Adoption and ex-post impacts of the integrated rice-fish farming system technology on the welfare of small-scale farmers in Liberia: An application of marginal treatment effect model

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Abstract

In this study, we analyze the heterogeneity in the impacts of the integrated rice-fish farming system technology (IRFFST) on welfare indicators such as yield, production, food security, quantity of fish consumed, and poverty reduction in Liberia. We employ the marginal treatment effects (MTE) approach to estimate the treatment effects heterogeneity and policy-relevant treatment effects (PRTE) on cross-sectional survey data of 967 rice farmers. The findings show substantial heterogeneity in benefits from the adoption of IRFFST concerning both observed and unobserved household characteristics. Among the determinants of the adoption, the key determinants are access to credit, access to irrigation in lowlands, farm size, and access to extension services. The empirical results show that the adoption of the IRFFST significantly reduces household food insecurity and increases rice yield, production, and quantity of fish consumed in the household. On average, a random farmer selected among the rice farmers had their yield and food consumption score increase by 648 kg and 8.28 points, respectively. Overall, the article provides evidence that promoting IRFFST is important to improve the welfare of rural people, especially for marginalized poor indigenous small-scale rural farm households in Liberia. However, necessary interventions are needed to overcome the inhibiting factors for more widespread adoption of this promising technology, which is considered a promising model for adapting to climate change, reducing poverty in rural area and sustainable agriculture in developing countries.

Keywords: Integrated Rice-Fish farming System Technology, adoption, impact, MTE, household welfare, Africa.

1. Introduction

Agriculture represents more than one-third of the gross domestic product (GDP) of African countries. It can contribute towards major continental priorities, such as eradicating poverty and hunger, boosting intra-Africa trade and investments, rapid industrialization and economic diversification, job creation, and shared prosperity. It is the leading source of employment, income, food, and nutrition security. Agriculture is the mainstay of the economy and is also a key sector for human development and economic growth in Liberia. According to the World Bank (2019), over 75 percent of the population relies on agriculture for their livelihood. The sector contributes 25-35 percent to Liberia's GDP. With over 4 million acres of arable land, Liberia has the potential for commercial agricultural production. Rice is rapidly gaining importance as a staple food and is now one of the largest sources of food energy in SSA. It represents the basic food for more than 750 million people in SSA (USDA, 2020). Rice consumption is growing faster in Africa and particularly West Africa than in any part of the World. In West Africa, about 310 million people derive about 20% of their daily calories from rice. However, rice demand in this region is growing faster than local supply, leading to substantial rice imports and dependence on international rice prices.

Aquaculture and fishing are important sources of income and contribute to food and nutrition security by producing food of very high nutritional quality. Besides, there is an economic activity that has the potential to be as important as agriculture for the population, in terms of food security and socio-economic development (Avadí et *al.*, 2022; Kaminski et *al.*, 2020).

Hence, a sustainable increase in food production broadly to achieve food self-sufficiency and improve the well-being (i.e. reduce poverty) of small-scale farmers under continuing rise in population, economic growth, changing food habits, rapid urbanization, and severe climate change situation are crucial to economic growth and development. This increase in food production will have to be achieved by using less land, with less water, labor, and chemicals (Doss, 2006; IRRI, 1998; Khush, 2001). As farmers intensify production through increased use of chemical inputs, concerns about the negative effects of such practices on human health and the environment are growing. Therefore, improved crop management practices that lead to productivity gains with minimum adverse effects on the quality of the natural resource base are needed to reduce the importation bills and to achieve Sustainable Development Goals (SDG) in Liberia. Integrated rice-fish culture, an age-old farming system, is such a farming system technology that could produce rice (a source of carbohydrates) and fish (a source of high-quality animal protein) sustainably at a time by optimizing scarce resource use through the complementary use of land and water (Frei and Becker, 2005; Edward et *al.*, 1988).

The Development of Smart Innovation through Research in Agriculture (DeSIRA) initiative is a five-year agricultural research project funded by the European Union that aims to develop climate-resilient, integrated technological innovations to enhance understanding of the opportunities and constraints for uptake of these innovations by farmers and to inform policymakers and partners engaged with expanding scale about the potential of these technologies to contribute to climate resilience and sustainability. Through the project, technologies for evaluation and promotion include the Integrated Rice-Fish Farming System (IRFFS) in Liberia. The overall objective of the project is "to achieve food security and improved nutrition for all".

The study addressed two research questions: (i) What drives the adoption and intensity of adoption of IRFFS technology in Liberia? (i) What is the impact of the adoption of IRFFST on farmer's welfare (yield, income, food security, nutrition security, poverty, etc)? To the best of our knowledge, this study will be the first of its kind to identify socio-economic factors affecting the adoption of the IRFFST systems in marginalized extreme poverty settings and the impact of the adoption on farmers' welfare in Liberia. The results of this study will provide valuable insights for other developing countries with similar agroecological, socioeconomic, and institutional settings for tackling extreme poverty and marginal situations. This study helps provide recommendations to policymakers and extension agents on how to scale the IRFFS technology to improve the livelihood of rice farmers in Liberia.

The rest of this paper is organized as follows. The next section briefly presents the description and dissemination of the IRFFST system technology in Liberia and discusses the methodology in the section "Methodology". Next, we present and discuss the results in the section "Results". Finally, we conclude the study and discuss its policy implications.

2. Description and dissemination of the integrated rice-fish farming system technology in Liberia

The "Integrated Rice-Fish Farming System" (IRFFS) is part of the project funded by the European Union (EU). This development-based initiative was launched in January 2020 to enhance rice and fish value chains for improved food, nutrition, and economic security for all through targeted research and extension in Liberia.

Rice-fish culture involves stocking paddy fields (main crop) with fingerlings to obtain two crops, that is, fish in addition to the main crop (Figure 1). The strategy has been practiced for thousands of years by Asian farmers. It promotes species diversification and nutrient recycling (Coche, 1967) and ensures a more economic utilization of land resources (Dang et *al.*, 2007). Integrated rice-fish culture aims to increase agricultural productivity from water, while improving the financial sustainability of investments in irrigation (Vincke, 1979). The relationship between "rice" and "fish" is a win-win relationship. Benefits of rice-fish culture include a reduction in the use of chemical fertilizers and the recycling of the nutrients by the fish through feeding and depositing of faeces in the soil. This increases the uptake of nutrients such as phosphorus and nitrogen by rice; and contributes to improved use of land. Other gains from rice-fish integration include an increase in income from the production of both fish and rice and the spreading of biological as well as economic risks (Little and Edwards, 2003). Moreover, the weeding done by fish allowed farmers to save weeding costs. The DeSIRA initiative also includes the multiplication and introduction of improved and climate-smart rice varieties such as NERICAL-19, IR841, and ARICA2. NERICAL-19 is the most appreciated variety in Liberia because of its tolerance to iron toxicity and its height (farmers prefer medium height (120 cm) variety that is easy to harvest). Also, focus was put on fish seed and feed production. Nile tilapia (*Oreochromis Niloticus*) fries and fingerlings from improved broodstocks tilapia (*Oreochromis Niloticus*) were massively produced and provided to farmers. Farmers were provided with improved Tilapia (distribution of Fingerlings). Tilapia (*Oreochromis Niloticus*) contract fewer diseases, mature quickly, and can grow in environments where other species are unable to survive. Tilapia has become the third most important fish in aquaculture after carp and salmonids, with production exceeding 1.5 million metric tons in 2002 (Fessehaye, 2006). Also, extension workers from the Central Agricultural Research Institute (CARI) and stakeholders in various aspects of aquaculture undertake training in the following topics: (i) pond construction and fishpond fertilizing; (ii) fish feed production and feeding; (iii) fish predators and competitor's prevention; (iv) good fingerlings production and monitoring, record keeping, business model and marketing, etc.

Fig 1. Integrated rice-fish farming systems in Liberia

3. Methodology

3.1. Study area

The impact survey of the Development of Smart Innovation through Research in Agriculture (DeSIRA) initiative was conducted in five counties (regions) of Liberia: Margibi, Maryland, Gbarpolu, River Gee, and Grand Gedeh (Figure 1). In all counties, the impact survey was conducted in the target region of the project in Liberia.

Liberia has a tropical climate, which means that it is hot and humid throughout the year and gets plenty of rain. While temperatures in Monrovia and along the Liberian coast generally range between 73F and 89F (23C and 32C), it is slightly hotter inland. The humidity makes it seem hotter than it is, but there is an almost constant, refreshing breeze along the coast. The year can be divided into a wet and a dry season. Between late April and mid-November, it is hot, wet, and cloudy, with frequent heavy rain showers. Between December and March, it is dry with hot days and cool nights. The south of Liberia has an equatorial climate, experiencing rainfall throughout the year, but the northern regions are tropical and strongly influenced by the West African Monsoon. Most of Liberia has one wet season between May and November.

Liberia is one of the wettest countries in the world, with the heaviest rainfall occurring from May to October[1]. The country's average annual rainfall is relatively high, nearly exceeding 2,500 millimeters (mm). Rainfall is highest along the coast but decreases towards Liberia's interior plateaus and low mountains, where average rainfall reaches approximately 2,030 mm per year[2]. Southern areas of the country receive rain year-round, while the rest of the country experiences two seasons due to the West African Monsoon[3]. The wet season typically occurs in the summer months between May and November, with average temperatures of 25°C. The dry season typically occurs in the winter months, from December to April. The dry season is dominated by the harmattan winds with average temperatures between 24 to 27°C. Relative humidity reaches 90%–100% during the rainy season and 60%–90% during the dry season[4].

Liberia is recognized as highly vulnerable to climate change. Further, the pandemic has demonstrated the compounding impacts of adding yet another shock on top of the multiple challenges that vulnerable populations already face in day-to-day life, with the potential to create devastating health, social, economic, and environmental crises that can leave a deep, long-lasting mark.

The agriculture system of Liberia is 80% subsistence involving shifting cultivation. The major crops are natural rubber, rice, cassava, bananas, and palm oil. In Liberia, rice is the primary staple crop, cultivated by 74% of farmers. Rice is highly sensitive to increased humidity temperatures and intense rainfall, and to the pests that thrive in these conditions.

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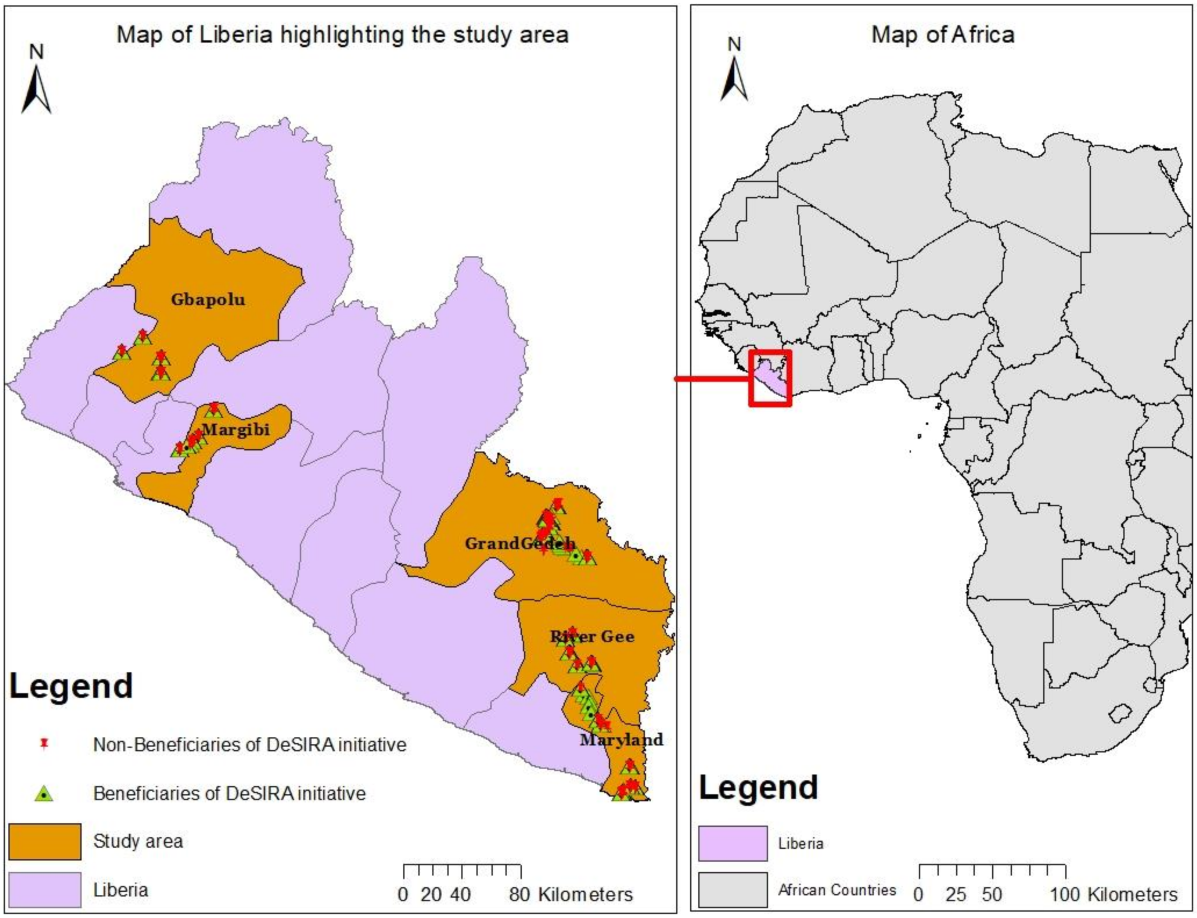

Fig 1. Map highlighting the study area and the distribution of actors surveyed in Liberia

3.2. Data collection, sampling, and sample size

The study was conducted in five counties (regions) of Liberia: Margibi, Maryland, Gbarpolu, River Gee, and Grand Gedeh. These regions were selected purposively for two main reasons: their major rice production areas and the IRFFST was first introduced in these areas through training and demonstration by AfricaRice and national scientists in Liberia. Data was collected in June 2023.

A two-stage random sampling technique was used to select farmers' beneficiaries and non-beneficiaries of the DeSIRA initiative in the study area. In the first stage, villages were randomly selected from the list of villages involved in the DeSIRA initiative where activities were conducted and from where farmers were trained in the rice-fish farming system. From each selected village, the list of all rice farmers was developed through an e-registration survey, and then, rice farmers were randomly selected. In total, 967 rice farmers including 446 rice farmers beneficiaries and 521 rice farmers non-beneficiaries of DeSIRA were randomly selected and interviewed. This resulted in the number of rice farmers to investigate in each village for the ex-post impact survey (Table 1).

Data were collected by enumerators selected based on their experience and trained in the use of the CSPro application on tablets. Computerized data collection has avoided many of the biases associated with paper questionnaires, such as errors in recording responses, changing variable values, and recording test responses for numeric variables. Four main categories of data were collected: socioeconomic and demographic characteristics, information on knowledge, perception, and constraints faced by adopters of the rice-fish farming system, inputs, and outputs in production activity, information on income, food security, poverty, decision-making in the household, etc.

Table 1. Number of actors surveyed per county

Counties in Liberia	Pooled	Beneficiaries	Non-beneficiaries	Male	Female
Margibi	233	49	184	127	106
Maryland	201	140	61	99	102
Gbarpolu	197	68	129	100	97
River Gee	128	69	59	58	70
Grand Gedeh	208	120	88	124	84
Total	**967**	**446**	**521**	**508**	**459**

3.3. Econometric Approach

3.3.1. Technology adoption model

The decision to adopt the system (IRFFS) can be modeled under the assumption that farmers choose between adoption and non-adoption of IRFFS (Abdulai and Huffman, 2014). Let us assume that a smallholder farmer is risk-neutral and chooses among climate-smart agricultural technologies, including IRFFS, to maximize the expected benefit from adoption. Thus, a smallholder farmer i will choose to adopt a climate-smart agricultural technology only if the expected benefits from adoption (T_{i1}^*) are greater than the expected benefit from non-adoption (T_{i0}^*), meaning that $T_i^* = T_{i1}^* - T_{i0}^* > 0$. Although T_i^* is unobservable, it is possible to observe the choice made by the i^{th} farmer. The net benefit T_i^* can therefore be expressed in a latent variable framework with respect to household characteristics as:

$$T_i^* = Z\gamma - U_D \qquad \text{with } \; T_i = \begin{cases} 1 \; if \; T_i^* > 0 \\ 0 \; if \; T_i^* \leq 0 \end{cases} \qquad (1)$$

where T_i is the observed adoption status, which takes the value 1 if the farmer adopts IRFFS and 0 if not, γ is a vector of parameters to be estimated, Z is a vector of exogenous variables that explain adoption decisions, and U_D is the random error term assumed to be normally distributed. The error term captures the measurement errors and unobserved factors that are not correlated with Z but may influence the decision to adopt IRFFS. The probability of adopting an IRFFS can be expressed as:

$$\Pr(T_i = 1) = \Pr(T_i^* > 0) = \Pr(U_D > -\gamma' Z) = 1 - F(-\gamma' Z) \quad (2)$$

where F is the cumulative distribution function of U_D.

3.3.2. Impact assessment analysis

To assess the impact of IRFFS on outcome, we employed the marginal treatment effect framework, which allows us to estimate the treatment effect heterogeneities across households and simulate the effects of policy changes on outcomes such as yield, income, food security, and poverty. To assess the impact of IRFFS, we use the “mtefe” command of STATA to estimate the parametric normal approach of the marginal treatment effect model. The MTE method was used in many studies for impact assessment (Shahzad and Abdulai, 2021). Previous studies have used methods like Heckman’s treatment effect model or endogenous switching regression (ESR) model to account for selection bias (e.g., Di Falco *et al.*, 2011; Abdulai and Huffman, 2014; Issahaku and Abdulai, 2020, Arouna *et al.*, 2023).

Suppose that the outcomes (yield, income, food security, and poverty) are linear functions of farm and socioeconomic characteristics as follows:

$$Y_i = \beta X_i + \alpha T_i + \vartheta_i \quad (3)$$

where Y represents the observed outcome; α and β are parameters to be estimated; ϑ is an error term; T is the adoption status and its probability is estimated in Equation (2); and X is a vector of observed variables such as characteristics of rice farmers, households, farms, and institutions. However, there were also unobserved variables that influence both treatment selection and outcomes, such as farmers’ motivation and innate ability, which are in the error term ϑ. Estimation of Equation (3) can result in biased estimates because of the correlation between the two error terms ($cov(U_D, \vartheta) \neq 0$). In other words, potential selection bias will occur when unobservable factors (ϑ) of Equation (3) are correlated with unobservable factors (U_D) of Equation (1). This selection problem can be overcome in a randomized control trial (RCT) design where farmers would be assigned randomly to adopter and nonadopter groups such that the use of the new technology is the only difference between adopter and nonadopters (Heckman and Vytlacyl, 2005; Shahzad and Abdulai, 2021). However, since adoption of IRFFS is a nonrandom experimental design with adopters self-selecting into adoption, this leads to a selection bias problem. We therefore employ an approach that accounts for selection bias in the estimation.

Previous studies have used methods like Heckman's treatment effect model or endogenous switching regression (ESR) model to account for selection bias (e.g., Di Falco *et al.*, 2011; Abdulai and Huffman, 2014; Issahaku and Abdulai, 2020). However, many studies have documented the limitations of these approaches (e.g., Dubbert *et al.*, 2021; Abdul-Mumin and Abdulai, 2022). In particular, the ESR model accounts for selection bias by aggregating the unobservable heterogeneity, although the heterogeneity tends to vary across households (Carneiro *et al.* 2011). We therefore use the marginal treatment effect (MTE) approach to account for heterogeneity across households.

MTEs were introduced by Björklund and Moffitt (1987), later generalized by Heckman and Vytlacil (2007), and can be identified under regular IV assumptions (conditional independence and separability). MTE measures average gains in outcomes for households with values of variables X and the unobserved resistance to treatment V (the propensity not to be treated). The estimated propensity score $\hat{P}(z) = Pr(U_D > -\gamma' Z)$ (Equation 2) defines the range of V over which MTE is identified. MTE is defined as the partial derivative of the conditional expectation of Y with respect to $P(Z)$ and

$$MTE = \frac{\partial E(Y|X=x, P(Z)=p)}{\partial_p} = x_0(\beta_1 - \beta_0) + \frac{\partial K(p)}{\partial p} \quad (4)$$

Equation 4 can be estimated with the joint normality assumption (parametric estimation) or without the normality assumption (parametric). In this study, we relax the trivariate normality assumption and estimate Equation 4 using parametric techniques for local derivatives, known as local instrumental variables (LIV) (Heckman *et al*., 2006). In addition, MTE is used to derive different parameters of interest. These include ATE, ATE on the treated (ATT), and on untreated (ATUT) which are well known in the impact assessment literature. Carneiro *et al*. (2010) also introduced marginal policy-relevant treatment effects (MPRTEs), which can be computed from the MTEs.

MPRTEs are fundamentally easier to identify than PRTEs (Carneiro *et al*., 2010), particularly because they do not require full support conditions. Marginal changes to propensity scores will not drive the scores outside the common support. Carneiro *et al*. (2011) suggest three ways to define distance to the margin. The first MPRTE, labeled MPRTE1, corresponds to a marginal change in a variable entering the first stage, such as an instrument. MPRTE2 corresponds to a policy that would increase all propensity scores by a small amount, while MPRTE3 corresponds to a policy that increases all propensity scores by a small fraction or proportion.

The validity of the results largely depends on the quality and relevance of the instruments. The instrument used in the estimation is *contact with the extension service*. Indeed, the choice of these variables was explained by the fact that *contact with an extension service* can provide information knowledge, and training on IRFFS and influence the adoption but will not directly affect the outcomes. Only farmers having information on IRFFS can adopt them. However, information and knowledge cannot directly influence the outcomes (yield, production, FCS, etc.). Contact with extension services fulfilled the exclusion restriction as defined by Abadie (2003). We also test the validity of the instrument. Following Di Falco *et al*. (2011), we performed a simple falsification test: if a variable is a valid instrument, it will affect the technology adoption decision, but it will not affect the outcome variables. The results showed that *contact with extension services* is jointly statistically significant in explaining the adoption of IRFFS, but not the direct outcomes.

4. RESULTS

We started this section with an analysis of the drivers of the adoption of the IRFFST. Finally, we present the impact of the adoption of the IRFFS on different outcomes (yield, income, production, quantity of fish consumed in the household, food security, and poverty headcount ratio) of rice producers.

4.1. Socioeconomic and demographic characteristics of rice producers

Table 2 describes the socioeconomic and demographic characteristics of rice producers surveyed in Liberia. Mean difference tests showed that the hypothesis of no difference between adopters and nonadopters of the IRFFS is rejected for most characteristics. These results underscored the presence of selection into adoption, and heterogeneity between adopters and nonadopters must be considered in the impact assessment of the IRFFS technology. Specifically, descriptive statistics showed that adopters and non-adopters of the IRFF are distinguishable in terms of household characteristics.

Evidence from Table 2 shows that the mean age of the producers was 44 years old, and female farmers are involved in rice production as well as male farmers in Liberia (47% of females). Approximately 73% of farmers were married a sign of independence and maturity as cultural norms in Liberia villages. The mean household size of the sample surveyed is 5 people and they are majority Christian (96%). Furthermore, approximately 56% of respondents received formal education, and adopters of IRFFS had higher levels of education (61%). The most spoken language is Kpelle, followed by Grabo (35%) and Krahn (16%). Five Liberian counties are involved in this study: Margibi (24%), Maryland (21%), Gbarpolou (20%), River Gee (13%), and Grand Gedeh (22%). Moreover, 92% of rice producers were engaged in production activities as their main occupation.

Only 6% of the respondents reported that they had recently obtained credit for agricultural production. 44% of adopters of IRFFS are members of farmers associations and 96% of adopters have contacts with extension agents. All adopters of IRFFS received training on IRFFS. Moreover, all adopters are far from institutions such as the extension agent office, nearest input dealer, mechanized service provider, nearest market, and AfricaRice center in Liberia. In addition, the cultivated area is 1.13 ha and 66% highlighted that the land tenure is inherited.

Finally, approximately 28% and 21% of respondents had experienced flood and drought, respectively.

Table 2. Socioeconomic and demographic characteristics of rice producers

Variables	Pooled (n= 967)	Adopters of IRFFS (n=446)	Non-adopters of IRFFS (n=521)	Mean difference [a]
Household characteristics				
Age of rice farmer (year)	44.74 (12.28)	44.65 (11.78)	44.82 (12.70)	-0.17
= 1 if male (%)	0.53 (0.49)	0.51 (0.50)	0.54 (0.49)	-0.03
= 1 if married (%)	0.73 (0.44)	0.73 (0.44)	0.72 (0.44)	0.01
Household size (Number)	5.60 (2.68)	5.78 (2.82)	5.44 (2.55)	0.339*
= 1 if formal education	0.56 (0.49)	0.61 (0.48)	0.51 (0.50)	0.097***
= 1 if Christian religion	0.96 (0.20)	0.96 (0.18)	0.95 (0.21)	0.01
= 1 if the language is Kpelle	0.37 (0.48)	0.23 (0.42)	0.49 (0.50)	-0.259***
= 1 if the language is Grabo	0.35 (0.47)	0.47 (0.49)	0.25 (0.43)	0.225***
= 1 if the language is Krahn	0.16 (0.36)	0.22 (0.41)	0.10 (0.30)	0.124***
= 1 if living in Margibi	0.24 (0.42)	0.11 (0.31)	0.35 (0.47)	-0.243***
= 1 if living in Maryland	0.21 (0.40)	0.31 (0.46)	0.12 (0.32)	0.197***
= 1 if living in Gbarpolou	0.20 (0.40)	0.15 (0.35)	0.25 (0.43)	-0.095***
= 1 if living in River Gee	0.13 (0.33)	0.16 (0.36)	0.11 (0.31)	0.041*
= 1 if living in Grand Gedeh	0.22 (0.41)	0.27 (0.44)	0.17 (0.37)	0.100***
= 1 if agriculture is main activity (%)	0.92 (0.26)	0.93 (0.25)	0.92 (0.27)	0.01
Institutional characteristics				
= 1 if access to credit (%)	0.06 (0.22)	0.06 (0.23)	0.06 (0.22)	0.00
=1 if member of farm association (%)	0.31 (0.46)	0.44 (0.49)	0.19 (0.39)	0.248***
=1 if contact with extension (%)	0.51 (0.50	0.96 (0.18)	0.12 (0.32)	0.845***
= 1 if trained in IRFFS	0.82 (0.38	0.99 (0.06)	0.18 (0.38)	0.818***
Distance to extension agent (km)	14.54 (26.60	17.13 (28.83)	12.32 (24.35)	4.806***
Distance to nearest input dealer (km)	9.86 (13.66	12.33 (17.40)	7.76 (8.81)	4.572***
Distance to mechanized service provider (km)	9.92 (14.93	12.34 (19.76)	7.85 (8.38)	4.488***
Distance to nearest market (km)	8.83 (11.25	9.53 (13.81)	8.23 (8.44)	1.300*
Land and farm characteristics				
Available area (ha)	1.97 (2.70	1.76 (2.18)	2.15 (3.06)	-0.393**
Cultivated area (ha)	1.13 (0.80	1.07 (0.82)	1.17 (0.78)	-0.105**
= 1 if lowland area	0.70 (0.45	0.79 (0.40)	0.63 (0.48)	0.157***
= 1 if land tenure is inherited	0.66 (0.47	0.65 (0.47)	0.66 (0.47)	-0.01
=1 if information on new rice varieties	0.30 (0.45	0.53 (0.49)	0.10 (0.30)	0.428***
= 1 if experiencing a flood	0.28 (0.44	0.43 (0.49)	0.15 (0.35)	0.283***
= 1 if experiencing drought	0.21 (0.40)	0.30 (0.45)	0.14 (0.34)	0.160***

[a] *T test was used to test for differences in socioeconomic characteristics between adopters and nonadopters. * Significant at 10%; ** significant at 5% and *** significant at 1%. () standard deviation; n=Number of rice farmers*

4.2. Statistics of outcomes variables

Table 3 describes the selected outcome characteristics of rice farming households by IRFFS adoption status, as well as the mean difference between the adopter and nonadopter groups. Mean difference tests showed that the hypothesis of no difference between adopters and nonadopters of IRFFS can be rejected for most of the variables. These results underscore the presence of selection into adoption, and as such the heterogeneity between adopters and nonadopters needs to be considered in assessing the impact of IRFFS. Results show several outcome variables also significantly differ between IRFFS adopters and non-adopters. For example, on average the household yield, production, food consumption score, and quantity of fish consumed by IRFFS adopters are significantly higher than non-adopters. The poverty headcount ratio of adopters of IRFFS households is higher than non-adopting households but it is not significant.

The average food consumption score is 57.71 units for the whole sample. About 73% of farmers perceived that they are food secure and 96% are adopters of IRFFS. In addition, we have 70% of the poor in the population of adopters while we have 75% of the poor in the population of adopters. This implies that IRFFS can be used in Liberia for poverty reduction in rural areas. Adopters' households consume more fish per month than non-adopters (32.7 kg). Furthermore, household expenditure is US$ 1,948 per year. Non-adopters of IRFFS expend more money than adopters (US$ 2,047.05). Results underscore the presence of selection into adoption and heterogeneity between adopters and non-adopters must be considered in the impact assessment of IRFFS.

Table 3. Characteristics of outcomes variables and mean difference

Variables	Pooled (n=967)	Adopters of IRFFS (n=446)	Non-adopters of IRFFS (n=521)	Mean difference [a]
Outcomes variables				
Yield (kg/ha)	1460.343 (1121.38)	1826.649 (1110.09)	1146.76 (1033.37)	679.88***
Production (kg)	1192.902 (1155.72)	1617.186 (1304.69)	829.69 (859.08)	787.49***
Food consumption score (FCS)	57.71 (22.95)	60.77 (22.98)	55.09 (22.61)	5.685***
Self-perception of food security status in the household (%)	0.73 (0.44)	0.96 (0.19)	0.54 (.49)	0.420***
Poverty headcount ratio (%)	0.72 (0.44)	0.70 (0.45)	0.75 (.43)	-0.046
Quantity of fish eat in the household per month (kg)	25.40 (32.31)	32.72 (36.37)	19.13 (26.86)	13.592***
Household expenditure per year ($ USD)	1,948.16 (3525.12)	1,832.64 (3263.89)	2,047.05 (3734.53)	-214.408

[a] *T test was used to test for differences in socioeconomic characteristics between adopters and nonadopters. * Significant at 10%; ** significant at 5% and *** significant at 1%. () standard deviation; n=Number of rice farmers*

4.3. Determinants of the adoption of the integrated rice-fish farming system technology

The selection equation in the MTE parametric model allowed the analysis of factors affecting the adoption of the IRFFST. It is evident that households' decision to adopt IRFFS technology is influenced by a wide range of variables. The results show that eleven variables out of 21 significantly influence the adoption of IRFFS (Table 4). Knowledge, information indicators, land, and farm characteristics such as living in Maryland, household size, contact with extension agents, use of NERICA varieties, access to credit**,** lowland ecology, and having access to irrigation are positively associated with the probability of adopting IRFFS. This suggests that the likelihood of adopting new technologies such as IRFFS is higher for households that had access to irrigation, contact with extension agents, use NERICA varieties, live in Maryland, and have more people in the household than for those that did not. Policy options that aim to increase access to knowledge, land, and farm characteristics will positively affect the adoption of IRFFS. IRFFS adoption increases with household size increase, and this implies that farmers with more people in their household have more family labor to adopt IRFFS. In addition, the significance of contact with extension in the selection equation underscores the relevance of using these variables in our identification strategy. Contact with agricultural extension services is supposed to facilitate better awareness, access to agricultural technologies, and adoption (Jaleta *et al.*, 2018). Resource endowment variables such as access to credit, household size, lowland ecology, and having access to irrigation for crop production also positively affect the probability of a household adopting IRFFS. This implies that farmers with more resources may be less risk averse and therefore more likely to invest in new technology, such as IRFFS, or that households with large household members and having access to irrigation in lowlands may be more likely to adopt IRFFS. Access to credit had a positive and significant effect on the adoption of IRFFS. This is expected as increasing access to credit is particularly important as about 94% of rice farmers did not have access to credit facilities. Increased access to institutional support services such as extension, credit, and market access should thus be a major part of efforts aimed at promoting adoption of modern technologies. Furthermore, coefficient of access to irrigation in lowland is positive and statistically significant, and this implies that for adoption and diffusion of IRFFS technology irrigation is a complementary input which is necessary.

Interestingly, the association between IRFFS adoption and use of NERICA varieties is positive and significant, this implies that adopters of IRFFS are more willing to adopt improved technologies such as improved varieties. The negative coefficient of being married implied that married farmers are less likely to adopt IRFFS. This was not expected because IRFFS keeps husband and wife together on rice-fish farming activity. Based on the perception of rice-fish farming actors, IRFFS keeps the wife and husband together in rice-fish farming activity. Similarly, the negative coefficient of language is Grabo, using Gizzi varieties and living in the Gbarpolou region implied that farmers who speak the Grabo language, use Gizzi varieties, and living in Gbarpolu are less likely to adopt IRFFS.

Surprisingly, the coefficient of being a member of a farm association is negative and statistically significant. This was not expected because belonging to a farmers' association was supposed to help farmers have access to information and all facilities for new technologies adoption. Membership in associations such as cooperatives enhances adoption by reducing information, credit, labour, and insurance market imperfections (Wossen *et al.*, 2015).

Table 4. Determinants of adoption of the integrated rice-fish farming system technology

Variables	Coefficients	Standard errors
= 1 if male (%)	0.11	0.19
= 1 if married (%)	-0.43*	0.23
= 1 if the language is Krahn	0.19	0.31
= 1 if the language is Grabo	-1.02***	0.32
= 1 if living in Maryland	0.62**	0.27
= 1 if living in Gbarpolou	-0.66**	0.30
= 1 if using Gizzi varieties	-0.76***	0.26
= 1 if contact with extension agent (%)	2.36***	0.23
= 1 if using NERICA varieties	2.32***	0.23
= 1 if using Suakoko varieties	-0.21	0.26
= 1 if lowland and have access to irrigation	0.56**	0.22
Food expenditure ($ USD)	0.00	0.00
Age of rice farmer (year)	0.00	0.01
Household size (Number)	0.10***	0.04
= 1 if formal education	-0.12	0.19
= 1 if agriculture is main activity (%)	0.44	0.27
= 1 if access to credit (%)	0.95**	0.40
= 1 if member of farm association (%)	-0.46**	0.19
= 1 if information on new rice varieties	0.22	0.20
School expenditure	0.00	0.00
Health expenditure	0.00	0.00
Constant	-3.13***	0.53
Number of observations	967	
Log of likelihood	-139.27	
Wald Chi-square	1056.18	
McFadden Pseudo R^2	0.79***	

***, ** and * significant at 1%, 5% and 10%, respectively.

4.4. Impact of the integrated rice-fish farming technology on rice yield

Figure 2 depicts the MTE curve for the impact on rice yield. With the distribution of the estimated MTE, we found evidence of a positive impact of IRFFS on rice yield for an average person in the population of rice farmers (Table 5). On average, a random farmer selected among the rice farmers had their rice yield increase by 648.78 kg/ha (ATE), equivalent to a 44% increase.

When considering only the population of adopters, the impact on rice yield was 713.98 kg/ha (ATT), equivalent to a 39% higher yield from the use of IRFFS. The results also reveal that the treatment effects on untreated (ATUT) are lower than that of ATE and ATT, indicating positive selection on unobserved gains. Moreover, it is clear from the estimates that nonadopters would have gained had they adopted IRFFS (593.22 kg/ha). Table 5 also presents other parameters, namely, LATE and MPRTEs. LATE is positive and significant. This implies that the adoption of IRFFS increased the yield of compliers. Similarly, policy measures that shifted the value of the instruments (contact with extension) had a positive impact on rice yield.

Table 5. Impact estimates of IRFFS on rice yield

Treatment effect	Treatment category		Parametric MTE model		
	Without adoption	With adoption	Treatment effect	Boot. Std. Err	Change (%) [a]
Rice yield (kg/ha)					
ATE	811.56	1460.34	648.78***	96.28	44%
ATT	1112.67	1826.65	713.98***	142.42	39%
ATUT	1146.76	1739.98	593.22***	120.16	34%
LATE			724.49***	91.60	
$MPRTE_1$			706.42**	325.15	
$MPRTE_2$			333.30	233.87	
$MPRTE_3$			-236.16	780.89	
Observations			967		
Test of observable heterogeneity, p value			0.00		
Test of essential heterogeneity, p value			0.00		

*[a] % change in outcome between with adoption and without adoption; *** significant at 1%; ** significant at 5%.*

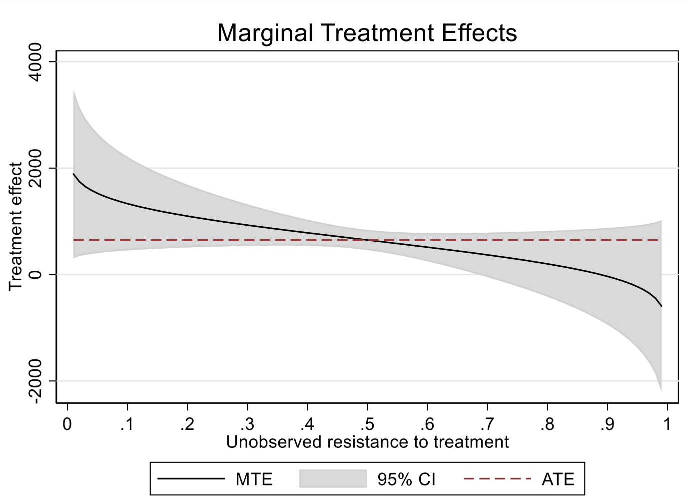

Fig. 2 Distribution of the MTE for impact on rice yield

4.5. Impact of the integrated rice-fish farming technology on rice production

The estimates also reveal that the MTE of adoption of IRFFS on production increased in resistance to adoption, reflecting the fact that the marginal return to adoption is higher for individuals with a higher propensity to adopt IRFFS (Fig 3). We find evidence that the adoption of the IRFFS significantly reduced the increase in rice production (Table 6). An average person increases rice production by 932 kg. The results show that adoption increases the production by 771.14 kg for an average adopter. Similarly, the average untreated farmer would experience an increase of 1069.16 kg by adopting IRFFS.

Table 6. Impact estimates of IRFFS on rice production

Treatment effect	Treatment category		Parametric MTE model		
	Without adoption	With adoption	Treatment effect	Boot. Std. Err	Change (%) [a]
Rice production (Kg)					
ATE	260.76	1192.9	932.14***	99.59	78%
ATT	846.04	1617.18	771.14***	147.32	48%
ATUT	829.69	1898.85	1069.16***	124.30	56%
LATE			874.32***	94.75	
$MPRTE_1$			2148.12***	336.35	
$MPRTE_2$			1367.19***	241.92	
$MPRTE_3$			2935.40***	807.78	
Observations			967		
Test of observable heterogeneity, p value			0.00		
Test of essential heterogeneity, p value			0.00		

[a] *% change in outcome between with adoption and without adoption; *** significant at 1%.*

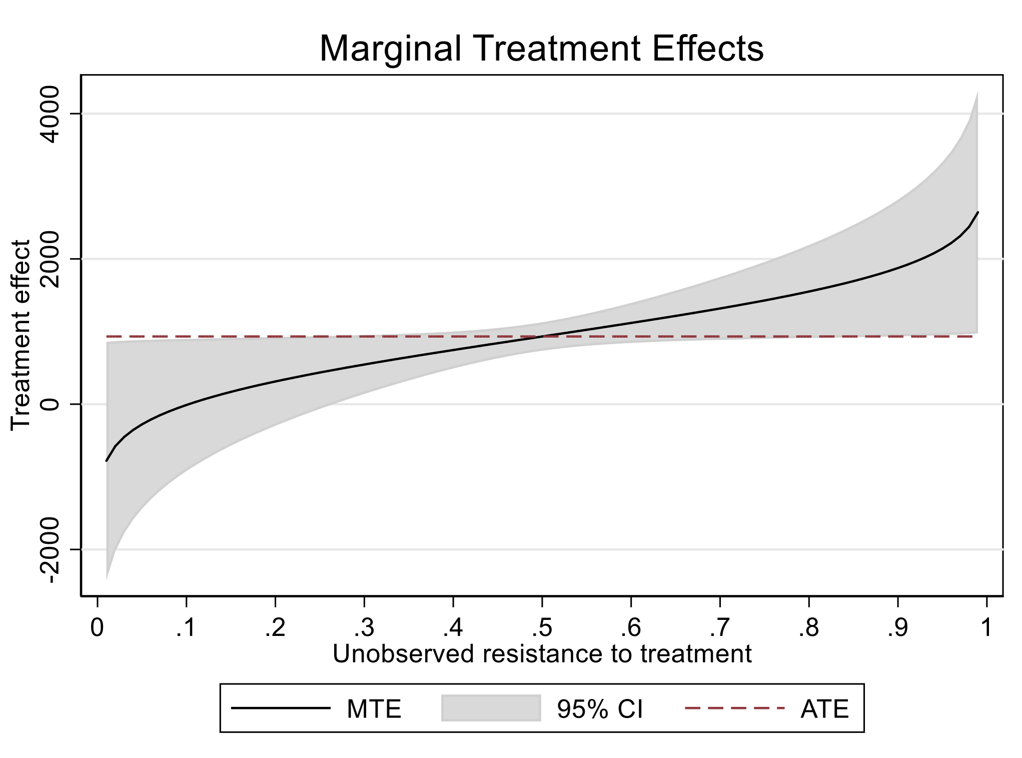

Fig. 3 Distribution of the MTE for impact on rice production

4.6. Impact of the integrated rice-fish farming technology on food security

To assess the impact of IRFFS on food security, we used two complementary indicators: the food consumption score (FCS) and Self-perception of food security status in the household. The FCS is a composite indicator developed by the World Food Programme (WFP, 2009). It is an indicator that reflects food availability, access to food, and food consumption at the household level. The FCS is therefore a good indicator to evaluate the food security situation of households. We added to the food consumption score the self-assessment of the food security situation of the household by rice farmers in Liberia. The impact of IRFFS was assessed on the percentage of people who said that their household is food secure.

We found evidence of a positive impact of IRFFS technology adoption on food security in the household of rice farmers. MPRTE1 and MPRTE2 estimates were also significant and positive in Table 7. On average, a random farmer selected among the rice farmers had their food consumption score increase by 8.28 points (14%), while the food consumption score increases by 9.84 points

(15%) in the population of untreated farmers and 6.46 points (11%) in the population of the treated farmer by adopting IRFFS (Table 7).

The self-perception of food security status in the household increases by 56% for an average person in the population of rice farmers. We observed a 41% increase for treated farmers while we would have observed a 44% increase for untreated farmers if they had adopted IRFFS.

Table 7. Impact estimates of IRFFS on food security

Treatment effect	Treatment category		Parametric MTE model		
	Without adoption	With adoption	Treatment effect	Boot. Std. Err	Change (%) [a]
Food consumption score (unite)					
ATE	49.43	57.71	8.28***	1.94	14%
ATT	54.31	60.77	6.46**	2.87	11%
ATUT	55.09	64.93	9.84***	2.42	15%
LATE			3.83***	1.85	
$MPRTE_1$			36.36***	6.56	
$MPRTE_2$			23.48***	4.72	
$MPRTE_3$			67.87***	15.77	
Observations			967		
Test of observable heterogeneity, p value			0.00		
Test of essential heterogeneity, p value			0.00		
Self-perception of food security status in the household (%)					
ATE	0.32	0.73	0.41***	0.03	56%
ATT	0.57	0.96	0.39***	0.04	41%
ATUT	0.54	0.96	0.42***	0.04	44%
LATE			0.46***	0.03	
$MPRTE_1$			0.38***	0.11	
$MPRTE_2$			0.24***	0.07	
$MPRTE_3$			-0.04	0.26	
Observations			967		
Test of observable heterogeneity, p value			0.00		
Test of essential heterogeneity, p value			0.00		

[a] *% change in outcome between with adoption and without adoption; *** significant at 1%; ** significant at 5%.*

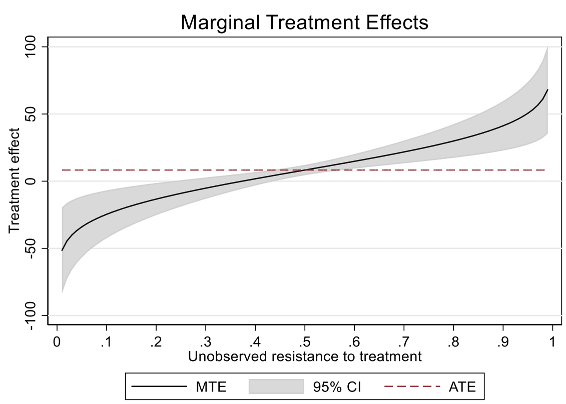

Fig. 4 Distribution of the MTE for impact on FCS

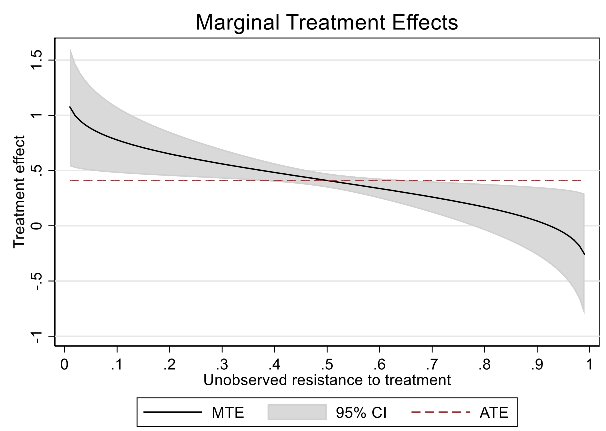

Fig. 5 Distribution of the MTE for impact on self-perception of food security status in the household

4.7. Impact of the integrated rice-fish farming technology on poverty headcount ratio

The MTE curve for the poverty headcount ratio (Fig. 6) shows that rice farmers who are most likely to adopt IRFFS experienced a significant decrease in the poverty headcount ratio. We find evidence that the adoption of the IRFFS significantly reduced the poverty headcount ratio (Table 8). The results show that adoption of the IRFFS technology reduces the poverty headcount ratio by nearly 15% in the population of treated farmers.

Table 8. Impact estimates of IRFFS on poverty headcount ratio

Treatment effect	Treatment category		Parametric MTE model		
	Without adoption	With adoption	Treatment effect	Boot. Std. Err	Change (%) [a]
Poverty headcount ratio					
ATE	0.73	0.72	-0.01	0.03	-1.4%
ATT	0.81	0.7	-0.11**	0.05	-15.7%
ATUT	0.75	0.82	0.07*	0.04	8.5%
LATE			-0.01	0.03	
$MPRTE_1$			0.22**	0.11	
$MPRTE_2$			0.22***	0.08	
$MPRTE_3$			0.85***	0.26	
Observations			967		
Test of observable heterogeneity, p value			0.00		
Test of essential heterogeneity, p value			0.00		

[a] *% change in outcome between with adoption and without adoption; *** significant at 1%; ** significant at 5%, ** significant at 10%.*

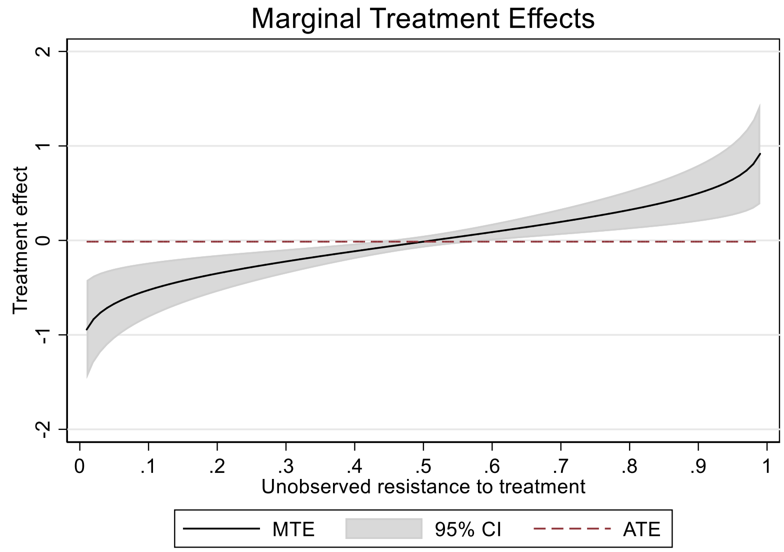

Fig. 6 Distribution of the MTE for impact on poverty headcount ratio (Parametric approach)

4.8. Impact of the integrated rice-fish farming technology on the quantity of fish consumed in the household per month

The impact of IRFFS adoption was assessed on the quantity of fish consumed in the household per month. The results show that the estimated MTE on the quantity of fish consumed in the household per month is higher among farmers who were most reluctant to adopt IRFFS. We find evidence that adoption of IRFFS increased quantity of fish consumed in the household per month for an average household in the population of rice farmers and for current adopters (Table 9). On average, a random farmer selected among the rice farmers had increased the quantity of fish consumed in their household per month by 7.92 kg (equivalent to a 31% increase) due to the adoption of IRFFS. However, nonadopters would have gained had they adopted IRFFS. MPRTE1 estimates were also significant and positive in Table 9. Treated rice farmers increased their quantity of fish consumed in their household per month by 9.89 kg.

Table 9. Impact estimates of IRFFS on quantity of fish consumed in the household per month

Treatment effect	Treatment category		Parametric MTE model		
	Without adoption	With adoption	Treatment effect	Boot. Std. Err	Change (%) [a]
Quantity of fish consumed in the household per month (kg)					
ATE	17.48	25.4	7.92***	2.81	31%
ATT	22.83	32.72	9.89 **	4.16	30%
ATUT	19.13	25.37	6.24 *	3.51	25%
LATE			5.62**	2.67	
$MPRTE_1$			23.98 **	9.50	
$MPRTE_2$			10.71	6.83	
$MPRTE_3$			21.59	22.83	
Observations			967		
Test of observable heterogeneity, p value			0.00		
Test of essential heterogeneity, p value			0.00		

[a] *% change in outcome between with adoption and without adoption; *** significant at 1%; ** significant at 5%.*

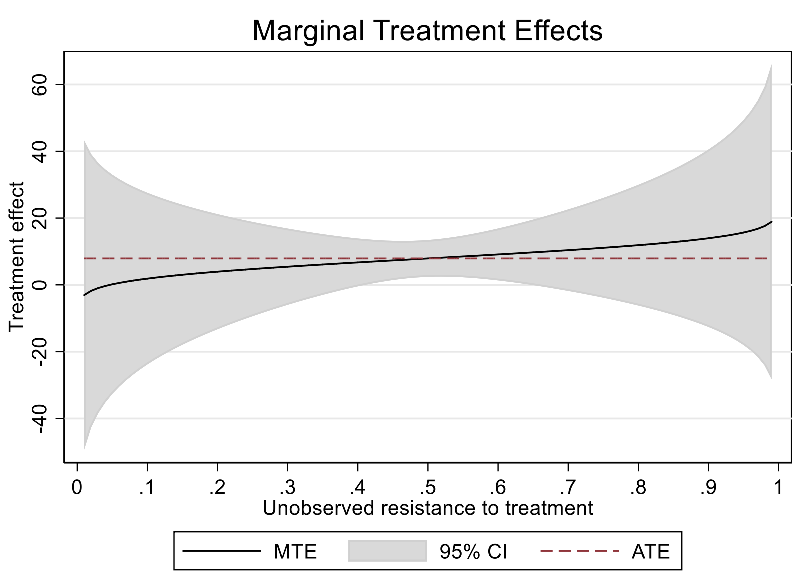

Fig. 7 Distribution of the MTE for impact on quantity of fish eat per month in the household (Parametric approach)

Conclusion

This study was conducted as part of the implementation of the "Development of Smart Innovation through Research in Agriculture (DeSIRA) initiative" in Liberia. DeSIRA initiative mainly focuses on the promotion and dissemination of Rice-fish farming systems in Liberia. The report presents the methodology used to collect and analyze data for the impact study of DeSIRA. The general objective was to assess the determinants of adoption and welfare impact of the DeSIRA initiative in Liberia. Improving poverty, food, and nutrition security situations are Liberia's and many African country's policy priorities. In this respect, the IRFFST system technology is expected to play an important role by supplying rice, fish, and vegetables together in a sustainable way in Liberia. However, to the best of our knowledge, there have not been any quantitative micro-econometric studies that examined the factors affecting IRFFS adoption and its impact on welfare in terms of rice yield, rice income, annual household income, food security and poverty status in Liberia. From a policy perspective, this is crucial since IRFFS are expected to improve the level of food and nutrition security and poverty situation in Liberia. Rice-fish farming systems have potential applications in developing countries and in adapting to climate change, making them a promising model for sustainable agriculture. This study attempts to fill this gap by evaluating the part of the outcomes of a development project that promoted integrated aquaculture-agriculture based livelihood options among the socio-economically marginalized indigenous community in Bangladesh, using cross-sectional survey data from the project areas. The project was implemented during 2020–2023 by AfricaRice-Liberia, the WorldFish, CARI and its partner organizations in Liberia.

Among the determinants of the adoption, the key determinants are access to credit, irrigation, farm size, being trained on IRFFS and access to extension services. Finally, we emphasize the need for additional in-depth research to identify the factors affecting IRFFS technology adoption and its impacts on other dimensions of welfare, food, and nutrition security in addition to those investigated here. Moreover, future research should also collect extensive amount of qualitative data in addition to the quantitative data to understand further on the adoption, diffusion, and the impact pathways of the integrated rice fish farming system in Liberia and elsewhere in Africa.

After completing the field visits, farmer interviews, field observations, relevant discussions with local authorities, and data analysis, the recommendations emerging from this survey are as follows: replicate integration rice-fish farming system all over the country; encourage private sector involvement in training of farmers in Liberia in their own certified seed production and fingerlings to increase the accessibility of seeds, improve food security and reduce poverty; provide rice-fish value chain actors with the financial resources necessary for the implementation of the different activities at the start of the agricultural season; call on policymakers to encourage and incentivize private seed producers to produce and commercialize certified seeds such as NERICA L19 to farmers (e.g. by means of subsidies), in order to improve farmers' access to improved rice seeds in Liberia; encourage and incentivize private sector in the production of fingerlings for fish production; rural infrastructure development (electricity, water, roads, etc) should also be developed to increase youth involvement in rice-fish value chain in Liberia; farmers, farmer organizations, traders (middleman), policy makers, private organizations and civil society groups can integrate for policy making and doing applied adaptive research to suit with farmers need and that will accelerate the adoption and diffusion of rice-fish technology. Government and donor organization can support self-organizing innovation systems that already developed by the local farmers in many parts of Liberia for development of rice-fish system technology; government should take some innovative policy initiatives like land reform and property rights for tenant farmers, subsidies irrigation technologies especially for resource poor farmers or expansion of public irrigation system development initiative in resource poor areas; organizational (or institutional) development like water user association, farmers group, and cooperative can help smallholders access to water and market.

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