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How does climate-smart aquaculture affect fish productivity among smallholder farmers in Kakamega County, Kenya? A multinomial endogenous switching regression

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Abstract

Climate change and its pronounced effects have greatly disfranchised the livelihoods of aquafarmers. To leverage these negative effects of climate change, climate-smart aquaculture (CSA) practices have been developed for adoption by farmers. However, it is not known whether these practices have made any meaningful contribution to farmers in terms of their livelihoods and resilience to the vagaries of climatic change. This paper examines the effects of climate-smart aquaculture practices on fish productivity in Kakamega County, Kenya. Using a multistage sampling technique, 220 respondents were selected and a multinomial endogenous switching regression was used for analysis. The paper highlights that group membership and extension services increase the propensity for adopting CSA practices. In addition, the paper underscores the importance of combining various CSA practices to enhance fish productivity. Notably, the combination of dam line use, tanks and adjusted stocking times has a substantial effect on fish productivity. The paper therefore recommends the importance of prioritising and revitalising agricultural services that accelerate the uptake of CSA practices so as to boost productivity and, ultimately, improve the livelihood of farmers.

Key words: farmers, climate-smart aquaculture, multinomial endogenous switching regression, productivity, Kakamega County, Kenya

1. Introduction

Climate change is profoundly disrupting the global fish industry and aquatic ecosystem, and threatening fish productivity. As a result, the ability of global fisheries to meet the growing global demand for fish and fish products is increasingly at risk (Das *et al*. 2020; Mendenhall *et al*. 2020; Paukert *et al*. 2021). According to Naylor *et al*. (2021), global fish demand is expected to double by 2050, exerting more pressure on the fisheries sector. With capture fisheries stagnating, attention is shifting towards aquaculture farming to bridge the demand gaps in food and nutritional adequacy (Belton *et al*. 2018; Tacon 2020; Boyd *et al*. 2022). The Food and Agricultural Organization of the United Nations (FAO) (2022) posits a need to escalate global aquaculture production to 140 million tons by 2050 to meet the increasing future demand. Global aquaculture production has continued to increase, although at a slower rate than a decade ago, raising concerns about the sustainability of this sector as a result of increasing anthropogenic activities (Ahmed *et al*. 2019; OECD/FAO 2021). This deceleration in growth poses a significant risk to the majority of the populace who rely on aquaculture for food and economic development, potentially jeopardising their livelihoods (Muringai *et al*. 2021).

Notwithstanding the importance of aquaculture farming in bridging the gap between capture fisheries production and demand, the sector has been greatly affected by climate change. The vagaries of climate change have disrupted the aquatic ecosystem on which fish depend, triggering disease outbreaks and fish deaths (Barange *et al*. 2018; Collins *et al*. 2020). Reported instances of high temperatures, salinisation, receding water levels and extreme weather events have heightened the vulnerability of aquaculture to climatic change (Mehrim & Refaey 2023; Awotunde 2024). Sub-Saharan Africa has the potential to increase aquaculture farming due to its endowment of vast aquatic resources. Despite this, the continent has been greatly affected by climatic changes, resulting in the loss of fish habitats, declining fish landings and reduced catchability, further pushing the area to a state of food and nutrition insecurity and destitution (Silas *et al*. 2020; Muhala *et al*. 2021; Ngarava *et al*. 2023).

In Kenya, fish production is estimated at 180 000 tonnes per year, with aquaculture contributing approximately 13% against a demand of about 553 000 tonnes per year (Kenya National Bureau of Statistics [KNBS] 2020). This significant gap necessitates a greater focus on aquaculture farming to achieve the recommended per capita consumption of 20 kilograms per person per year (FAO 2020). Moreover, the overreliance on imported frozen fish highlights the urgency to enhance domestic production for a sustainable and secure fish supply (Adekola *et al*. 2022; Ogello *et al*. 2022). Aquaculture farming in Kenya therefore has been identified as a means to bridge food and nutritional security and poverty gaps among rural fish farmers (Munguti *et al*. 2021). Kenya’s long-term development blueprint, Vision 2030, underscores the importance of aquaculture farming in achieving food and nutrition security in the country (Government of Kenya 2019). As a result of various policies initiated by the government in line with its economic stimulus programme and Vision 2030, there has been tremendous growth in the aquaculture sector, establishing it as a vital supplier of fish to both rural and urban areas (Kenya Marine and Fisheries Research Institute [KMFRI] 2021). Despite the numerous efforts, the sector continues to be affected negatively by climatic hazards, thereby limiting its growth rate (Adekola *et al*. 2022; Munguti *et al*. 2023).

The continued disruption caused by climate change has necessitated the evolution and validation of climate-smart aquacultural practices to equip farmers to cope with the vagaries of climate change (Onada & Ogunola 2016). A number of climate-smart aquacultural practices have been developed for adoption by fish farmers, including borehole construction, embarkment creation, adjusted stocking time, use of dam lines, use of tanks, recirculating fish systems, construction of dykes and placing ponds close to water sources, among others (Asiedu *et al*. 2017; Muringai *et al*. 2021; Ahmed *et al*.

2019; Oparinde 2021). A number of studies have recognised the need for Kenya to develop and escalate climate-smart innovations to help build a resilient aquaculture system and tap into the potential benefits of fish farming (Galappaththi *et al*. 2020; Munguti *et al*. 2023; Islam *et al*. 2024). Furthermore, Kenya has developed technologies, innovations and management practices (TIMPs) for aquaculture through the Kenya Climate Smart Agriculture Projects (KCSAP) with the intention of escalating productivity and building resilience to the vagaries of climate change affecting aquafarmers.

Fish farmers have adopted various climate-smart aquacultural practices, either on their own or in combination, to enhance resilience against climatic variabilities. However, their specific effects on productivity have remained largely unexplored. This study aims to address this knowledge gap by examining the effect of various CSA practices adopted by aquaculture farmers on fish productivity in Kakamega county, Kenya. The findings underscore how the productivity outcomes of these practices shape aquafarmers' planning, investment decisions and adoption strategies for achieving optimal results.

By addressing this critical aspect, this paper adds value to the broader discourse on food security, climate resilience and improved livelihood among fish farmers in Kenya. The rest of the paper is structured as follows: Section 2 presents the methodology; Section 3 presents the results; while conclusions and policy recommendations are presented in Section 4.

2. Materials and methods

2.1 Study area and sampling design

The study was carried out in Matungu sub-county in Kakamega County. Matungu sub-county has a total area of 367 km^2, with a population of 167 014 (KNBS 2020) The sub-county is located between longitudes 34º 52' 34.36" East and latitude 0º 39' 4.17" North. It comprises five wards: Namamali, Mayoni, Koyonzo, Kholera and Khalaba. The area receives an average annual rainfall of 1 747 mm and has an average annual temperature of 23.5°C. It records the most rainfall in the months of March, April and May, and only short rainfalls are recorded from October to November. Agriculture is the main economic activity in this area, with the major crops being maize, beans, sweet potatoes, sorghum and cassava, along with fish farming.

A multistage sampling technique was used to select fish farmers. In the first stage, Kakamega County was purposively selected, since it is one of the counties in which fish farming is a priority value chain. Secondly, Matungu sub-county was purposively selected based on its high fish production potential. In the third stage, three wards (Namamali, Mayoni and Koyonza) were purposively selected. A systematic random sampling technique then was used to select 220 respondents for interview with the help of a source list acquired from the office of the county director in the fisheries department.

Since the exact population of fish farmers in the selected wards is known, the desired sample size was derived from Yamane's (1967) approach, as shown in Equation (1).

$$n = \frac{N}{1+N(e^2)}, \tag{1}$$

where n is the sample size, Z is the confidence level ($\alpha = 0.05$), N denotes the proportion of the population of interest (fish farmers) in the study area, while E is the acceptable error (level of precision). With a population size of 489 registered fish farmers in Matungu sub-county, a sample size of 220 respondents was determined.

The study relied on primary data collected from respondents using a semi-structured questionnaire administered by well-trained enumerators. A pilot test was conducted to test the validity of the tool installed on phones as Open Data Kit (ODK). The data was then subjected to analysis using Stata software.

2.2 Econometric estimation of the effects of CSA practices on productivity

In assessing the effect of CSA practices on fish productivity in Kakamega County, a two-stage multinomial endogenous regression (MESR) model was employed following Dubin and McFadden (1984) and Bourguignon *et al*. (2007). MESR is advantageous in the sense that it allows the estimation of individual as well as joint impacts of CSA practices on productivity. The model proceeds in two stages. In the first stage, households are assumed to face a choice of *K* mutually exclusive practices to cope with changes in the climate. A multinomial logit is then used to determine the choice of CSA practices. Farmers are assumed to maximise their utility, *Yi*, by comparing the productivity that will be provided by *K* alternative CSA practices. The requirement for a farmer to choose any strategy, *j*, over other alternatives, *K*, is that $Y_{ij} > Y_{ik}$, $k \neq j$; in other words, *j* provides higher productivity than any other strategy. The study assumes that productivity is a ratio of production in kilograms per hectare, as used by Mitra *et al*. (2019), i.e. productivity = production/hectare.

Y_{ij}^{*} is a latent variable that represents the expected productivity, which contains both the observable household and pond characteristics and unobservable features, expressed as:

$$Yij^{*} = BjXi + Eij \tag{2}$$

Xi denotes the observed exogenous variables (household and pond characteristics), and the error term E_{ij} denotes the unobserved characteristics. Xi is a covariate that is assumed to be uncorrelated with the idiosyncratic unobserved disturbance term, E_{ij}, such that $E\left(E_{y}\middle|X_{i}\right) = 0$ under the assumption that E_{ij} are independent and identically Gumbel distributed, as under the independent irrelevant alternatives (IIA) hypothesis. The probability that a farmer i chooses a strategy j was specified by a multinomial logit model (McFadden 1974).

$$P_{ij} = p\left(E_{ij} < 0\middle|X_{i}\right) = \frac{\exp\left(B_{j}X_{i}\right)}{\sum_{K=1}^{j} \exp\left(B_{k}X_{i}\right)} \tag{3}$$

P_{ij} denotes the probability that individual i adopts option j, X_i is the i^{th} household's characteristics, and B_j is the vector of parameters related to option j. The second stage seeks to evaluate the effect of CSA practices on productivity. The paper adopted a multinomial endogenous switching regression model (MESR) as proposed by Bourguignon *et al*. (2007). The farm household was subjected to a number of K regimes, with regime $j = 1$ being the reference category (non-responsive). The productivity status of each possible regime is defined as:

$$\begin{array}{ll} Regime1{:}\ Q_{1R} = B_{iR}Z_{iR} + E_{iR} & if \quad i = 1 \\ \qquad\qquad \vdots \qquad\quad \vdots & \\ Regimej{:}\ Q_{inR} = B_{iR}Z_{iR} + E_{iR} & if \quad i = j \end{array}$$

In the above equation, $Q_{inR}{}'s$ represents productivity, where the i^{th} farmer is in regime j, and the error terms, $E_{iR}'{}'s$, are distributed with $E(E_{iR}|X,Z) = 0$ and variance $\left(E_{ij}\middle|X,Z\right) = \sigma_j^2$. Q_{iR} is observed if, and only if, CSA practices are used. This occurs when $Y_{ij}^* > \overset{max}{K \neq 1}(Y_{ik})$ if the error terms in regime 1 and regime j are not independent. A consistent estimation of B_{iR} requires the inclusion of the selection correction terms of the alternative options in the above equation. MESR has the following linearity assumption, provided that the correlation between the two error terms will be equal to zero.

$$E\left(U_{ij}\middle|\mathcal{E}_{i1} \dots \dots \mathcal{E}_{ij}\right) = \sigma_j \sum_{k \neq j}^{j} rj(\mathcal{E}_{ik} - E(\mathcal{E}_{ik})) \tag{4}$$

Using the above assumption, Equation (3) will be expressed as follows:

$$Regime1: Q_{i1} = Z_i\alpha_1 + \gamma_1\delta_1 \ if \ i = 1$$
$$\begin{matrix} . & . & . \\ . & . & . \end{matrix}$$
$$Regime\ j: Q_{ij} = Z_i\alpha_j + \gamma_j\delta_j \ \ if \ i = j$$

γ_j is the covariance between error terms, while δ_j is the inverse Mills ratio computed from the estimated probabilities in Equation (3), as follows:

$$\delta_j = \sum_{k \neq j}^{j} Pj[\frac{P_{ik}\ln(P_{ik})}{1-P_{ik}} + \ln(P_{ij})] \tag{5}$$

P in the above equation represents the correlation coefficient of error terms, while $\gamma_j\delta_j$ are error terms with an expected value of zero.

In the multinomial choice setting expressed earlier, there were $j - 1$ selection correction terms, one for each alternative CSA practice.

The average treatment effects due to uptake of CSA practices was computed by comparing the expected value of the outcome of adopters and non-adopters in actual and counterfactual scenarios, as determined by:

Productivity status with usage

$$E(Q_{i1}|i = 2) = Z_i\alpha_1 + \sigma_i\Lambda_2 \tag{6a}$$

$$E(Q_{i1}|i = j) = Z_i\alpha_1 + \sigma_j\Lambda_j \tag{6b}$$

Productivity status without usage

$$E(Q_{i1}|i = 2) = Z_i\alpha_1 + \sigma_i\Lambda_2 \tag{7a}$$

$$E(Q_{i1}|i = j) = Z_i\alpha_1 + \sigma_1\Lambda_j \tag{7b}$$

The average treatment effects on the treated (ATT) are defined by the difference between (6a) and (7a), which is given by:

$$ATT = E(Q_{i2}|i = 2) - E(Q_{i1}|i = 2) = Z_i(\alpha_1\alpha_2) + \Lambda_2(p_2 - p_1) \tag{8}$$

The right-hand side denotes the expected change in adopters' productivity if the adopters' characteristics had the same return as that of non-adopters.

It is important to note that the adoption of CSA practices is not a monolithic process, but rather a nuanced decision influenced by individual farmer tastes and preferences, and the application of these practices is specific to an enterprise (Oparinde 2021). Hence, farmers are likely to choose a variety of CSA practices. The multifaceted uptake pattern underscores the critical need to understand the myriad of factors driving the selection of different CSA practices when formulating policy interventions to enhance the uptake of these practices. A number of different CSA practices were adopted by the farmers, such as embarkment creation, pond covers, site selection, use of dykes, dam lines, building of ponds close to water sources, use of boreholes, use of tanks and adjusted stocking time, among others. For this paper, we focused on the utilisation of dam lines, tanks and adjusted stocking time. These specific CSA practices were singled out due to their prevalent adoption by farmers. These practices were taken up either on their own, or by combining a number of practices, depending on the farmers' own preferences.

3. Results

3.1 Descriptive statistics

The descriptive statistics of the variables considered are presented in Table 1.

Table 1: Descriptive statistics of variables used

Variables	Description	Mean
Continuous variable	**Variable description and its measurement**	
Age	Age of the decision maker in years	48.76
Education level	Years of education of decision maker	10.32
Household size	The number of members present in the household	6.34
Land size	Land size owned by the household in acres	3.92
Experience	Decision-maker farming experience	7.90
Number of ponds	Number of ponds owned by the household	1.90
Year of CSA implementation	Period in years the CSA practices have been implemented	3.80
Extension	Number of contacts with extension services	4.98
Categorical variables	**Percent**	
Gender	% of male decision makers	.62
Off-farm income	% of respondents with access to off-farm income	.48
Training	% of respondents who received CSA training	.67
Group membership	% of respondents who are members of farm groups	.65
Credit access	% of respondents with access to credit	.36
Government subsidies	% of respondents with access to government subsidies	.15

The mean age of the respondents was 49 years, suggesting that the fish farmers were active and within the productive economic age. The aquafarmers had at least 10 years of schooling, with approximately eight years of farming experience. Given their experience, it is reasonable to expect that older farmers have access to resources, and are knowledgeable and well-grounded. This could stimulate their decision to invest in aquaculture farming due to its high startup costs and the risks associated with changes in climatic conditions. Younger farmers do not have adequate resources to invest in fish farming, which serves as a plausible explanation for why they are crowded out from this venture. Oparinde (2021) found similar results regarding age and experience distribution among fish farmers in Nigeria; the majority of the farmers involved had a mean age of 50 years and seven and more years of experience.

The results on gender indicate that 62% of the respondents were male, implying that fewer females were involved in fish farming. A plausible explanation could be that fish farming requires production resources that are mostly owned by male-headed households. The findings corroborate those of Obayelu *et al*. (2014), who found that male-headed households were more involved in fish farming due to its demand for production resources and high start-up costs.

The results further reveal that 67% of the respondents had access to training and that 75% had access to subsidies, thus pointing out why they had adopted different CSA practices in fish farming. A reasonable explanation could be that training accelerates information diffusion among fish farmers, therefore increasing the ease with which a certain practice is incorporated into fish farming. Furthermore, access to government subsidies leverages the pressure on production costs, hence necessitating the practice of fish farming. The results are in agreement with Tanti *et al*. (2022), who posited that training and access to subsidies were the key elements that influenced farmers' involvement in farming.

3.2 The CSA practices adopted among fish farmers in Kakamega County

The results of various CSA practices adopted by fish farmers are presented in Table 2. The results show that aquafarmers adopted both single CSA practices, and combinations of others. Twenty-five percent of the farmers adopted a combination of dam lines and use of tanks (Dam_Tank), 29% of the farmers adopted the use of dam lines, 12% adopted the use of adjusted stocking time, 5% implemented a combination of dam lines, use of tanks and adjusted stocking schedule (Da_Ta_St), and 5% of the farmers adopted the combination of dam line and adjusted stocking schedule (Dam_Stock). A scrutiny of Table A1 in the Appendix shows that 75% percent of fish farmers used at least a certain combination in the production process. The majority of the farmers used the combination Dam_Tank and dam lines, while a few used the combination Da_Ta_St and Dam_Stock.

Table 2: CSA practices adopted by fish farmers

Combinations	Frequency	Percent	Cumulative
Adjusted stocking time	26	11.82	11.82
Da_Ta-St	12	5.45	17.22
Dam_Stock	10	4.55	21.82
Dam line	63	28.64	50.45
Dam_Tank	54	24.55	75.00
Non_Adopters	55	25.00	100.00
Total	220	100.00	

3.3 Determinants of factors influencing the choice of CSA Combinations among fish farmers

The results of the multinomial endogenous switching regression are presented in Table 3. This is a two-step model in which the results of a multinomial logit model (MNL) are presented in the first part, showing the results of the factors that influence the choice of different CSA combinations. The marginal effects of the multinomial logit model are presented. These posit the expected change in the choice of CSA practices due to a unit change in the independent variables. The second phase shows the treatment effects of CSA practices on productivity.

Education had a significant positive effect on the choice of combination involving the use of dam lines and tanks (Dam_Tank) at the 1% level. Educated farmers were more likely to use the Dam_Tank combination compared to non-users of any package. An increase in one year of schooling increases the probability of choosing this combination by 2%. Sardar *et al*. (2021) observed that farmers with a high level of literacy are better equipped to navigate the challenges posed by climatic variability.

They are more adept at accessing and evaluating information, enabling them to implement CSA practices that align with their individual preferences.

Table 3: Marginal effects of the determinants of choice of CSA practices

Variable	**Adj_stock**		**Dam_Stock**		**Da_Ta_St**		**Dam_Tank**		**Dam liner**	
	Dy/dx	P-value	Dy/dx	P-value	Dy/dx	P-value	Dy/dx	P-value	Dy/dx	P-value
Age	-.001	0.791	-.000	0.802	.002	0.778	-.001	0.778	-.003	0.284
Gender	-.019	0.737	.026	0.439	-.001	0.971	.034	0.588	.034	0.623
Education	-.005	0.531	-.005	0.199	.000	0.880	.021	0.014**	-.000	0.980
Group mshp	.000	0.993	.002	0.709	.010	0.000***	.011	0.126	-.018	0.124
Land size	-.006	0.632	-.003	0.577	.000	0.932	-.005	0.719	-.013	0.339
Experience	.001	0.059*	.000	0.146	.003	0.026**	-.000	0.434	.000	0.571
HH_size	-.024	0.275	-.033	0.047**	-.028	0.066*	.044	0.007***	.007	0.697
No_ponds	.014	0.553	-.016	0.455	-.035	0.077*	-.015	0.714	-.036	0.479
Subsidies	.065	0.419	.021	0.621	.018	0.724	.110	0.143	-.121	0.163
Stocking density	.000	0.247	-.000	0.351	.003	0.008***	.000	0.431	.000	0.085*
Extension	.003	0.609	-.000	0.424	.001	0.704	.004	0.644	.002	0.044**
Credit access	-.000	0.560	.000	0.149	.000	0.292	.000	0.158	-.000	0.710
Training	-.051	0.356	.035	0.453	.131	0.014**	.006	0.922	-.010	0.899
Distance	.004	0.148	-.002	0.115	.001	0.427	.003	0.922	.004	0.415

Notes: *, ** and *** represent significance at the 10%, 5% and 1% levels respectively; non-adopters were used as a base category; mshp = membership

The findings show a statistically significant and positive correlation between group membership and the adoption of a combination of dam lines, tanks and adjusted stocking time (Da_Ta_St), at the 1% level. Membership of a group enhances the likelihood of adoption of this combination among aquafarmers by 10%. This can largely be attributed to the role of group membership in facilitating access to credit through pooling resources, thereby potentially expediting the adoption of CSA practices. These results are in line with the findings of Oparinde (2021), who indicated that group membership enhances easy access to resources and knowledge sharing, resulting in increased adoption of CSA practices among adopters compared to non-adopters.

Farming experience had a positive and significant influence on the choice of adjusted stocking time, at 10%, and of the combination Da_Ta_St, at the 5% level. Experienced farmers were more likely to use this combination as opposed to the non-use of any combination. The probability of using adjusted stocking time and the Da_Ta_St combination increases by 1% and 3% respectively for experienced farmers. This is likely because experiential knowledge allows them to adopt and redefine their approaches over time (Do & Ho 2022). They furthermore are better equipped to anticipate and manage risks associated with climatic variability, drawing on their past experiences to make informed decisions on the adoption of CSA practices. Notably, Ojo and Baiyegunhi (2020) posit that experiential knowledge has a significant influence on the uptake of climate change adaptation strategies.

The study revealed that the size of a household has a varying effect on the adoption of different combinations. It is negatively related to the choice of Dam_Stock and Da_Ta_St, while positively related to the choice of Dam_Tank. An increase in the household size by one member reduces the probabilities of adopting Dam_Stock and Da_Ta_St, by 33% and 28% respectively. On the other hand, the size of the household increases the likelihood of selecting Dam_Tank, by 44%. Large households are faced with decision-making dynamics that can either facilitate or impede the adoption of these combinations, depending on the level of consensus and preferences at the level of the family unit. In addition, large households may have access to a broader social network, potentially increasing their exposure to information about CSA practices and credit access. The results are in line with the findings of Onyenekwe *et al*. (2023), who pointed out that large households are inclined to implement multiple climate adaptation strategies as a precautionary measure against adverse climatic events.

The number of ponds owned by fish farmers was negatively correlated with the uptake of the Da_Ta_St combination. An increase in the number of ponds by one reduces the probability of adopting this package by 35%. It therefore follows that farmers with a large number of fish ponds have little capacity to use this combination compared to the non-usage of any combination. This is due to increased opportunity costs associated with managing multiple ponds, which require a significant amount of capital, effort and time. This potentially limits their capacity to invest in this combination. In contrast, Oparinde (2021) noted that the number of fish ponds owned by farmers resulted in an increased uptake of climate smart aquaculture practices.

The results show a positive and significant relationship between the stocking density of fingerlings and the likelihood of adopting the Da_Ta_St combination and the use of dam lines, with probabilities at the 1% and 5% levels respectively. An increase in the quantity of fingerlings stocked increased the probability of using these combinations, by 0.3% and 0.01% respectively. This is most likely because the uptake of these practices reduces the risks associated with losses, making CSA practices necessary. These assertions find support in a study conducted by Mensah *et al*. (2024), who reported that stocking density influenced the adoption of climate smart aquaculture insurance products among smallholder fish farmers.

The number of extension services to which fish farmers have access positively and significantly influences their preference for a combination that involves the choice of dam lines. Notably, an increase by one in the number of extension contacts received has a probability of influencing the choice of this combination by 2%, holding other factors constant. Extension services increase information sharing and knowledge transfer among farmers. Informed farmers stand a better chance of adopting a number of CSA practices and technologies that are intended to protect them against climatic variabilities. Kolapo and Kolapo (2023) argue that the propensity of adoption of agricultural technology is positively influenced by information services offered by extension workers to farmers.

There is a positive and significant relationship between training and the adoption of the Da_Ta_St combination at the 5% level. It seems that an increase in the number of times fish farmers have access to training increases the probability of choosing CSA practices by users of this combination by 13%, opposed to non-usage of any combination. Training escalates the level of awareness and capacity building, which are a prerequisite for the adoption and implementation of CSA practices. Through training farmers, are able to understand the overall benefits associated with the adoption of climate smart practices (Ahmed *et al*. 2023).

3.4 Effects of CSA practices on productivity

The second stage of MESR revealed the effects of CSA practices on productivity. The results are presented in Table 4. Productivity is defined as a ratio of fish output to the area of fish ponds in hectares. The average treatment effect on the treated (ATT) and average treatment effects on the untreated (ATU) were both positive and negative, suggesting that fish farmers realise both high and low productivity, depending on the CSA combination adopted. The results show that there is a significant increase in productivity among aquafarmers who use the following CSA practices: adjusted stocking time, dam line, and the combination involving the use of dam lines, tanks and adjusted stocking time (Da_Ta_St).

Table 4: Effects of CSA packages on fish productivity

		Productivity	
Combination		**Treated**	**Untreated**
Adjusted stocking time	Treated	7 265.04	6 783.05
	Untreated	6 579.63	6 624.47
	Level effect	686.42 *	158.58
Da_Ta_St	Treated	12 656.96	8 991.00
	Untreated	6 455.69	7 011.45
	Level effect	6 201.27 ***	1 979.56***
Dam_Tank	Treated	6 321.69	6 564.42
	Untreated	6 425.41	7 066.22
	Level effect	-103.72	-501.80***
Dam line	Treated	7 171.38	6 974.75
	Untreated	6 580.23	6 645.84
	Level effect	592.15 *	328.91
Dam_Stock	Treated	6 212.13	4 702.69
	Untreated	6 988.91	6 754.63
	Level effect	-776.73	-2 046.96

Note: * and *** represent significance at the 10% and 1% levels respectively

Among the fish farmers who adopted different combinations, high productivity (ATT) was reported among farmers who used Da_Ta_St, at 6 201.27 kg/ha, followed by Adj_stock, at 686.42 kg/ha, and lastly dam liner, at 592.15 kg/ha. Thus, aquafarmers may increase their productivity if they apply CSA practices both on their own and in combination. Based on the results, higher synergy was derived from the utilisation of a consortium of different CSA practices than from a single practice. In the counterfactual scenario, productivity would be 1 979.56 kg/ha higher if farmers adopted Da_Ta_St. Some farmers, however, will be worse off if they adopt the Dam_Tank combination, as it would reduce their productivity (ATU) by 501.80 kg/ha, suggesting that the uptake of other CSA practices is a better option.

4. Conclusions and recommendations

Aquaculture serves as a critical response to the rising demands for fish, uplifts fish farmers' livelihoods and bolsters economic growth, particularly in the context of climate change. Climate smart aquaculture has emerged as a pivotal strategy to mitigate the risks posed by climate change. Therefore, this paper sought to investigate the effects of climate smart aquaculture practices on fish productivity utilising data collected from Matungu sub-county, Kakamega County.

The study asserts the significant contribution from adopting different combination of CSA practices to enhance fish productivity. However, not all combinations result in high productivity. High productivity is realised through the uptake of CSA practices that involve the use of the Da_Ta_St combination, as well as the use of dam lines and adjusted stocking time, while the use of Dam_Tank presents a disutility. Furthermore, the findings indicate that the propensity for choosing CSA practices is influenced by education, group membership, experience, household size, number of ponds, fish stocking density, extension services and training. Moreover, the study underscores the significant contribution of adopting various combinations of CSA practices to enhancing fish productivity. High productivity is found when CSA practices are adopted in combination.

This study underscores the importance of developing a robust framework to revitalise aquaculture and improve the capacity building of fish farmers through knowledge diffusion that is escalated by education, access to extension services and training. It is further important to foster social networks among fish farmers by encouraging the formation of farmer groups. This will help encourage the adoption of CSA practices, thus mitigating the effects of climate change and boosting fish productivity.

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Appendix

Table A1: Model variables hypothesised on the influence of CSA on productivity

Variable	**Description**	**Measurement**	**Sign**
Dependent			
Productivity	Productivity of fish	Ratio of production to area of pond in metres	
Independent			
Age	Age of household head in years	Continuous	+/-
Gender	Household gender (male = 1, female = 0)	Dummy	+/-
HH size	The size of the household	Continuous	+/-
Level of education	Number of years spent in school	Continuous	+/-
Experience	Experience of farmers in years	Continuous	+/-
Off-farm income	Income from non-farm activities	Continuous	+/-
Training	Number of times training received in a year	Continuous	+/-
Credit account	Whether fish farmers have access to credit	Dummy (1 = yes, 0 = otherwise)	+/-
Number of ponds	Number of ponds owned	Continuous	+/-
Stocking density	Number of fingerlings stocked in a pond	Continuous	+/-
Source of seed	Source of the fingerlings used	Dummy (1 = government hatchery, 2 = private, 3 = both)	+/-
Duration of practice	Number of years CSA has been used	Discrete	+/-
Extension	Whether fish farmers access extension services	Dummy (1 = yes, 0 = otherwise)	+/-
GMSHP	If farmers belong to a fish farmer association/group	Dummy (1 = yes, 0 = otherwise)	+/-
Pond size	The size of the pond (in square metres)	Continuous	+/-
Labour	Number of adults present in the HH	Continuous	+/-
Government subsidies	Access to government support programmes	Dummy (1 = yes, 0 = otherwise)	+/-