of major cereals, including rice, may halve by 2025 because of climate variability.

Due to these challenges, the Tanzanian government has been struggling to take some measures to stimulate the sector, such as the imposition of an import tariff of 75 percent in early 2005 followed by the formulation of policies and programs like the National Rice Development Strategy in 2009, National Agricultural Policy (NAP) in 2013, Agricultural Sector Development Strategy–II (2015/16–2024/16) and Agricultural Sector Development Programme–II (2015/16–2024/25). Among others, these policies emphasize on application of fertilizers, improved seed, development of irrigation infrastructures, and removal of the export ban. Moreover, early in the 2010s, the government, through the Ministry of Agriculture Food Security and Cooperatives (MAFSC), involved training extension staff and farmers in the System of Rice Intensification (SRI) management practices for enhancing rice production in Tanzania. The SRI practices elaborated by Stoop et al. [6], URT [18], Kahimba et al. [25], and Tusekelege et al. [26] are the primary campaign by the MAFSC aiming to increase rice yield per ha and in conjunction with a reduction of hunger and poverty by 2025. Even with readily made policies and programs, there has been a slow improvement of the sector, mainly due to poor adoption of improved farming practices, poor agricultural practices, climate variability and change, poor institutional development, limited human, financial, and physical resources [3,24].

Moreover, the low adoption of improved agricultural practices for farmers is due to many factors, including the risks and uncertainties linked to the process of farm production and unreliable markets. Diagne et al. [27] argued that the adoption of new agricultural technology depends on farmers' knowledge of their existence; that is, farmers adopt a technology if they have a complete understanding of modern technology. From economic perspectives, farmers decide to choose a new technology based on the benefits of technology [28]. Although rice farming systems' agronomic benefits may be easy to recognize, the economic benefits are not. The unrealized potential of new farming technologies may offset the adoption rate of the respective technologies, especially when the farmer has limited full information about the technology and its potential.

In this study, we compare the economics of traditional and improved rice farming management practices by considering the risk associated with price, yields, and production costs that affect the net returns of the practices under study. The analysis helps determine the farming system with the highest distribution of profits under different price seasons, such as during harvesting and low supply, when the price is relatively high. We considered price volatility because rice is one of the cash crops to most smallholder farmers in Tanzania. The study also considered that since rice is an essential crop, farmers may sell their produce during harvesting or later when the price is higher. This study employs a Monte Carlo simulation model, which was also applied by Ribera et al., Richardson et al., Rezende and Richardson, and Mwinuka et al., [29–32,33] to evaluate the economic performance of each alternative rice farming system. The contribution of the present study to the body of knowledge in Tanzania is the application of a Monte Carlo simulation approach, which incorporates stochastic/random variables like prices and yields that farmers cannot control with certainty. Data from household surveys, focus group discussions, and secondary sources were used to quantify and parameterize the model. This study informs the rice farming communities and policies that focus on food security and poverty eradication and the suitable agronomic techniques for sustainable agriculture.

2. Materials and Methods

2.1. Location of the Study Area

The study was conducted in six villages of the Morogoro region, Tanzania (Figure 1) which is in the mid-eastern part of the Tanzania mainland and lies between latitude 7°53'34.80" South and longitude 36°54'21.60" East. The region is the largest rice producer in the country, producing between 300,000 to 350,000 tons per year. Rice is the second most dominant crop in the region after maize and is grown on approximately 180,000–250,000 hectares annually. The more substantial part of the study area receives average annual rainfall between 800 and 1100 mm; higher rainfall between 1200–1300 mm is collected around the Nguru mountains. The top of the Nguru mountains receives >1300 mm. The mean annual temperature in the study area ranges between 16 °C and 25 °C [34,35]. The rainfall is bimodal, falling between October and December and March and May [36,37]. The study sites/farms are surrounded by rivers with flowing water throughout the year, making irrigation easier.

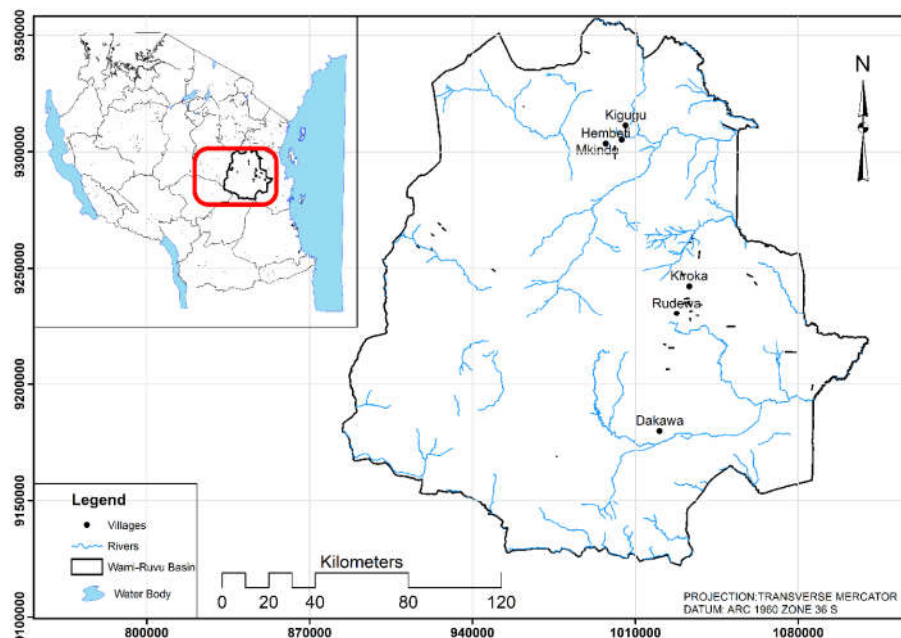


Figure 1. Study sites.

2.2. Data Type and Characteristics

The villages for this study were purposefully selected based on the presence of either traditional or improved rice farming practices. Data were collected using a snowball sampling strategy described in detail by Atkinson and Flint [38], Browne [39], Sedgwick [40], Naderifar et al. [41]. A total of six villages: three from Mvomero district (Kigugu, Hembeti, and Mkindo) and three from Kilosa district (Dakawa, Rudewa, and Kiroka) were included in the analysis. Although rivers surround the rice farms in the study area, most of the farmers depend on rain-fed farming systems. The data represent farms under different management practices, some of which are better adapted to climate variability, and some grow their rice in both rainy and dry seasons. Rice production in the selected villages is a crucial economic activity generating income and the primary food source. Although there were varying levels of productivity, the households used in the study claimed to be dependent on rice farming for over 80% of their livelihoods. The differences were linked to the different use of rice-farming technologies, including the application of inorganic fertilizers, the predominant use of local seed varieties, the emerging demand for improved varieties, mainly SARO 5 or TXD 306; and adoption of the System of Rice Intensification (SRI) practices. The SRI is considered a water-saving technology, which has led to a notable increase in crop productivity [2,19,25]. The technology is not only found to be the best farming approach for sustainable agriculture but also used as a coping strategy for climate change and variability, and it has been proved to save up to 50% of water [27]. The SRI is a package of practices developed to improve the productivity of rice farming with less water. The technology was introduced in Tanzania in the 2010s and has started to spread throughout the country. In Tanzania, the SRI practice has proved yield levels range from 7.0 to 11.0 tons per ha [2,26,27]. Some of the SRI practices include the use of young seedlings of 8–12 days old, wider spacing, transplanting of single seedling, fertilizer alternative wetting and drying, and weed management [19]. The SRI does not require more water than the traditional farming systems [26].

Since the study included non-homogeneous rice farmers, the snowball technique was convenience sampling to obtain households with similar characteristics. Five alternative rice farming systems were identified and used to stratify the sampling design within the study area. The five farming systems based on management practices are described as follows:

1. **Baseline**—farms using traditional methods comprising application of saved local seed varieties (*supa shinyanga, mbawa mbili, supa pamba, Kabangala, tule na bwana; kisegeese; mwarabu, rangi mbili; ngome, zambia*), no fertilizer and higher seed rate between 75–100 kg/ha is used as farmers prefer broadcast planting method. Weeding is done manually and typically done twice before harvest, and no specific spacing is applied. Continuous flooding is dominant with neither irrigation nor water control.
2. **Alt.1**—applying the traditional practices (**Baseline**), but farmers use improved varieties (mainly SARO5 and IR64) instead of local varieties. Farmers in this group prefer transplanting of seedlings instead of broadcasting, which is done between 21–35 days with limited fertilizer application, and no specific spacing is applied.
3. **Alt.2**—farms supplemented with improved varieties, transplanting of seedlings (no specific spacing is applied), and application of fertilizer at the rate of 50 kg bags per ha. The main types of fertilizers used are Urea and NPK, and occasionally, farmers use organic fertilizers.
4. **Alt.3 and Alt.4**—this dedicated group of farmers apply some but not all the SRI practices, i.e., SRI partial adopters (**Alt.3**) and those claiming to use all the specified SRI practices (**Alt.4**). The specific practices under SRI in Tanzania involve (1) stepwise selection and preparation of quality viable seeds; (2) nursery plot development and careful management; (3) land/field leveling for easy infield water management; (4) transplanting one young seedling (at two leaves) per hill while using 25 cm × 25 cm or 25 cm × 30 cm spacing; (5) quickly transplanting within 30 min of gently removing seedlings from their nursery and not inverting the seedlings; (6) wetting and drying of the field (water control) to improve soil aeration and promote root elongation; (7) timely weeding done every 10–12 days after transplanting and repeated in the same interval until harvest; and (8) intensive application of fertilizer, especially one which is rich in nitrogen

and phosphorus. A pictorial demonstration of some necessary steps involved in SRI practices in Tanzania is shown in Appendix A. Also, it should be noted that rice production under SRI is done twice a year. Therefore, yield under SRI scenarios included harvests for both rain and dry seasons as the farmers under SRI have gone a step further to use the water from rivers for irrigation during the dry season.

2.3. Yield Data

Yields for three seasons starting from 2015/16, 2016/17, and 2017/18 for each scenario were used for this analysis collected. Each scenario has a total of 45 rice farms per season. The yield data for each scenario, therefore, makes a total of 135 observations ($45 \times 3 = 135$). The main reason for using three seasons' data is to capture the stochastic nature of yield (y), which is a random variable. Yield is a vital variable in this analysis. Table 1 displays the distribution of yield (t/ha) for different rice farming systems under study.

Table 1. Yield distribution (t/ha/year) under different farming systems.

| | 2015/16 | | | 2016/17 | | | 2017/18 | | |
|----------|---------|------|-------|---------|------|-------|---------|------|-------|
| | Mean | Min | Max | Mean | Min | Max | Mean | Min | Max |
| Baseline | 1.66 | 0.71 | 3.42 | 1.52 | 0.55 | 4.05 | 1.64 | 0.60 | 3.77 |
| Alt.1 | 2.32 | 0.78 | 3.81 | 2.11 | 0.7 | 3.8 | 1.99 | 0.47 | 3.07 |
| Alt.2 | 4.34 | 2.15 | 5.42 | 3.98 | 1.83 | 3.67 | 3.03 | 2.31 | 5.00 |
| Alt.3 * | 6.58 | 5.22 | 8.34 | 5.78 | 5.26 | 7.5 | 6.72 | 4.00 | 8.43 |
| Alt.4 * | 13.47 | 6.78 | 19.86 | 13.34 | 5.92 | 20.04 | 13.47 | 6.1 | 19.10 |

Source: field survey, * scenario 3 and 4 included harvests for both rainy and dry seasons.

2.4. Price Data

The price for rice is also a random variable as it fluctuates with time for each variety (local or improved). For example, during data collection, it was argued by farmers and key informants that the price for local varieties under *Baseline* is, to some extent, higher than the price for improved varieties (under Alt.1 to Alt.4). During the harvesting season (April–September), the price for rice is low. However, the price rises when the supply is low, particularly during October through March for all the scenarios presented in Table 2. The table shows the summary statistics in terms of average, minimum, and maximum price per season per variety. For each variety, we collected a total sample of 45 price data. Rice prices for local varieties during low supply (non-harvesting) and high supply (harvesting) seasons are denoted by Local_P1 and Local_P2, respectively. Meanwhile, rice prices for improved varieties are indicated by Improved_P1 and Improved_P2 for low and high supply seasons, correspondingly.

Table 2. Summary statistics of rice prices (in US\$/ton) in the study area for the year 2018.

| Statistics | Low Supply | | High Supply | |
|---------------------|------------|-------------|-------------|-------------|
| | Local_P1 | Improved_P1 | Local_P2 | Improved_P2 |
| Average (US\$/t) | 339.3 | 531.4 | 232.0 | 448.9 |
| Minimum (US\$/t) | 311.1 | 488.9 | 217.8 | 400.0 |
| Maximum (US\$/t) | 400.0 | 577.8 | 244.4 | 511.1 |
| No. of observations | 45 | 45 | 45 | 45 |

Source: field survey.

2.5. Cost of Production Per Scenario

Data on production cost and input prices for each scenario were also corrected. These costs include seed, nursery preparation (for SRI farms), land preparation, transplanting/seedling, weeding, post-emergence pesticides, bird scaring, wetting and drying, fertilizers, harvesting/cutting/threshing,

postharvest handling, and storage costs (Appendix B). *Alt.1* to *Alt.3* use transplanting means of planting; hence it needs 20 to 50 kg/ha of seeds costing between US\$8.9 to 17.8. *Baseline* usually applies traditional (broadcasting) planting and needs 50 to 70 kg/ha of seeds, which cost between US\$13.3 to US\$21.3 thousand. Of all the farming systems, *Alt.4* needs between 7 and 10 kg/ha of seeds. The seeds are obtained through careful seed selection to get pure and quality seeds for high germination probability. The process costs between US\$17.8 to US\$35.6, as more than 70 kg is needed to obtain the quality seeds.

Land preparation involves plowing and harrowing for *Baseline* to *Alt.2*, but *Alt.3* and *Alt.4* go beyond to leveling, puddling, and marking transplanting grids. *Baseline* and *Alt.1* did not use fertilizers, but *Alt.4* used more fertilizers, causing the highest cost of all scenarios. *Alt.4* also involved wetting and drying of the field to improve soil aeration and promote roots elongation that claimed to allow plant root growth and subsequent plant vigor and health. The minimum and maximum cost for all scenarios were US\$235.6–416.9, US\$262.2–473.3, US\$417.8–717.8, US\$564.4–962.2, and US\$817.8–1213.3 for all scenarios, correspondingly.

2.6. Monte Carlo Simulation for Economic Comparison between Rice Farming Systems

The Monte Carlo simulation procedures outlined by Richardson et al. [30,42] were used to evaluate the net cash income (NCI) distributions for each scenario. Since we have a total of 135 production data per scenario, the *first step* was defining, parameterizing, simulating, and validating the stochastic variables. Yields and prices are the key variables in calculating stochastic production and receipts. Typically, yields and prices are correlated with each other. Therefore, a multivariate empirical (MVE) distribution described by Richardson et al. [43] was estimated and employed to simulate the two variables using the observed values. The residuals (deviations from the observed mean) from surveyed yield and price for each scenario were used to estimate the parameters for the MVE yield and price distribution. An MVE distribution is an appropriate tool to account for many variables at once and can eliminate the possibility of values exceeding reasonable values like negatives in surveyed data [29].

An MVE yield and price distribution are presented in Equation (1) and Equation (2), respectively, and are defined by the fractional deviations from mean and cumulative probabilities. It also accounts for the correlated uniform standard deviates ($CUSD_{yp}$) with yp representing the row of the correlation matrix of price and yield. The MVE distribution is simulated in Simetar, an acronym for Simulation and Econometrics To Analyze Risk (or Simulation for Excel to Analyze Risk in an Excel add-in and is available at www.simetar.com). In other words, Simetar is a simulation language written for risk analyses that provides a transparent method for simulating the effects of risk and presents the results as probability distributions [42,43].

The *second step* was to simulate the MVE distribution in Equations (1) and (2) for at least 500 iterations using the Latin Hypercube (LHC) sampling procedures defined by Richardson et al. [42]. The LHC procedure ensures that a sample of only 500 iterations is necessary to reproduce the parent distributions. A simulation of 500 iterations was needed to have an adequate sample to capture the inherent risk in the yield and price datasets. The *third step* was to validate the simulated distribution to ensure that the random variables were simulated correctly and demonstrate the appropriate properties of the parent distributions. The probability distribution functions (PDFs) of observed and simulated yields and prices were drawn for comparison; as shown in Appendix C, the PDFs for LHC 500 simulated values and the observed yields and prices have similar shapes confirming that the LHC simulated the observed distribution accurately.

The *fourth step* involved simulating the stochastic production (Equation (3)) and receipts (Equation (4)) for each scenario. Therefore, the stochastic production and revenue were combined with the stochastic cost of production to simulate the probability distribution for net income, our targeted key output variable (KOV) for this study. Likewise, production costs were made stochastic using the GRKS probability distribution as the costs differ from one farmer to another for each scenario analyzed. Gray, Richardson, Klose, and Schumann developed GRKS probability distribution

to simulate subjective probability distributions based on minimum, average/model, and maximum values [42]. The GRKS in this study was used to include all the cost options used by smallholder farmers who are either pessimistic, average, or optimistic. The GRKS is simulated in Simetar using the command =GRKS (min, midpoint, max) and generates random costs. Equation (5) was therefore used to simulate the stochastic production cost for each rice farming scenario. Appendix D shows the probability distribution functions (PDFs) and the cumulative distribution functions (CDFs) for each scenario with *Alt.4* presenting the highest production cost of all scenarios followed by *Alt.3* and *Alt.2*. Table 3 defines the symbols used in the equations.

$$\tilde{y}_i = \bar{y}_i * (1 + EMP(S_y, P(S_y), CUSD_{yp})) \quad (1)$$

$$\tilde{p}_\omega = \bar{p}_\omega * (1 + EMP(S_p, P(S_p), CUSD_{yp})) \quad (2)$$

$$\tilde{\mu}_i = \tilde{y}_i * a_i \quad (3)$$

$$\tilde{R}_i = \tilde{p}_\omega * \tilde{\mu}_i \quad (4)$$

$$\tilde{C}_i = \sum(GRKS(Min_{Vi}, Average_{vi}, Max_{Vi})) \quad (5)$$

$$N\tilde{C}I_i = \tilde{R}_i - \tilde{C}_i \quad (6)$$

Table 3. Definition of symbols used in the model.

| Symbols | Definitions |
|----------------------|---|
| ~ | A tilde represents the stochastic variable |
| <i>i</i> | Rice farming alternatives (<i>Baseline, Alt.1, Alt.2, Alt.3, Alt.4</i>) |
| <i>a_i</i> | Hectares (ha) allocated for each alternative <i>i</i> |
| \tilde{y}_i | Stochastic rice yield per ha for alternative <i>i</i> |
| $N\tilde{C}I_i$ | Stochastic production for alternative <i>i</i> which is the product of hectares and yield [$\tilde{y}_i * a_i$] |
| ω | Rice variety (local and improved) |
| \tilde{p}_ω | Stochastic rice price influenced by seasonal volatility for variety ω (<i>Local_P1, Local_P2, Improved_P1, Improved_P2</i>) |
| \tilde{R}_i | Stochastic receipt/revenue which is a product of stochastic production and price [$\tilde{p}_\omega * \tilde{\mu}_i$] |
| V_i | Variable cost (US\$/ha) given by the summation of all costs included in rice production per each scenario in a range of Min and Max [including seed, plow, harrow, planting, weeding, bird scaring, fertilizer, post-emergence herbicides, harvesting/threshing, postharvest handling, and storage] |
| F_i | The fixed cost equated to zero for this analysis [F = 0] |
| \tilde{C}_i | Stochastic Total production cost for each rice farming system computed as [$a * (\tilde{v}_i + F_i)$] |
| $\tilde{\pi}_i$ | Net income which is calculated as the receipt minus total cost [$\tilde{R}_i - \tilde{C}_i$] |
| S_y | Fraction deviations from a mean or sorted array of random yields for scenario <i>i</i> |
| S_p | Fraction deviations from a mean or sorted array of the random price for variety ω |
| $P(S_y)$ | Cumulative probability function for the S_y values |
| $P(S_p)$ | Cumulative probability function for the S_p values |
| $CUSD_{yp}$ | Simetar function to simulate correlated uniform standard deviates of random variables. |
| $EMP()$ | Simetar function used to simulate an MVE distribution. |

The *final step* was to simulate the probability distributions of net income for each rice farming system in Equation 6 for over 500 iterations using LHC simulation criteria expressed in the *second step* above. The results of the 500 simulated samples were used to estimate the empirical probability distributions of success (NCI) for each scenario and to compare the scenario with the best distribution per hectare. A comparison of the scenarios is well-elaborated in Section 2.7.

2.7. Scenario Ranking

In ranking the scenarios, we used two ranking approaches—the Stoplight function and the stochastic efficiency with respect to a function (SERF). The Stoplight function is a Simetar function that produces charts to summarize the probability that the scenarios will be less than the specified lower target or that the scenarios will exceed the targeted maximum value. It also provides the likelihood of each scenario falling between specified targets [42]. The probability of falling below the minimum target (possibility of unfavorable) is presented in red color, the probability of exceeding the maximum target (probability of favorable) is shown in green, and the probability of falling between the two targets (probability of cautionary) is colored amber. However, through a participatory discussion with rice farmers, the minimum and maximum targets were set at \$500 and \$1000 to reflect the historical annual rice net returns per ha.

SERF uses certainty equivalents (CEs) and a range of absolute risk aversion coefficients (ARACs) to rank many risky alternatives simultaneously. Each option can be compared and ranked at each ARAC [42,44,45]. SERF's advantage over the conventional stochastic dominance analysis with respect to a function (SDFR) is that SERF involves comparing each alternative with all the other options simultaneously, not pairwise. On the other hand, the SERF approach compares the CE of all risky alternative scenarios for all risk ARACs over the range and chooses the scenario with the highest CE at each ARAC value, hence assisting decision-makers with different risk attitudes. The ARCs range from zero (risk-neutral), normal, moderate, and extremely risk-averse person. Following the formula proposed by Hardaker et al. [44], the extreme or upper ARAC value for this study was calculated using Equation 7 as follows:

$$ARAC_U = \frac{r_U(w)}{w} \quad (7)$$

where $r_U(w)$ is the risk aversion coefficient with respect to wealth (w) and was proposed by Anderson and Dillon [46] to be set equal to 4 (very risk-averse). Hardaker et al. [44] suggested that the average wealth for alternatives can be used to calculate the upper ARAC in Equation 7. In our study, we analyzed the scenarios based on price seasonality (April–September and October–March). On a yearly basis, the average wealth for each case was used to compute the upper ARAC.

3. Results

Simulation results on economic viability for each scenario are presented seasonally (low or high supply) and on an annual basis. Table 4 presents the summary statistics for and the probability of generating negative NCI for each scenario. All the five scenarios show positive mean values of NCI for both low and high supply seasons. However, during the low supply, the average NCI is high. The high supply season shows negative minimum values of NCI for the first three scenarios congruently (US\$-140.9, US\$-289.4, and US\$-203.1). In comparison, the low supply season shows negative minimum values for the first two scenarios (US\$-14.9 and US\$-77.3). Consequently, the first three scenarios for the aggregated/annual price also show negative minimum values of NCI for the first three scenarios (US\$-126.2, US\$-213.9, and US\$-75.3).

Generally, the low supply season has the highest NCI distribution for all scenarios compared to the counterpart with *Alt.4* dominating in terms of average, minimum, and maximum values, followed by *Alt.3* and *Alt.2* (Table 4). The high NCI for scenarios 4 and 3 is not only influenced by the highest price offered during low supply but also due to high yield per unit area. On the other hand,

during the harvesting season, the results show that *Baseline*, *Alt.1*, and *Alt.2* have 17.9%, 21.6%, and 6.9% likelihood of negative NCI, respectively. *Alt.3* and *Alt.4* have zero probability of negative returns. Meanwhile, the non-harvesting season has 0.43% and 1.14% chances of negative NCI for *Baseline* and *Alt.1* with a zero chance for the last three. For the aggregated/annual results, the table shows 3.59%, 9.62%, and a 0.57% likelihood of negative NCI values for *Baseline*, *Alt.1*, and *Alt.2*, respectively, with *Alt.3* and *Alt.4* both having a zero probability.

Likewise, the Stoplight charts in Figures 2–4 show the probability of NCI to be less than the lower target of US\$500, the likelihood of exceeding the upper target of US\$1000, and the probability of falling between the two targets. In Figure 2, when farmers decide to sell their rice during harvesting season, the probability of NCI being less than the minimum target is 83%, 96%, 46%, 16%, and 3% for *Baseline*, *Alt.1*, *Alt.2*, *Alt.3*, and *Alt.4*, respectively. The probability of exceeding the maximum target is higher for *Alt.4* (71%), followed by *Alt.3* (19%), and 1% for *Baseline*. Meanwhile, *Alt.1* and *Alt.2* have a zero probability. The probability of falling between two targets is lower for *Alt.1* and *Baseline* and higher for the rest of the scenarios.

When farmers sell their rice during low supply season, the results show that the probability of NCI being less than the minimum target decreased to 54%, 34%, and 3% for *Baseline*, *Alt.1*, and *Alt.2*, correspondingly, with a zero probability for the last two scenarios. In the meantime, *Alt.3* and *Alt.4* have a 100% probability of exceeding the maximum threshold, followed by *Alt.2* (68%), *Alt.1* (18%), and a 13% probability for *Baseline*. The possibility of falling between the two targets was 32%, 45%, and 29% for *Baseline*, *Alt.1*, and *Alt.2*, respectively.

Table 4. Summary statistics and the probability of negative annual net income from the stochastic simulation for control and alternative scenarios (US\$ ha⁻¹).

| Scenarios | Mean | SD | CV | Min | Max | Probability (NCI < 0) |
|--|--------|--------|-------|--------|--------|-----------------------|
| <i>Income during harvesting season (April–September)</i> | | | | | | |
| Baseline | 240.2 | 259.8 | 108.1 | −140.9 | 1073.7 | 17.9 |
| Alt.1 | 168.6 | 188.1 | 111.6 | −289.4 | 645.0 | 21.6 |
| Alt.2 | 432.8 | 266.4 | 61.5 | −203.1 | 904.6 | 6.9 |
| Alt.3 | 765.9 | 245.3 | 32.0 | 227.8 | 1401.0 | 0.0 |
| Alt.4 | 2094.5 | 1166.3 | 55.7 | 283.4 | 4016.3 | 0.0 |
| <i>Income during low supply season (October–March)</i> | | | | | | |
| Baseline | 558.0 | 386.8 | 69.3 | −14.9 | 1705.4 | 0.43 |
| Alt.1 | 677.8 | 376.3 | 55.5 | −77.3 | 1600.4 | 1.41 |
| Alt.2 | 1370.2 | 513.6 | 37.5 | 221.8 | 2274.3 | 0.00 |
| Alt.3 | 2197.2 | 463.9 | 21.1 | 1178.1 | 3496.1 | 0.00 |
| Alt.4 | 4979.7 | 2199.7 | 44.2 | 1665.6 | 8851.5 | 0.00 |
| <i>Annual net income</i> | | | | | | |
| Baseline | 399.2 | 338.4 | 84.8 | −126.2 | 1516.6 | 3.59 |
| Alt.1 | 424.9 | 318.5 | 75.0 | −213.9 | 1348.6 | 9.62 |
| Alt.2 | 899.7 | 470.0 | 52.2 | −75.3 | 2227.9 | 0.57 |
| Alt.3 | 1485.7 | 545.2 | 36.7 | 308.6 | 3147.2 | 0.00 |
| Alt.4 | 3537.2 | 1885.9 | 53.3 | 527.7 | 8312.9 | 0.00 |

Notes: SD = standard deviation, CV = coefficient of variation, NCI = net cash income.

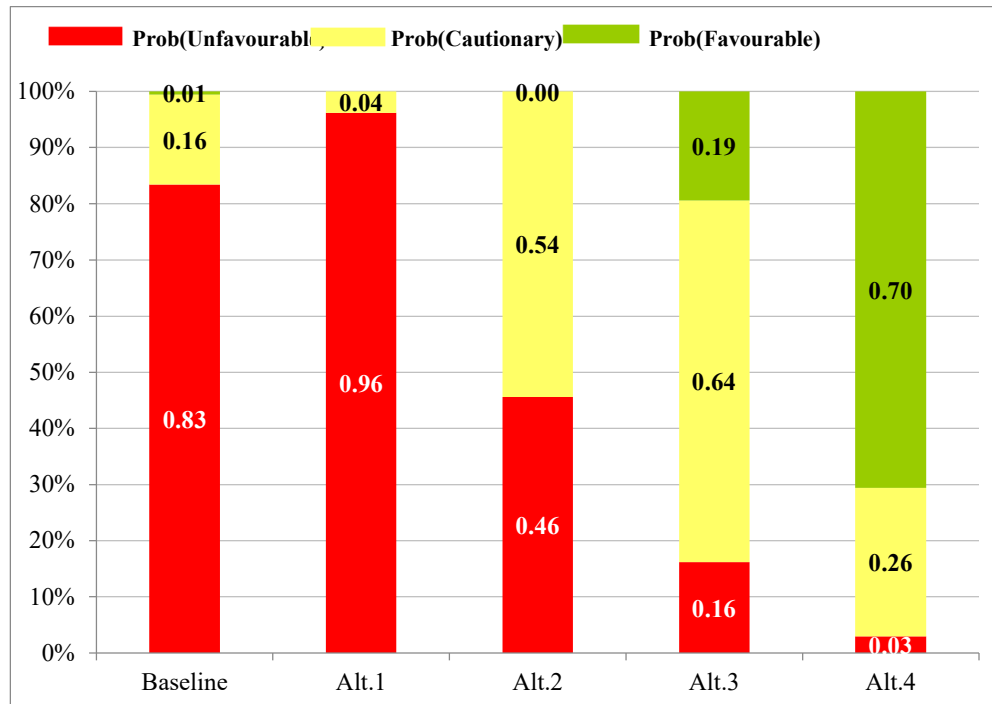


Figure 2. Stoplight chart for probabilities of NCI being less than US\$500 and greater than US\$1000 for alternative rice farming systems when transactions are made between April–September.

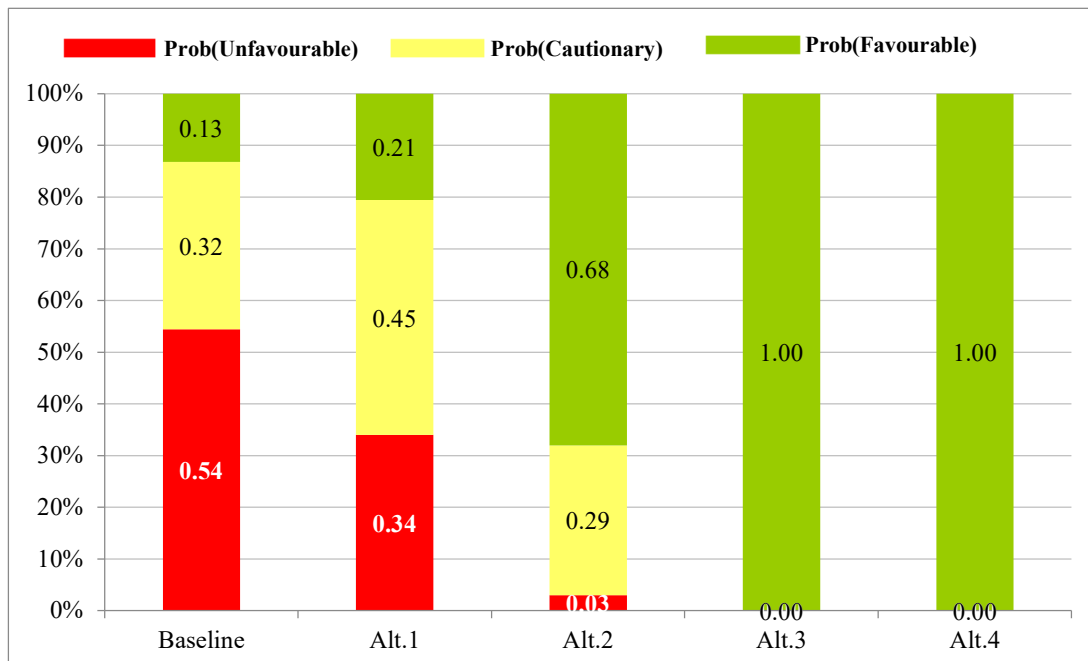


Figure 3. Stoplight chart for probabilities of NCI being less than US\$500 and greater than US\$1000 for alternative rice farming systems when transactions are made between October–March.

Figure 4 was developed to show the distribution of NCI of all scenarios annually. The results show that the first four scenarios have a 66%, 60%, 21%, and 2% probability that annual NCI will be less than \$500, respectively, with *Alt.4* having a zero probability. The probability of exceeding the

maximum target is higher for *Alt.4* (94%), followed by *Alt.3* (80%), and *Alt.2* (41%), while the first two have less than 10% probability of being above the maximum target. It is worth mentioning that the higher NCI for *Alt.4*, *Alt.3*, and *Alt.2* are associated with increased production due to either applying SRI technologies, improved seeds, or fertilizers.

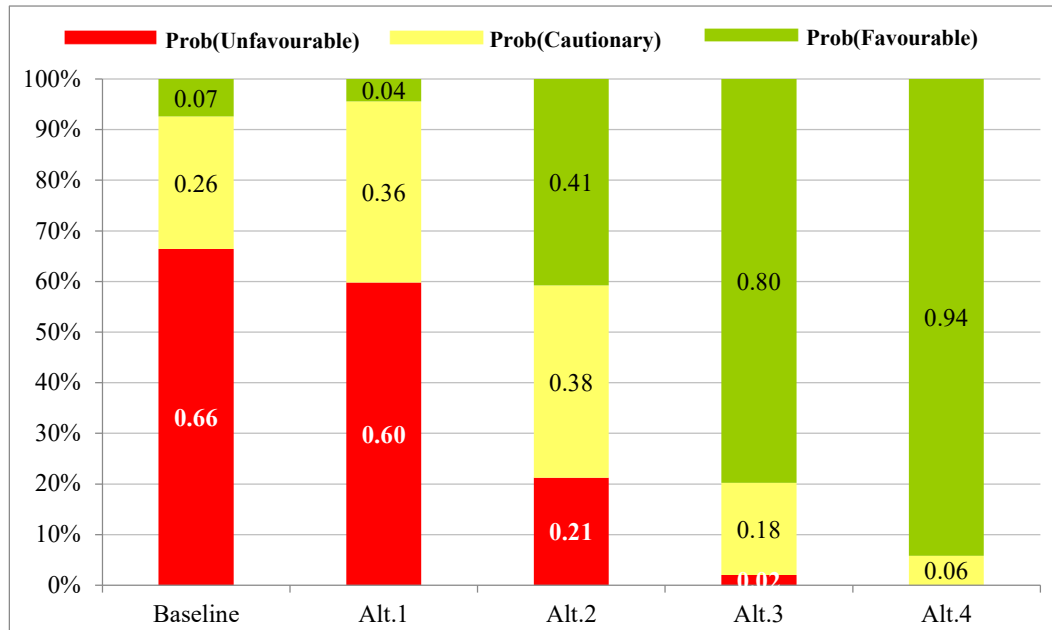


Figure 4. Stoplight chart for probabilities of annual NCI being less than US\$500 and greater than US\$1000 for alternative rice farming systems.

The scenarios were also ranked using a stochastic efficiency with respect to a function (SERF) where the scenarios are ranked based on the decision-maker utility for income and risk. Figure 5; Figure 6 present the results for low and high supply seasons, respectively. Regardless of the time of the transaction, *Alt.4* provides the most top certainty equivalents for all realistic risk aversion coefficients, followed by *Alt.3* and *Alt.2*. This indicates that *Alt.4* is highly preferred by all classes (risk-neutral to risk-averse) of decision-makers over all other scenarios analyzed, followed by *Alt.3* and *Alt.2*. The certainty equivalents (CEs) for *Alt.4* were the highest, followed by *Alt.3* and *Alt.2*. In the meantime, *Alt.1* has the lowest CEs at all levels of ARAC values when the transaction is to be made between April and September (Figure 5). In contrast, when the purchase is to be done between October and March, the CEs for *Alt.1* are slightly higher than for *Baseline* due to the relatively high production for *Alt.1* (Figure 6).

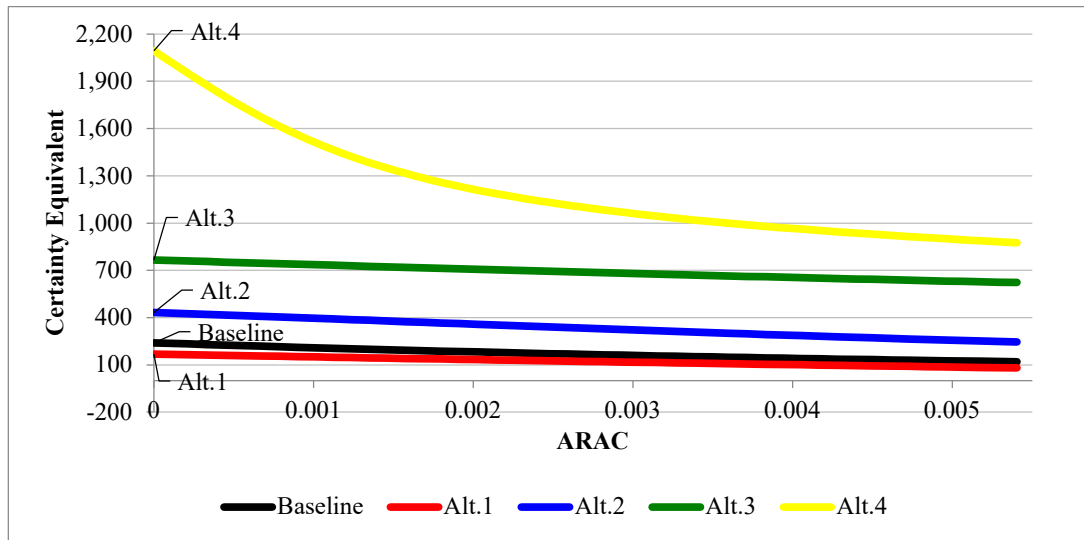


Figure 5. Stochastic efficiency with respect to a function (SERF) under a negative exponential utility function of NCI when the transaction is made between April–September.

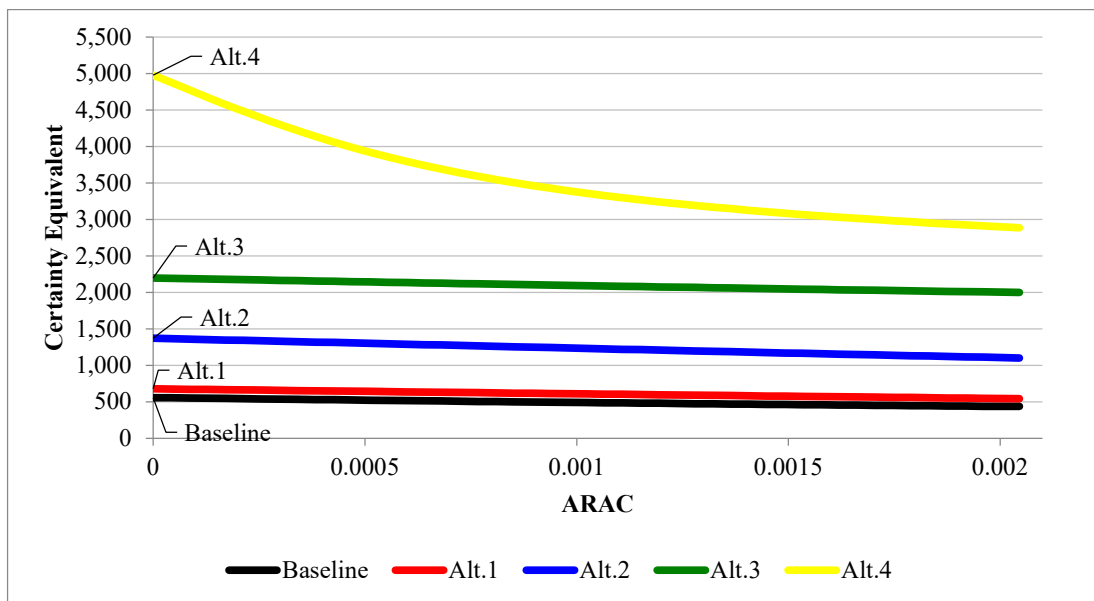


Figure 6. SERF under a negative exponential utility function of NCI when the transaction is made between October–March.

Figure 7 represents the SERF of annual NCI for all scenarios. Likewise, *Alt.4* shows the highest certainty equivalents, followed by *Alt.3* and *Alt.2* correspondingly. This implies that all risk-neutral and risk-averse decision-makers consistently prefer the three scenarios over all other scenarios. The CEs for *Alt.1* are, to some extent, higher than for *Baseline* at all values of ARAC. The differences indicate that all classes of decision-makers prefer less the latter (neutral and risk-averse decision-makers) because the equivalent certainty line for *Alt.1* is above the certainty equivalent for *Baseline* for ARAC levels of 0 to 0.0030.

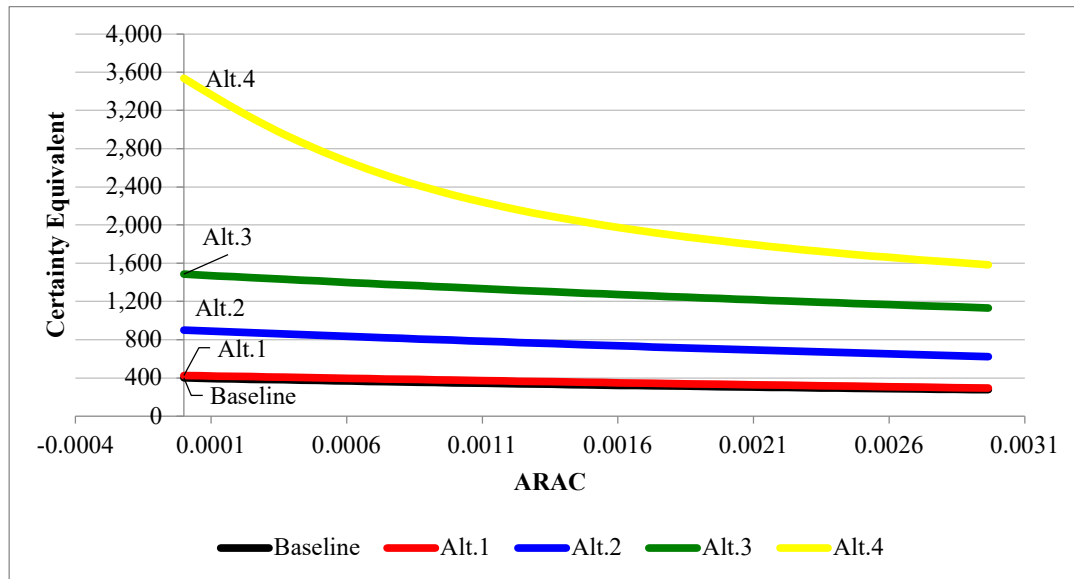


Figure 7. SERF under a negative exponential utility function of annual NCI.

4. Discussion

By considering the annual net income distribution, rice farms under *Alt.4* (SRI adopters) had the highest income distribution regardless of seasonal variability in price followed by *Alt.3* (partially SRI adopters) and it was relatively low for the non-SRI adopter. The high variation in income depends upon the degree of adoption of the technology [10]. The income gap between the traditional and improved practices, especially SRI adopters and non-adopters, was consistent with case studies in Asia, Latin America, and Africa [10]. For example, in the Philippines, Llanto et al. [47] and Cruz et al. [48] assessed the impact of SRI practices under the Australian RiceCheck program. The two studies reported that farmers who adopted at least three key SRI practices earned gross profit margins nearly twice as large compared to farmers under the traditional system. Similar observations were also reported in Sri Lanka [49]. In Viet Nam, the same assessment was conducted and revealed that farmers who adopted some of the SRI technologies have seen their income increase between 11% to 40% [50]. In China, farmers who took the improved farm management practices enjoyed an increase in net income by 48% [51].

In India, a study to assess the impact of integrated crop management on rice farms' profitability was conducted and found a massive increase in net income. The study reported a more than threefold profit increase (from US\$105/ha to US\$369/ha) to farmers who adopted improved management practices like early transplanting, one seedling per hill, square transplanting; early and frequent mechanical weeding; and intermittent irrigation [51–53]. Although the studies did not report on the economic contribution in Indonesia and Cambodia, the improved rice practices recorded an increase of between 10–50% and 50–100% on yield/ha to farmers who adopted the program [51,54,55]. The positive impact of improved rice production practices was also reported in Brazil, Venezuela, Costa Rica, and Nicaragua [10]. In sub-Saharan Africa, eastern Africa, in particular, studies conducted by Tusekelege et al. [26] and Bell [17] show that rice farms under SRI practices yielded ≥ 5.5 tons/ha, but the studies did not elaborate on the economic viability of the technologies.

Our results show that rice farms using all the recommended SRI practices generated the highest net cash income, followed by rice farms which partially implemented the principles. Farms under SRI practices have 80% and 94% probabilities of NCI being greater than US\$1000 for partial and full adopters. The chances of negative net revenue were low even when transactions were to be made during high supply. The high yield per unit area resulted from the application of a tailor-made improved technology package. The next-best performing scenario was the farms supplemented with both improved seeds (SARO 5) and fertilizers. The scenario utilizing traditional farming system

technologies was the least preferred of the five scenarios analyzed. Those using a combination of conventional practices plus improved seed were the second least preferred. For all scenarios, especially under SRI practices (partially or fully), farmers earn reasonable profits if they store their produce until the peak price season. Although local varieties gained higher prices than the improved varieties, SRI users (partially or fully) were economically better off than their counterparts due to higher yields. Women play a significant role in SRI practices as they were observed to be the most critical participants in training and supply of labor. In addition, some of the women are now shifting from traditional methods to applying the new farming system. A successful story in Appendix E by Mwanaidi H. Hamza was observed in Mkindo village. Mwanaidi received the SRI training in 2011, and she started using the technology with great success, which led her to be the focal person in all issues related to SRI in the country.

Many rice producers (mainly smallholder farmers) in Tanzania continue to use traditional management practices, which has led to the sector's continuous low performance [18,24,56,57]. The results of this study provide useful information to compare the risks and benefits of producing under traditional management practices and the benefits of producing under improved alternative management practices so that farmers would be able to make better management decisions. These results suggest that even if the rice farmers in Morogoro do not adapt to SRI practices, the technology would still be the preferred technology for risk-neutral and risk-averse decision-makers.

The policy brief on the impact of COVID-19 on food security and nutrition highlighted that food systems need to be transformed to work better with nature and climate. It emphasizes that the food systems should be more efficient, sustainable, and resilient, requiring careful management of land, soil, and water [23]. The SRI has the features described under the policy brief that the transformed food system should provide a return on investment. It should also be resilient to climate change achieved through water and energy-saving irrigation, conservation agriculture, controlled environment farming, and gender mainstreaming [56]. Women have often been found to adopt SRI technology in Tanzania with high success (Appendix E). Since the SRI technology is one of the Tanzanian climate change coping strategies [18,56], there is a need for the government and other stakeholders to create a conducive environment for the technology to be implemented in different potential areas in the country.

5. Conclusions

The purpose of this paper was to compare rice farming systems' economic viability under alternative management practices in the Morogoro region, Tanzania, using a Monte Carlo simulation model. We categorized our sample into five alternative scenarios: (1) farms using traditional management practices; (2) farms using improved seed varieties; (3) farms using improved varieties plus fertilizers; (4) farms applying some of the SRI practices; and (5) farms using all the recommended SRI practices. A Monte Carlo simulation model was developed based on stochastic variables, including yields, prices, input, and labor costs, to estimate distributions of economic returns for alternative strategies for better management decisions. A complete Monte Carlo simulation model was used to simulate the net cash revenue per season and per year. Thus, a Monte Carlo simulation model was considered in this paper to incorporate risk faced by farmers by incorporating probability factors for random variables that farmers cannot control with certainty. The simulation results of the model for all the alternative management practices were presented in charts and probabilities to provide a wide distribution of the key output variables.

The findings of this study have vital policy implications for Tanzania's government as it aims to end hunger and reduce poverty by 50% in 2025 through doubling agricultural production. Considering that rice is one of the crops targeted to drive Tanzania out of hunger and poverty, the results of this study suggest the benefits of investing in improved rice farming technologies, particularly SRI principles. The application of SRI practices has demonstrated the potential to increase rice yields and income of farmers. Given the availability of potential areas (including rivers and nine basins) for rice production in Tanzania, they can be utilized to produce more rice in the country.

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Conflicts of Interest: The authors declare that they have no conflict of interests in relation to this paper.

Appendix A. Important Steps in SRI Farming System



Figure A1. Appendix 1: selection and preparation of quality viable seeds (by egg and salt solution); 2: sprouted seed for sowing in the nursery; 3: nursery plots; 4: land/farm preparation for easy water management; 5: marking 25cm x 25 cm transplanting grids in the field; 6: a two-leaf seedling appropriate for transplanting; 7: seedling transplanting and 8: fertilizer application. Source: Modified from the Tanzania SRI Training Manual for Extension Staff and Farmers (URT, 2015).

Appendix B

Table A1. Estimated costs of production (US\$/ha) per hectare for rice under different farming systems in Tanzania.

| Variable cost | Baseline | | Alt.1 | | Alt.2 | | Alt.3 | | Alt.4 | |
|--|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|---------------|
| | Min | Max | Min | Max | Min | Max | Min | Max | Min | Max |
| Seed: Traditional | 13.3 | 21.3 | | | | | | | | |
| Seed: Improved *** | | | 8.9 | 17.8 | 8.9 | 17.8 | 8.9 | 17.8 | 17.8 | 35.6 |
| Nursery preparation | | | | | | | | | 35.6 | 44.4 |
| Ploughing | 17.8 | 22.2 | 17.8 | 22.2 | 17.8 | 22.2 | 17.8 | 22.2 | 17.8 | 22.2 |
| Harrowing | 17.8 | 22.2 | 17.8 | 22.2 | 17.8 | 22.2 | 17.8 | 22.2 | 17.8 | 22.2 |
| Leveling and puddling | | | | | | | 31.1 | 44.4 | 31.1 | 44.4 |
| Marking transplanting grids | | | | | | | 22.2 | 35.6 | 22.2 | 35.6 |
| Planting: broadcasting | 17.8 | 22.2 | | | | | | | | |
| Seedling: transplanting | | | 31.1 | 44.4 | 31.1 | 44.4 | 44.4 | 71.1 | 80.0 | 111.1 |
| Weeding: 1st round | 44.4 | 111.1 | 44.4 | 111.1 | 44.4 | 111.1 | 66.7 | 133.3 | 66.7 | 133.3 |
| Weeding: 2nd round | 35.6 | 44.4 | 35.6 | 44.4 | 35.6 | 44.4 | 44.4 | 66.7 | 44.4 | 66.7 |
| Weeding: 3rd round | | | | | 35.6 | 44.4 | 44.4 | 66.7 | 44.4 | 66.7 |
| Bird scaring | 22.2 | 35.6 | 22.2 | 35.6 | 22.2 | 35.6 | 22.2 | 35.6 | 22.2 | 35.6 |
| Post-emergence pesticides | | | 4.4 | 6.7 | 4.4 | 6.7 | 4.4 | 6.7 | 13.3 | 22.2 |
| Field wetting and drying (water control) | | | | | | | | | 35.6 | 53.3 |
| Fertilizer: 1st round DAP | | | | | 26.7 | 48.9 | 26.7 | 48.9 | 44.4 | 57.8 |
| Fertilizer: 2nd round UREA | | | | | 26.7 | 48.9 | 26.7 | 48.9 | 44.4 | 57.8 |
| Fertilizer: 3rd round UREA | | | | | 26.7 | 48.9 | 26.7 | 48.9 | 44.4 | 57.8 |
| Harvesting/threshing | 44.4 | 88.9 | 48.9 | 111.1 | 66.7 | 133.3 | 88.9 | 155.6 | 133.3 | 177.8 |
| Postharvest handling | 13.3 | 26.7 | 13.3 | 31.1 | 26.7 | 44.4 | 35.6 | 80.0 | 57.8 | 88.9 |
| Storage | 8.9 | 22.2 | 17.8 | 26.7 | 26.7 | 44.4 | 35.6 | 57.8 | 44.4 | 80.0 |
| Total | 235.6 | 416.9 | 262.2 | 473.3 | 417.8 | 717.8 | 564.4 | 962.2 | 817.8 | 1213.3 |

*** for SRI farming system seed farmers considering a carefully seed selection and preparation to obtain quality seed for high germination probability.

Appendix C. Probability Distribution Functions (PDF) Charts for the Simulated Sample (in Red) vs. Observed Yields and Prices Sampled (in Black)

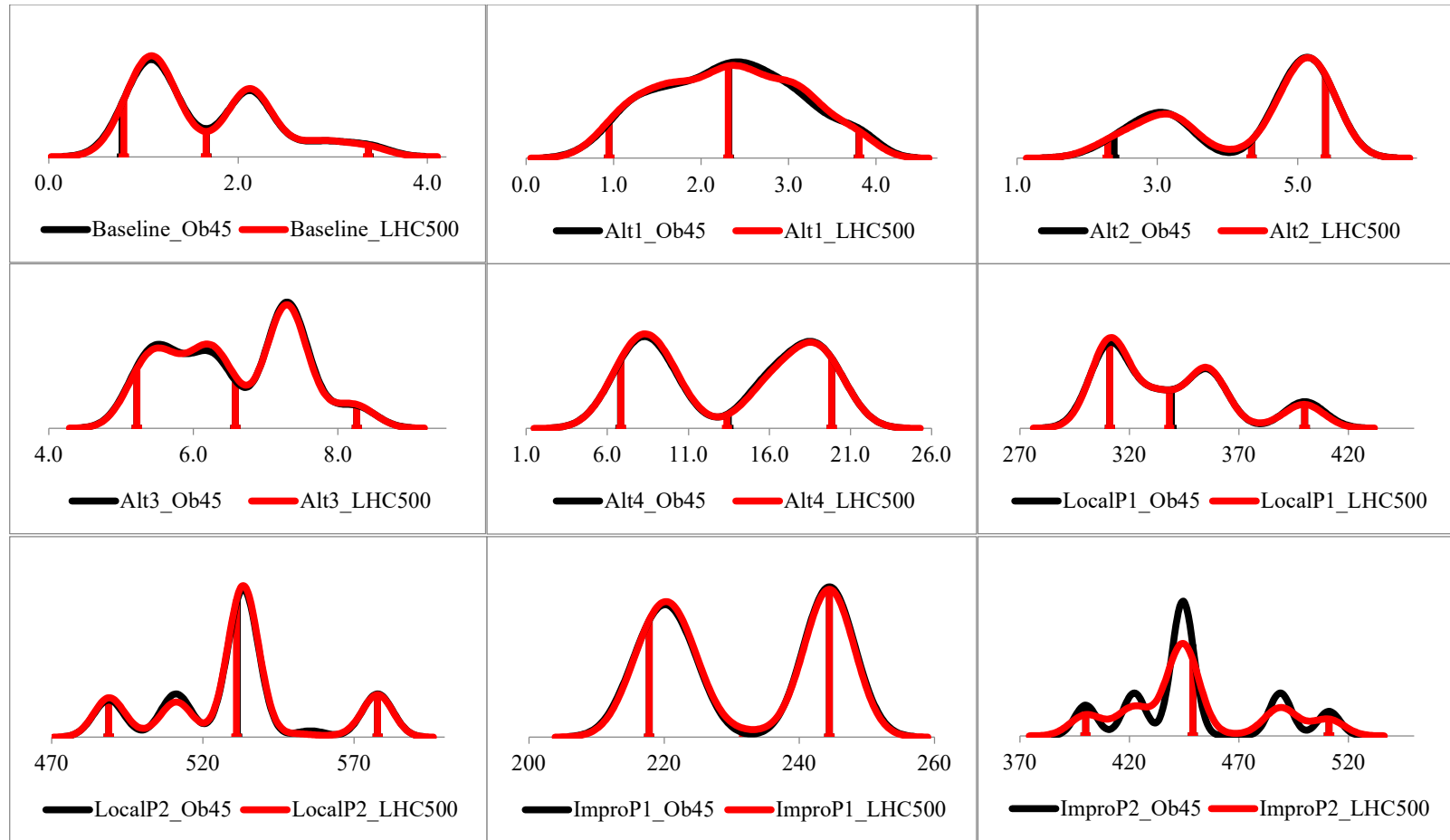
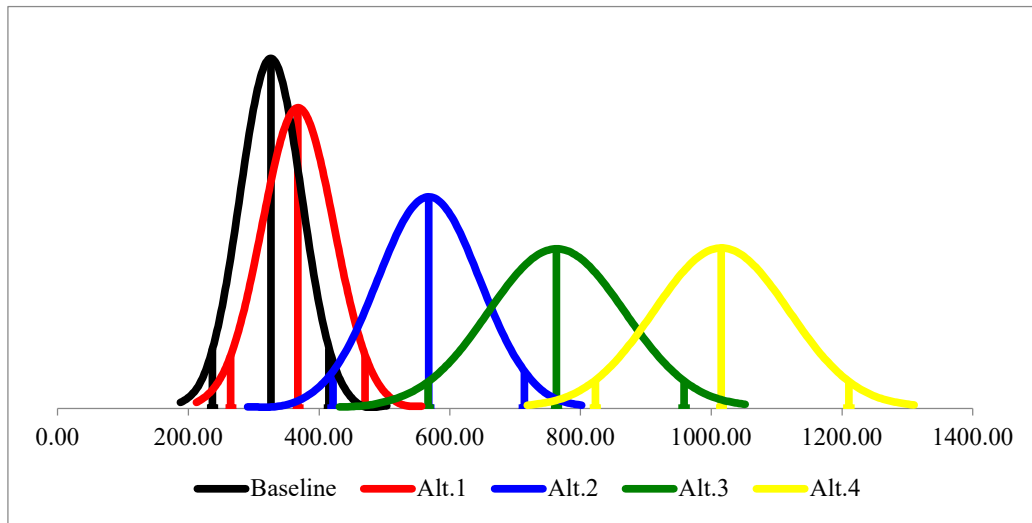
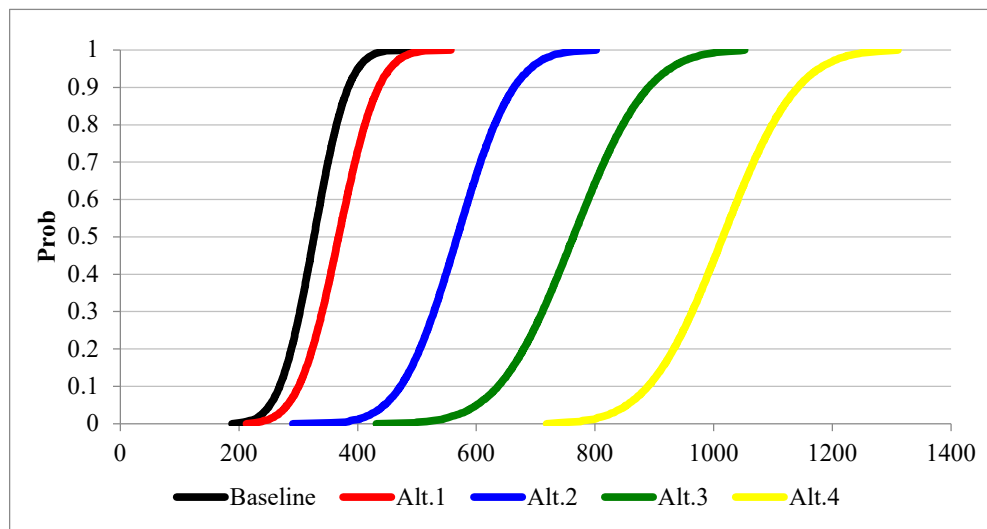


Figure A2.1. Probability distribution functions for observed vs. 500 simulated stochastic yields and prices: black charts represent the observed sample yields (Baseline_Ob45 to Alt.4_Ob45) and price (LocalP1_Ob45, LocalP2_Ob45, ImproP1_Ob45, ImproP2_Ob45); red charts represent the 500 simulated sample yields (Baseline_LHC500 to Alt.4_LHC500) and price (LocalP1_LHC500, LocalP2_LHC500, ImproP1_LHC500, ImproP2_LHC500). Prices are in TZS. US\$1= TZS 2250.

Appendix D. PDFs and CDFs of Production Cost per ha (US\$/ha) for Rice under Different Farming Systems (Alt.0–4) in Tanzania



(a)



(b)

Figure A3. (a) PDFs of production costs per ha and (b) CDFs of production costs per ha used in the model.

Appendix E. SRI Success Story of Mwanaidi H. Hussien Who Is One of the First Farmers to Adopt the Technology

Mwanaidi is one of the first farmers to start using SRI technology soon after she attended the training conducted by the Sokoine University of Agriculture. She is now a focal person in Mkindo village in Mvomero district. The Ministry of Agriculture (MoA) has awarded her prizes for being an example in harvesting more rice per unit area following SRI practices. She is now used by the MoA

and other stakeholders to conduct SRI training and demo plots for other farmers. SRI technology has significantly changed her life. Her own success story is as shown in Box 1 below.

Box A1. SRI Success Story.

“I’m Mwanaidi H. Hussien (Mama Shahidi) joined SRI in 2011 after receiving training from Sokoine University of Agriculture under the supervision of Profs. Mahoo and Kahimba. Since rice farming is my main economic activity, the following year (2012), I applied the knowledge to my own 1 acre. Fortunately, the harvest was four times higher (47 bags) compared to previous yields. In 2013 and 2014, the harvest ranged between 45 to 48 bags and reached 50 bags in 2015. Through SRI, I have achieved the following:

- In the year 2025, I was awarded a prize of 5,500,000 TZS by Morogoro agricultural Authority as the best farmer of the year.
- In terms of food security my family has never suffered from food shortage anymore.
- I always keep ten (10) bags (1 ton) of rice for my family and sell the rest.
- I am now capable of sending my kids to English medium schools and afford the costs.
- I have renovated my house and installed with electricity plus tap water.
- I also conduct SRI pieces of training to my fellow farmers. Taking care of one young orphan boy.
- I built a small fish pond and a vegetable garden around my house, which gives me a small amount of money for my family”



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