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To cite this article: Quanli Wang *et al* 2023 *Environ. Res. Lett.* **18** 015002

ENVIRONMENTAL RESEARCH
LETTERS

CrossMark

OPEN ACCESS

RECEIVED
7 April 2022

REVISED
20 October 2022

ACCEPTED FOR PUBLICATION
13 December 2022

PUBLISHED
3 January 2023

LETTER

Sustainable intensification of small-scale aquaculture production in Myanmar through diversification and better management practices

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Keywords: aquaculture, sustainable intensification, food security, nitrogen use efficiency, phosphorus use efficiency, benefit-cost ratio, yield

Supplementary material for this article is available online

Abstract

Small-scale aquaculture systems can contribute significantly to food and nutritional security, poverty alleviation, and rural development, especially in developing countries. However, the intensification of aquaculture systems often has negative environmental outcomes. The adoption of diversification practices (e.g. polyculture, pond-dike cropping (PDC)) and better management practices (BMPs) has been identified as a possible approach to intensify sustainably small-scale aquaculture production. This study assesses the sustainability outcomes of the adoption of diversification practices and BMPs in small-scale production models. We focus on Myanmar, a developing country characterized by a rapidly expanding small-scale aquaculture sector. We analyze 624 household surveys with small-scale aquaculture producers in central and northern Myanmar. We estimate the effects of diversification practices and BMPs on different sustainability outcomes, namely economic outcomes (i.e. aquaculture yield and benefit-cost ratio), environmental outcomes (i.e. nitrogen and phosphorus use efficiency), and food security outcomes (i.e. fish self-consumption and household dietary diversity) through linear mixed-effects models. Our results reveal that diversified production models (whether integrating or not integrating BMPs) could have significant positive effects on economic and food security outcomes, as well as phosphorus use efficiency, compared to 'unimproved monoculture'. However, such production models do not seem to have any major effect on nitrogen use efficiency. The adoption of BMPs on diversified production models seems to have little (if any) added effect on any of the studied sustainability outcomes, which suggests the need to improve existing BMPs or even develop new BMPs fit for Myanmar's context. These findings have implications about the possible contribution of diversification practices and BMPs for enabling sustainable intensification in small-scale aquaculture settings in Myanmar, and other rural developing contexts.

1. Introduction

Aquaculture is one of the fastest expanding food production sectors globally, with an annual increase of 8.6% in terms of tonnage over the last three decades (FAO 2018). It has been emerging as a major source of animal protein in many parts of the world, contributing significantly to food and nutritional security

(Subasinghe *et al* 2009). In many developing countries small-scale aquaculture[6] in homestead ponds has become particularly important not only for food and nutritional security (Castine *et al* 2017), but also for rural livelihoods, poverty alleviation, and broader economic growth (Nasr-Allah *et al* 2020).

To meet the growing fish demand the aquaculture sector has experienced significant intensification in many parts of the world, usually through monocultural models characterized by the extensive use of pelleted feed and agrochemical inputs (Edwards 2015). Despite their possible productivity gains (Joffre *et al* 2018) such approaches to intensification may cause environmental impacts such as eutrophication, acidification, freshwater ecotoxicity, and biodiversity loss (Henriksson *et al* 2021). As a result many scholars have pointed to the need to enhance the sustainability of small-scale aquaculture systems through multiple interventions, including the promotion and adoption of environmentally-friendly technologies for innovative transformation (Belton *et al* 2021). Sustainable intensification in this context refers to interventions seeking to increase yield and food supply while using fewer resources (Henriksson *et al* 2021).

In an aquaculture context diversification generally refers to the production of multiple species across different scales. This includes three main strategies: (a) increase the number of cultivated species, (b) increase the evenness of cultivated species, and (c) increase the diversity within currently cultivated species by developing new strains (FAO 2016). Examples of diversification strategies include pond polyculture[7] and pond-dike cropping (PDC)[8], which have been traditionally employed in many developing contexts (Ahern *et al* 2021). For small-scale aquaculture producers, pond polyculture generally entails the semi-intensive farming of low-value herbivorous or omnivorous fish (e.g. carp, tilapia), and PDC includes land-based crop production (e.g. vegetables and fruits) (Thomas *et al* 2021). Empirical evidence suggests that such diversification practices have the potential to improve farm productivity (Dey *et al* 2010), household food consumption and nutrition (Murshed-E-Jahan and Pemsl 2011), and reduce risks associated with water scarcity (Ahmed *et al* 2014). Sustainable intensification practices based on diversification have been promoted in many parts of the world to enhance fish production, income generation, and food security and minimize the negative environmental impacts of aquaculture systems, including small-scale systems (Henriksson *et al* 2018).

However, such traditional diversification-oriented approaches to sustainable aquaculture intensification also face several challenges. For instance, they entail the application of manure-based fertilizer to ponds, which may cause oxygen depletion (Prabu *et al* 2019). Furthermore, if the pond water is used to irrigate pond-dike crops, the farm products may become contaminated by antibiotics or other drugs (Bostock *et al* 2010). Irrigation with pond water may also reduce soil microbial functional diversity and change community structure (Chen *et al* 2017). Collectively such challenges may have significant ramifications for productivity, human health and the environment (e.g. through water pollution), and essentially the sustainability of small-scale aquaculture intensification through diversification-oriented approaches (Aung *et al* 2021).

To address the aforementioned challenges, there have been calls to enhance the productivity and sustainability of such aquaculture systems through the design, dissemination and adoption of improved aquaculture techniques such as better management practices (BMPs)[9] (Henriksson *et al* 2021). Depending on the context, BMPs are promoted to increase aquaculture production and profitability, reduce negative environmental impacts through improved input efficiency, and generally enhance the sustainability of small-scale aquaculture systems (Dickson *et al* 2016, Henriksson *et al* 2017). In fact several recent studies have explored the sustainability outcomes of BMP adoption in small-scale aquaculture settings, pointing for example to their ability to enhance fish farm profitability (Dickson *et al* 2016), alleviate poverty (Kassam and Dorward 2017), and mitigate negative environmental impacts (Henriksson *et al* 2019).

However, there are many major knowledge gaps at the interface of small-scale aquaculture systems, diversification, BMPs and sustainability. First, there is a lack of comparative studies with robust evidence about the sustainability outcomes/impacts of different diversified small-scale aquaculture systems, especially in developing countries. Usually, the studies exploring the sustainability of such systems focus on individual diversification approaches (Castine *et al* 2017) and/or single (or small sub-sets of) sustainability outcomes/impacts (Kassam and Dorward 2017). On the other hand, there is equally little literature

[6] Small-scale aquaculture is characterized by subsistence or semi-subsistence nature, limited investment in assets and operational costs, largely reliance on family labor, and usually fish farms operated by a household with an area less than 0.5 acre (Htoo *et al* 2021).

[7] Polyculture is defined as rearing/breeding two or more in a particular production system (e.g. pond) at the same time (Thomas *et al* 2021).

[8] Pond-dike cropping is defined as a terrestrial farm system near the pond that for the production of vegetables and/or fruit trees (Ahmed *et al* 2014).

[9] For the purpose of this study BMPs refer to a range of technical options that producers can deploy to improve aquaculture production practices in site-specific conditions (Tucker and Hargreaves 2008). This can include very diverse techniques seeking to increase production (e.g. proper species selection, quality seed selection, proper stock density), or reduce negative environmental impacts (e.g. natural food adequacy test in water, alternatives to antibiotic, limitations in drugs and chemicals use), among others (Tucker and Hargreaves 2008, WorldFish 2021).

examining how the adoption of BMPs in diversified small-scale aquaculture systems can further affect different dimensions of sustainability.

The sustainable intensification of small-scale aquaculture systems is particularly important in Southeast Asian countries, where most aquaculture production and growth take place (therefore suffer most of the impacts of aquaculture production) (Garlock *et al* 2020), and where represent the potential to expand in the future, enhance food security and rural livelihoods, and reduce environmental impacts (Henriksson *et al* 2021). Myanmar is such an example considering its large aquaculture sector, which ranked 9th globally in terms of aquaculture fish production and 7th in inland aquaculture production for finfish in 2018 (FAO 2020). Although fish are a major source of protein and micronutrients for many households in the country, with domestic consumption absorbing 80% of the national aquaculture production (Belton *et al* 2015), many small-scale households struggle to sustain food production/consumption and income generation from their small ponds (Karim *et al* 2020). Furthermore, most of small-scale farms tend to rely on traditional technologies (including diversified models such as those mentioned above), and do not seek technological change due to multiple constraints (Belton *et al* 2018). In this sense understanding the sustainability outcomes of different diversification approaches (whether traditional or including BMPs) can provide a significant evidence base to inform future interventions seeking to intensify sustainably small-scale aquaculture in the country.

In this paper, we assess the sustainability outcomes of the adoption of diversification practices and BMPs by small-scale aquaculture producers in Myanmar. In particular, we explore the performance of different production models across multiple sustainability dimensions, namely: (a) aquaculture yield, (b) aquaculture benefit-cost ratio (BCR), (c) nitrogen use efficiency, (d) phosphorus use efficiency, (e) fish self-consumption, and (f) household dietary diversity score (HDDS). We use linear mixed-effects models (LMM) populated with primary data collected through a survey with small-scale aquaculture producers in several rural areas of Myanmar (section 2). Individual objectives include to (a) identify the prevalence of different production models using diversification practices and BMPs (section 3.1), (b) estimate the sustainability performance of each production model (section 3.2), and (c) assess the effect of the adoption of diversification practices and/or BMPs on the six sustainability outcomes (section 3.3). A significant contribution of this analysis is not only to assess the sustainability outcomes of diversification-oriented production models compared to monocultural models, but to also assess the added effects of BMPs adoption. Finally, we critically discuss how the adoption of diversification practices and BMPs can contribute to the sustainable intensification of small-scale aquaculture systems in Myanmar and beyond (section 4).

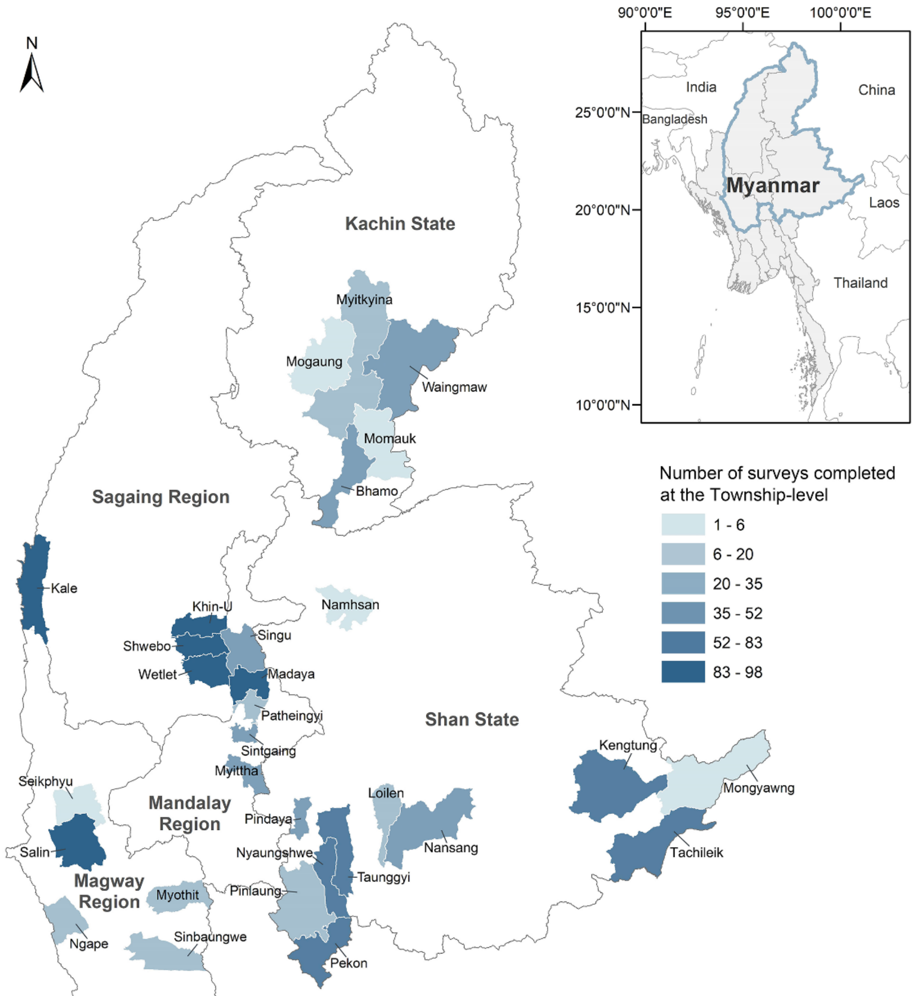
2. Materials and methods

2.1. Study site

Myanmar is one of the major aquaculture producers in Southeast Asia (FAO 2021). Aquaculture production has increased almost elevenfold over the past two decades, from 98.9 thousand tones in 2000 to 1082.1 thousand tones in 2019 (FAO 2021). Currently, more than 95% of Myanmar's aquaculture production comes from freshwater fish (Karim *et al* 2020), with large farms being a major source of freshwater fish production (Belton *et al* 2015). One of the most striking features of aquaculture in Myanmar is that small-scale aquaculture was almost absent since land-use regulations were thought to hinder the conversion of paddy land to ponds (Belton *et al* 2018). However, the small-scale aquaculture sector has been expanding rapidly throughout the country often via overseas development assistance for projects that seek to enhance food security and rural development over the past decade (Htoo *et al* 2021).

Although many areas in Myanmar have a good potential for small-scale aquaculture production (Karim *et al* 2020), we focused our analysis on five states/regions in the Central Dry Zone (i.e. Mandalay, Magway, Sagaing), and Northern and Eastern Regions (i.e. South Shan and East Shan, Kachin) (figure 1). These states/regions share similar socioeconomic and demographic characteristics such as religion (dominated by Buddhism), age structure (the highest proportion of the population is 10–19 yr old), education level (males tend to be more educated than females), livelihoods (almost half of the population is employed), and poverty (approximately 30% poverty rate) (Box S3, supplementary material).

We developed a set of criteria and an extensive scoping approach for township inclusion from the five states/regions in the study (Box S4, supplementary material). The selection criteria include: (a) the availability of resource endowment to enable small-scale aquaculture (i.e. percentage of agriculture land, area of fish ponds), (b) demographic characteristics (i.e. population density, income per capita), and (c) social risk and security (i.e. access to safe sanitation, percentage of underweight children, internally displaced persons). In addition, these areas are characterized by low-income generation capacity, food insecurity and livelihoods challenges, poor access to sanitation, poor access to farming technologies, high weather variability and risk of natural disasters, and physical security threats from conflict (Torbick *et al* 2017, WorldFish 2021). In this sense small-scale aquaculture has great potential to improve rural livelihoods and food security in these areas. Following these criteria, we assigned each township



State/Region	Proposed sample size	Number of surveys completed	Number of surveys for analysis
Sagaing	240	312	223
Shan	540	368	139
Mandalay	300	215	127
Magway	129	138	97
Kachin	105	79	38
Total	1314	1112	624

Figure 1. Location of study areas and distribution of sample size.
Note: In the administrative structure of Myanmar, States/Regions constitute the first-order division (i.e. highest), Districts constitute the second-order administrative division, Townships constitute the third-order administrative divisions, and the fourth and lowest level administrative division is the Ward for urban areas and Village for rural areas.

in the identified states/regions a normalized score and then selected the five townships with the highest scores, with a high score indicating the high potential for small-scale aquaculture, and 30 townships were finally selected (see more details in table S1, supplementary material).

2.2. Data collection and analysis

2.2.1. Data collection

First, through the support of local organizations we established a list of current small-scale aquaculture producers in the study regions. Specifically, we conducted a preliminary survey and gathered the number of ponds for villages in the 30 study townships. In total, we identified 541 villages (see village distribution in table S1, supplementary material) from the pre-selected townships based on the availability of ponds (i.e. number of ponds from high to low). We then conducted a further preliminary survey to collect information on current aquaculture producers in the selected villages.

Second, we randomly selected 1314 households (target sample households) from the list of current small-scale aquaculture producers in the selected villages (figure 1 and table S1 in supplementary material). This list contains basic household information, such as the number of ponds and phone numbers of each small producer. The selected households are those of farmers with a total pond area of <0.5 acres, which are defined as small-scale aquaculture producers.

After well-trained enumerators conducted pilot surveys with aquaculture farmers in selected study areas, the survey protocol was revised and deployed through phone interviews due to the COVID-19 restrictions. Then, we conducted a detailed household survey from 15 September 2020 to 15 January 2021, completing a total of 1112 household surveys from the proposed household list. On average each telephone interview lasted 122 min. The data were captured and digitized in tablets using the data collection tool: *Kobotoolbox*.

The questionnaire includes (a) household and farm characteristics, (b) characteristics of production models (i.e. diversification practices and BMPs), (c) aquaculture production, cost, and income, (d) aquaculture feed and fertilizer input, and (e) fish consumption and food security. More information about the main analytical variables is outlined in the next section.

2.2.2. Analytical approach and variables

We used six outcome variables and several explanatory variables divided into three levels, namely (a) diversification practices and/or BMPs (seven variables), (b) individual BMPs (ten variables), and (c) household and farm characteristics (ten variables).

The six outcome variables include (a) aquaculture yield (in kg ha^{-1} yr^{-1}), (b) aquaculture benefit-cost ratio (BCR), (c) nitrogen use efficiency (%), (d) phosphorus use efficiency (%), (e) fish self-consumption (in kg yr^{-1}), and (f) household dietary diversity score (HDDS). These six sustainability outcomes reflect different aspects of aquaculture sustainability related to economic performance (a–b above), environmental impacts (c–d above), and food security in terms of social impacts (e–f above). Table S2 (supplementary material) contains detailed information on the variables used in the analysis, such as definition, mean, and standard deviation. Table S3 (supplementary material) outlines the methodological approach used to estimate each of the six sustainability outcomes.

First, for the aquaculture yield variable (in kg ha^{-1} yr^{-1}) we estimated the total aquaculture production for all harvested fish species from all household ponds over the past 12 months. We then estimated the aquaculture BCR (score). For this variable we aggregated all major and minor aquaculture-related incomes and costs within the household in the past 12 months. A BCR >1 implies that the aquaculture economic benefit is higher than the cost, and essentially that the households' aquaculture activity is cost-effective.

Second, feed and fertilizer are the primary sources of nitrogen and phosphorus in aquaculture systems to promote plant and animal growth (Zhang *et al* 2015). Here, we estimated total nitrogen and phosphorus use efficiency (%) over the past 12 months as a ratio of the nitrogen and phosphorus output in kg (from the fish body) to the input in kg (from feed and fertilizer) (see table S3, supplementary material). We captured aquaculture input and output through survey questions on annual feed input (e.g. commercial pellet feeds, rice bran, fish meal), fertilizer input (e.g. urea, poultry droppings), and fish output (e.g. the production of common carp, rohu, tilapia). The coefficients used to calculate the nitrogen and phosphorus input and output, including the nitrogen and phosphorus composition of feed, fertilizer, and fish species (table S4, supplementary material), were identified based on coefficients that are Myanmar-specific (if available) or general, as identified in previous publications and reports (Tacon *et al* 2009, Tacon and Metian 2013, Bogard *et al* 2015, Agboola *et al* 2019, Lin *et al* 2020).

Third, for fish self-consumption (in kg yr^{-1}) we estimated the quantity of fish consumed at the household level over the past 12 months, coming from the household's own ponds. The HDDS is used as a proxy of the nutritional status of the household level through self-reporting food intake across twelve food categories in the previous 24 h (Swindale and Bilinsky 2006). Data for the HDDS was collected by asking respondents a series of Yes/No questions for different food items, with the different items combined into twelve food groups (tables S3 and S5, supplementary material). The HDDS (score) was calculated as the sum of all food groups consumed by each household, and ranges from 0 to 12 (Aung *et al* 2021).

The first level of explanatory variables comprises of the eight production models identified in the study area: (a) 'polyculture only', (b) 'PDC only', (c) 'polyculture + PDC', (d) 'BMPs only', (e) 'polyculture + BMPs', (f) 'PDC + BMPs', (g) 'polyculture + PDC + BMPs', and (h) 'no polyculture, PDC, or BMPs'. The production models (a)–(c) and (e)–(g) contain diversification-oriented models sometimes in conjunction with improved technique (i.e. BMPs). Conversely the production model (d) and (h) are not diversification-oriented, with the former using improved techniques (essentially being 'improved monoculture') and the latter not using improved techniques (essentially being 'unimproved monoculture') (table S6, supplementary material).

The second level of explanatory variables reflects the individual BMPs. We considered ten types of sub-practices in the specific local context, including (a) proper species selection, (b) quality seed selection, (c) proper farm site selection, (d) proper stock density, (e) natural food adequacy test in water, (f) alternatives to antibiotics, (g) use of organic feed, (h) use of liming products, (i) limitations in drugs and chemicals use and (j) proper post-harvest fish handling. Table S7 (supplementary material) explains in more depth each of these BMPs and how it was established in our survey. Table 1 presents the hypothesis of the effects of diversification practices and BMPs on the six sustainability outcomes.

The third level of explanatory variables contains a series of household characteristics (i.e. age of household head, gender of household head, education level, region, household size) and farm

Table 1. Expected mechanisms of how diversification practices and BMPs affect the sustainability outcomes.

Production model	Mechanism
Polyculture	• Increases nutrient use efficiency and yield through species complementarity. • Promotes aquaculture BCR through reduction of input cost and increase in fish income using species complementarity. • Benefits fish consumption and HDDS through increases in yield and fish income that can be used for food purchases from polyculture.
PDC	• Provides diverse vegetables that contribute to HDDS increase. • Benefits aquaculture yield and BCR using the leaves of vegetables as farm by-product feeds for fish. • Improves nutrient use efficiency through providing supplementary feeds (leaves of vegetables) for fish.
BMPs	• Increases aquaculture yield and BCR through BMPs such as proper species selection, quality seed selection, proper stock density, use of liming products, and proper post-harvest fish handling. • Improves nutrient use efficiency through BMPs such as natural food adequacy test in water, proper stock density, use of organic feed, and use of liming products. • Benefits fish consumption and HDDS through increases in yield and fish income from BMPs adoption.

Note: The combinations of the different models explored in this study (i.e. 'polyculture + PDC', 'polyculture + BMPs', 'PDC + BMPs' and 'Polyculture + PDC + BMPs') are expected to provide the different effects synergistically.

characteristics (i.e. access to credit, aquaculture technologies, aquaculture training, extension support and participation to fish group). These variables were used to investigate the extent to which these factors would influence the different sustainability outcomes.

To determine the prevalence of diversification practices and BMPs, we developed networks to present to what extent the fish species, crop species and individual BMPs were jointly used at the household level. Networks were created through two elements, (a) nodes, which indicate fish species, crop species and individual BMPs used by households (except for 'unimproved monoculture'), (b) edges, which denote the combined frequency between nodes (i.e. fish species, crop species, and individual BMPs). We conducted the network analysis through the *igraph* package of R version 4.0.4 (Csardi and Nepusz 2006).

2.2.3. Empirical analysis

The original data (n = 1112 households) from the survey were processed prior to the analysis. The extra answers beyond the proposed classification in variables were recategorized. To finalize the final selected sample of the surveyed households for analysis, first, we removed 14 households located outside the proposed townships. Second, we excluded 315 households that reported zero value of aquaculture production since farmers failed to harvest anything or miss-reported harvested numbers. Third, we also omitted 90 households that miss-reported the aquaculture cost and 35 households that miss-reported feed or fertilizer input. Furthermore, we identified 34 extreme values regarding outcome variables based on the top 95th percentiles (Shukla *et al* 2019) and omitted them to minimize bias (Nyambo *et al* 2019). In the end, after data processing we selected and used 624 valid household-level samples in the empirical analysis.

Before fitting the empirical models, we measured variance inflation factors (VIF) to check the multicollinearity between explanatory variables through the *car* package of R version 4.0.4 (Nkomoki *et al* 2018). The VIF test shows that there is no significant multicollinearity among the explanatory variables, suggesting the relative independence of the variables (table S8, supplementary material).

We used linear mixed-effects models (LMM) to estimate the effects of the different explanatory variables outlined in section 2.2.2 on the different sustainability outcomes. The LMM is a generalization of the regression approach, which considers both the fixed effects and random effects on the outcome variables (Barca *et al* 2019). The model is usually applied when there is non-independence in the dataset and to help explain processes (Wenng *et al* 2020). Considering that spatial-autocorrelation may exist within a study village as found in other studies in agricultural and aquacultural settings (Boillat *et al* 2019), we used the village as the random effect variable in all models.

The LMM allows for the integration of continuous and categorical data (Kuznetsova *et al* 2017, Boillat *et al* 2019) and can be expressed as follows:

$$Log\boldsymbol{Y} = \boldsymbol{X}\beta + \boldsymbol{Z}\mu + \varepsilon$$

where $LogY$ is the vector of the log-transformed outcome variable (i.e. six sustainability outcomes); $\boldsymbol{X}$ denotes the fixed variables (i.e. diversification practices and/or BMPs, individual BMPs, household and farm characteristics); $\boldsymbol{Z}$ indicates the random predictor (i.e. the village); β and μ represent the vector of a parameter related to fixed-effects and random-effects respectively; ε is the observation error vector.

We used standard LMM to conduct three rounds of analysis to compare the effects of different production models on sustainability outcomes. We compared: (a) diversification models (with and without BMPs) vs. unimproved monoculture, (b) diversification models with BMPs vs. diversification models without BMPs, and (c) production models with individual BMPs vs. production models without individual BMPs. Table S6 in the supplementary material summarizes these different comparisons.

To further explore the observed heterogeneity (Dias and Belcher 2015), we developed an extended LMM with the inclusion of variables related to household and farm characteristics to test whether these factors would influence sustainability outcomes. In the extended LMM we included five household characteristics and five farm factors (section 2.2.2). The coefficient estimates (CEs) and the 95% confidence intervals (CIs) of explanatory variables denote the effect size (i.e. the direction and magnitude of the effects) of (a) diversification practices and/or BMPs, (b) individual BMPs, and (c) household and farm characteristics (Nakagawa and Cuthill 2007).

Models' goodness-of-fit was assessed through the Bayesian information criterion (BIC) (Aguilar *et al* 2018, Starkweather 2010). The lower the BIC the better the model fit. The LMM was conducted using the *lme4* package of R version 4.0.4 (Bates *et al* 2014).

2.2.4. Sensitivity analysis

To explore the robustness of the results, we conducted a sensitivity analysis by identifying the influential outliers using Cook's Distance (Su *et al* 2021). In general, observations with a Cook's Distance more than three times the mean can be considered as influential outliers. After excluding such influential outliers (figure S3, supplementary material), we conducted again the analysis for the standard LMM and extended LMM to test the effects of these outliers on the results.

2.3. Limitations

Despite its multi-dimensional approach and robust analysis of the sustainability outcomes of adopting diversification practices and BMPs, our study has a series of limitations. The four most important ones relate to (a) farmer selection, (b) comprehensiveness of sustainability outcomes, (c) uncertainty of nitrogen and phosphorus use efficiency estimations, and (d) actual implementation of BMPs.

Regarding (a), there are no comprehensive lists of small-scale aquaculture producers in Myanmar or accurate estimates about their total numbers and distribution across regions/townships. To identify the farmers participating in this study we relied on a list of small-scale producers developed with the assistance of local partners. Although we aimed to be as comprehensive as possible in the identification of farmers in each area, it is likely that the lists were not complete. This possibly inserts biases in the sampling distribution between the study regions and townships.

Regarding (b), we focused on two environmental outcomes, namely nitrogen and phosphorus use efficiency. However several other environmental outcomes can be equally important when exploring sustainable intensification such as ecotoxicity, greenhouse gas emissions, and acidification (Henriksson *et al* 2017, 2018). We focused on these specific environmental outcomes because eutrophication is one of the main environmental issues in freshwater aquaculture, which is mainly caused by the nutrient inputs from feed and fertilizer (Zhang *et al* 2015).

Regarding (c), we calculated nitrogen and phosphorus use efficiency based on the nutrient compositions of feed, fertilizer, and fish species from general and Myanmar-specific reports and literature (table S4, supplementary material). To the extent possible we prioritized the use of coefficients (e.g. rice bran, fish meal, small indigenous species) from Myanmar-specific resources. However, for coefficients that Myanmar-specific resources were unavailable items we used nutrient compositions from general reports and literature (Tacon *et al* 2009, Bogard *et al* 2015). It should also be noted that the nutrient compositions of feed, fertilizer, and fish species vary depending on the species grown and the quality of the feed (Kong *et al* 2020). Furthermore, in this study we did not consider the input of nitrogen and phosphorus from PDC systems or other natural sources through the runoff into the pond, which may cause uncertainties in the assessment of nitrogen and phosphorus use efficiency (Boyd *et al* 2007).

Regarding (d), in this study we assumed the proper implementation of the different BMPs by all relevant households. However, several factors such as the capacity and the availability of resources (in the broadest sense) of small-scale producers can affect their ability to implement BMPs effectively, dictating at the same time to a large degree the actual outcomes of their adoption. This assumption might insert uncertainties in the assessment of the actual outcomes of BMPs adoption.

3. Results

3.1. Prevalence of diversification practices and BMPs

Figure 2 shows the adoption rates for diversification practices and BMPs across the entire sample, while table S9 (supplementary material) presents the adoption rates for each study region. The aggregate results in table S2 (supplementary material) suggest that most households in the study area have adopted some form of diversification, either related to polyculture (77.88% of households) or PDC (51.12% of households). Although many households have adopted 'polyculture only' (26.44% of households), much

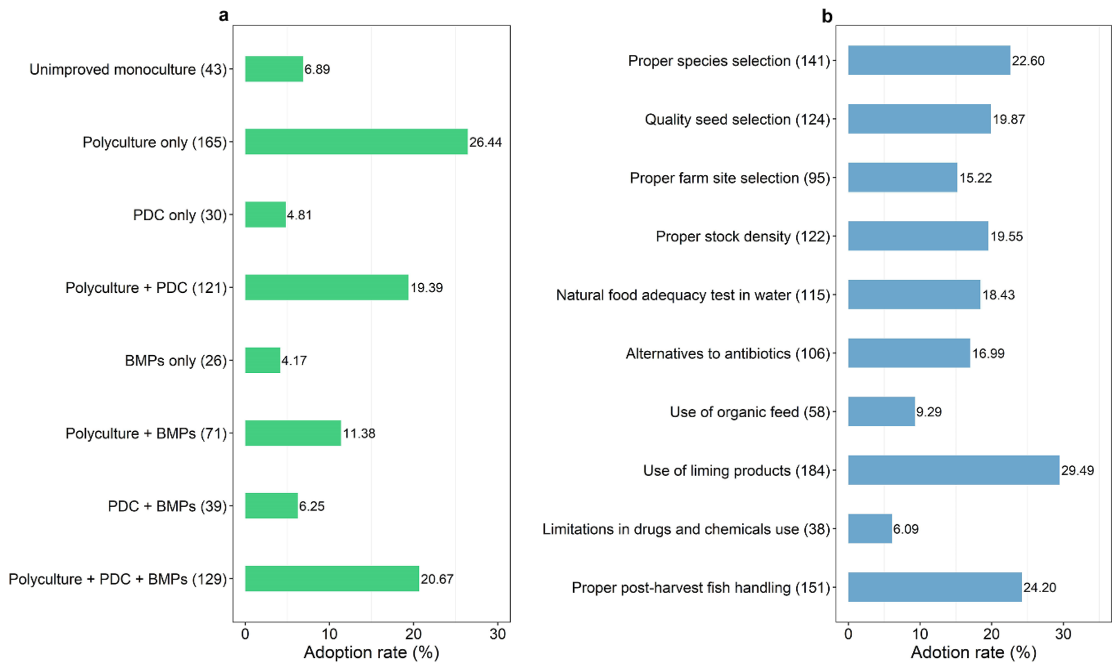


Figure 2. Adoption rates of diversification practices and BMPs.
Note: panel (a) adoption rates of diversification practices and/or BMPs, and panel (b) adoption rates of individual BMPs. The numbers in parentheses of the vertical axis denote the number of households adopting each practice.

fewer households have adopted 'PDC only' (4.81% of households). At the same time 42.47% of the households have adopted at least some BMPs (table S2, supplementary material), usually in conjunction with some diversification strategies (figure 2(a)). It is interesting to note that comparatively few households have not adopted any diversification strategies (11.06% of households), of which 4.17% have adopted 'BMPs only' and 6.89% 'unimproved monoculture'.

Coming to the adoption of individual BMPs, we observe relatively low adoption rates for individual BMPs (figure 2(b)). The highest adoption rate is for the use of liming products (29.49% of households), followed by proper post-harvest fish handling (24.20% of households) and proper species selection (22.60% of households). These findings indicate that smallholder households tend to prefer BMPs associated with the increase in fish production. Conversely, low adoption rates are observed for BMPs associated with the limitations of drugs and chemicals (6.09% of households) and the use of organic feed (9.29% of households). These results imply that BMPs targeting the improvement of environmental performance are relatively overlooked by small-scale producers in the study region. The remaining five BMPs (i.e. proper farm site selection, alternatives to antibiotics, natural food adequacy in water, proper stock density, and quality seed selection) have similar adoption rates ranging from 15% to 20% of the households.

The adoption networks of diversification practices and BMPs (figure 3), suggest that the households that have adopted polyculture-oriented models tend to rely on combinations of fish species such as silver barb (*Barbonymus gonionotus*), rohu (*Labeo rohita*), and common carp (*Cyprinus carpio*) (see large node size and edge weight in figure 3(a)). Small indigenous species are much less prevalent in the sampled households (figure 3(a)). For pond-dike species, the sampled households mainly conduct the combined cultivation of roselle, long bean, mustard, and bottle gourd on their pond dikes (figure 3(b)). BMPs such as the use of liming products, proper species selection, quality seed selection, proper stock density, and proper post-harvest fish handling are often jointly adopted (figure 3(c)). This implies that for smallholder households the main aim of adopting BMPs is to increase fish production rather than reduce environmental impacts.

3.2. Sustainability performance of production models

Overall, for most sustainability outcomes the households adopting diversification strategies (with or without BMPs) tend to perform better than households relying on 'unimproved monoculture', though the differences are not always statistically significant (figure 4).

Specifically, aquaculture yield is higher for all groups adopting diversification strategies, BMPs, and their combinations compared to the 'unimproved monoculture', but the differences are not statistically significant (figure 4(a)). Similar trends are also found for aquaculture BCR, though households adopting

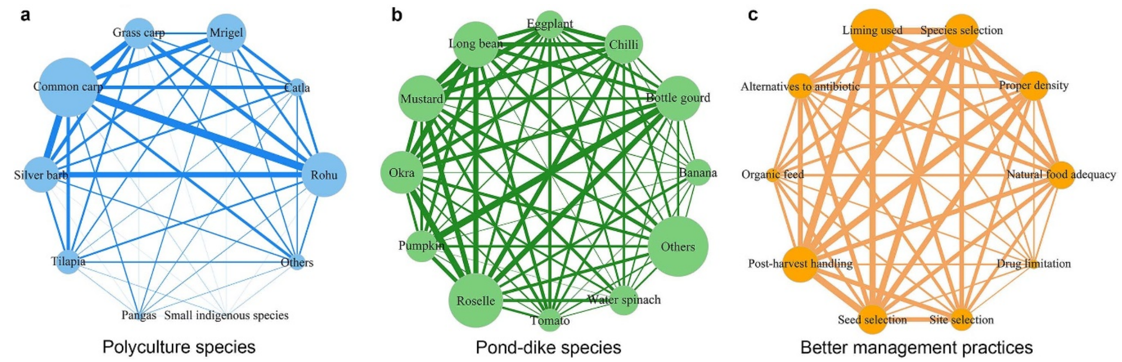


Figure 3. Adoption networks of fish, plants and BMPs in diversification-oriented models.
Note: Node size denotes the adoption frequency of an individual BMP, fish or crop species with a larger node indicating a higher adoption frequency. In other words, a larger node size suggests that a larger proportion of households have adopted the specific fish/plant species and BMP. Edge weight is proportional to the combined frequency between individual BMPs, fish, or crop species, with increasing line width suggesting a higher combination frequency. In other words, the thicker the line connecting two nodes, the more households have adopted the specific combination of fish, crops or BMPs.

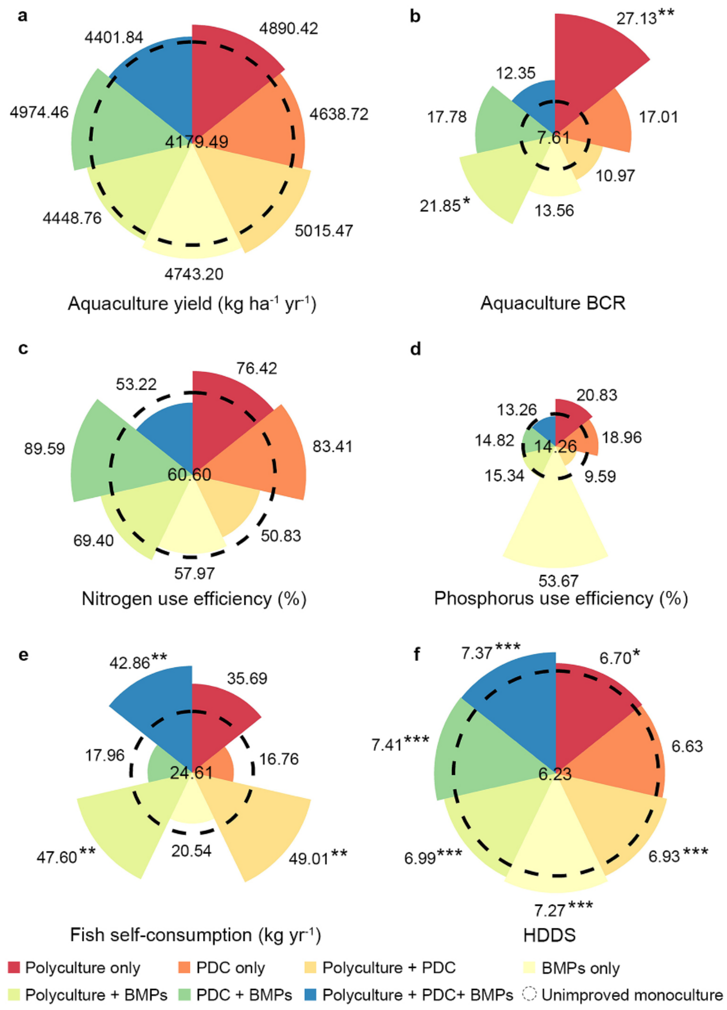


Figure 4. Sustainability performance for the different production models.
Note: The broken circle line represents the average values (numbers in the center of the circle) of each outcome for the unimproved monoculture model. The differences are estimated through the t-test. '***' $p < 0.01$; '**' $p < 0.05$; '*' $p < 0.1$.

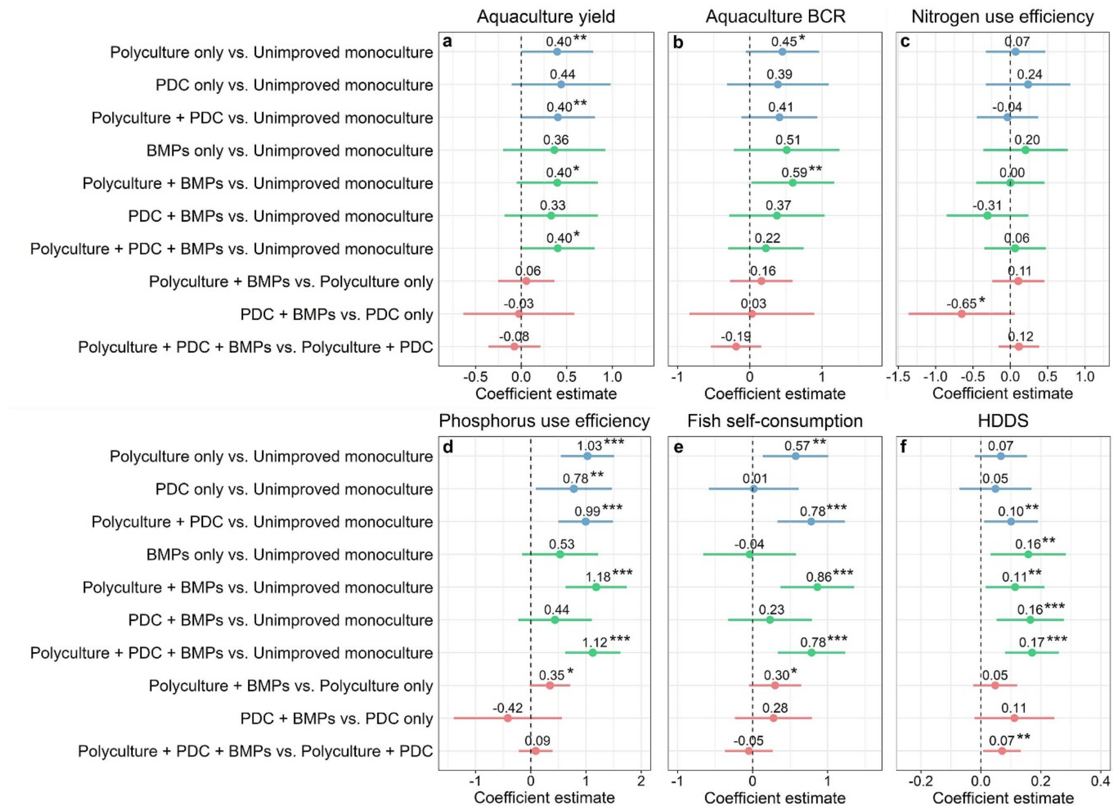


Figure 5. Effects of production models on sustainability outcomes.
Note: BCR = Benefit-cost ratio. HDDS = Household dietary diversity score. PDC = Pond-dike cropping. BMPs = Better management practices. Blue bars denote the effects of production models not adopting BMPs compared to 'unimproved monoculture'. Green bars represent the effects of production models adopting BMPs compared to 'unimproved monoculture'. Red bars indicate the effects of diversified production models adopting BMPs compared to diversified production models not adopting BMPs. Bars around the coefficient estimates (CEs) indicate 95% confidence intervals (CIs). '***' $p < 0.01$; '**' $p < 0.05$; '*' $p < 0.1$.

'polyculture only' have significantly higher BCR compared to 'unimproved monoculture' (figure 4(b)).

Regarding environmental performance, all production models have high nitrogen use efficiency compared to phosphorus use efficiency. Several production models, i.e. 'polyculture + PDC', 'BMPs only', and 'polyculture + PDC + BMPs' have lower or similar nitrogen use efficiency compared to 'unimproved monoculture', but the differences are not statistically significant (figure 4(c)). Although for most production models phosphorus use efficiency (except for 'polyculture + PDC', and 'polyculture + PDC + BMPs') is better compared to 'unimproved monoculture', again all differences are not statistically significant (figure 4(d)).

In terms of food security performance, fish self-consumption for the production models 'polyculture + PDC', 'polyculture + BMPs', and 'polyculture + PDC + BMPs' is significantly higher than 'unimproved monoculture' (figure 4(e)). The other groups have lower fish self-consumption than 'unimproved monoculture', but the differences are not statistically significant. Finally, the differences in HDDS between all production models and 'unimproved monoculture' are significantly higher (except for 'PDC only') (figure 4(f)).

3.3. Effects on sustainability outcomes

Figure 5 reports the effects of different production models on the different sustainability outcomes using the standard LMM. These results are quite similar with those obtained through the extended LMM (table S10, supplementary material). However, as the standard LMM has a better goodness-of-fit compared to the extended LMM indicated by the BIC values (table S11, supplementary material), in the subsequent sections we focus on the standard LMM results. We present the regional variation (Box S1) and effects of household and farm characteristics (Box S2) in the supplementary material.

For the sensitivity analysis (i.e. robustness check), we should note that in the LMM we detect several observations in which Cook's Distance is higher than three times the mean, considering the influential outliers (Figure S3, supplementary material). We exclude the outliers and recalculate the adoption effects of (a) diversification practices and/or BMPs, and (b) individual BMPs. Our sensitivity analysis reveals that the results are robust as the coefficient estimates are similar to the original coefficient estimates (table S12–14, supplementary material).

3.3.1. Effects of production models on sustainability outcomes

Overall, when compared to 'unimproved monoculture', most production models that contain diversification practices without BMPs (blue bars in figure 5), and with BMPs (green bars in figure 5), have significant positive effects on the economic (i.e. aquaculture yield, BCR, figures 5(a) and (b)), phosphorus use efficiency (figure 5(d)) and food security (i.e. fish self-consumption, HDDS, figures 5(e) and (f)) sustainability outcomes. Conversely, we do not detect such effects on nitrogen use efficiency (figure 5(c)). When comparing diversified production models with and without BMPs (red bars in figure 5), some of the production models adopting BMPs have a significant positive effect on environmental and food security outcomes (figures 5(d), (e) and (f)). However, the addition of BMPs to diversified production models does not seem to provide clear-cut economic benefits.

First, regarding economic outcomes, our results generally display that the adoption of diversification practices and their combinations without BMPs (blue bars in figures 5(a) and (b)) has positive effects on aquaculture yield and BCR compared to 'unimproved monoculture', though not always statistically significant. Some of the more clear-cut benefits for aquaculture yield are observed for the adoption of 'polyculture only' (CE = 0.40, 95%CI = 0–0.79) and 'polyculture + PDC' (CE = 0.40, 95%CI = −0.01–0.81) (figure 5(a)). Significant effect for aquaculture BCR is observed for 'polyculture only' (CE = 0.45, 95%CI = −0.06–0.96) (figure 5(b)).

Similar findings are also observed when comparing to 'unimproved monoculture' production models that integrate BMPs into diversification practices (green bars in figures 5(a) and (b)). Some of the more significant effects for aquaculture yield are observed for 'polyculture + BMPs' (CE = 0.40, 95%CI = −0.05–0.84), and 'polyculture + PDC + BMPs' (CE = 0.40, 95%CI=−0.01–0.81) (figure 5(a)). A significant effect for aquaculture BCR is observed for 'polyculture + BMPs' (CE = 0.59, 95%CI = 0.02–1.17) (figure 5(b)).

However, when comparing diversified production models with and without BMPs, we see that the adoption of BMPs does not seem to have any significant positive effect to both economic outcomes (red bars in figures 5(a) and (b)). In this sense the adoption of BMPs in diversified systems does not seem to provide any additional value in terms of economic outcomes.

Second, regarding environmental outcomes, the adoption of diversification practices and their combinations without BMPs, i.e. 'polyculture only' (CE = 1.03, 95%CI = 0.55–1.51), 'PDC only' (CE = 0.78, 95%CI = 0.09–1.47) and 'polyculture + PDC' (CE = 0.99, 95%CI = 0.50–1.49) have significant positive effects on phosphorus use efficiency compared to 'unimproved monoculture' (blue bars in figure 5(d)). When integrating BMPs into diversification practices, significant positive effects are observed for 'polyculture + BMPs' (CE = 1.18, 95%CI = 0.63–1.74) and 'polyculture + PDC + BMPs' (CE = 1.12, 95%CI = 0.62–1.62) compared to 'unimproved monoculture' (green bars in figure 5(d)). However, there is no significant difference in terms of nitrogen use efficiency when compared to 'unimproved aquaculture' (figure 5(c)).

When comparing diversified production models with and without BMPs we observe a significant positive effect for phosphorus use efficiency for 'polyculture + BMPs' (CE = 0.35, 95%CI = −0.02–0.71), compared to 'polyculture only' (red bars in figure 5(d)). While a negative effect for nitrogen use efficiency is observed for 'PDC + BMPs' (CE = −0.65, 95%CI = −1.36–0.06), compared to 'PDC only' (red bars in figure 5(c)).

Third, regarding food security outcomes, figures 5(e) and (f) show that generally adopting diversification practices without BMPs (blue bars in figure 5) could contribute to food security in terms of fish self-consumption and HDDS when compared with 'unimproved monoculture', although the effects are not always statistically significant. Specifically, for fish self-consumption, some significant positive effects are found for 'polyculture only' (CE = 0.57, 95%CI = 0.14–1.01), and 'polyculture + PDC' (CE = 0.78, 95%CI = 0.33–1.23). Such effects are also observed for HDDS for 'polyculture + PDC' (CE = 0.10, 95%CI = 0.01–0.19).

When embedding BMPs in diversification practices, most production models have significant positive effects on fish self-consumption and HDDS compared to 'unimproved monoculture' (green bars in figures 5(e) and (f)). In terms of fish self-consumption, significant positive effects are detected for 'polyculture + BMPs' (CE = 0.86, 95%CI = 0.37–1.35), and 'polyculture + PDC + BMPs' (CE = 0.78, 95%CI = 0.34–1.23). In particular, all production models are found to have significant positive effects to HDDS, namely 'BMPs only' (CE = 0.16, 95%CI = 0.03–0.28), 'polyculture + BMPs' (CE = 0.11, 95%CI = 0.02–0.21), PDC + BMPs (CE = 0.16, 95%CI = 0.05–0.28), and 'polyculture + PDC + BMPs' (CE = 0.17, 95%CI = 0.08–0.26).

More so, when comparing diversified production models with and without BMPs (red bars in figures 5(e) and (f)), then integrating BMPs into diversification practices could offer some benefits to food security. For example, the 'polyculture + BMPs' model performs better in fish self-consumption than 'polyculture only' (CE = 0.30, 95%CI = −0.05–0.65). Similarly the 'polyculture + PDC + BMPs' production model generates higher HDDS compared to the same model without BMPs (CE = 0.07, 95%CI = 0.01–0.13).

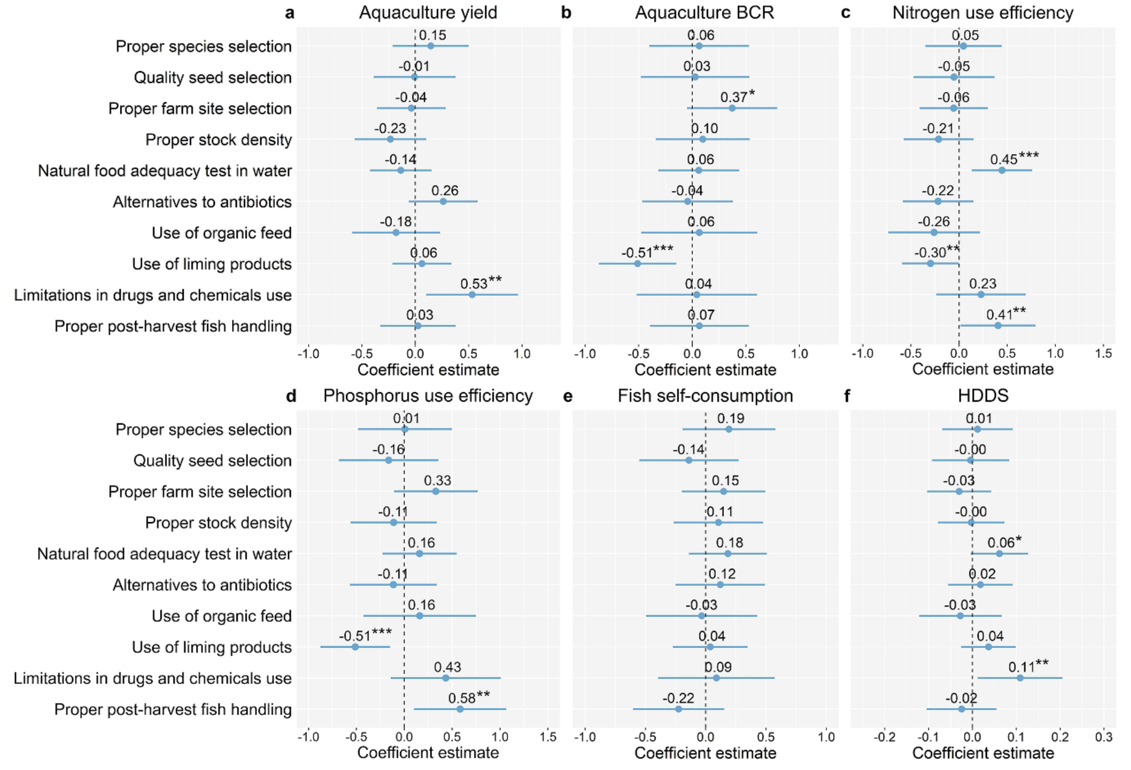


Figure 6. Effects of individual BMPs on sustainability outcomes.
Note: BCR = Benefit-cost ratio. HDDS = Household dietary diversity score. Bars around the coefficient estimates (CEs) indicate 95% confidence intervals (CIs). '***' $p < 0.01$; '**' $p < 0.05$; '*' $p < 0.1$.

In terms of the results of figures 5(e) and (f) more critically we see some interesting patterns between production models and food security outcomes. First, for fish self-consumption when compared to 'unimproved monoculture' only the polyculture-based models have significant positive effects on fish self-consumption (see blue and green bars in figure 5(e)). In this case production models containing PDC have significant positive effects only if combined with polyculture (i.e. 'polyculture + PDC' and 'polyculture + PDC + BMP'). Second, when compared to 'unimproved aquaculture', only diversified models combining BMPs tend to have significant positive effects on HHDS, while diversified models not containing BMPs have fewer clear-cut effects (see blue and green bars in figure 5(f)). Third, the adoption of BMPs in diversified systems does not seem to provide extra food security benefits for both fish self-consumption and dietary diversity (see red bars in figures 5(e) and (f)).

3.3.2. Effects of individual BMPs on sustainability outcomes

In terms of economic outcomes (figures 6(a) and (b)), in most cases the adoption of an individual BMP does not seem to have significant effects. However, we have to point out that these are highly aggregated samples that contain very diverse production models. Nevertheless we observe a positive effect on aquaculture yield through the adoption of the 'limitations in drugs and chemicals use' BMP ($CE = 0.53$, $95\%CI = 0.10$–0.96). In terms of aquaculture BCR, a significant positive effect is also found for the 'proper farm site selection' BMP ($CE = 0.37$, $95\%CI = -0.05$–0.79), while the 'use of liming products' BMP could have a negative effect ($CE = -0.51$, $95\%CI = -0.87$ to -0.15).

In terms of environmental outcomes (figures 6(c) and (d)), we find that adopting the BMP 'natural food adequacy test in water' could significantly increase nitrogen use efficiency ($CE = 0.45$, $95\%CI = 0.13$–0.76). Similar positive signs are found for the BMP 'proper post-harvest fish handling' (nitrogen use efficiency: $CE = 0.41$, $95\% CI = 0.02$–0.80; phosphorus use efficiency $CE = 0.58$, $95\%CI = 0.10$–1.07). Conversely, adopting the BMP 'use of liming products' seems to negatively affect nitrogen and phosphorus use efficiency ($CE = -0.30$, $95\%CI = -0.59$–0, $CE = -0.51$, $95\%CI = -0.88$ to -0.15, respectively).

In terms of food security outcomes (figures 6(e) and (f)), the adoption of BMPs such as 'limitations in drugs and chemicals use' ($CE = 0.11$, $95\%CI = 0.01$–0.21) and 'natural food adequacy test in water' ($CE = 0.06$, $95\%CI = 0$–0.13) can have significant positive effects on HDDS. However, there is no significant difference in fish self-consumption.

4. Discussion

4.1. Synthesis of findings

Notably, our results demonstrate that the small-scale aquaculture producers in the surveyed area have a sound yield, achieving fish production of 4179.49–5015.47 kg ha^{-1} yr^{-1} across all production models (figure 4(a)). Similarly, the aquaculture BCR is quite positive ranging from 7.61 to 27.13 in all cases (figure 4(b)). All production models have high nitrogen use efficiency of 50.83–89.59% (figure 4(c)), while phosphorus use efficiency is relatively low, ranging from 9.59–20.83% (except for 'BMPs only': 53.67%) (figure 4(d)). Fish self-consumption can be considered quite sufficient standing at 16.76–49.01 kg yr^{-1} (figure 4(e)), with households having acceptable household dietary diversity of 6.23–7.37 for all production models (figure 4(f)). The above suggests that the small−scale aquaculture systems have multiple positive sustainability outcomes, which nevertheless vary between the different production models.

In terms of effects on economic outcomes, on the one hand that the adoption of aquaculture diversification practices can indeed offer certain benefits related to yield and BCR (blue bars in figures 5(a) and (b)). This finding is consistent with previous studies that integrating polyculture and PDC in small-scale aquaculture contexts could enhance economic performance (Karim *et al* 2011, Limbu *et al* 2017). This is mainly because fish growth could be promoted through complementarity among species, and such polyculture systems allow the production of multiple products with commercial value (Thomas *et al* 2021). In particular, the combined adoption of polyculture and PDC results in the highest aquaculture yield (figure 4(a)), possibly due to the runoff of nutrients from PDC systems (fertilization) into the pond (Karim *et al* 2011). On the other hand the economic benefits can also increase when integrating BMPs into diversification practices, i.e. 'polyculture + BMPs' (green bars in figures 5(a) and (b)). This reflects recent studies that the adoption of BMPs in polyculture systems had greater potential to achieve economic growth (Dickson *et al* 2016, Kassam and Dorward 2017), possibly due to the compatibility among the combined taxa of fish species (i.e. proper species and seed selection BMPs) or stock density optimization.

In terms of effects on environmental outcomes, phosphorus use efficiency ranges from 9.59 to 20.83% (except for 'BMPs only' with 53.67%) in all production models, which is similar to the results (8.70–21.20%) from a review study in China (Zhang *et al* 2015). We observe that adopting diversification practices and their combinations without BMPs can increase phosphorus use efficiency (blue bars in figure 5(d)). Previous studies also found that integrating a semi-intensive polyculture system with PDC can enhance nutrient use efficiency through the connections between terrestrial and aquatic production units (Karim *et al* 2011, Thomas *et al* 2021). Such positive effects for phosphorus use efficiency are also observed when integrating BMPs into diversification practices, i.e. 'polyculture + BMPs', and 'polyculture + PDC + BMPs' (green and red bars in figure 5(d)). A recent study also suggested that the adoption of BMPs in tilapia polyculture systems could offer a significant improvement in environmental performance regarding eutrophication, as this might be linked to the adoption of BMPs such as natural food adequacy test in water, and improved feed management (Henriksson *et al* 2017). However, such production models do not seem to have any major effects on nitrogen use efficiency (blue and green bars in figure 5(c)). This observed lack of significant effects might be likely because the surveyed farms already had high nitrogen use efficiency (50.83–89.59%) in different production models (figure 4(c)), resulting in that the differences might not be significant between production models. Such underlying mechanisms need to be understood better in order to achieve sustainable intensification through diversification and BMPs in Myanmar and possibly other developing contexts. Furthermore, for individual BMPs we can see that the use of liming products has negative effects on nitrogen and phosphorus use efficiency (figures 6(c) and (d)), possibly because farmers do not check liming requirements. This points to the possible need for extension support to indicate further good practices to improve the performance of BMPs, such as using liming products only as needed (Tucker and Hargreaves 2008).

In terms of effects on food security outcomes, our findings point to the vital role that some diversification practices can play in the food security of small-scale aquaculture households (figures 5(e) and (f)). To begin with, the adoption of some diversification practices can provide essential benefits for fish self-consumption and HDDS, as indeed evidenced in other small−scale aquaculture contexts (Ahmed *et al* 2014, Castine *et al* 2017). For example, species diversification in polyculture models could increase fish consumption in producing households, while diverse fish species rich in micronutrients can be an integral part of the diets and food security of small-scale producers (Dam Lam *et al* 2022). Similar to our results, diversified aquaculture systems integrating polyculture and PDC have also been found to improve household dietary diversity through the intake of vegetables and fish rich in micronutrients (Ahern *et al* 2021). However, our results suggest that the adoption of BMPs in diversified systems does not seem to have significant effects for food security outcomes. Indeed, although previous studies have explored the effects of BMPs on profitability (Dickson *et al* 2016), poverty alleviation (Kassam and Dorward 2017), and environmental performance (Henriksson *et al* 2017), there is scarce literature examining the food security outcomes of BMPs adoption. In this sense our findings contribute to current BMPs literature suggesting that integration of BMPs into diversification practices might not add substantial value in terms of food security benefits to small-scale aquaculture households.

4.2. Implications for sustainable intensification

As mentioned in the Introduction the adoption of diversification practices and BMPs have been core elements for the sustainable intensification of small-scale aquaculture production (Henriksson *et al* 2021). Our study makes two important observations for their actual potential to achieve sustainable intensification. First, while many of the studied diversified production models (with or without BMPs) can have significant positive effects on most economic, phosphorus use efficiency, and food security outcomes compared to 'unimproved monoculture' (blue and green bars in figures 5(a), (b), (d), (e), and (f)), we see practically no effect for nitrogen use efficiency (blue and green bars in figure 5(c)). Second, the adoption of BMPs for each diversified production model has practically no effect for practically all sustainability outcome (red bars in figure 5). Collectively these suggest that (a) although diversification and BMPs can have certain sustainability benefits, their full potential for sustainable intensification might be constrained in the absence of nitrogen use efficiency, and (b) the adoption of BMPs in diversified production models has virtually no added effect for the studied sustainability outcomes. This suggests the possible need for context-specific improvements in the studied BMPs or even the development of new BMPs. Below we discuss potential implications and ways forward.

Nevertheless, our findings point out the strong potential of diversification for enhancing economic, phosphorus use efficiency and food security outcomes. First, we highlight the importance of polyculture since polyculture-based models such as 'polyculture + PDC', 'polyculture + BMPs' and 'polyculture + PDC + BMPs' have significant positive effects on aquaculture yield, phosphorus use efficiency, fish self-consumption, and HDDS (figures 5(a), (d), (e), and (f)). In such models the combination of silver barb (*Barbonymus gonionotus*) in the upper layer, rohu (*Labeo rohita*) in the middle layer, and common carp (*Cyprinus carpio*) or mrigel (*Cirrhinus cirrhosus*) in the bottom layer (the main polyculture species in the sampled households) (figures 3(a) and 7) might add significant value. In this polyculture system, the foraging behaviors of carp can benefit rohu and silver barb through resuspending nutrients accumulated in the sediment into the water body (Thomas *et al* 2021) (figure 7). In such polyculture system, we also observe that the differences in yield between production models are small (figure 4(a)), which likely because most small-scale aquaculture ponds are unaerated, and the production volumes are limited by the oxygen budget. To further improve sustainability performance, we suggest applying mechanical aerators (if financially feasible) to provide oxygen and keep the aerobic organisms suspended and mixed with water to increase nutrient use efficiency and aquaculture yield and BCR. Second, the integration of PDC into the polyculture model can have added value for dietary diversity in terms of HDDS as the producing households not only benefit from high fish self-consumption which characterizes polyculture-based models, but also diverse vegetables from the land around the pond (figures 5(e) and (f)). In addition to the crop species currently cultivated (figure 3(b)) the possible addition of vegetables rich in micronutrients (e.g. orange sweet potato, dark green leafy vegetables) can have added nutritional benefits (Ahern *et al* 2021) (figure 7).

Furthermore, we should note that in diversified small-scale aquaculture systems, it is hard to simultaneously achieve maximum potential yield and minimize environmental footprint, as there are several tradeoffs, especially when considering the full life-cycle of inputs, such as feed, water, and energy (Henriksson *et al* 2021). Such challenges could be addressed through targeted interventions that are readily available, including BMPs (Henriksson *et al* 2021). However, the low adoption rates for individual BMPs (ranging from 8% to 28%) among the sampled households are observed (figure 2(b)). For example, environment-related BMPs such as limitations in drugs and chemicals use, use of organic feed, and alternatives to antibiotics are much less popular compared to other BMPs targeting productivity gains (figure 3(c)). On the one hand, compared to the environment-related BMPs, BMPs aiming at productivity gains (e.g. proper species selection, quality seed selection) are often more easily accessible for households, likely due to observation from neighbors, friends, and family. Likewise, some adoption challenges are the resource constraints and the often insufficient knowledge and skills of small-scale aquaculture households (Belton *et al* 2018). On the other hand, farmers will likely invest in and adopt BMPs aiming at the environmental performance if they receive incentives and signals from government policies that set clear goals, if they expect that the investment will be profitable, and if they have the right education, information, and motivation (Viatte 2001, Piñeiro *et al* 2020). These strongly imply the provision of economic or in-kind incentives from governments or NGOs, such as providing fish seed, feed, and alternatives to antibiotics for the targeted farmers. In addition, to achieve the full potential of BMPs for sustainable intensification in small-scale production contexts, there should be greater efforts to ensure both that farmers are not excluded from

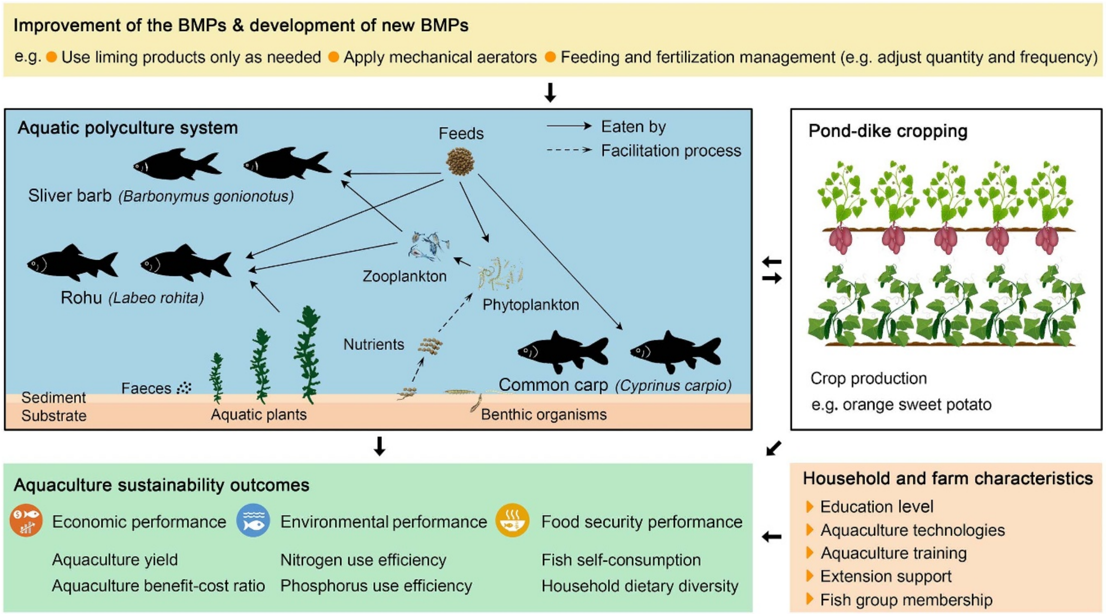


Figure 7. Proposed adoption of diversification practices and BMPs for sustainable intensification. Figure related to aquatic polyculture system was adapted from Thomas *et al* (2021). John Wiley & Sons. © 2020 Cambridge Philosophical Society.

adopting such BMPs and that BMPs are implemented properly (Aung *et al* 2021, Henriksson *et al* 2021).

Toward that end, it is crucial to improve the extension capability through future interventions from appropriate government agencies and NGOs. We suggest several pathways to improve these processes to help small-scale producers establish sustainable aquaculture production systems. First, there is a need to improve the necessary training packages, such as identifying context-specific needs and solutions and injecting economic, environmental, and food security concerns into the process of developing and introducing diversification practices and BMPs (Viatte 2001, Dam Lam *et al* 2022). It would be necessary to improve the BMPs to fit the local contexts, for example by fine tuning certain operation variables, and even develop new BMPs to improve sustainability outcomes in the local context (figure 7). For example, feeding and fertilization management can be a new BMP that focuses on lowering the nutrient inputs (e.g. 10% less fertilizer, 15% less feed or only feeding 5 out of 7 d), while maintaining production. Second, a participatory method would require the promotion of farmer awareness about the merits of such farming practices (e.g. productive, input-efficient, and environmentally beneficial) and facilitate the dissemination of these practices. In particular, a key point for such participation will be to involve and empower all relevant local actors (and especially women and women-led households) across multiple entry points (e.g. household level, community level) (Dam Lam *et al* 2022). Furthermore, a communication approach should be implemented to engage such actors in self-reflection exercises that best accommodate the intervention context (e.g. lessons learned, workshops, practical training), where socioeconomic barriers and resource limits can be identified, and their possible effects on the expected outcomes become clear (Htoo *et al* 2021). Finally there would be a need to ensure the proper implementation of BMPs over time, for example by asking farmers to record properly all inputs and outputs from their aquaculture operation in the first few cycles to both receive feedback on whether they implement properly the BMPs and how to further improve them. Such an integrated approach combining different techniques and actively considering the barriers to their adoption and proper implementation could possibly reconcile different sustainability dimensions and achieve sustainable intensification in small-scale aquaculture systems.

5. Conclusion

The adoption of diversification practices and BMPs can contribute to the sustainable intensification of small-scale aquaculture production in developing contexts. This is usually based on their positive effect for farm productivity, rural livelihoods, food security, and environmental performance. This study uses data from 624 small-scale aquaculture households in Myanmar to provide important information on how the adoption of diversification practices and BMPs influences different dimensions of sustainability. Collectively our results suggest that while the adoption of diversification practices and BMPs can have certain sustainability benefits in terms of improved economic, phosphorus use efficiency, and food security outcomes, the absence of strong positive effects for nitrogen use efficiency might question their full potential for sustainable intensification. Furthermore, the adoption of BMPs in diversified production models seems to have virtually no effect on any of the sustainability outcomes explored, raising questions about their added value for the sustainable intensification of small-scale production systems and suggesting improvement of the BMPs and the development of new BMPs. Overall, while such production models adopting diversification practices and BMPs can help achieve localized progress across multiple sustainable development goals (SDGs) such as no poverty (SDG 1), zero hunger (SDG 2), and life below water (SDG 14) directly or indirectly, improvements in their design, dissemination and implementation would be necessary to ensure they meet their full potential for sustainable intensification.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Acknowledgments

This study was conducted as part of the baseline assessment of the Fish for Livelihood (F4L) project funded by the USAID. WorldFish Myanmar leads F4L project implementation in collaboration with a range of development and private sector entities. The F4L project baseline study was conducted with financial support from USAID and the CGIAR Research Program on Fish Agri-Food Systems (FISH) led by WorldFish. This work also acknowledges the Ministry of Education, Culture, Sports, Science and Technology, Japan (201517) and the China Scholarship Council (201906310001) for a PhD scholarship to Quanli Wang.

Conflict of interest

The analysis presented in this study is based on data collected as part of the baseline study of the Fish for Livelihood (F4L) project. The aim of the F4L project is to provide support packages to small-scale aquaculture producers designed and implemented by WorldFish Myanmar in collaboration with partners. Some of the co-authors in this study are affiliated with WorldFish.

Authors contribution

Quanli Wang and Alexandros Gasparatos contributed to the study conception and design. Material preparation, data collection and analysis were performed by Quanli Wang, Eric Brako Dompreh, Syed Aman Ali and Alexandros Gasparatos. The first draft of the manuscript was written by Quanli Wang and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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