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Diversification strategies have a stabilizing effect for income and food availability during livelihood shocks: Evidence from small-scale aquaculture-agriculture systems in Myanmar during the COVID-19 pandemic

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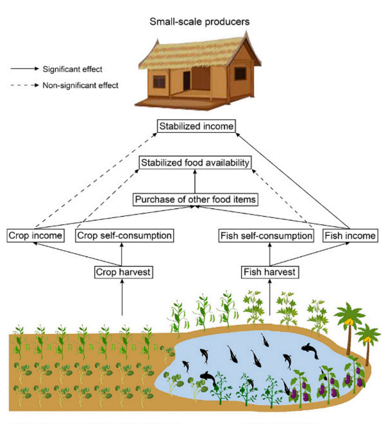
HIGHLIGHTS

- Elicited the multivariate pathways linking diversification practices and coping against livelihood shocks
- Unraveled how diversification strategies helped cope with COVID-19 pandemic through structural equation modeling
- Isolated effects of different diversification practices among small-scale aquaculture-agriculture producers in Myanmar
- Polyculture and integrated aquaculture-agriculture systems stabilized income, food availability or both during the pandemic
- Higher food availability stabilization came through purchase of food items from higher income, rather than self-consumption

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: Diversification is an important strategy used by millions of small-scale food producers globally to improve yields, farm profitability, and food security. Diversification can also enable small-scale producers to cope better with livelihood shocks. However, it is not always clear through which pathways diversification

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Food security
Income
COVID-19 pandemic

practices can stabilize livelihoods and food security in small-scale production systems, especially in the context of the recent COVID-19 pandemic.
OBJECTIVE: In this study we examined whether and how diversification practices stabilized income and food availability in small-scale food production systems during the COVID-19 pandemic. The diversification practices explored in this study included fish polyculture and integrated aquaculture-agriculture (IAA), and their combination. We compared small-scale systems employing different combinations of these diversification strategies, with systems that did not contain them.
METHODS: We analyzed 300 surveys of small-scale aquaculture producers in Myanmar. Structural equation modeling was applied to examine the multivariate relationships between the adoption of diversification practices among the small-scale producers, and whether and how the adoption stabilized their livelihoods during the COVID-19 pandemic in Myanmar.
RESULTS AND CONCLUSIONS: We find that the integration of diversification practices in different small-scale aquaculture-agriculture (SSAA) production systems had generally positive effects for the stabilization of income, food availability or both during the COVID-19 pandemic. The novelty of the study is the unraveling of the differentiated pathways between production models that enabled these stabilization processes emerge. We find major divergences in the stabilization potential between polyculture and IAA, both in terms of the magnitudes of the stabilization effects and the pathways. Polyculture generally offered more significant stabilizing effects than IAA. Surprisingly the highest and more significant positive effects for the stabilization of food availability came through the purchase of food items from extra fish/crop income, rather than their increased self-consumption.
SIGNIFICANCE: Overall, the SSAA production systems combining different diversification practices could form proactive strategies to help small-scale food producers cope with livelihood shocks.

1. Introduction

Diversification practices are used by millions of small-scale food producers globally for subsistence purposes (Ciaian et al., 2018), sales of farm output (Meraner et al., 2015) or both (Anderzén et al., 2020). In general, diversification refers to the strategy of adopting multiple production activities or practices to achieve some production goals, whether increasing yields/productivity, gaining access to specific markets and/or stabilizing farm output against production shocks (Thomas et al., 2021; Van Der Ploeg et al., 2009). There are many different examples of diversification practices among small-scale farmers (Beillouin et al., 2019; Bellon et al., 2020), pastoralists (Wang et al., 2019) or aquaculture producers (Karim et al., 2011; Wang et al., 2023).

Diversification has been shown to have many benefits for small-scale food producers. For example, several studies have found that diversification can increase yields (Wang et al., 2023) and have positive effects on livelihoods (Anderzén et al., 2020) or food security (Bellon et al., 2020). Furthermore, diversification can have environmental benefits by conserving biodiversity (Sánchez et al., 2022) or promoting the provision of multiple ecosystem services from agroecosystems (e.g. nutrient cycling, soil fertility, water regulation, pollination, pest control) without compromising yields (Tamburini et al., 2020).

Importantly for this paper, diversification is a promising strategy against livelihood shocks[1] caused by climatic extremes (Altieri et al., 2015; Arslan et al., 2018) or pest outbreaks and pathogen transmission (Feliciano, 2019). Furthermore, diversification could reduce the vulnerability of small-scale producers to broader systemic shocks, such as sudden market price fluctuations or changes in government policies (Schroth and Ruf, 2014). Studies have pointed to the benefits of on-farm diversification during seasonal income and food shortages (Anderzén et al., 2020), or unexpected events such as the COVID-19 pandemic (Kuuwill et al., 2022).

More specific to our study, diversification is practiced by millions of small-scale aquaculture-agriculture (SSAA) producers in developing countries (Short et al., 2021; Wang et al., 2023), through practices such as fish polyculture and integrated aquaculture-agriculture (IAA). In particular, these diversification practices refer to species diversification, namely, the production of multiple fish and crop species (FAO, 2016), rather than technical diversification through, for example, the adoption of better management practices (BMPs). Specifically, polyculture encompasses a large family of aquaculture models that rely on the simultaneous production of two or more fish species in a single production system (e.g. pond) (Thomas et al., 2021). IAA encompasses production models that combine two or more aquacultural and agricultural activities to integrate resource flows (e.g. material, energy) between the fish and crop production sub-systems to improve productivity (Murshed-E-Jahan and Pemsl, 2011; Thomas et al., 2021). The adoption and sustained implementation of such diversification practices can increase fish yields (Dey et al., 2010), promote farm profitability (Tran et al., 2020), improve food access (Tran et al., 2020), and enhance dietary diversity and income through self-consumption and sales of fish and crop products (Ahern et al., 2021). Diversification practices have also been linked to positive environmental outcomes such as improved nutrient use efficiency (Wang et al., 2023), and reduced water scarcity risk (Ahmed et al., 2014).

Furthermore, several studies have suggested that aquaculture diversification practices can help households cope with livelihood shocks (Nadarajah and Eide, 2020; Tran et al., 2020). This is particularly important considering the high exposure and sensitivity of millions of SSAA producers in developing countries to natural and human-induced livelihood shocks related to long-term climate change, extreme weather events, disease outbreaks, policy changes, economic downturns, and even pandemics (Gephart et al., 2017; Lebel et al., 2021; Short et al., 2021; Leung and Bates, 2013; Tran et al., 2020). For example, climatic events such as floods, droughts, and rainfall/temperature fluctuations have been shown to affect fish reproduction, grow-out operations, and parasite infestation (Ahmed and Diana, 2016). Disease outbreaks could cause high cumulative fish mortality, having significant ramifications for fish production and food security (Leung and Bates, 2013). More recently the COVID-19 pandemic has been recognized as one of the greatest shocks and disruptions to SSAA producers in recent memory in many parts of the world (Islam et al., 2021; Short et al., 2021). For example, the containment measures disrupted access to ponds and broader aquaculture/agriculture input and product logistics, and decreased market demand and prices, leading on many occasions to reduced fish/crop production, income, and food availability (Belton et al., 2021; Lebel et al., 2021). The outcomes of the livelihood shocks outlined above are often exacerbated by the fact that many SSAA producers live in regions characterized by high poverty rates, few off-farm income and employment opportunities, and high vulnerability to labor market disruptions (Boughton et al., 2021; Kang et al., 2021). Moreover,

[1] For the purpose of this study, livelihood shocks refer to expected or unexpected disruptions caused by natural or human-induced factors that significantly affect the ability of small-scale producers to maintain their normal livelihoods from food production.

many SSAA producers broadly lack access to improved farm technologies and rely on poor infrastructure and mechanization services (Htoo et al., 2021; WorldFish, 2018).

To address some of the aforementioned challenges posed by livelihood shocks, there have been calls to enhance the capacity of SSAA producers to proactively adopt and implement diversification practices (Short et al., 2021; Tran et al., 2020). However, there are many major knowledge gaps at the interface of SSAA systems, diversification, and livelihood shocks. First, despite some evidence that SSAA diversification practices can stabilize livelihoods against weather shocks (Tran et al., 2020), climate change (Nadarajah and Eide, 2020), and seasonal food insecurity (Ahmed and Garnett, 2011), there is a general lack of robust evidence about the actual mechanisms through which this stabilization happens. Most studies exploring diversification performance in SSAA systems, tend to examine the direct relationships between diversification and single outcomes such as food security (Wang et al., 2023), and adaptive capacity (Tran et al., 2020). However, there is a lack of robust empirical studies examining the multiple pathways (multivariate relationships) linking diversification adoption, SSAA production, and livelihood shocks.[2] Second, there is generally very little literature on whether and how diversification practices stabilized the livelihoods of small-scale food producers during the COVID-19 pandemic, especially for SSAA systems in developing countries.

In this paper, we aimed to bridge these gaps by examining the multivariate relationships between the adoption of diversification practices by SSAA producers, and whether and how such practices enabled them to cope with livelihood shocks. Here we isolated the effects of different diversification practices in households that engage in SSAA production. The main novelty of this study is that beyond simply exploring the effects of individual diversified production models on individual livelihood outcomes, we unraveled the multivariate pathways of how these manifested. This can shed light on how diversification strategies mediate livelihood shocks and help small-scale producers cope with them, especially in SSAA contexts in developing countries that are quite understudied.

We used a structural equation modeling (SEM) approach, populated with primary data collected through a survey of SSAA producers in several rural areas of Myanmar (Section 2). Individual objectives include to (a) describe the most prevalent diversification practices and determinants of diversification adoption in the study area (Section 3.1), (b) assess the livelihood outcomes of different diversification practices, and examine what factors affect these outcomes (Section 3.2), and (c) unravel whether and how (i.e. pathways) diversification practices stabilized income and food availability during the COVID-19 pandemic (Section 3.3). Finally, we critically discussed the differentiated pathways from diversification to livelihood stabilization, as well as whether diversification practices can indeed form proactive strategies against livelihood shocks in Myanmar and elsewhere (Section 4).

2. Materials and methods

2.1. Research approach

In this study we focused on polyculture and IAA, which are the two SSAA diversification practices most commonly adopted in our study area of Myanmar. These diversification practices are also quite popular among SSAA producers in many other developing contexts (Ahmed and Garnett, 2011; Dey et al., 2010; Karim et al., 2011; Limbu et al., 2017). In particular, we explored whether and how the adoption of these diversification practices contributed to the stabilization of household livelihoods during a livelihood shock, namely the COVID-19 pandemic (Fig. 1). As our focus is on the pathways that mediate these stabilization processes, we focused on households that already performed small-scale aquaculture (Section 2.2), rather than comparing households that had adopted aquaculture with households that had not adopted aquaculture.

We used the SEM approach to show how the adoption of these diversification practices contributed to a series of intermediate and final outcomes associated with livelihood stabilization, which were identified through a literature review (Dam Lam et al., 2022; Short et al., 2021; Tran et al., 2020). The intermediate outcomes include fish/crop harvest, fish/crop income, fish/crop self-consumption, and purchase of other food items. The final outcomes are the stabilization of income and food availability during the COVID-19 pandemic.

Following a review of the literature we identified three hypothetical pathways that lead to the stabilization of income and food availability (see also Fig. 1). Key here is that diversification practices enable the production of multiple crop and fish species, which in turn enable farmers to target different markets and/or meet many of their nutritional needs through self-consumption. By virtue of being able to tap into multiple fish and crop species for selling and self-consumption, the SSAA producers using diversification practices have theoretically a better capacity to meet their income and nutritional needs if shocks disrupt some of the channels used to produce food, sell farm output, and/or buy food.

In more detail (Fig. 1), the first hypothetical pathway leads to the stabilization of food availability via higher fish/crop production and self-consumption among diversified farmers. The second hypothetical pathway leads to the stabilization of income via increases in fish and/or crop production, and related sales among diversified producers. The third hypothetical pathway leads to the stabilization of food availability via increased farm income and a better ability of diversified producers to purchase food from external markets.

However, there are certain on-the-ground realities that complicate the robust elicitation of these effects and pathways. First, it is not uncommon for SSAA producers to adopt multiple diversification practices within the same farm (Wang et al., 2023). This can complicate efforts to isolate the effect of individual diversification practices. Second, it is not uncommon even in the same geographic area for SSAA producers to have differentiated capacity to properly implement SSAA systems, including diversification practices (Limbu et al., 2017). This latter reality might create uncertainties in areas where knowledge and capacity differentials exist.

To reduce to the extent possible the effect of capacity differentials (e.g. asset base, location-specific issues), we selected SSAA producers that had benefited from a recent intervention that provided information and materials/resources to improve their aquaculture performance (see Section 2.2). As all SSAA producers within the study sample had received the same training and support, arguably some of the knowledge and capacity differentials were bridged. Furthermore, we conducted a redundancy analysis (RDA) to identify possible effects of characteristics associated with capacity such as exposure to the intervention, years of aquaculture experience, and access to off-farm income and credit (Section 2.4.2). To isolate the effects of individual diversification practices we divided the sampled SSAA producers into different group combinations (see Section 2.4.2).

2.2. Study site

Small-scale aquaculture has increased in importance in many countries of South and Southeast Asia, where the sector presents a great opportunity to improve rural livelihoods and food security (Aung et al., 2021; Dam Lam et al., 2022). Myanmar is one of the largest aquaculture producers globally. In 2021 it ranked as the 9th largest aquaculture fish producer in the world, and the 7th largest finfish producer (FAO, 2022). Despite the steady increase of aquaculture exports in the past decades, most aquaculture output (roughly 80%) is still consumed domestically (Belton et al., 2018; Belton et al., 2015). Currently, most freshwater fish

[2] It should be pointed out that when exploring such pathways it is important to also consider some of the household and farm characteristics mediating the expected outcomes (Aung et al., 2021; Lebel et al., 2021).

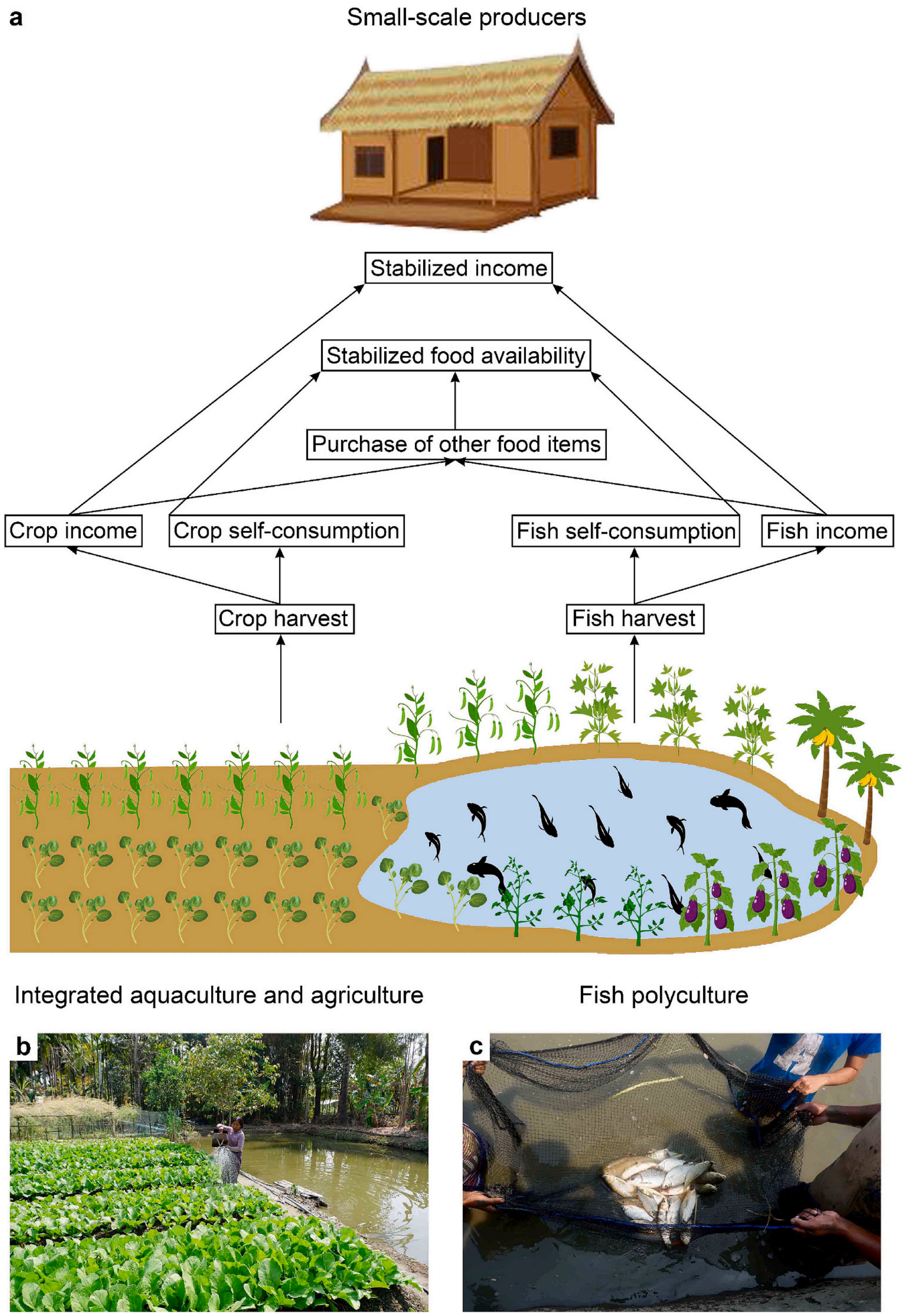


Fig. 1. Possible pathways through which SSAA diversification strategies stabilize livelihoods against shocks (a), and common diversification strategies in Myanmar (b-c). The most prevalent diversification practices considered in this study include integrated aquaculture-agriculture (IAA) (b) and fish polyculture (c). Photo credit: the authors.

production in Myanmar comes from large farms (Karim et al., 2020), but the small-scale sector has been expanding rapidly in the past decades (Aung et al., 2021).

SSAA producers are scattered across Myanmar, especially in rural areas, and usually adopt traditional management approaches and technologies that rely on the cultivation of native carp species with semi-intensive models (Karim et al., 2020). Diversification practices such as polyculture, pond-based IAA, and rice-fish farming systems are widespread in some areas, but overall adoption rates remain relatively low (Aung et al., 2021; Wang et al., 2023). Furthermore, the adoption and performance of diversification practices depend on information access, farm group membership, and extension services (Aung et al., 2021), among others.

The growth of small-scale aquaculture in Myanmar has been partly driven by interventions and support from international organizations (Htoo et al., 2021; WorldFish, 2018). However, many small-scale producers still struggle to sustain food and income (Karim et al., 2020) due to several challenges that form the backdrop of this expansion, namely contradictory land use policies, unplanned growth of small-scale farms, poorly developed domestic markets, and lack of improved farming technologies (Aung et al., 2021). This makes small-scale producers quite sensitive to livelihood shocks, especially during critical months of the production cycle characterized by income and food shortages (Karim et al., 2020). In this context it is not surprising that the containment measures implemented during the COVID-19 pandemic (which contributed to a severe recession[3] and market disruptions) affected many small-scale producers (Belton et al., 2021).

This combination of a growing small-scale aquaculture sector with a high prevalence of diversification practices and experiencing the negative outcomes of the COVID-19 pandemic provides an ideal context to understand whether and how diversification strategies stabilized livelihoods against livelihood shocks caused by the COVID-19 pandemic.

As outlined in Section 2.1 to avoid the possible effects of capacity differentials we decided to study SSAA producers that had experienced the same intervention. In particular this study was done at the margins of a larger impact assessment study of a development intervention (MYSAP Inland). Box. S1 in the Supplementary Material summarizes the characteristics of the intervention, which was implemented between 2018 and 2020. During the time of the pandemic (2020−2021) extension support and training services were sustained through virtual means such as Teams, Zoom, and Viber (Htoo et al., 2021).

The intervention provided SSAA producers with season-long extension and training services including (a) supply of quality fish seeds and crop seeds, (b) training on better management practices (BMPs), and (c) training on improved household nutrition practices. For (a) the main focus, diversification, was fish polyculture and integrated agricultural activities on pond dikes or home gardens (i.e. IAA). For (b), BMPs refer to a range of technical options that producers can deploy to improve aquaculture sustainable production in site-specific conditions (Tucker and Hargreaves, 2008; Wang et al., 2023). The training services provided ten individual BMPs for beneficiaries (Table S1, Supplementary Material). For (c), households received training on how to improve household nutrition such as the benefits of balanced and diverse diets.

The intervention was provided to a total of 1504 direct beneficiary households that had ponds <0.5 acres across three distinct phases: 2018–2019 (Season 1), 2019–2020 (Season 2), and 2020–2021 (Season 3). The intervention mainly focused on the townships of Kale, Shwebo, and Kengtung which share largely similar characteristics (Fig. 2). For example, these areas have sufficient agricultural land and water areas that provide sufficient resource endowment for SSAA production systems. These townships are also largely rural with a population that engages in the primary sector. In addition, nationwide and local restrictions due to COVID-19 were imposed in the study areas in 2020, which posed threats to farm production and household livelihoods (Boughton et al., 2021).

2.3. Data collection

For our analysis, from the 1504 MYSAP beneficiary households we excluded the 414 households that received the intervention in 2020–2021 (Season 3), as this period overlapped with the survey recall year (2020). We also excluded 25 beneficiaries from Pinlaung township due to its small sample size. In the end, the final sample contained 1065 beneficiaries located in Kale ($n = 260$), Shwebo ($n = 428$), and Kengtung ($n = 377$). We then followed a proportionate distribution rule to divide 300 surveys (the sample of this analysis) across the different townships as follows: Kale ($n = 74$), Shwebo ($n = 120$), and Kengtung ($n = 106$) (see Table S2 in Supplementary Material). To select the specific households in each township we created three household lists (one for each township) and generated a random number for each household in a given list using the *RAND* function in Microsoft Excel. We contacted households to participate in the survey in descending order in each list until we met the sample numbers for each township, as specified above. If a household was not available or willing to participate in the survey, we moved the next household in each randomized list.

The households that agreed to participate were surveyed through a detailed structured questionnaire consisting of modules eliciting (a) household and farm characteristics, (b) characteristics of production models (i.e. polyculture, IAA, BMPs), (c) fish/crop production, income, and consumption, (d) household income and expenditure, and (f) perceived effects of COVID-19 pandemic on income and food availability.

Data were collected between 15th March and 2nd April 2021. Due to the ongoing COVID-19 restrictions and security situation in some areas following the February 2021 coup, 24.67% of households (n = 74) were surveyed through face-to-face interviews and 75.33% ($n = 226$) were interviewed by phone. The data were captured by trained enumerators in Burmese and digitized in tablets using the data collection platform *Kobotoolbox*.

2.4. Data analysis

2.4.1. Analytical variables

The main variables used in this study contain a combination: (a) intermediate outcomes, (b) final outcomes, (c) production models, and (d) household and farm characteristics (see also Section 2.1). Table 1 contains the variables and units, and provides summary statistics for the entire sample.

For intermediate outcomes we included variables that reflect household fish and crop production. First, in terms of fish production, we estimated the total fish harvest (kg yr^{-1}), fish income (USD yr^{-1}), and fish self-consumption (kg yr^{-1}) for all harvested fish species from all household ponds in 2020 (12 months). Second, in terms of crop production, we aggregated the total crop harvest (kg yr^{-1}), crop income (USD yr^{-1}), and crop self-consumption (kg yr^{-1}) for all harvested crop species from pond dikes and/or home gardens in 2020 (the agricultural production from other plots was excluded). For the production, sales, and self-consumption of fish and crops, respondents reported this information for each individual fish and crop species produced during the previous production cycle using a 12-month recollection period and were then aggregated. We also considered the purchase of other food items (USD yr^{-1}) as an intermediate outcome that might be affected through increases in fish and crop income. We captured the cost of purchased food items through questions about the annual expenditure of food items in 2020.

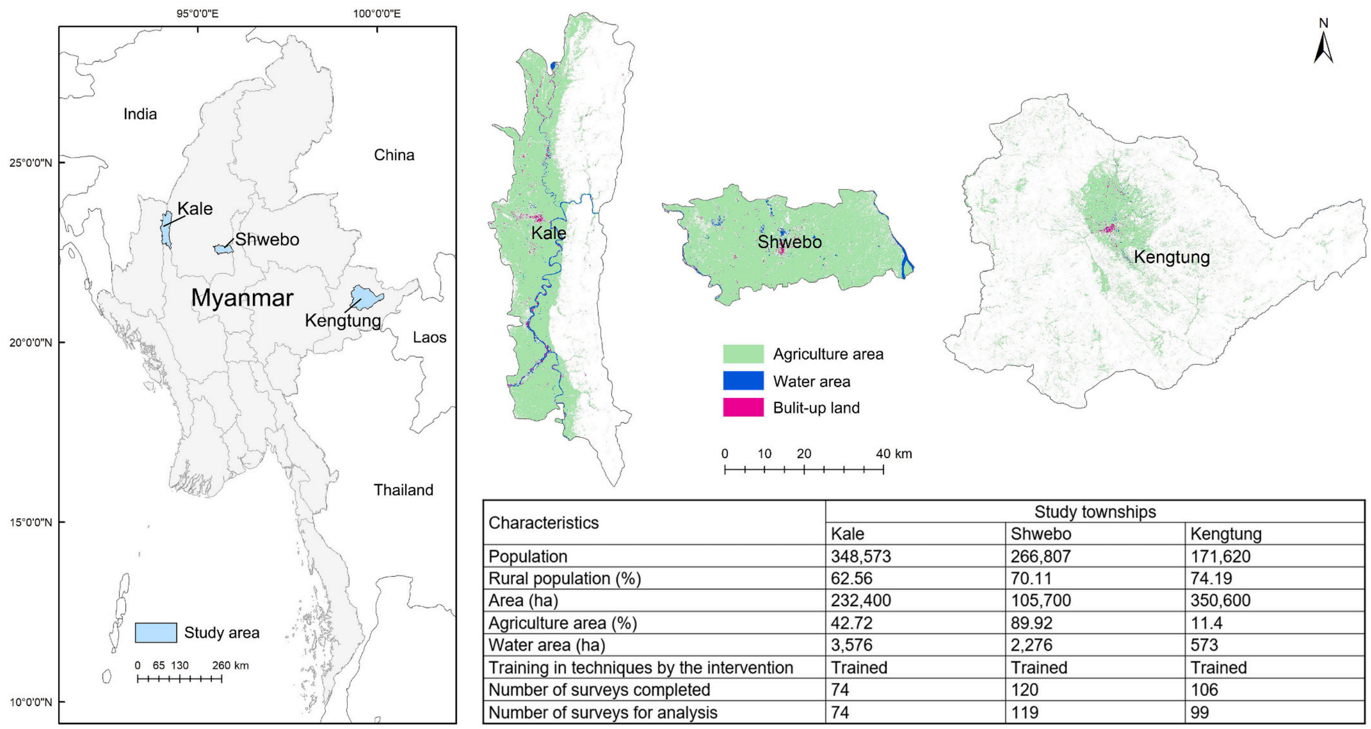
For final outcomes we examined the stabilization of income and food availability during the COVID-19 pandemic. In particular, we elicited perceptions of how and to what extent the COVID-19 pandemic affected income and food availability in 2020 compared to the 2019 levels (i.e. before the COVID-19 pandemic). These perceptions were elicited through 7-level Likert Scale Response Options, including ‘1 - decreased significantly’, ‘2 - decreased moderately’, ‘3 - decreased slightly’, ‘4 - remained the same’, ‘5 - increased slightly’, ‘6 - increased moderately’, ‘7 - increased significantly’.

Finally, household and farm characteristics were used to investigate the extent to which these factors potentially influence intermediate and final outcomes. Following a review of the small-scale aquaculture literature (e.g. Dam Lam et al., 2022; Oparinde, 2021; Wang et al., 2023) we identified a series of household and farm characteristics that can influence these outcomes, including (a) years of education, (b) household size, (c) off-farm income access, (d) credit access, (e) farm area, (f) pond distance to homestead, (g) years of aquaculture experience, (h) years of intervention, and (i) participation to fish groups (e.g. production, market, water management).

2.4.2. Empirical analysis

Our analysis consists of three steps, (a) prevalence of production

[3] Surveys suggest that poverty rose in 2020 at an alarming rate around the country, while food insecurity also increased sharply in some parts (Marivoet et al., 2020).



Characteristics	Study townships		
	Kale	Shwebo	Kengtung
Population	348,573	266,807	171,620
Rural population (%)	62.56	70.11	74.19
Area (ha)	232,400	105,700	350,600
Agriculture area (%)	42.72	89.92	11.4
Water area (ha)	3,576	2,276	573
Training in techniques by the intervention	Trained	Trained	Trained
Number of surveys completed	74	120	106
Number of surveys for analysis	74	119	99

Fig. 2. Location of study areas and key characteristics of study townships. Land use and cover data were adapted from Gong et al. (2019).

Table 1
Summary statistics for the analytical variables.

Variable	Unit	Mean	SD
Intermediate outcomes			
Fish harvest	kg yr^{-1}	173.78	389.33
Fish income	USD yr^{-1}	260.04	270.93
Fish self-consumption	kg yr^{-1}	14.53	20.63
Crop harvest	kg yr^{-1}	99.87	270.93
Crop income	USD yr^{-1}	43.84	184.17
Crop self-consumption	kg yr^{-1}	33.58	51.95
Purchase of other food items	USD yr^{-1}	342.32	563.34
Final outcomes			
Stabilized income during the COVID-19 pandemic	Likert Scale Options 1–7	2.39	1.07
Stabilized food availability during the COVID-19 pandemic	Likert Scale Options 1–7	2.78	1.13
Production models			
Polyculture	1 = Yes, 0 = No	0.83	0.38
IAA	1 = Yes, 0 = No	0.79	0.41
BMPs	1 = Yes, 0 = No	0.95	0.22
Household and farm characteristics			
Years of education	Years	5.97	4.25
Household size	Number	3.98	1.77
Off-farm income access	1 = Yes, 0 = No	0.76	0.43
Credit access	1 = Yes, 0 = No	0.06	0.23
Farm area	ha	0.18	0.21
Pond distance to home	Walking minutes	8.48	9.11
Years of aquaculture experience	Years	8.92	7.52
Years of intervention	Years	1.50	0.50
Participation to fish groups	1 = Yes, 0 = No	0.25	0.43

Note: SD = Standard deviation, IAA = Integrated aquaculture-agriculture, BMPs = Better management practices. The fish income, crop income, and purchase of other food items were captured in Myanmar Kyat, and converted into United States Dollars (USD) (1 USD = 1381.05 Kyat in 2020).

models and determinants of diversification adoption (Step 1), (b) differences in performance between production models and relative importance of household and farm characteristics to intermediate and final outcomes (Step 2), and (c) pathways linking diversification and livelihood outcomes (Step 3).

For Step 1 (Section 3.1) we conducted network analysis to identify the prevalence of production models through the *igraph* package of R version 4.0.4 (Csardi and Nepusz, 2006). In particular, we developed networks to visualize the extent of use of different fish species, crop species, and individual BMPs at the household level. Networks were created based on two elements, (a) nodes, which denote fish species, crop species, and individual BMPs used by households, and (b) edges, which indicate the combined frequency between nodes (i.e. fish species, crop species, and individual BMPs). Furthermore, we used binomial regression models to examine the potential factors influencing the adoption of diversification practices, including household and farm characteristics, and the effects of the COVID-19 shocks (Table 1). The binomial regression model was applied for dichotomous response variables (and in particular the adoption of polyculture and IAA) and sought to understand whether the potential factors affected the adoption of these practices. For this analysis we used the *glm* function of R version 4.0.4.

For Step 2 (Section 3.2) we initially estimated variance inflation factors (VIF) through the *car* package (Fox et al., 2012) of R version 4.0.4, to check multicollinearity among the selected variables. We confirmed that no multicollinearity was present among the explanatory variables (Table S3, Supplementary Material). Then, we estimated the performance of the main SSAA production models (see Step 3 below for models) for each of the intermediate and final outcome variables outlined in Section 2.4.1. The differences in performance between production models were assessed through the one-way ANOVA test. Second, to explore the relative importance of household and farm characteristics to the intermediate and final outcomes, we performed redundancy analysis (RDA) fitted by R-package *vegan* (Dixon, 2003) and permutation test through the *anova* function in R version 4.0.4. By extending multiple linear regression, the RDA allows for the inclusion of multiple response variables on multiple explanatory variables (Kroll et al., 2021; Su and Gasparatos, 2023). This approach has been applied to model aquaculture outcomes through sociodemographic predictors (Carrassón et al., 2021). In this study we used household and farm factors as explanatory in a forward selection in RDA and used the intermediate and final outcomes as the dependent matrix. A permutation test (1000 permutations) was performed to assess the significance of explanatory variables in determining the relative importance of intermediate and final outcomes (Martín-López et al., 2012).

For Step 3 (Section 3.3), we normalized the intermediate and final outcome variables, as they have different physical units (e.g. kg yr^{-1}, USD yr^{-1}, 7-level Likert Scale). For this normalization process we used the *scale* function of R version 4.0.4. We then applied structural equation modeling (SEM) through R-package *lavaan* (Rosseel, 2012) to delineate whether and how different diversification strategies such as 'polyculture', 'IAA', and 'polyculture+IAA' (see Table 1) enabled the stabilization of income and food availability during the COVID-19 pandemic. The SEM approach has been used to examine and understand multivariate relationships (Chen et al., 2023; Jonsson et al., 2012; Ren et al., 2023), including different phenomena in small-scale food production systems such as agriculture (Abid et al., 2020; Raza et al., 2019), aquaculture (Kamaruddin and Baharuddin, 2015), and fisheries (Amadu et al., 2021), among many other applications.

Here we explored three hypothetical pathways (see Section 2.1) to the stabilization of income and food availability during the COVID-19 pandemic. We focused on the two main diversification practices used by the sampled SSAA producers, namely polyculture and IAA, often in conjunction with other improved production practices (i.e. BMPs). In this study, the diversification practices considered are polyculture and IAA, while BMPs denote improved techniques that extend beyond the scope of diversification practices.

Considering that it is not uncommon for SSAA producers to adopt multiple diversification practices, we isolated to the extent possible the effects of individual diversification practices using the comparison groups outlined in Table 2. Detailed information about each production model is outlined in Table S4 of Supplementary Material. We should point out that from the final analysis, we excluded the groups 'polyculture only' ($n = 7$), 'polyculture+IAA' (n = 7), and 'IAA only' ($n = 1$) due to their relatively small sample sizes.

For each of these five group comparisons, we began with the most complete model, removing the model variables that do not contribute substantial information. The final selected model among the several alternatives for each group comparison was based on goodness-of-fit statistics. As recommended in the literature, we used two common indices to evaluate the goodness-of-fit of the SEM: (a) the standardized root mean square residual (SRMR) where a value of < 0.08 indicates a good model fit, and (b) the comparative fit index (CFI) where a value of > 0.90 indicates a good model fit (Chen et al., 2023; Ren et al., 2023). Table S5 (Supplementary Material) outlines the values of each of the models presented in Section 3.3.

Finally we assessed the robustness of the results through a sensitivity analysis that identifies influential outliers using the top 95th percentiles of fish yields (values above the 95th percentile are considered outliers) (Shukla et al., 2019). After removing the influential outliers (14 extreme outliers), we conducted again the SEM for the five comparison groups to test the effects of these outliers on the results (Fig. S1a-b, Supplementary Material).

Table 2
Group comparisons to isolate the effects of diversification practices.

Isolated diversification practice	Diversified group	Comparison group
Polyculture	Polyculture + BMPs + IAA ($n = 185$)	BMPs + IAA ($n = 38$)
	Polyculture + BMPs ($n = 43$)	BMPs only ($n = 11$)
IAA	Polyculture + BMPs + IAA (n = 185)	Polyculture + BMPs (n = 43)
	BMPs + IAA (n = 38)	BMPs only (n = 11)
Polyculture + IAA	Polyculture + BMPs + IAA (n = 185)	BMPs only (n = 11)

Note: IAA = Integrated aquaculture-agriculture, BMPs = Better management practices.

2.5. Acknowledgements and limitations

We must acknowledge here that the aim of this paper is not to provide an actual impact assessment study of the performance of the MYSAP Inland intervention. The interested reader is diverted elsewhere for this type of analysis (Dompreh et al., 2023). Here we instead unraveled whether and how diversification strategies stabilized livelihoods against livelihood shocks using the COVID-19 pandemic as a case study. For this reason, we focused only on the beneficiaries of the intervention as they have received the same training and material to adopt and implement improved aquaculture production practices. We believe that this minimizes to some degree the possible effects of capacity differentials among SSAA producers to properly implement aquaculture production compared to using a random sample of SSAA producers in rural Myanmar (Section 2.1). Furthermore, through careful matching we tried to isolate the effects of individual diversification practices to avoid possible synergistic effects in households that adopt multiple diversification practices (Section 2.1). We believe that collectively these methodological decisions reduce the uncertainty of the results, but at the same time need to be kept in mind when generalizing the findings.

We also need to acknowledge that our study has certain limitations due to: (a) reliance on perceived changes in income and food availability between 2019 and 2020, (b) data collection through phone interviews, (c) long recall period for intermediate outcome variables, and (d) small sample sizes for some comparisons.

Regarding (a) instead of asking respondents about the actual levels of food availability and income in 2019 (i.e. the year prior to the COVID-19 pandemic), we asked the respondents' perceived change due to the pandemic. There were two reasons influencing this decision. First, from our own experience in Myanmar and elsewhere it becomes extremely uncertain and difficult for small-scale food producers to perfectly recall the multiple income/expenditure streams and production levels beyond one production year in the past. Second, even if the respondents could manage to recall relatively accurately the actual levels, many other factors can still between-year variability such as the climate or other household circumstances. We believe that asking explicitly the respondents to isolate the effect of the COVID-19 pandemic on income and food availability led to a relatively accurate (though still uncertain) estimate of the possible livelihood disruptions caused by that specific shock.

Regarding (b), our survey was conducted during the COVID-19 restriction period in 2021 and following the military coup of February 2021. During this period the government instituted a series of containment policies including a mix of phased full and partial 'lockdowns' at sub-national levels (Belton et al., 2021), while there were security concerns in some parts of the country. For this reason, most households were interviewed by phone, which might have contributed to misreporting, especially among some respondents (e.g. older or less educated). This might have caused missing data or extreme values for certain variables. To prevent this to the extent possible, we provided extensive training to the enumerators to be able to critically assess the quality of the elicited data during interviews. We also identified and excluded problematic data during the data-cleaning process. Moreover, we tested whether the SEM results would change between different data collection approaches. We conducted the SEM analysis using only surveys from phone interviews after removing 11 influential outliers using the top 95th percentiles of fish yields (Shukla et al., 2019) ($n = 208$) (Fig. S1c, Supplementary Material). The path coefficients (effect magnitudes and directions) from the phone interview sub-sample (Fig. S1c, Supplementary Material) are similar with those from the entire sample (Fig. S1a-b, Supplementary Material). Despite some small deviations in the effect magnitudes, the significance of all path coefficients remains notably consistent. Unfortunately, it was not possible to conduct the SEM analysis using only the face-to-face surveys due to the insufficient sample size ($n = 73$) for the five comparison groups.

Regarding (c), long recall period for production and consumption variables used in this study (12 months) might cause recollection difficulties to respondents and almost certainly underestimates such variables (Beegle et al., 2012; Deininger et al., 2012). We aimed to reduce such effects through two methodological decisions. First, we deliberately sampled only beneficiaries of the MYSAP programme, as a central aspect of the intervention was to train SSAA producers to keep regular pond/farm record books to record detailed information about fish and crop harvests, self-consumption, and sales. These entries span six of the seven intermediate outcomes (Table 1), with the exception of the variable 'Purchase of other food items'. At the time of the survey all respondents had received 1 or 2 full years of training on all aspects of the intervention, including on how to keep the record book. Such diaries can provide more accurate information for production and assist survey-based methods (Beegle et al., 2012). Although it is not clear whether the respondents used the logbook during the survey, it is likely that the regular book-keeping assisted respondents in accurately recollecting most production and consumption variables. Second, to assist respondent recollection and improve data quality we asked the production-sales-consumption questions in the same loop for any given individual fish and crop species. This meant that for each crop/fish species the related questions for income generation (variables 'fish income' and 'crop income'; Table 1) and self-consumption (variables 'fish self-consumption' and 'crop self-consumption'; Table 1) were asked immediately after the production questions (variables 'fish production' and 'crop consumption'; Table 1). Furthermore, we coded in *Kobotoolbox* the questions in each of these loops to help identify discrepancies if the sums for production, sales, and self-consumption did not add up, and instructed enumerators to spend extra time in these questions to ensure that the quantities balance. However, it is possible that the long recall period might have created uncertainties for the food purchase variable (variable 'Purchase of other food items'; Table 1). Nevertheless, we believe such effects to be relatively minor considering that food is the main recurring household expense.

Regarding (d), due to the differentiated prevalence of some diversification practices within the sample, we ended up with small sample

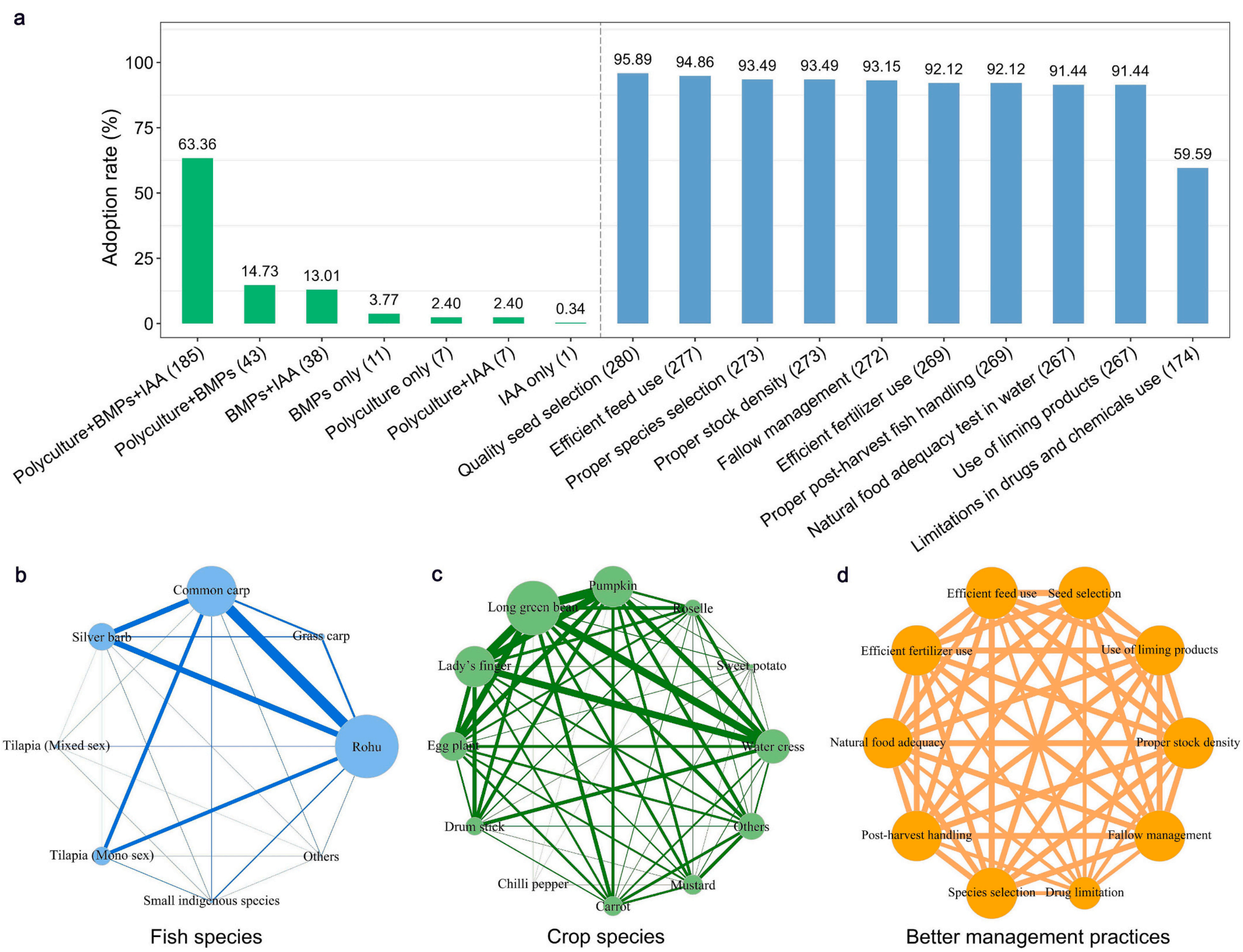


Fig. 3. Prevalence rates and networks of diversification practices and BMPs. IAA = Integrated aquaculture-agriculture, BMPs = Better management practices. In Panel (a) the number in the parenthese of the x-axis denotes the number of households implementing each production model or individual BMP. In Panel (b)-(d) the node size denotes the prevalence of an individual fish/crop species and BMP within the sample, with a larger node size indicating a higher prevalence within the sample. In other words, a larger node size implies that a larger proportion of households produces the individual fish/crop species and implements an individual BMP. Edge weight is proportional to the combined frequency between individual fish/crop species and BMPs. Wider lines connecting two nodes denote that more households produce the specific combinations of fish/crops or implement the combination of BMPs.

sizes for some groups. For example, only 11 producers adopted 'BMPs only' (Table 2). Despite the possible uncertainty caused by small and/or unbalanced sample sizes, many studies in the SEM literature have used comparatively small and unbalanced samples without seemingly negative effects (Amadu et al., 2021; Kamaruddin and Baharuddin, 2015; Raza et al., 2019). To address to the extent possible the possible effects caused by small and/or unbalanced samples, we conducted a sensitivity analysis to assess the robustness of the results to potential data outliers. After excluding the potential outliers, the adjusted path coefficients are similar to the original path coefficients, which suggests the results are relatively robust (Fig. S1, Supplementary Material).

3. Results

3.1. Prevalence of diversification practices and determinants of diversification adoption

Fig. 3 presents the prevalence rates and networks of diversification practices and BMPs within the sample. Most SSAA producers implemented diversification practices in conjunction with BMPs. In particular, 63.4% implemented 'polyculture + BMPs + IAA', 14.7% implemented 'polyculture + BMPs', and 13.0% implemented 'BMPs + IAA'. In Fig. 3a green bars show the prevalence of the different production models, and blue bars the prevalence of individual BMPs.

Fig. 3b suggests that most sampled SSAA producers implemented polyculture models that combined rohu (*Labeo rohita*), common carp (*Cyprinus carpio*), and silver barb (*Barbonymus gonionotus*). Tilapia (*Oreochromis mossambicus*) and small indigenous species,[4] were much less prevalent in polyculture systems. For crop species, most households farmed combinations of long green bean (*Phaseolus vulgaris*), okra (*Abelmoschus esculentus*), pumpkin (*Cucurbita pepo*), watercress (*Nasturtium officinale*), and eggplant (*Solanum melongena*) on their pond dikes and/or home gardens (Fig. 3c). When looking at the BMPs networks, most individual BMPs were jointly implemented except for limitations in drugs and chemicals use (Fig. 3d).

In terms of the determinants of diversification adoption, results suggest that longer exposure to the intervention is associated with significantly higher adoption of polyculture and IAA (Box. S2, Supplementary Material). However, the intensity of the experience of the COVID-19 shock in terms of the perceived effects of the COVID-19 pandemic on income and food availability does not seem to be significantly associated with adoption, whether positively or negatively. Box. S2 in the Supplementary Material provides a detailed overview of the determinants of diversification adoption.

3.2. Differences in intermediate and final outcomes between production models

As outlined in Section 3.1 'polyculture + BMPs + IAA', 'polyculture + BMPs', 'BMPs + IAA', and 'BMPs only', were the most prevalent production models within the sample. To isolate to the extent possible the effects of individual diversification practices we used the comparisons outlined in Table 2. Fig. 4 shows differences in intermediate outcomes between the different groups.

Specifically, when integrating polyculture into 'BMPs + IAA', and 'BMPs only' systems, we identify that the respective models (i.e. 'polyculture + BMPs + IAA' and 'polyculture + BMPs') have significantly higher fish harvest, fish income, fish self-consumption, and purchase of other food items (Fig. 4a-c and g). When comparing the production model that implemented and did not implement IAA (i.e. 'polyculture + BMPs + IAA' vs. 'polyculture + BMPs'), the addition of IAA seems to lead to the production model that has significantly higher crop harvest, crop income, and crop self-consumption (Fig. 4d-f). Households implementing this model are also characterized by the higher purchase of other food items, but the difference is not statistically significant (Fig. 4g). When embedding jointly polyculture and IAA (i.e. 'polyculture +BMPs + IAA' vs. 'BMPs only'), we find that the former is characterized by significantly higher fish and crop self-consumption and purchase of other food items (Fig. 4c, f, and g). Furthermore, the fish/crop harvest and fish/crop income are higher for this comparison, though the differences are not statistically significant (Fig. 4a-b and d-e).

Fig. 5 shows differences in the levels of perceived effects of the COVID-19 pandemic on income and food availability. In more detail, SSAA producers that had additionally implemented 'IAA' and 'polyculture + IAA' tend to report significantly higher stabilization for income and food availability (namely for the comparison 'polyculture + BMPs + IAA' vs. 'polyculture + BMPs'; and the comparison 'polyculture + BMPs + IAA' vs. 'BMPs only'). Similar findings are also observed for the groups that had additionally implemented polyculture, though the differences are not statistically significant.

Fig. 6 presents in more detail the main perceived effects for each study group. As expected a high proportion of SSAA producers for each group reported negative effects (see purple bars in Fig. 6a-b). However, comparatively speaking a higher proportion of the SSAA producers that reported either no or low effect from COVID-19 had adopted some form of diversified production practices, whether polyculture, IAA, or both (see yellow and light purple bars in Fig. 6a-b). Interestingly comparatively more of the SSAA producers that did not adopt any diversification practices (i.e. 'BMPs only'), reported a significant reduction in income and food availability (see deep purple bars in Fig. 6a-b).

The RDA identifies associations between household and farm characteristics, with intermediate and final outcomes (Fig. 7). The permutation test for RDA indicates statistically significant associations between the relative importance of these multiple variables for all study groups ($p < 0.001$, from 1000 permutations in the two cases).

In terms of intermediate outcomes (Fig. 7a), the RDA1 (x-axis) explains 24% of the total variance, which generally reveals synergies between all intermediate outcomes. Notably, practically all household and farm characteristics are found to be positively associated with all intermediate outcomes (with the exception of pond distance to homestead). Particularly, farm area is found to have the highest positive effect on all intermediate outcomes (longest arrow), whereas an increased distance between the pond and homestead has a negative effect on all intermediate outcomes. Higher household sizes, increased access to credit, or off-income activities, tend to be positively associated with higher purchases of other food items. Moreover, participation in fish groups or longer aquaculture experience is also associated with higher fish harvest, fish income, and crop self-consumption.

In terms of final outcomes (Fig. 7b), the RDA1 (x-axis) explains 10.6% of the total variance, suggesting positive associations between the stabilization of income and the stabilization of food availability during the COVID-19 pandemic. Interestingly, longer exposure to the intervention and longer aquaculture experience tend to have higher positive associations with the stabilization of income and the stabilization of food availability during the pandemic. Similarly access to credit or off-farm income is also positively associated with the stabilization of income and food availability during the pandemic. Conversely, increased pond distance, larger household sizes, participation in fish groups, and higher education are all negatively associated with the stabilization of income and food availability during the pandemic.

3.3. Pathways to the stabilization of income and food availability

The SEM approach examines the pathways linking the adoption of diversification practices, with intermediate outcomes, and the stabilization of income and food availability during the COVID-19 pandemic.

[4] Small indigenous species are mainly produced for self-consumption as they rich in essential micronutrients (e.g. vitamin A, vitamin B12, iron, and calcium) and are commonly farmed alongside fish used for income generation (Karim et al., 2020; Rizaldo et al., 2023; Wang et al., 2023).

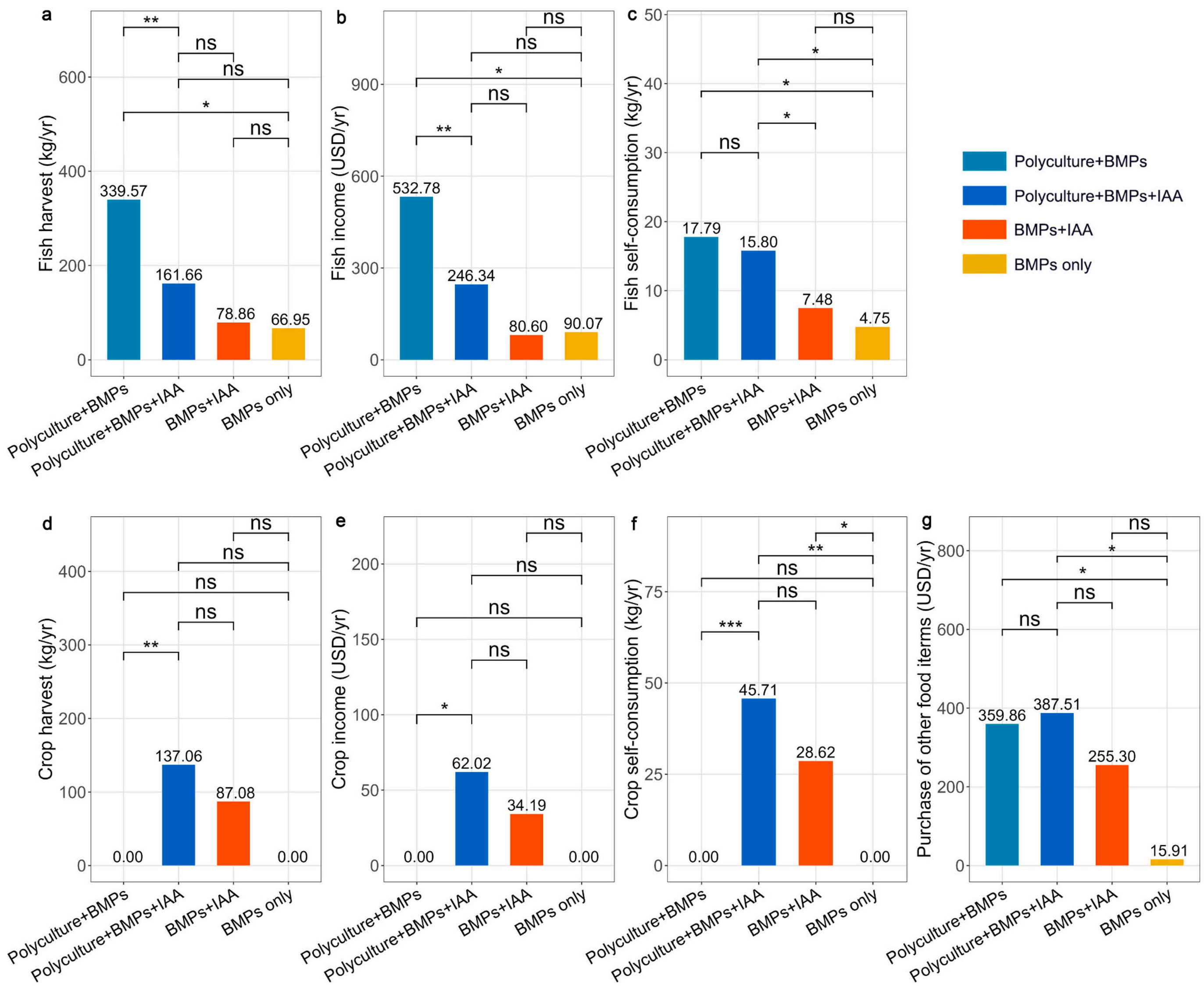


Fig. 4. Differences in the levels of the intermediate outcomes between the different production models. IAA = Integrated aquaculture-agriculture, BMPs = Better management practices. The number in the bar chart denotes the mean score for each intermediate outcome for each group. The horizontal square brackets represent the pairwise comparisons between the production models at the opposite tips of the brackets. Symbols above each square bracket denote the statistical significance of the differences in each intermediate outcome as follows: '*' $P < 0.05$, '**' $P < 0.01$, '***' $P < 0.001$, and 'ns' not significant. This figure does not show all possible group comparisons, but only for the group comparisons identified in Table 2.

In general, our results suggest that most impact pathways based on the SEM approach have better performance (goodness-of-fit) and could better explain the multivariate relationships between variables (Fig. 8).

Overall, the SEM results suggest significant positive interconnections between the adoption of diversification practices (i.e. polyculture and IAA), livelihood outcomes, and stabilized income and food availability during the COVID-19 pandemic (Fig. 8). However, as described below the pathways vary between diversified production models and livelihood outcomes.

To isolate the effect of polyculture we compare production models that adopted and did not adopt polyculture (Fig. 8a-b). Here the additional adoption of polyculture in the 'BMPs + IAA' production model significantly stabilized income and food availability during the COVID-19 pandemic through two pathways. First, the SSAA producers adopting polyculture had higher fish harvest and fish income by selling excess products, thereby stabilizing income to some extent during the pandemic. Second, the adoption of polyculture could increase fish harvest and fish income, enabling higher food purchases from markets, and thus stabilizing food availability during the pandemic. Interestingly the adoption of polyculture in the 'BMPs only' production models had similar effects to intermediate outcomes but did not have a significant effect on the stabilization of income and food availability (Fig. 8b).

To isolate the effect of IAA we compare production models that adopted and did not adopt IAA (Fig. 8c-d). Embedding IAA in the 'BMPs only' production model stabilized significantly food availability (but not income) during the COVID-19 pandemic (Fig. 8d). Specifically, through the additional adoption of IAA, the SSAA producers could increase crop harvest and crop income, which could improve the purchases of other food items, ultimately leading to more stabilized food availability during the pandemic. However, integrating IAA into the 'polyculture + BMPs' model does not seem to have significant effects on the stabilization of income and food availability during the pandemic (Fig. 8c).

To isolate the joint effect of IAA and polyculture we compare the 'polyculture + BMPs + IAA' production model with the 'BMPs only' production model (Fig. 8e). In this case embedding polyculture and IAA in the 'BMPs only' production model, we find that the additional adoption of 'polyculture + IAA' stabilized significantly income and food availability but only through the increased fish income and food

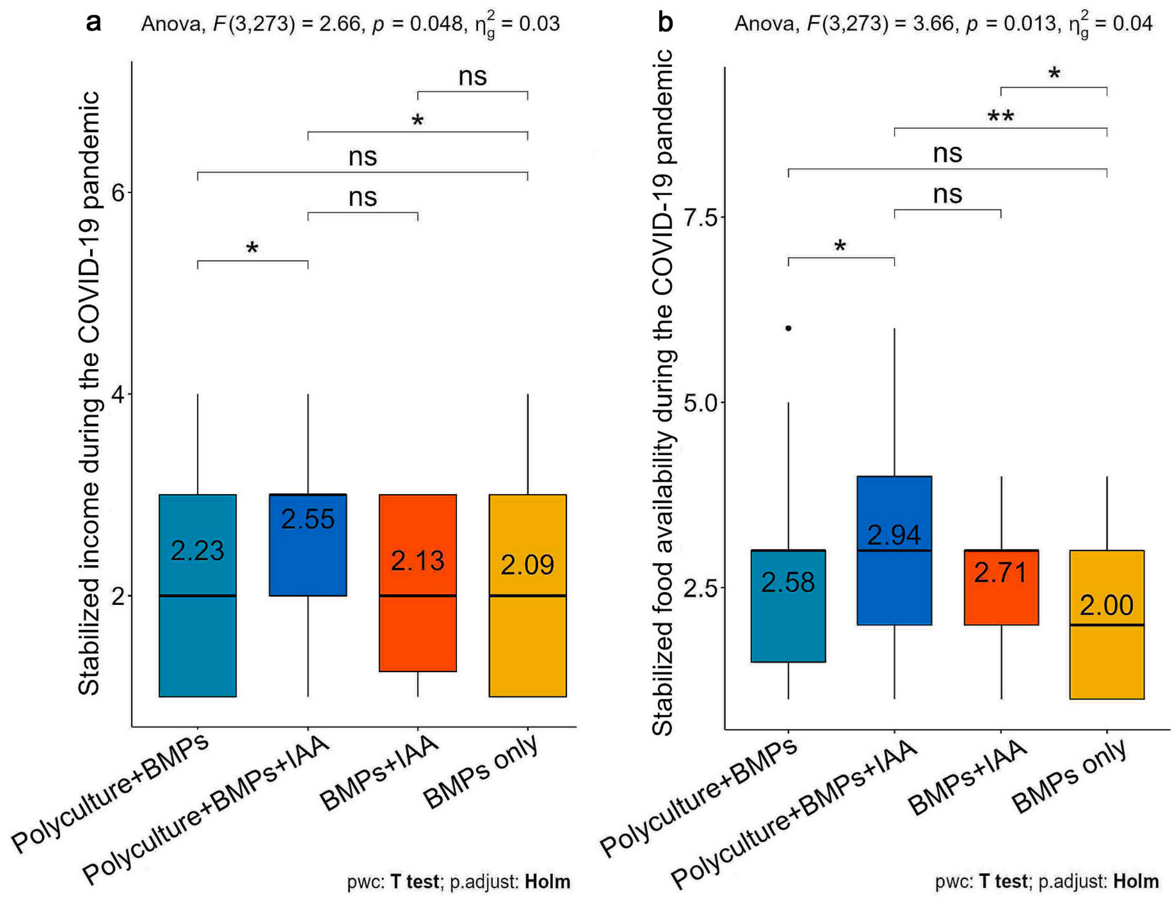


Fig. 5. Differences in the levels of the final outcomes between the different production models. IAA = Integrated aquaculture-agriculture, BMPs = Better management practices. The horizontal square brackets represent the pairwise comparisons between the production models at the opposite tips of the brackets. Symbols above each square bracket denote the statistical significance of the differences in each final outcome as follows: '*' $P < 0.05$, '**' $P < 0.01$, '***' $P < 0.001$, and 'ns' not significant. This figure does not show all possible group comparisons, but only for the group comparisons identified in Table 2.

purchase pathway. Even though the adoption of IAA significantly increased crop income and crop self-consumption, this does not seem to have culminated to stabilized income and food availability.

4. Discussion

4.1. Differentiated pathways to livelihood stabilization

As mentioned in the Introduction, small-scale food producers are sensitive to unexpected shocks and disruptions caused by natural disasters (e.g. long-term climate change, extreme weather), economic downturns (e.g. declines in prices of farm products), or the COVID-19 pandemic (Belton et al., 2021; Short et al., 2021). When exposed to such shocks small-scale food producers often experience declines in income, food security, and well-being (Altieri et al., 2015; Arslan et al., 2018; Boughton et al., 2021).

Consistent with most studies at the interface of the COVID-19 pandemic and rural livelihoods (Belton et al., 2021; Mueller et al., 2021; Nchanji et al., 2021; Snow et al., 2021), we also find that the pandemic posed considerable and pervasive challenges for rural livelihoods in Myanmar (Fig. 6), with 82.9% and 68.8% of the respondents reporting negative effects from the pandemic on household income and food availability respectively. In terms of specific disruptions at the household level, we find that 19.0% of respondents were unable to access their ponds, 22.6% were unable to purchase aquaculture inputs, 47.8% faced challenges in selling their aquaculture products, 23.6% were unable to access markets to buy food, and 40.9% reported closure of off-farm workplaces (40.9%) (Fig. S2, Supplementary Material). These findings are similar to a recent study from Myanmar, which indicates that lockdown measures (e.g. movement restrictions) limited farm accessibility, availability of aquaculture inputs, and fish sales, leading to lower fish sales in 2020 compared to a typical year (Belton et al., 2021). More broadly, at the sectoral level the COVID-19 pandemic caused increases in aquaculture input prices (e.g. pelleted feeds), transportation fees, and labor wages, as well as decreases in fish market prices compared to the pre-COVID-19 levels (Belton et al., 2021; Lebel et al., 2021).

The main novelty of our study is not only that it confirms that the integration of diversification practices in different SSAA production models can have generally positive effects for the stabilization of income, food availability or both during the livelihood shocks posed by the COVID-19 pandemic, but that this stabilization unfolded through slightly different pathways in each case. In more detail (a) the adoption of polyculture stabilized income and food availability by increasing fish production and related income (Fig. 8a), (b) the adoption of IAA stabilized food availability through increasing crop production and related income, though the model performed less well than polyculture (Fig. 8d), and (c) the joint adoption of polyculture and IAA stabilized income and food availability, with however polyculture playing a more pivotal role in achieving these outcomes mainly through increased fish production and related income (Fig. 8e). When looking critically at the above patterns it is possible to make two interesting observations.

First, in all cases the adoption of diversification practices has a significant positive effect on the production, income and self-consumption of crops and fish (grey boxes in Fig. 8a-e). However, although this significantly higher self-consumption always seems to have some

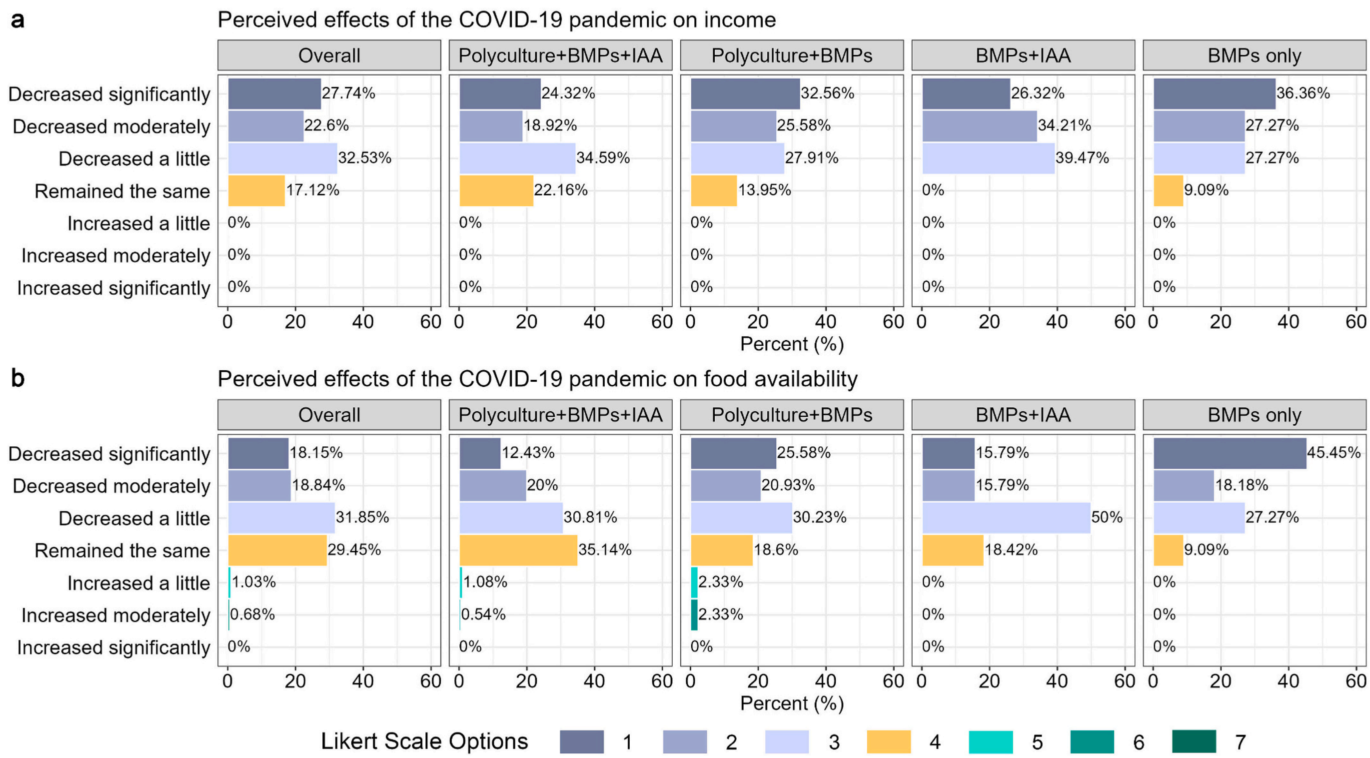


Fig. 6. Perceived effects of the COVID-19 pandemic on income and food availability for the different production models. IAA = Integrated aquaculture-agriculture, BMPs = Better management practices. The number in the bar plot indicates the fraction of respondents choosing each specific response.

positive effect on the stabilization of food availability, this effect is never significant. The only significant positive effect on the stabilization of food availability comes through the improved ability of diversified producers to purchase food items due to significantly higher fish income (Fig. 8a and e) and crop income (Fig. 8d). This is highly likely due to the fact that diversifying aquaculture and agricultural products has great potential to unlock numerous commercial values, and expand available markets for these farmed species (Thomas et al., 2021; Wang et al., 2023).

Second, although the additional adoption of IAA has significant positive effects on practically all intermediate outcomes (grey boxes in Fig. 8c-e), it has mostly negligible effects on the final outcomes of stabilization of food availability and income (yellow boxes in Fig. 8c-e). This is observed both when IAA is adopted alone (Fig. 8c-d) or in conjunction with polyculture (Fig. 8e). Comparatively polyculture has much more significant effects on the final outcomes (Fig. 8a and e). The only occasion that IAA has a significant effect on the final outcomes is for the comparison of the 'BMPs + IAA' and 'BMPs only' groups (Fig. 8d). This latter group basically denotes SSAA producers that engage in fish monoculture. In this case it can be argued that even some minimal diversification can have some positive effects on livelihood stabilization. This is particularly important considering that there are no significant differences in fish production (Fig. 4a) and fish income (Fig. 4b) between these groups. This reflects a recent study reporting that the additional adoption of IAA can provide an additional source of income that can substantially increase net cash flow from crop income, despite crop income being lower than fish income (Limbu et al., 2017). We need to point out that these minimal effects of IAA are likely due to the fact that pond dikes and gardens in the IAA production models prevalent in the study area are not used to produce staple crops (e.g. rice) to increase food consumption, but crops that can diversify diets and/or provide extra income (e.g. long green bean, okra, pumpkin, watercress, eggplant; Fig. 3c).

4.2. Study implications: Diversification as a proactive strategy for livelihood shocks

When adapting to the challenges posed by livelihood shocks, SSAA producers (much like other types of small-scale food producers) tend to implement 'reactive' measures following the onset of the shocks (Belton et al., 2021). For example, during the COVID-19 pandemic, studies have shown that SSAA producers adopted different 'reactive' strategies such as (a) pausing temporarily or shortening the duration of aquaculture operations, (b) minimizing operating costs (e.g. lowering labor expenses by hiring fewer workers, reducing wages, reducing input procurement, using cheaper inputs, reducing stocking rates), (c) borrowing working capital, (d) reducing food consumption (Belton et al., 2021; Lebel et al., 2021). Similar 'reactive' measures have been reported in other small-scale food production contexts around the world, both during the COVID-19 pandemic (Boughton et al., 2021), as well as other shocks such as extreme weather events (Mwinjaka et al., 2010).

Arguably, such 'reactive' measures might be necessary and possibly unavoidable to cope with livelihood shocks (especially rather unexpected shocks such as the COVID-19 pandemic). However, it is important to note that these types of measures are also likely to reduce productivity and income, as well as undermine livelihoods, well-being, and longer-term resilience (Belton et al., 2021).

Conversely, 'proactive' strategies anchored on diversification have been proposed and implemented in different contexts to enable small-scale food producers to cope with livelihood shocks (Anderzén et al., 2020; Lebel et al., 2021; Shameem et al., 2015; Short et al., 2021; Tran et al., 2020). For instance, on-farm diversification strategies such as the joint production of coffee, honey, and staple crops could help small-scale farmers deal with persistent livelihood shocks during months characterized by income and food scarcity (Anderzén et al., 2020). Aquaculture diversification such as the adoption of shrimp-tilapia polyculture has the potential to improve access to food and enhance adaptive capacity in the face of weather shocks (Tran et al., 2020).

Our study not only provides further evidence that diversification

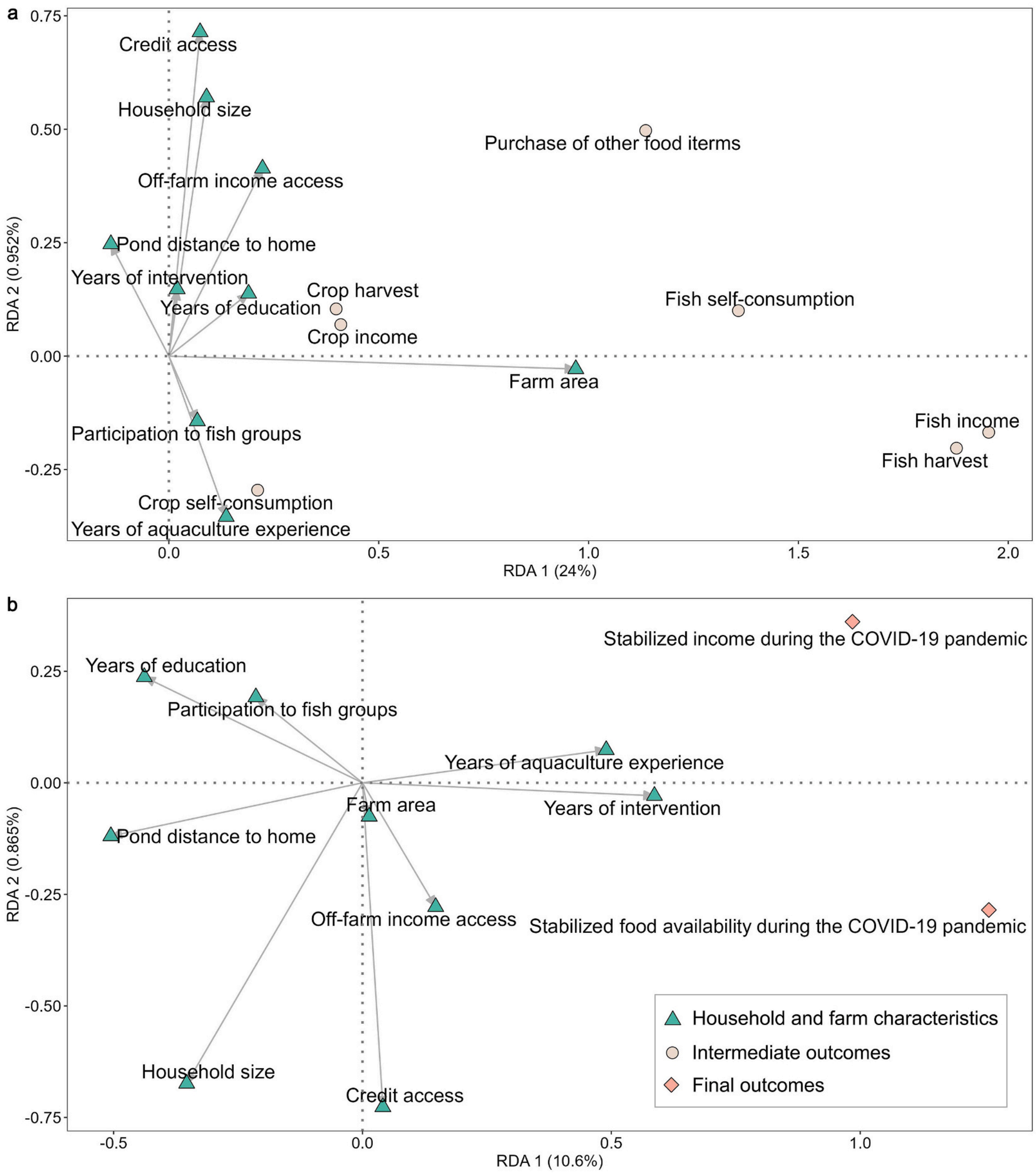


Fig. 7. Effects of household and farm characteristics on intermediate and final outcomes. The arrows represent the relationships between the response variables (intermediate or final outcomes) and the explanatory variables (household and farm characteristics). The length of an arrow denotes the strength of the relationship, i.e., the explanatory variables with longer arrows are more strongly related to the response variables. The direction of the arrow indicates the direction of the relationship (positive or negative). If the arrow points toward the response variable, it indicates a positive relationship, otherwise a negative relationship.

strategies can indeed have a stabilizing effect for livelihoods but more importantly identifies how this is achieved (i.e. through which pathways) (Section 3.3 and 4.1). Our findings also point to some critical aspects that should be considered when promoting and upscaling such practices in Myanmar and other similar developing small-scale contexts.

First, beyond choosing the appropriate diversification practices, it is also important to consider the selection of appropriate species. In the polyculture systems in the study area, the most prevalent fish combination is common carp in the bottom layer, rohu in the middle layer, and silver barb in the upper layer (Fig. 3b). The main underlying logic is that the foraging behaviors of common carp in the bottom layer help resuspend the nutrients accumulated in the sediment into the water body, thereby supporting the growth of rohu and silver barb (Thomas et al., 2021; Wang et al., 2023). Although this species configuration can increase farm output and boost sales (Figs. 4 and 8) it also seems to have minimal effect on the stabilization of food availability through self-consumption (Fig. 8a-b, and e). In this context it might be worthwhile to explore whether the greater adoption of other locally available but less popular species such as tilapia and small indigenous fish (Fig. 3b) that are rich in micronutrients (e.g. vitamin A, calcium, and iron), could improve food availability among small-scale households and vulnerable groups (e.g. children, and women) during livelihood shocks (Ahmed and Garnett, 2011; Dam Lam et al., 2022). For IAA systems, results suggest that the most popular crops include long green bean, okra, pumpkin, watercress, and eggplant on pond dikes and/or home gardens (Fig. 3c). However, again there seems to be no food availability benefits through the self-consumption of these crops (Fig. 8c-d, and e). Beyond these crop species, the possible addition of micronutrient-rich crops that can be readily adopted in diets (e.g. orange sweet potato, dark green leafy vegetables) could have some food availability benefits during livelihood shocks (Ahern et al., 2021). However, future research would be needed to identify the feasibility and acceptability of such options.

Second, beyond the adoption of diversification practices, we also find that some household and farm characteristics seem to be associated

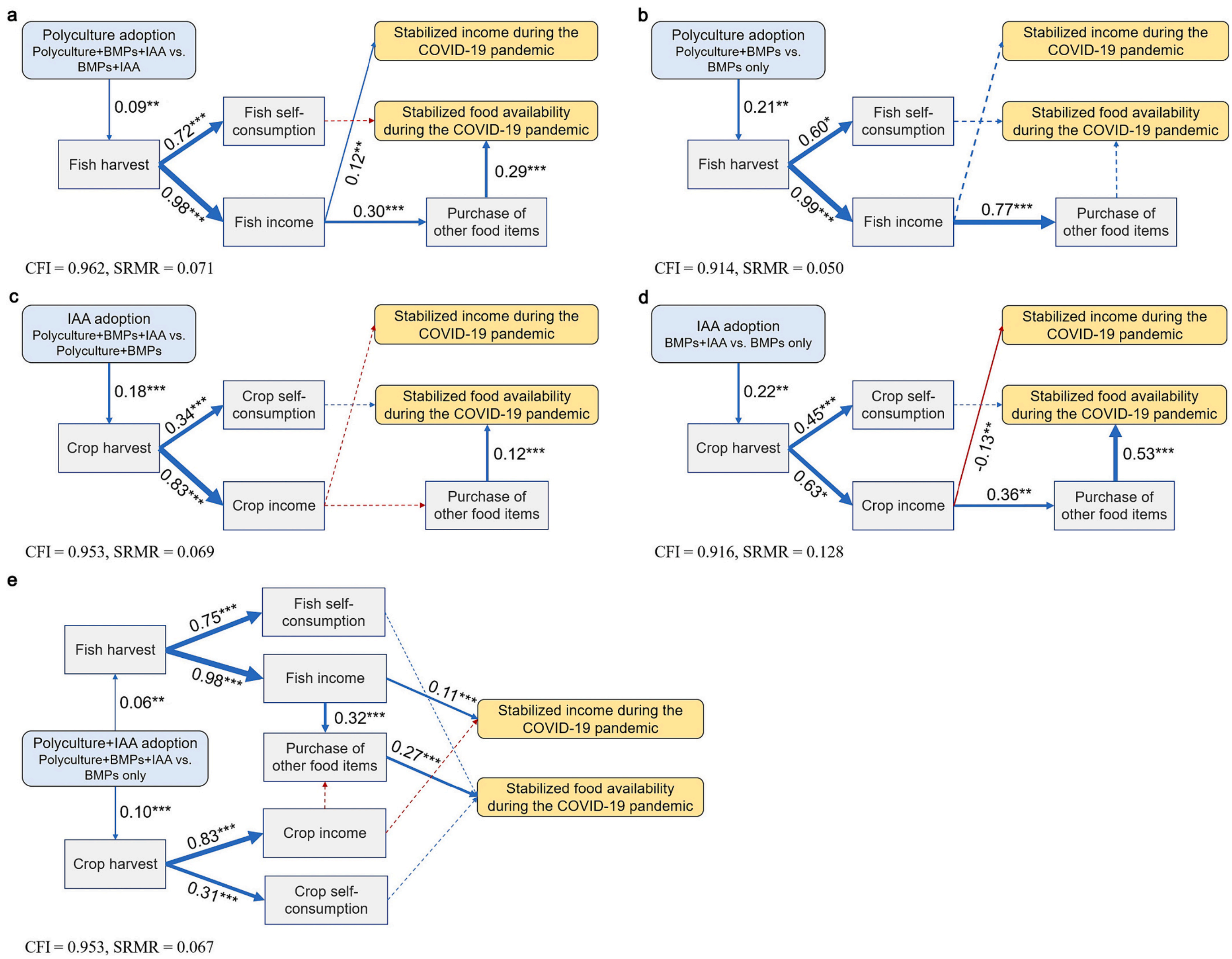


Fig. 8. Pathways linking the adoption of diversification practices, with the intermediate and final outcomes. IAA = Integrated aquaculture-agriculture, BMPs = Better management practices, CFI = Comparative fit index, SRMR = Standardized root mean square residual. Blue boxes indicate diversification practices, grey boxes intermediate outcomes and yellow boxes final outcomes. The blue lines indicate positive effects, and the red lines indicate negative effects. Solid lines represent significant effects and dashed lines represent non-significant effects. Thicker lines connecting boxes denote higher intensity of standardized path coefficients, while the numbers around the lines denote standardized path coefficients. '*' $P < 0.05$, '**' $P < 0.01$, '***' $P < 0.001$. For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.

strongly with the stabilization of income and food availability (Fig. 7b). In particular, in our specific study context access to credit and off-farm income, farm experience, and years of intervention can be equally important factors in stabilizing livelihoods during shocks. Although such factors might not be the same in every context (let alone have the same association), it would be important to identify and consider them when promoting diversification practices.

5. Conclusion

Diversification is a farming strategy commonly utilized by millions of small-scale food producers across the world due to its positive (but also context-specific) effects on yields, income, food security, and ecosystem services. In this study we shed more light on the potential of different diversification practices to stabilize livelihoods during shocks, focusing on SSAA producers in Myanmar during the COVID-19 pandemic as a case study. Our findings suggest that the COVID-19 pandemic and associated measures indeed had considerably adverse effects on rural livelihoods. The novelty of this study is that beyond confirming that the integration of diversification practices in different SSAA production systems can have generally positive effects for the stabilization of income, food availability, or both during the COVID-19 pandemic, it highlights the slightly different pathways through which stabilization occured in each case. In more detail, there were major divergences between polyculture and IAA on the magnitudes of the stabilization effects and the underlying pathways. Polyculture generally offered more significant stabilizing effects than IAA. Furthermore, in practically all cases we observed a significant stabilization of food availability, this came through purchases of food from the increased fish/crop income, rather than self-consumption from increased fish/crop production. We also find that beyond diversification practices certain household and farm characteristics such as years of intervention, farm experience, off-farm income access, and credit access were also positively associated with livelihood stabilization. Overall, our findings suggest that SSAA production systems combining different diversification practices and actively considering other influencing factors could help small-scale food producers cope with livelihood shocks and at the same time achieve localized progress across multiple SDGs, such as no poverty (SDG 1) and zero hunger (SDG 2).

CRediT authorship contribution statement

Quanli Wang: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Cristiano M. Rossignoli:** Funding acquisition, Project administration, Resources, Supervision, Writing – review & editing. **Eric Brako Dompreh:** Data curation, Investigation, Writing – review & editing. **Jie Su:** Software, Writing – review & editing, Methodology. **Don Griffiths:** Data curation, Investigation, Writing – review & editing. **Khaing Kyaw Htoo:** Data curation, Investigation. **Hsu Myat Nway:** Data curation, Investigation. **Michael Akester:** Project administration. **Alexandros Gasparatos:** Conceptualization, Funding acquisition, Supervision, Writing – review & editing, Resources.

Declaration of competing interest

The analysis presented in this study was based on data collected as part of the impact assessment study of the inland component of the Myanmar Sustainable Aquaculture Programme (MYSAP Inland). The aim of the MYSAP Inland was to provide support packages to small-scale aquaculture producers designed and implemented by WorldFish Myanmar in collaboration with other partners. Some of the co-authors in this study are affiliated with WorldFish. We confirm that there are no known financial and non-financial conflicts of interest associated with the outcomes of this publication.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2024.103935.

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