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Smallholder aquaculture diversifies livelihoods and diets thus improving food security status: evidence from northern Zambia

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Abstract

Background Much has been made of the potential for aquaculture to improve rural livelihoods and food and nutrition security in Africa, though little evidence exists to back such claims. This study, conducted in northern Zambia, assessed the benefits of adopting aquaculture by comparing a sample of households with ($n = 177$) and without fishponds ($n = 174$).

Results On-farm food production was assessed by summing all crop and livestock activities and calculating a production diversity score (PDS) of key food groups. Aquaculture households had greater crop diversification and were more associated with key nutritious foods grown on the farm, possibly due to additional water irrigation capabilities. A greater diversity of cultivated crops led to better household dietary diversity scores (HDDS). We further assessed the frequency of consumption of 53 food items (including 30 fish species) over a period of 4 weeks via a Food Frequency Questionnaire (FFQ). Using the Simpson's Index, aquaculture households had greater diversity and evenness in the distribution of foods and fish species consumed, particularly for foods grown on the farm. Using livelihood and dietary factors in a multilevel probit regression on the Household Food Insecurity Access Scale (HFIAS), we found that adopting aquaculture gave households almost two times more likelihood of improving their food security status. Households could further improve their food security outcomes by growing and consuming certain vegetables, especially those that could be integrated along pond dykes.

Conclusions The study suggests three clear pathways to food security. (1) Increasing wealth and income from the sale of fish and integrated vegetables and/or crops, which can be used to purchase a diversity of foods. (2) Increasing food and nutrition security via the direct consumption of fish and vegetables grown on the farm. (3) Improving irrigation capabilities in integrated aquaculture–agriculture systems that has direct impact on pathways 1 and 2. Aquaculture should be promoted in the region for its crop diversification and food security benefits, so long as it fits the local farming system and livelihood context. Moving away from productivist approaches to nutrition-sensitive aquaculture widens the scope of uncovering the many benefits of pond farming in smallholder systems.

Keywords Aquaculture, Crop diversification, Dietary diversity, Production diversity, Tilapia, Zambia, Food security, Pond farming, Nutrition, Integrated aquaculture and agriculture

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Introduction

Aquaculture is often touted to be able to alleviate poverty and improve food and nutrition security for small agricultural homesteads [1, 2]. Farmers in Africa cultivate a variety of aquatic species; however, the most frequently farmed fish are tilapias, farmed by smallholders and large commercial enterprises alike [3]. The proliferation of smallholder tilapia farming in Africa has had direct and indirect impacts on poverty reduction and improving food and nutrition security [4–6]. Pinpointing the exact pathways by which aquaculture leads to improved food security and nutrition outcomes are notably difficult to discern [7].

Given that aquaculture is a relatively new agricultural activity in much of Africa, it is worth assessing it as an agricultural intervention in the same way that biofortified crops or homestead gardens aim to improve household diets and food and nutrition security [8]. Aquaculture provides multiple pathways to food and nutrition security by (1) increasing purchasing power via the sale of fish to access more diverse diets [9]; and (2) increasing fish consumption via harvesting from ponds [10]. A third, and less acknowledged pathway, is that ponds provide water for irrigation capabilities and thus additional opportunities for horticulture [11]. These pathways aim to contribute to two key pillars of food and nutrition security, namely, improving the access and availability of certain foods via the interplay between farm production diversity and dietary diversity, as well as the diversity (and affordability) of purchased foods [12]. The interconnection in understanding the benefits of farming systems is a particularly important and often under-researched component in assessments of smallholder tilapia farmers in sub-Saharan Africa [13]. While crop diversification has been shown to benefit rural livelihoods and household diets in Africa, aquaculture as a livelihood activity is notably absent from this body of work [14–16].

In Asia, where aquaculture production has a longer tradition than in Africa, the links between food and nutrition security, incomes, and aquaculture are more explicit [17]. Aquaculture has had positive effects on income levels, employment and raising fish consumption levels in Bangladesh [18–20]. Fishponds contributed to rural economies by improving retail and labour opportunities in Myanmar [21]. Intercropping fish with rice and vegetables diversified livelihoods and improved incomes of households in the Philippines and Bangladesh [22, 23]. The adoption of aquaculture led to crop diversification in farming households in Bangladesh that adopted both aquaculture and horticulture actives, thus leading to better diet quality [11, 24]. Similar pathways to food security and poverty alleviation surely exist in Africa, meaning that small-scale tilapia farming has the potential to significantly improve the lives of farming households [25].

In Zambia, a burgeoning aquaculture sector has had positive effects on fish supplies, commercialising supply chains, and providing opportunities for fish farming amongst rural populations [26]. Much of the perceived positive impacts of aquaculture can be attributed to the fast-growing, capital-intensive commercial sector [27, 28]. Many donor-led organisations and the government of Zambia look favourably at aquaculture as a potential solution to poverty and food and nutrition insecurity in rural areas. Zambia is amongst the poorest and most food-insecure countries in the world, with one of the lowest rankings in the Global Hunger Index [29]. Making the linkages between agricultural livelihoods, diets and food and nutrition security is thus critical. Smallholder aquaculture in Zambia is, however, limited by low productivity, lack of markets, and underdeveloped supply chains, with little evidence of its impact on food and nutrition security [26]. Despite these barriers, farming households still persevere with tilapia pond farming, with anecdotal evidence that this provides some additional income or the occasional fish for dinner [10, 30]. The goal of this study is to assess the potential benefits of aquaculture to rural households.

Quantifying the benefits of aquaculture adoption is a difficult task given the vast social, economic, and agro-ecological differences in tilapia farming systems in the region, and even within villages in Zambia [30]. Previous approaches often failed to consider that many fish farmers in sub-Saharan Africa, and Zambia specifically, are primarily terrestrial crop and/or livestock farmers and only partake in fish farming as a secondary or tertiary livelihood activity [31]. Ponds are often studied in isolation, rather than looking at how they fit into diverse livelihood portfolios or how they are integrated with other agricultural activities, thereby missing important linkages in the farming system. Aquaculture farmers are rarely compared to their neighbours, who do not cultivate fish, which would provide more accurate assessments of food security and income benefits as compared to those who do not adopt aquaculture [32]. Finally, many studies overfocus on measuring (estimating) fish productivity in extensive systems through recall methods that are rarely accurate [33]. Such approaches further fail to account for the different ways and reasons why fish are cultivated and harvested, or the different benefits ponds provide throughout the year [30].

Our assessment begins with the assumption that the true value of tilapia pond farming lies not necessarily in how much fish is produced or how productive a pond is per se, but rather, in the total value ponds provide to a household, based on direct and indirect pathways to food and nutrition security [34]. To achieve a more accurate assessment, we selected a randomised sample of aquaculture and non-aquaculture households. We employed several methods to quantify household livelihoods, diets, and food and nutrition security by assessing the role of aquaculture in food production and consumption. The overall objective was to assess whether aquaculture contributes to dietary diversity and food and nutrition security via the above-mentioned pathways. Our specific research questions were: 1) do aquaculture households have more diverse livelihoods (i.e., crop diversification and/or non-farm activities?); 2) do aquaculture households have better access to foods (including fish) and more diverse diets? and 3) if aquaculture affects livelihoods and/or dietary diversity, does this ultimately improve food and nutrition security? This paper presents the methods in "Materials and methods" section, and the results and discussion in "Results" and "Discussion" sections, respectively, with a brief conclusion at the end.

Materials and methods

Study location

The study was conducted in Luwingu District in the Northern Province of Zambia in September 2017 (see Fig. 1). Luwingu has a total population of approximately 80,000 people as of the last census conducted in 2014 [35]. Over 80% of households are classified as rural agricultural households [36]. Most households engage in some form of farming, typically growing a combination of maize, cassava, beans, and groundnuts [37]. Farmers in the north of Zambia rarely engage in livestock and poultry, generally favouring traditional crops in a rotational system throughout the year [38]. The district is home to Lake Bangweulu, a major source of capture fisheries in the region, which is critical to the diets of local households [39]. According to the Department of Fisheries (DoF), approximately 400 households were officially registered as practicing aquaculture in 2017, accounting for around 3% of all households in the district. This was later verified by an updated census of fish farmers conducted by WorldFish in 2019 where 412 farmers were officially registered as practicing aquaculture [40].

Northern Province is home to 3255 fish farmers, more than a third of all fish farmers in the country, of which around 13% were registered in Luwingu (4.3% of all fish farmers in the country) [36]. Luwingu District has been the target of many donor-led aquaculture interventions over the last years, providing a suitable site to assess the benefits of adopting aquaculture [10, 26, 33]. The province has some of the highest rates of households living in poverty, with over 43% of households reported to belong to the lowest wealth quintile, according to the National Demographic and Health Survey [35]. Rural households in Zambia suffer from

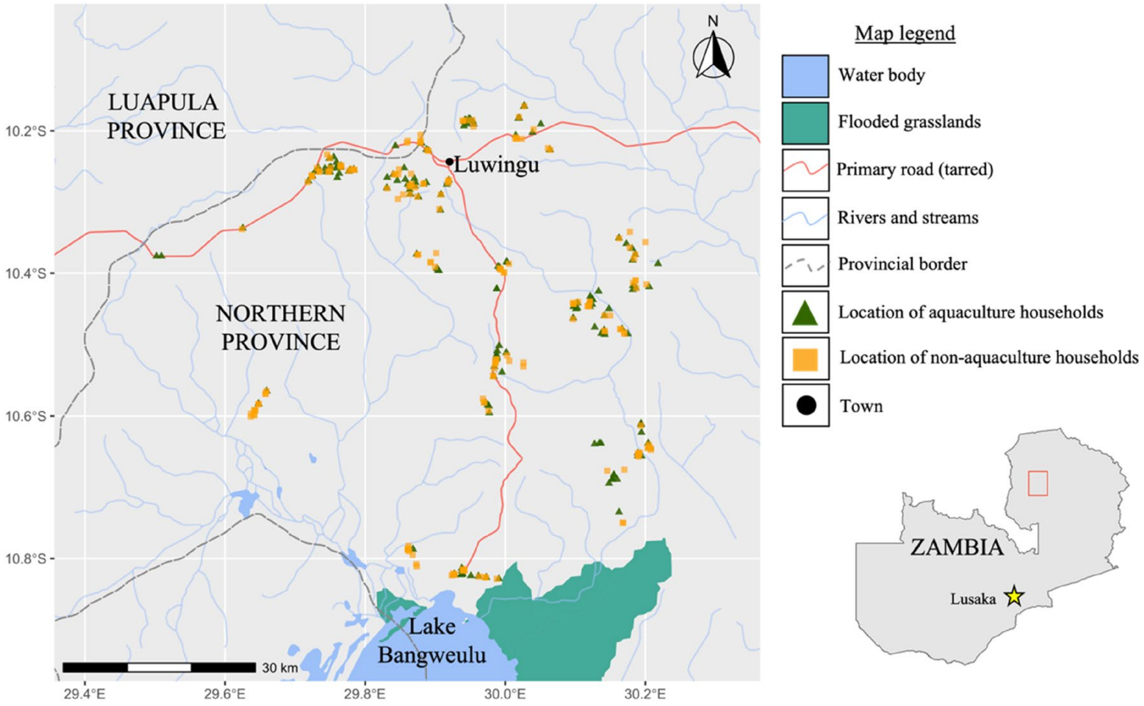

Fig. 1 Map of study site locations in Northern Province, Zambia. Data for the flooded grasslands biome are from Terrestrial Ecoregions of the World (TEOW) [41]; rivers and water bodies are from the HydroATLAS [42] and HydroATLAS-Zambia [43]

high levels of hunger and micronutrient malnutrition, with an estimated 19% of women and children suffering from critical micronutrient deficiencies [44, 45].

Study design and sample

Study participants were selected using convenience sampling methods. Given the small proportion of fish farmers to the general population in the district, probability sampling methods were deemed inappropriate. First, a sampling frame of all wards with registered fish farmers was established through consultations with DoF registrars (13 wards in total, with over 70 individual villages, 24 of which had registered fish farmers). To have a comparative sample of fish farmers, we aimed to interview close to 50% of all fish farmers in the district. The aim was to have half the study sample represented by aquaculture households and the other half represented by non-aquaculture households, to enable comparisons. Inclusion criteria for aquaculture households were either to have (1) stocked ponds at the time of survey, or (2) harvested fish in the preceding 12 months. For each selected village, the sampling frame for the households was generated using the village household registrar, in consultation with village authorities. A random number generator was used to select up to eight aquaculture households per village for inclusion in the study. In some villages, there were less than four households that conducted aquaculture, which meant some discretion was used to combine villages (if they were in proximity). The same procedure was repeated for non-aquaculture households based on how many aquaculture households were chosen.

A total of 382 households were selected to participate in this study, with just over half represented by fish farmers. We dropped 9 non-aquaculture households from the analysis, due to inaccurate responses. A further 22 aquaculture households were removed for not meeting the selection criteria. This meant that 9.5% of the sampled aquaculture households had abandoned production prior to the study and were removed from the analysis. A similar rate of pond abandonment in the region was found in other studies [26, 40]. The final sample size used in the analysis, therefore, was 351 households: 177 aquaculture households and 174 non-aquaculture households.

Quantitative scores and indices

All data were collected using tablets and coded in KoBo Toolbox (www.kobotoolbox.org). All analyses and graphical illustrations were computed using R Studio software (ver. 1.3.1056).

Household and livelihood characteristics

The first part of the survey was administered, in the local language, to the person responsible for agricultural production, who, in all cases, was the head of the household. Individual and household characteristics were obtained: sex and age of the household head, their marital and educational status, along with household size and estimated yearly income of the household. Given the skewed distribution of income (in Zambian Kwacha), this was converted to a logarithmic scale for analysis.

Using key informant interviews with government agricultural extension officers, we developed a list of livelihood activities, including farming and non-farming activities for the area. Farmers answered "Yes" or "No" if they participated in a livelihood activity in the previous 12 months, regardless of whether it generated an income or not. There were three quantitative scores developed from this list. The first was a total Crop and Livestock Score (CLS), which represents the total sum of all on-farm activities, excluding aquaculture. Crop diversity has been associated with better household diet quality in subsistence-orientated farming households [46]. Livestock and poultry were combined into one score given that few households engaged in these activities while all other individual crops and vegetables received their own score. The list did not include the number of animals on the farm, production yields or the amount of land under cultivation. Past studies have shown that a higher diversity of on-farm production activities (food and cash crops) led to improved dietary diversity and food security [14, 47].

The second score was the sum of all non-farm activities. The third score was a Production Diversity Score (PDS), which grouped only the food crops and livestock/poultry grown on the farm into key nutritional food groups for human consumption [48]. In places such as rural Zambia where subsistence food production is key to household food security, the PDS was determined to be an appropriate measure of the diversity of self-produced foods [46].

Notably in our study, we did not discern which of the foods captured in the PDS were consumed in the household and which were sold in markets. Based on the list of foods produced at household level we grouped these into 12 common food groups for human consumption: i) cereals and grains; (ii) white roots tubers; (iii) pulses; (iv) nuts and seeds; (v) dairy; (vi) meat; (vii) fish; (viii) eggs; (ix) dark green leafy vegetables (DGLV); Vitamin-A rich vegetables; (xi) fruit (xii) other vegetables (e.g., tomatoes, onions, okra, cabbage, etc.). We focused on the nutritional importance of these food by separating animal-source foods into dairy, meat, fish, and eggs, while also highlighting the nutritional importance of vitamin-A rich foods and DGLV, thus borrowing from several commonly used food group scores [49]. Some of these scores, such as the Minimum Dietary Diversity for Women (MDDW) group roots and tubers with grains and cereals. We separated white roots and tubers from those considered vitamin A-rich to highlight the importance of the latter to nutritional outcomes. In the absence of staple grains, many households often depend on white roots and tubers instead, which has important nutritional consequences given that they are less nutritious than certain key staple grains consumed in Zambia [44].

Dietary characteristics

The second part of the survey was made up of three components designed to assess dietary diversity. This part of the survey was administered to the person in charge of food preparation in the household. The first component was measured by the Household Dietary Diversity Score (HDDS). The HDDS is a continuous score (0–12) based on the total sum of food groups consumed in the past 24-h: (i) cereals; (ii) roots and tubers; (iii) vegetables; (iv) fruits; (v) meat, poultry, offal; (vi) eggs; (vii) fish and seafood; (viii) pulses/legumes/nuts; (ix) milk and milk products; (x) oil/fats; (xi) sugar/honey; or (xii) miscellaneous (condiments, sodas, sweets, etc.). Notably, the HDDS food groups differ from the PDS food groups as they contain oils/fats, sugar, and other miscellaneous food categories not typically cultivated on a farm.

The HDDS is a globally recognised score that reflects a household's economic access to different foods (self-grown and purchased), including food categories that may be considered as micronutrient-poor [50]. The HDDS has been validated against caloric availability, though it is not a measure of nutrient adequacy, therefore, there is no official recommendation of how many food groups households should consume [51]. The HDDS score is used as an independent and dependent variable in two separate regressions in this study, discussed in further detail below. For our study, we categorized households into three groups based on the HDDS score for comparative purposes: "Low HDDS" (≤4 food groups); "Average HDDS" (5–6 food groups); and "High HDDS" (≥7 food groups). This was determined by the fact that just over 50% of respondents (upper and lower quartile range) in both study groups consumed 5–6 food groups. These categories are not used in any predictive models but rather they serve as a useful categorical variable to visualise exploratory analyses, discussed in detail below. In addition, the number of meals consumed in the previous 24-h was also recorded as an indicator of a household's access to foods.

The second component in our assessment of dietary diversity used a Food Frequency Questionnaire (FFQ). The FFQ recalled the number of times certain foods were consumed by a household over a 4-week period (28 days). A total of 23 food items were listed (see Additional file 1: Appendix S1), including an additional list of 30 fish species that are typically consumed in the region (see Additional file 1: Appendix S2). The list of fish species, like the livelihood activities presented above, was determined through key informant interviews and a literature search [52].

Seven different frequency options were provided in the FFQ and then converted into a proportion of the number of times a food item was consumed: (i) 1 time in the past 4 weeks (e.g., $1/28 = 0.036$); (ii) 2–3 times in the past 4 weeks; (iii) 1 time per week; (iv) 2 times per week; (v) 3–4 times per week; (vi) 5–6 times per week; or (vii) 1 or more times per day. The conversion to a continuous variable was necessary for statistical analyses, discussed in more detail below. The benefit of the FFQ is that it provides greater detail on the quality of diets by including more food items and recording frequencies of consumption over time. FFQ methods have been validated as a measure of dietary diversity [53, 54]. We were further interested in individual fish species consumed in the household given that they each have different micronutrient profiles [10, 55]. The food items in the FFQ were grouped into the same food groups as the PDS above for better reflection of nutritional quality and diversity in the diet. Here we combined all fish into one category when compared to other food groups, though we maintained the longer list of individual fish species and analysed that separately.

We used the Simpson's Index [56] to analyse the diversity of the food groups and fish species. The Simpson's Index is often used by ecologists to measure biodiversity in ecosystems [57]. The index acts as a diversity score though notably different to the HDDS since it reflects the frequencies captured in the FFQ and attempts to understand if there is any overdependency on fewer food groups over time. The score has been regularly used in analyses of dietary and agricultural diversity [14, 58]. First, the index sums the number of food groups consumed, often referred to as species richness, though in this case refers to richness of different food items. The index then uses the frequency of the consumption of these items as a continuous variable. The Simpson's Index is used as a calculation of species evenness, which in this case refers to the distribution of the frequency of foods consumed. The main goal is to ascertain whether the household diet relied on a higher frequency of less food groups or whether the frequency of consumption was more evenly distributed across food groups. The results are bound between zero and one, indicating whether the number of foods were distributed and consumed evenly.

This is interpreted as the probability of any two foods selected at random from a single household and the likelihood that they will be different.

The consumption of specific fish species was treated separately as its own score using the Simpson's Index again. The total sum of all fish species consumed is considered (species richness), as well as the evenness of the distribution of consumption. These 30 fish species are later grouped into 10 categories for ease of analysis and interpretation based on their genus, family, size and/or source of capture (see Additional file 1: Appendix S2).

Food security status

The third and final part of the survey measured food security status using the Household Food Insecurity Access Scale (HFIAS) [59]. The scale consisted of nine occurrences related to food security and hunger, such as: "Did you or any household member go to sleep at night hungry because there was not enough food?" A recall period of 4 weeks is used offering three frequency options: (i) Rarely (1–2 times); (ii) Sometimes (3–10 times); and (iii) Often (> 10 times), or zero for non-occurrence. The responses are used to calculate the HFIAS score, a continuous measure of the degree of food insecurity in the household, ranging from 0 to 27. This is calculated into one of the following ordinal categories: (i) severely food insecure; (ii) moderately food insecure; (iii) mildly food insecure; (iv) food secure. Of the four pillars of food security (access, availability, utilization, and stability), the HFIAS score has been used successfully to measure the access component of food insecurity [60–62]. The HFIAS categories are used as the dependent variable described in a regression analysis below.

Data analysis

There were four multivariate analyses that assessed if household, livelihood, and dietary characteristics differed between aquaculture and non-aquaculture households, and whether any of these characteristics predicted dietary diversity and/or food security status. Differences between the two groups were calculated using chi-squared tests, Welch's *t* tests, and analysis of variance (ANOVA) for categorical and continuous variables, respectively. Bivariate correlations and multivariate regressions were computed to determine associations.

There were two exploratory multivariate analyses which developed indices that were used as factors in two multivariate regressions (see Fig. 2 for analytical flow). The first of the multivariate analyses was a multiple correspondence analysis (MCA), used to assess the associations between livelihood activities. The MCA provided an index of food production and diversity based on how food groups were correlated in a geometric space. The MCA is not a predictive model but rather an exploratory

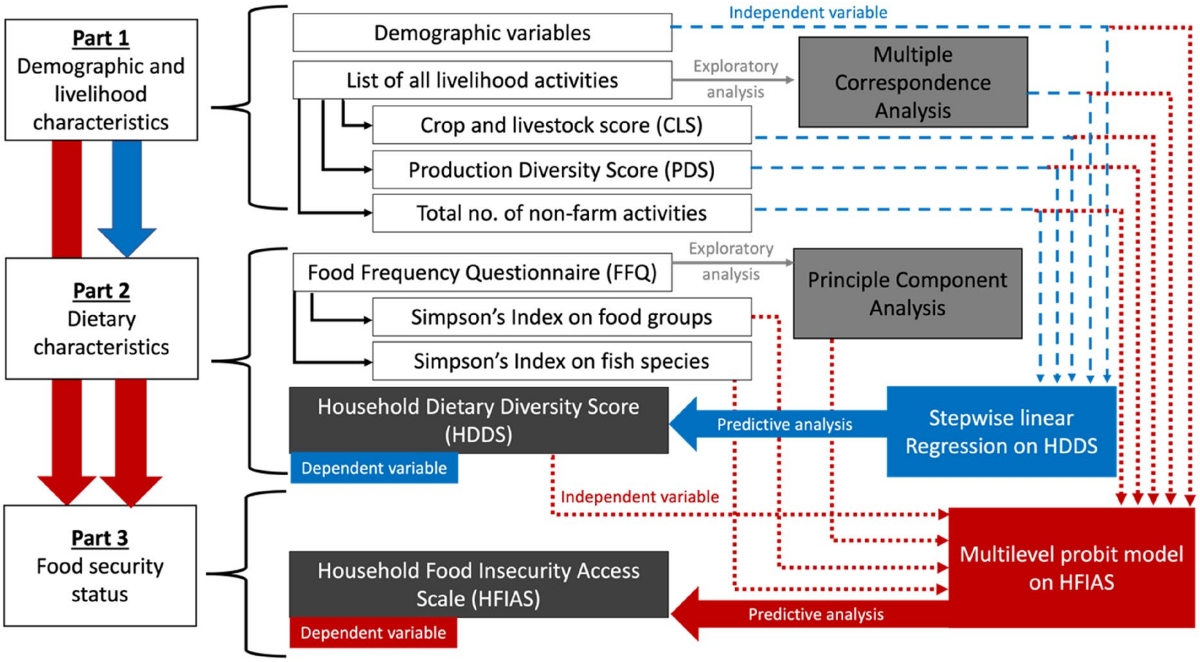

Fig. 2 Analytical flow and summary of all survey tools, scores, and analyses**.** Graphic depicts the logical flow of the study [left of diagram] with the demographic and livelihood characteristics predicting dietary characteristics and both, in turn, predicating food security status, while the four multivariate analyses [right of diagram] show the analytical flow of the study

analysis of how livelihood activities are clustered. An indicator matrix of all livelihood activities as binary categories (0 = "no", 1 = "yes") was assessed by way of cross-tabulation and covariance. The cumulative percentage of inertia, explained mostly by the first and second dimensions were adopted into the results. Using aquaculture and non-aquaculture groups, we further tested for differences in livelihood activities with a one-way ANOVA, presented below the 5% level.

The second multivariate analysis assessed the dietary characteristics captured in the FFQ. Here, a principal component analysis (PCA) was used to explore the relationships and associations of the frequency of consumption of different food groups. Like the MCA, but with continuous data, the PCA is an exploratory analysis that clusters variables in a way that identifies patterns and associations of foods in the diet over time [63]. This is presented as two additional indices (components 1 and 2) based on the eigenvectors of the data's covariance matrix and where most of the variance can be explained. Differences between aquaculture and non-aquaculture groups, and between low, average, and high HDDS groups were computed with a one-way ANOVA and presented below the 5% level.

The first multivariate regression aimed to determine the factors that predicted household dietary diversity. A stepwise multivariate linear regression was used to model the effect of household and livelihood characteristics on the HDDS. We included a household's involvement in aquaculture as a dummy variable (0 = "no", 1 = "yes"). Bivariate analyses were used to test associations between household and dietary characteristics, and only the results of significant associations were reported ($p < 0.05$). Independent variables included household characteristics: age, gender, education (of household head), and main income source. We further included the livelihood characteristics: CLS, PDS, number of non-farm activities, and the MCA dimensions.

Once understanding the relationships and associations between household and livelihood characteristics and their impact on dietary diversity, we assessed whether the same factors, and additional dietary characteristics (including the HDDS as an independent variable this time), explained food security status. Here, a multilevel probit regression was used to assess which factors predicted food security status (HFIAS). The ordinal category (4 levels) of the HFIAS from "severely food insecure" to "food secure" constituted the observable dependent variable. The same independent variables from the linear regression were used, and in addition we added the dietary characteristics: HDDS, number of meals, Simpson's Index of both food groups and fish species, and the PCA dimensions. All covariates were computed at the same time and then eliminated one by one if they were not significant below the 5% level. We then calculated the odds ratios to present which factors increased the likelihood of achieving a higher food security category.

Results

Household and livelihood characteristics

All households in the sample were involved in agricultural activities of some kind and just under half made their main income from selling staple crops such as maize and cassava (see Table 1). Aquaculture households were significantly wealthier on average than non-aquaculture households ($p < 0.05$). Only 13% of aquaculture households made their main income from aquaculture. Deriving the main income from vegetables (e.g., tomatoes, onions, and okra) was important for more aquaculture households (14.1%) than non-aquaculture households (4%). More non-aquaculture households made their main income from formal employment (teaching, civil service) and "other" non-farm activities, such as charcoal burning, brick making and house rentals, than aquaculture households.

When all livelihood sources were listed together (see Fig. 3), it was clear that cropping activities such as cassava, maize, beans, and groundnuts were the mainstay of household livelihoods in both study groups. More aquaculture households grew different vegetables such as rapeseed leaf, sweet potato, tomato, Chinese cabbage, onion, orange sweet potato, cabbage, and potato. More non-aquaculture households participated in fisheries activities than aquaculture households. Overall aquaculture households participated in more crop and livestock activities ($p < 0.001$), while non-aquaculture households participated in significantly more non-farming activities ($p < 0.01$). Aquaculture households had a significantly higher PDS ($p < 0.001$), meaning they grew a higher diversity of food groups that would be considered important for nutrient adequacy.

Dietary characteristics

There was no significant difference in the total HDDS between aquaculture (5.73 ± 1.34) and non-aquaculture households (5.46 ± 1.48) (see Table 3). The former group, however, consumed significantly more meals in the 24-h recall than the latter group ($p < 0.05$). A higher percentage of aquaculture households consumed seven or more food groups while a higher percentage of non-aquaculture households consumed four or less food groups, statistically significant at the 5% level. When viewing individual food groups in the 24-h dietary recall, a significantly higher percentage of aquaculture households consumed cereals and grains while more non-aquaculture households consumed roots and tubers (see Additional file 1:

Table 1 Household and livelihood characteristics

Household characteristics	**Aquaculture** $n = 177$		**Non-aquaculture** $n = 174$		
	Freq.	**%**	**Freq.**	**%**	
Sex of household head					
Female	12	6.8	27	15.5	*
Male	165	93.2	147	84.5	
Marriage status[†]					
Married male household head	159	89.8	140	80.5	
Unmarried female household head	12	6.8	27	15.5	
Unmarried male household head	6	3.4	7	4.0	
Age of household head					
< 35 years old	32	18.1	58	33.3	**
35–60 years old	117	66.1	86	49.4	
> 60 years old	28	15.8	30	17.2	
Household size					
Small (< 3 people)	17	9.6	27	15.5	**
Average (4–7 people)	85	48	100	57.5	
Large (> 8 people)	75	42.4	47	27	
Education level of household head					
Partial primary school	87	49.2	105	60.3	
Partial high school	76	42.9	57	32.8	
Finished high School	14	7.9	12	6.9	
Yearly income—Zambian Kwacha (ZMW)					
Median (interquartile range 25%—75%)	3000 (1200—6000)		1900 (800—4000)		*
Main income source					
Aquaculture	23	13.0	0	0.0	***
Staple crops (maize, cassava, millet.)	79	44.6	85	48.9	
Beans	28	15.8	26	14.9	
Groundnuts	16	9.0	21	12.1	
Vegetables (tomatoes, okra, etc.)	25	14.1	7	4.0	
Fisheries	1	0.6	15	8.6	
Employed	3	1.7	12	6.9	
Other	2	1.1	8	4.6	
Livelihood characteristics	Mean ± SD		Mean ± SD		
Total number of crops & livestock (CLS)	6 ± 2.65		4.47 ± 2.18		***
Total number of non-farm activities	0.21 ± 0.44		0.37 ± 0.56		*
Production diversity score (PDS)	5.26 ± 1.66		3.59 ± 1.46		***

All *p* values on mean differences between aquaculture and non-aquaculture groups calculated with chi-squared tests or Welch's *t* tests for categorical and continuous variables, respectively—statistical significance marked with * ($p < 0.05$) or ** ($p < 0.01$) or *** ($p < 0.001$)

[†] "Unmarried" signifies single, widowed, or divorced household-head. In all married male households, the main food preparer was the spouse (female). Only one elderly woman of all the female unmarried households had another person (daughter) cook for the household, while eight unmarried male households cooked for themselves (all young, single men); and the rest had a female household member cook for the household (e.g., sister, daughter)

Appendix S3). This validates separating roots and tubers into their own food group as it shows that some households relied more on the latter. There were no differences in the consumption of other food groups. Across the sample it was evident that all households relied on cereal, grains, and dark green leafy vegetables (DGLV); while fish was by far the most important animal-source protein compared to meats, eggs, or dairy.

When grouping the frequency of consumption of the 53 food items into 12 key food groups, we see significant differences (see Fig. 4). Aquaculture households consumed nuts and seeds, white roots and tubers, fruit, and meat, more frequently than non-aquaculture households ($p < 0.05$). Aquaculture households also consumed more "other vegetables", made up of onions, tomatoes, okra, and cabbage. Many of these vegetables were the same

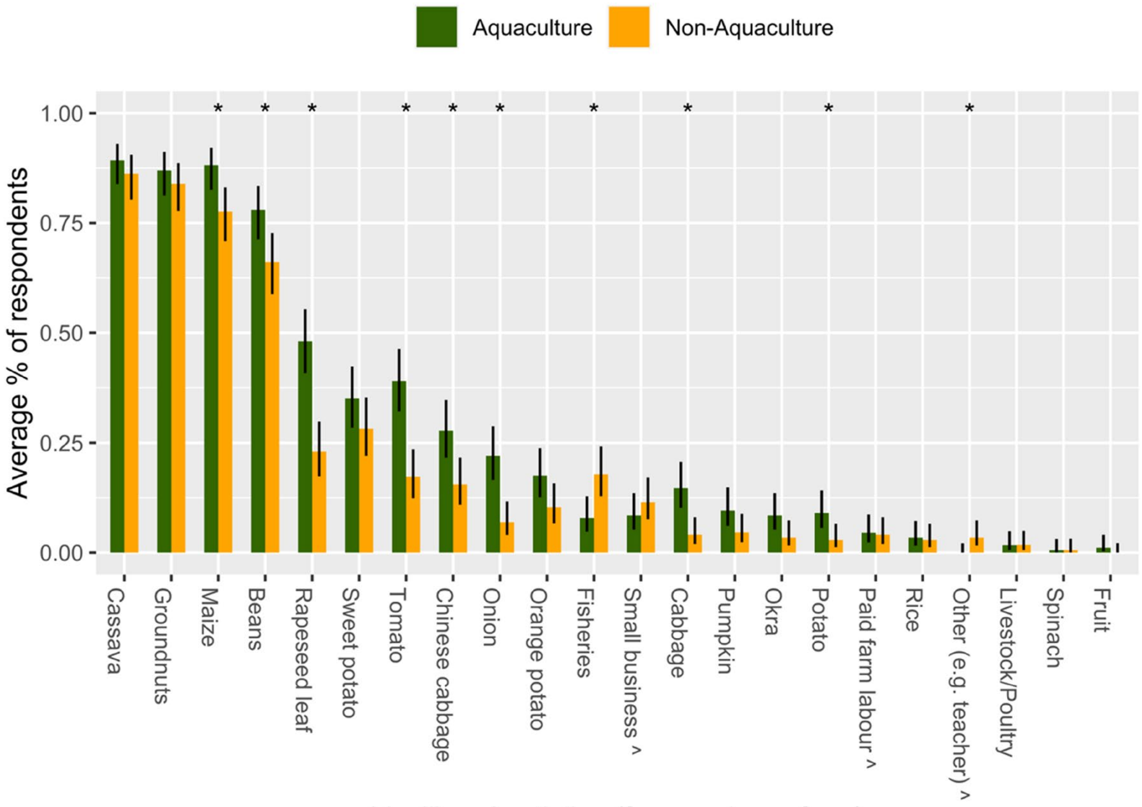

Fig. 3 Number of households (%) participating in various farming and non-farming activities. Each bar has standard error bars. Statistical significance at or below the 5% indicated with asterisk (*) and calculated using chi-squared test. Non-farm activities indicated with caret (^)

ones that more aquaculture households cultivated as compared to non-aquaculture households (see Table 1). Both groups consumed a similar frequency of fish over the previous 28 days ($p > 0.05$).

When viewing the total sum of the 12 food groups (species richness) the aquaculture households consumed more food groups on average over the previous 28 days than non-aquaculture households ($p = 0.007$) (Table 2). The aquaculture households had a significantly higher average Simpson's Index than the non-aquaculture households, indicating more diversity and evenness in the frequency and distribution of food groups consumed over time ($p = 0.001$).

When the individual fish species were grouped into broader categories, significant differences in the frequency of the consumption were evident (see Fig. 5). Aquaculture households consumed cultivated tilapia more often than non-aquaculture households, as well as smaller fish such as lake sardines and other wetland species (small swamp mix). Non-aquaculture households meanwhile consumed significantly more catfish. This was verified at the individual species level where aquaculture households consumed cultivated tilapias more frequently than non-aquaculture households, while one common catfish was consumed more frequently by the latter households (see Additional file 1: Appendix S4). There were no significant differences in the sum of fish species (species richness) consumed on average, though aquaculture households had a significantly higher Simpson's Index for fish species consumption than the non-aquaculture households ($p = 0.011$).

Multivariate analysis of livelihood characteristics

The MCA revealed three distinct patterns and associations of livelihood activities on two dimensions (explaining 26.6% of the variance) (see top panel in Fig. 6). Households that grew tomato were clustered closely with onion, rapeseed leaf, and Chinese cabbage; and these crops contributed to most of the variance on the first dimension of the MCA, suggesting households that grew these foods were the most different to the other households in the sample. Households that caught wild fish were more associated with groundnut and beans, though the latter two crops were common across the sample. Most households grew maize, closely clustered with sweet potato, cassava, and potato, meaning that these

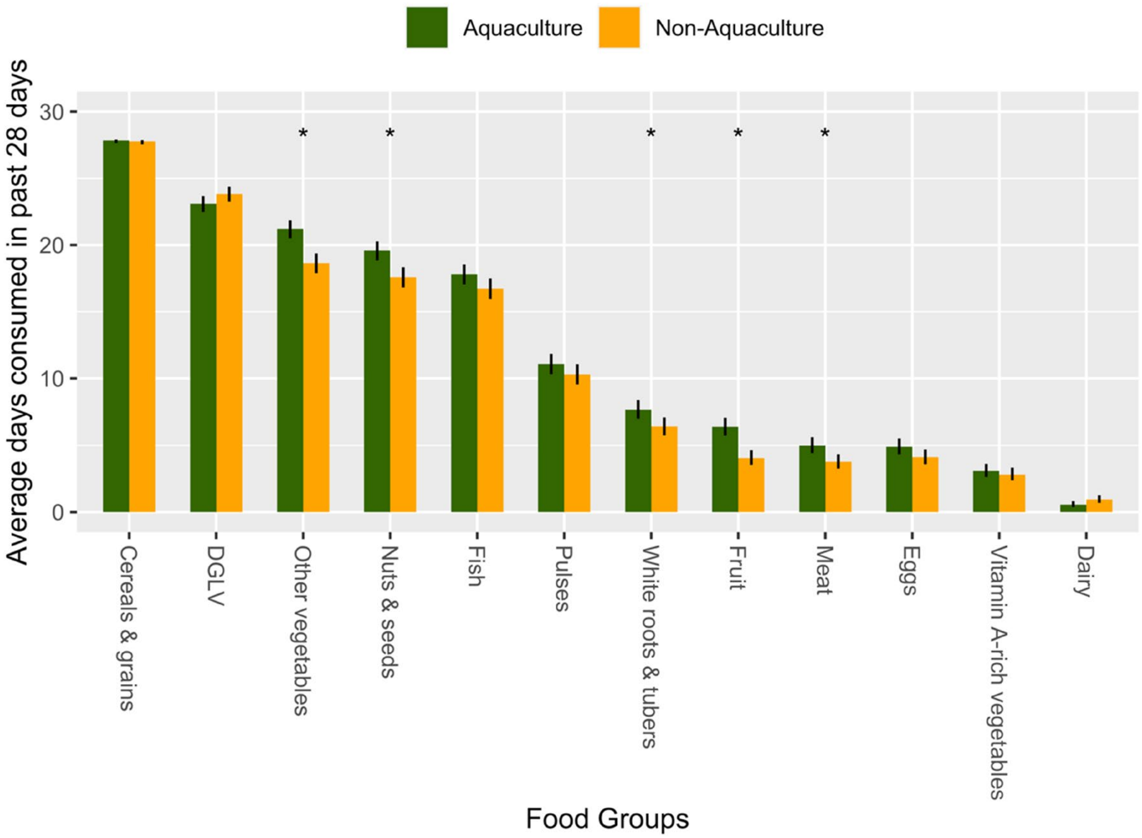

Fig. 4 Average daily rate (in past 28 days) of key food groups consumed in household. Each bar has standard error bars. Statistical significance at or below the 5% level indicated with asterisk (*) and calculated using a one-way ANOVA. *DGLV* Dark green leafy vegetables

crops did not contribute much to the variance across the sample. Certain notable outliers such as pumpkin, okra, and cabbage indicated that some households specialised in these crops, though this was notably a minority.

When disaggregated by farmer group and HDDS group (panels B and C in Fig. 6, respectively), there were clear differences, especially on dimension 1 of the matrix. Many of the households that relied on staple crops such as maize and cassava were made up of households from both study groups, but also from the lower HDDS group. Households with higher or average HDDS, and those that engaged in aquaculture, were more associated with crops such as tomato, onion, rapeseed leaf, okra, pumpkin, and cabbage, which contributed to most of the variance on dimension 1. When viewed together with Fig. 3 above, the MCA verified that significantly more aquaculture households cultivated a cluster of these latter crops than non-aquaculture households. A one-way ANOVA of MCA dimension 1 comparing the aquaculture households (mean = 0.12 ± 0.46) and non-aquaculture households (mean = − 0.13 ± 0.35) was statistically significant at the 1% level. There were no significant differences on dimension 2. The same was found with a one-way ANOVA comparing the low HDDS (mean = − 0.19 ± 0.26), average HDDS (mean = 0.04 ± 0.45) and high HDDS groups (mean = 0.07 ± 0.40), statistically significant at the 1% level. There were no statistical differences on dimension 2. This suggests that the ability to grow crops such as tomato, Chinese cabbage, rapeseed leaf, and onion (which more aquaculture households cultivated—see Fig. 3 above) may be a factor in explaining household dietary diversity. This validates the inclusion of the MCA dimensions as independent variables in the regression analyses presented below.

Multivariate analysis of food frequency in preceding 28 days

The PCA results of the food frequency should be interpreted by the magnitude and direction of the coefficients (Fig. 7). The larger the coefficient the more important the corresponding variable is in calculating the components (which together explain 33% of the variance in the diet over the previous 4 weeks). The direction of the coefficient indicates a positive or negative association with components. In Fig. 7, nuts and seeds, meat, vitamin-A-rich vegetables, pulses,

Table 2 Dietary characteristics of aquaculture and non-aquaculture households

Characteristics	**Aquaculture** $n = 177$		**Non-aquaculture** $n = 174$		
	Mean ± SD		**Mean ± SD**		
Total dietary scores from 24-h HDDS					
Total HDD score	5.7 ± 1.3		5.5 ± 1.5		
Total meals	3.1 ± 0.9		2.9 ± 0.9		*
Diversity of key food groups from FFQ[#]					
Simpsons Index for diet (0 to 1 indicating more diversity)	0.83 ± 0.04		0.81 ± 0.07		**
Richness of diet (total no. of food groups out of 12)	8.5 ± 1.6		8.0 ± 1.9		**
Diversity of fish from FFQ (28 days)					
Simpsons Index for fish species	0.65 ± 0.23		0.58 ± 0.29		*
Richness of fish (total no. of species)	5.1 ± 3.3		4.4 ± 3.3		
Total frequency of consumption of fish (daily rate)	1.1 ± 1.2		1.0 ± 1.4		
	Freq.	%	Freq.	%	
Household dietary diversity groups[†]					
Low HDDS: ≤ 4 food groups	28	15.8	45	25.9	*
Average HDDS: 5–6 food groups	96	54.2	91	52.3	
High HDDS: ≥ 7 food groups	53	29.9	38	21.8	

HDDS Household Dietary Diversity Score

[#] Food Frequency Questionnaire

[†] Statistical difference calculated with chi-squared test on six groups—aquaculture and non-aquaculture respondents in the three groupings based on HDDS

All other *p* values on mean differences between aquaculture and non-aquaculture groups calculated with one-way ANOVA, statistical significance marked with * ($p < 0.05$) or ** ($p < 0.01$) or *** ($p < 0.001$)

and white roots and tubers had negative loadings on component 1, and positive loadings on component 2. Fruit, dairy, egg, DGLV, and other vegetables such as tomato, okra, and onion were positively associated with both components. Only cereals and grains were negatively associated with component 2. When looking at the disaggregated results by farmer group and HDDS groups, we see that many non-aquaculture (and lower HDDS) households were negatively associated with component 1 and positively associated with component 2, suggesting that these households strongly relied on cereals and grains in their diet. The higher HDDS households meanwhile had a higher prevalence of dairy, fruit, eggs, and other vegetables in their diet, in addition to roots, tubers, nuts, and seeds. A one-way ANOVA of component 1 and aquaculture households (mean = 0.21 ± 1.52), and non-aquaculture households (mean = − 0.21 ± 0.21), was statistically significant ($p = 0.0128$). There was no significant difference on component 2 between these groups. The same was found when using a one-way ANOVA to compare differences between the low HDDS (mean = − 0.97 ± 1.14), average HDDS (mean = 0.152 ± 1.68) and high HDDS groups (mean = 0.056 ± 1.31), statistically significant at the 1% level. There were no differences between HDDS groups on component 2.

Stepwise linear regression with Household Dietary Diversity Score (HDDS)

Bivariate regressions were computed for each household characteristic and livelihood factor against the HDDS. Dimension 1 of the MCA ($\beta = 0.58$, SE = 0.18) and the PDS ($\beta = 0.15$, SE = 0.04) were statistically significant at the 1% level, but not significant in the multivariate analysis. This means that the types of crops grown may have had an impact on HDDS but not when accounting for other variables. The multivariate analysis with the household and livelihood characteristics, including aquaculture as a dummy variable, showed no significant results. After a backward elimination process, the only factors that had significant positive effects on the HDDS was the log of income and the CLS. The results in Table 3 should be interpreted as the log of income having the largest effect with a 0.19 increase in HDDS for every unit increase in income. The effect of the CLS was smaller but still significant. The HDDS improved by 0.08 points for every additional CLS category that was added to a household's livelihood portfolio.

Household food insecurity access score (HFIAS) and multilevel probit model

Table 4 presents the food security status of the aquaculture and non-aquaculture households as represented by

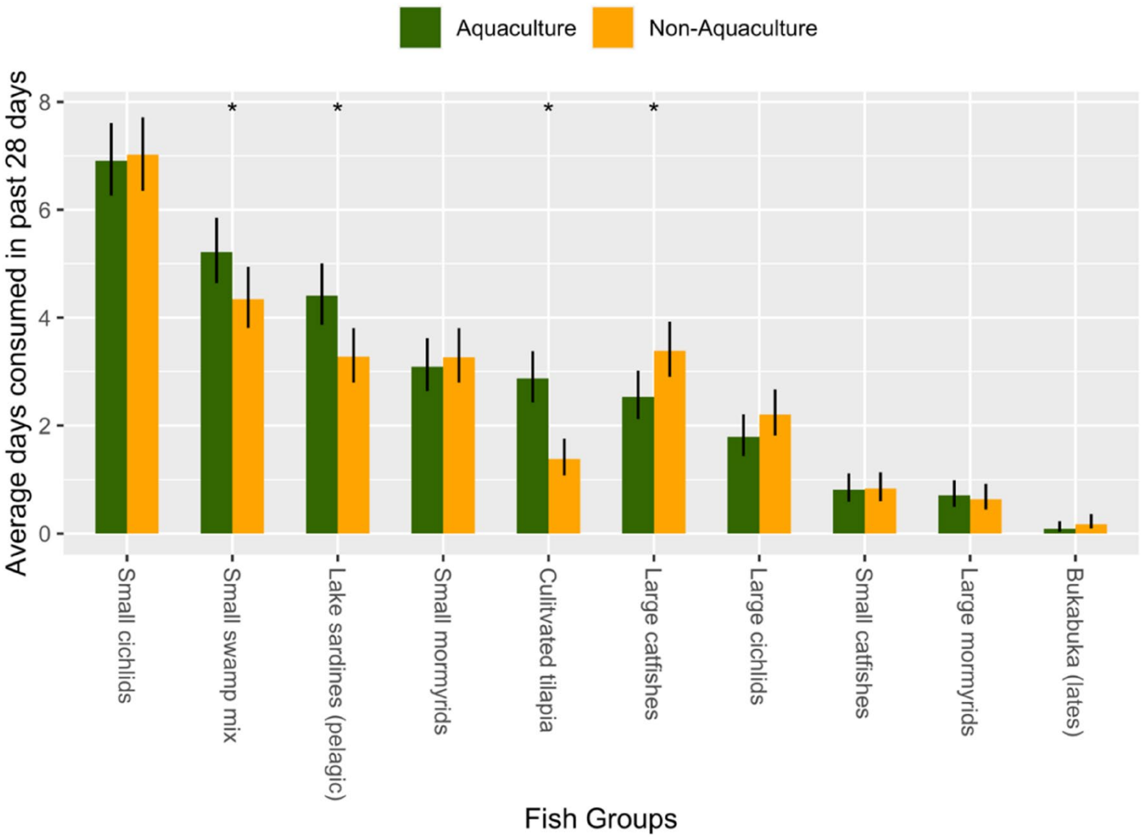

Fig. 5 Average daily rate (in past 28 days) of fish species consumed in household. Each bar has standard error bars. Statistical significance at or below the 5% level indicated with asterisk (*) and calculated using a one-way ANOVA

the HFIAS. Aquaculture households had slightly better food security status, although the overwhelming majority in both samples were found in the moderately and severely food insecure categories. A chi-squared test of HFIAS categories with the aquaculture versus non-aquaculture groups was statistically significant at the 1%, though this does not account for household, livelihood, or dietary differences between the two groups, hence the need for the multilevel probit regression.

The regression was first calculated with bivariate analyses of each factor against the HFIAS. The factors that were significant in the bivariate analyses were MCA dimension 2 ($\beta = 0.76$; SE = 0.33: $p = 0.0232$), the PDS ($\beta = -0.13$; SE = 0.06; $p = 0.017$); and PCA component 1 ($\beta = -0.15$; SE = 0.06; $p = 0.0167$). This suggests that the types of crops grown, as seen in the MCA and the PDS indices, mattered in predicting food security. The food groups that explained most of the variance along component 1 of the PCA also mattered in predicting food security. However, when we included these variables in a multivariate analysis, they did not have a significant impact.

Figure 8 presents the calculated odds ratios of the multilevel probit regression model. The coefficients, standard error and confidence intervals can be found in greater detail in Additional file 1: Appendix S5. The results should be read attentively, as a negative correlation with food insecurity translates to a positive association with food security. The main finding was that aquaculture as a livelihood activity had a significant positive effect on food security outcomes ($p = 0.003$). This gave households with ponds a 1.88 odds ratio of being more food secure even when accounting for income and other livelihood activities. Income (based on a logarithmic scale) was a significant predictor of household food security: for every double increase in Zambian Kwacha the log of odds of improving household food security increased by 0.21, meaning wealthier households were 0.81 times more likely to have a better food security outcome given that other variables were held constant ($p = 0.003$).

The age of the head of the household was negatively correlated with food insecurity. When the head of the household was above the age of 35 there was a higher likelihood of food security, which almost doubled when the head of the household was 61 years or older

Fig. 6 MCA of livelihood activities (**A**) and plotted by farmer group (**B**) and HDDS group (**C**). Only showing contribution of top 200 farmers to total variance

($p = 0.032$). The effect of household size, however, had a greater effect on food security. Households with an average number of members were 1.83 times more likely to be in worse food security categories and this almost doubled to 2.86 times if there were more than eight household members.

Certain dietary characteristics further affected the likelihood of reaching a better food security outcome. A household's dietary diversity score had a negative effect on food insecurity, meaning that for every 0.24 change in the HDDS score, there was a 0.79 odds ratio of improving food security ($p = 0.003$). The Simpson's Index score was the greatest predictor of food security in the model. For every 10% increase in the Simpson's Index, there was a two times higher likelihood of improving food security ($p = 0.006$). This could be further improved with a unit increase on PCA component 2, which gave a 0.82 odds ratio of improving food security ($p = 0.0308$). PCA Component 2 was mostly defined by cereals and grains but also by dairy, fruit, and other vegetables such as tomato, onion, and okra, that were less frequently consumed across the population sample, but also farmed by more aquaculture housheolds.

Discussion

The study evidenced that aquaculture households had a higher diversity of crops, more diverse diets, consumed a greater frequency and diversity of fish species, and that

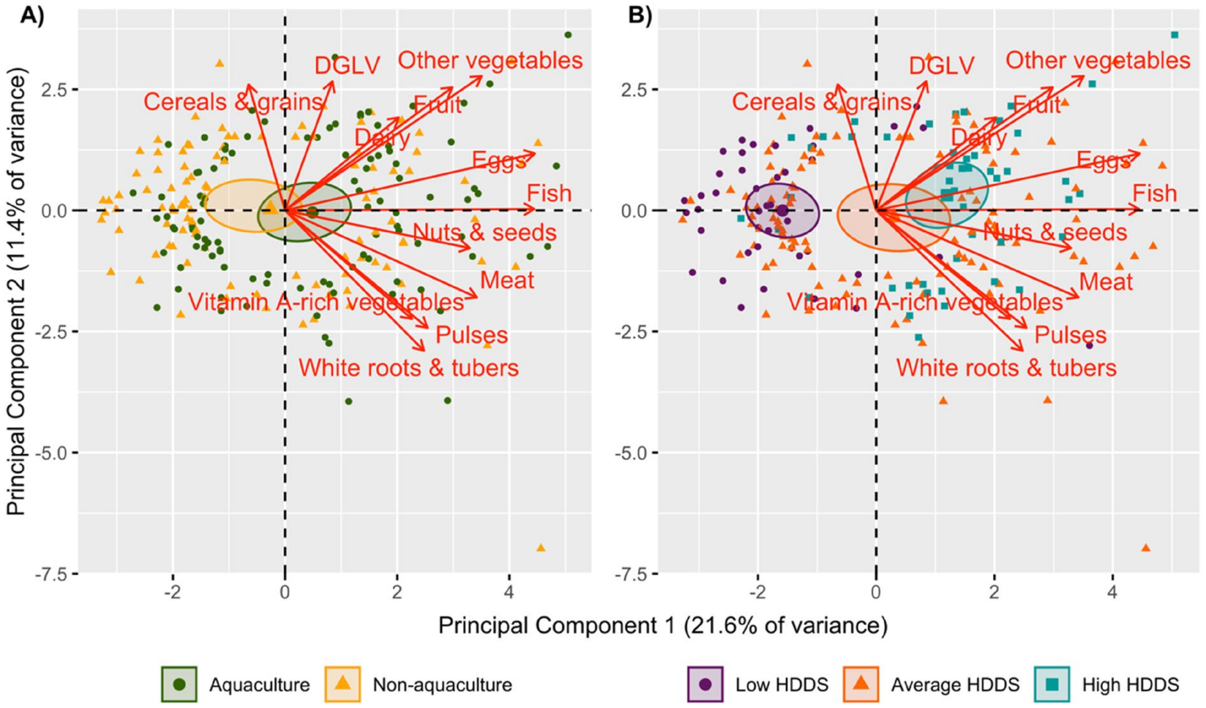

Fig. 7 PCA of food frequency and diet over 28 days, disaggregated by farmer group (**A**) and HDDS group (**B**). *DGLV* Dark green leafy vegetables

Table 3 Final model results of stepwise linear regression with HDDS

	Coef.	SE	*P*
Log (income + 1)	0.19	0.05	< 0.000
No. crops & livestock (CLS)	0.08	0.03	0.011

All other factors were not significant, including household characteristics: sex, age, household size, education level, and main income source; as well as livelihood characteristics including the PDS, number of non-farm activities and MCA dimensions 1 and 2.

adopting aquaculture as a livelihood strategy improved food and nutrition security compared to non-adopters. The mechanisms by which aquaculture plays a role in food and nutrition security is explored below via three distinct pathways.

The first pathway to food and nutrition security that aquaculture enables is that the sale of fish can provide additional income, which improves purchasing power, food provisioning and dietary diversity. Our study showed that adopting aquaculture increased household food security even after accounting for income, meaning that fish farming may have contributed to household wealth through the sale of fish. While we did not investigate the actual income derived from the sale of fish directly, aquaculture households in our sample were, on average, wealthier than non-aquaculture households. Certain demographic factors like family size and age of the household-head influenced food security outcomes,

Table 4 Household Food Insecurity Access Score (HFIAS) of respondents

HFIAS category	Total sample *N* = 351		Aquaculture *n* = 177		Non-aquaculture *n* = 174	
	Freq.	%	Freq.	%	Freq.	%
Food secure	54	15.4	36	20.3	18	10.3
Mildly food insecure	48	13.7	31	17.5	17	9.8
Moderately food insecure	117	33.3	58	32.8	59	33.9
Severely food insecure	132	37.6	52	29	80	46.0

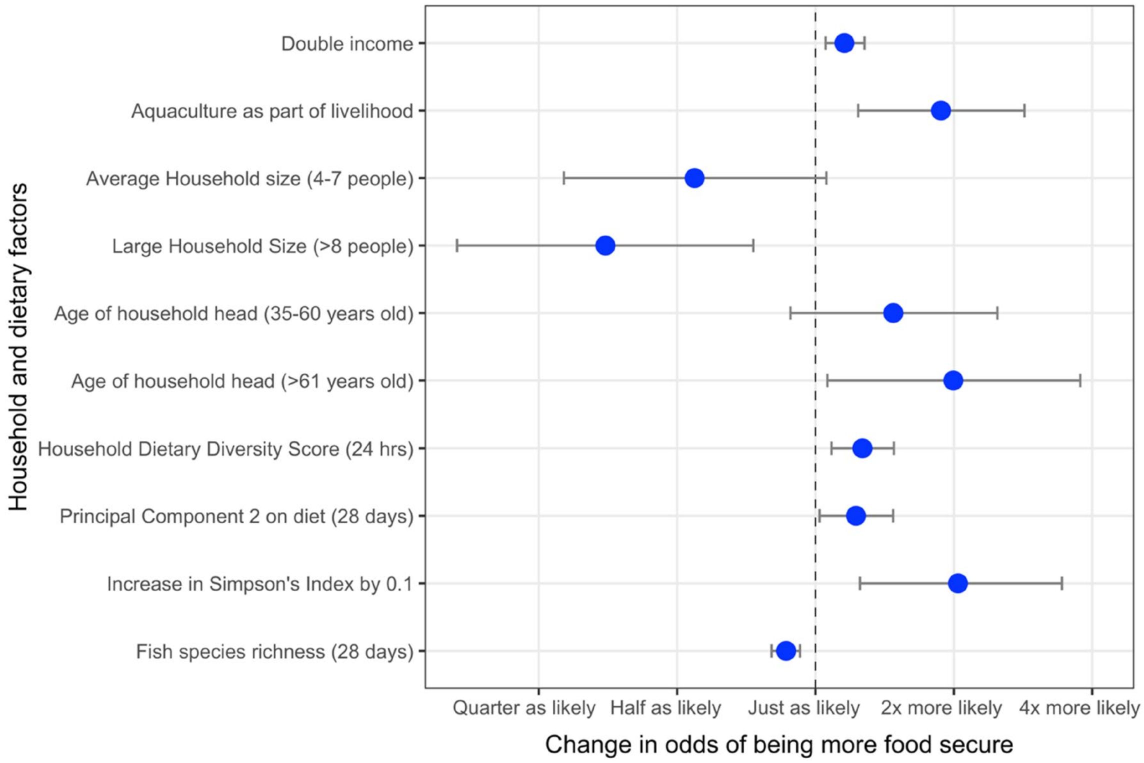

Fig. 8 Odds ratios and likelihood of food security (from severely food insecure to food secure). Results calculated from multilevel probit model using HFIAS categories

in addition to income. The results suggest that younger households had not amassed the assets, wealth, and knowledge to increase their food provisioning and on-farm resources, however, smaller families reduced the likelihood of food insecurity. Larger households were more likely to be food-insecure, though this was lessened with increasing age as households gained more experience, wealth, and on-farm resources. If households further invested in aquaculture and increased their incomes, they were even more likely to improve their food security status.

While we are unable to say whether aquaculture was a key activity that contributed to household income, it is likely that wealthier farmers had the capital needed to be able to invest in aquaculture [64]. Few aquaculture households in our sample made their main income from the sale of fish (only 13%) and aquaculture was clearly a supplementary source of income. Few farming households make their main income from aquaculture in sub-Saharan Africa, in general [65, 66]. Studies in Malawi and Ghana reported that aquaculture provided 12% and 8% to the total incomes of rural households, respectively [5, 67]. Another study in Malawi found that aquaculture households were generally better-off and had greater dietary diversity than non-aquaculture households due to incomes derived from fish farming [68]. One study in Zambia showed that fish farmers did not follow regular harvesting schedules and intermittently harvested and sold fish when certain immediate expenses arose (e.g., paying school fees) [30]. Most extensive aquaculture households in northern Zambia (over 70%) were estimated to produce less than 100 kg of fish per year, suggesting that the incomes derived from the sale of fish are minimal, though potentially not insignificant when measured as a contribution to diets [30]. Around half of the fish harvested from rural homestead ponds in Zambia are estimated to be sold while the rest are consumed in the household [69].

It is likely that the second pathway to food and nutrition security, namely, the direct consumption of fish from ponds may have played a larger role in improving food security. In the case of rural Zambia, in the same district to be exact, there is evidence of farming households consuming small tilapia and a range of other small indigenous fish species (which often gain entry into farmers' ponds) as compared to households without fishponds [10]. In our study sample, aquaculture households had higher dietary diversity as seen in both the Simpson's Index of food groups and the HDDS results. Aquaculture households consumed a greater variety of foods more frequently than non-aquaculture households, especially meats, nuts, and vegetables, many of which were likely purchased. Overall, both household types consumed a similar frequency of fish, yet aquaculture households consumed more different fish species over a period of four weeks. The Kaminski and colleagues [10] study showed that ponds played an important role in overall fish supply and nutritional quality, though aquaculture and non-aquaculture households consumed a similar quantity of fish. Aquaculture households, as in our study, consumed a greater diversity of fish species, especially small fish that were richer in micronutrients.

Almost half of all households in both groups consumed fish in the previous 24-h, suggesting that fish consumption in the area is very high, likely driven by proximity to large capture fisheries [39]. Aquaculture households in our study had higher frequencies of tilapia consumption than non-aquaculture households suggesting that, should fish supplies from capture fisheries dwindle, aquaculture could potentially provide a steadier source of fish. While our model showed that an increase in fish species diversity was negatively associated with food security, this may imply that wealthier, more food secure families depended on less diversity, but a greater frequency of fish species consumed (and probably purchased). This could mean that food-insecure households relied on whatever species of fish they could access while more food-secure households relied on more consistent sources of fish products they could afford, though this cannot be verified by our study.

The third and final pathway to food security is how ponds enable the growth and consumption of other foods on the farm via improved irrigation capabilties, i.e., crop diversification. Aquaculture households farmed a higher diversity of crops and food groups as compared to non-aquaculture households. These households were also more associated with a particular cluster of crops often found in homestead gardens [70]. The total number of crops cultivated by a household increased dietary diversity, which in turn was a positive predictor of food security. This has been verified by other studies in Zambia which suggest that crop diversification (and specifically crops produced for subsistence) had positive effects on dietary diversity, which translated to greater nutrient adequacy [71, 72]. Growing more diverse food groups seemed to matter less in our model and while production diversity is important to diet quality [73], access to markets for buying food and being able to sell farm produce can have a larger effect on dietary diversity [74]. The ability to diversify from a reliance on staple grains and improve homestead gardens and on-farm livestock management can have the highest impacts on dietary diversity [75].

From our study, the effect of aquaculture on food security was greater than crop diversity alone, and greater than engaging in non-farm activities. While there was a correlation between aquaculture and crop diversification, we did not assess to what extent the former impacted on the latter, and we did not determine which agricultural activities were more significant to wealth generation. One study in Zambia found that crop diversification had a positive and significant impact on income derived from the farm, as well as on household dietary diversity [73]. Such income diversification can make households more resilient to market and climate fluctuations [76]. And while households that adopted homestead gardens managed to increase crop diversity, and thus increase access to diverse foods, this did not always translate to an overall increase in nutrient adequacy for young children and mothers, specifically [70]. These nuanced benefits for different population groups may exist because of imbalances in gender roles, unequal food allocation and poor knowledge on nutrition and child feeding, for example [77]. Such issues were regrettably not included in this study. Certain social and cultural norms act as barriers to adopting and realising the benefits of agricultural interventions and future studies or development programmes should critically include gender transformative and behavioural change approaches when promoting and/or studying aquaculture [9, 71].

The specific crops that more aquaculture households in our sample diversified into were Chinese cabbage, tomato, onion, rape, and okra. While this study did not investigate how crops were planted, total yields, or the share of crops consumed in the household, there is evidence in the region of homestead garden crops planted close to or even around pond dykes [67]. Studies show that crops irrigated with pond water produced almost three times higher yields [78]. Rape, Chinese cabbage, tomato, and onion are typically planted in the late dry season gardens (September—November) and farmers with improved water irrigation would benefit by diversifying their crop selection and being able to grow these vegetables all year round [79]. Other crops like sweet potato and pumpkin are planted later in the rainy season after staple foods like maize and cassava are planted around December. Home gardens have been found to improve food security and dietary diversity in a wide range of settings [80–82].

In Zambia, seasonal fluctuations can have large repercussions on dietary quality for rural households and especially for pregnant and lactating women and children [83]. The rainy period starting around November is associated with variable levels of dietary diversity and the beginning of the lean period, which is at its peak by March [84]. This period also coincides with a national fishing ban starting in December till the end of February when fish resources become scarce [10]. Due to such fluctuations farmers often resort to harvesting their crops early or depend on the woodland systems for charcoal burning as a coping mechanism [85]. The ability to produce and sell more cash crops, such as tomatoes and onions, using water from the pond, especially in times of seasonal rain fluctuations, may provide farmers with an additional coping mechanism.

Integrating aquaculture and agriculture has proven to be a sound livelihood strategy in other parts of the world, which allows farmers to diversify their food sources and income-generating activities [11, 67]. Adopting and integrating fishponds into farming systems is an important and often undervalued contributor to food security in the African context. During times of severe drought, ponds can provide enough residual moisture and nutrients to produce vegetable crops [6, 86]. Wetland gardens have been shown to be a lifeline for farmers during lean periods in Africa [87], while farmers who successfully integrated agriculture with aquaculture reported better cash flows, especially in drought years [88]. Promoting the integration of agriculture and aquaculture in sub-Saharan Africa and greater efforts at finding the right combination of crops and local species of flora that complement fish cultivation, and vice versa, should be made [89]. Improving agroecological diversity and the additional ability to retain water in ponds may also provide farmers with increased resilience against climate shocks such as droughts and floods, though more effort needs to be made to evidence this [90, 91].

Given that many households in both groups in our study were still severely or moderately food insecure, aquaculture could be playing a vital role in preventing households from slipping further into food insecurity and poverty [92, 93]. Fishponds become more than just production system of single species but operate as a sort of "bank" or "insurance policy" allowing households to sell fish to pay for immediate costs, consume a vital animal-source protein, or provide water irrigation to diversify cropping strategies and extend growing seasons.

Conclusion

This study surveyed rural agricultural households in northern Zambia to better understand their household, livelihood, and dietary characteristics and determine which of these factors influenced household food security. The results suggest that aquaculture households had higher crop diversity, which was a key factor in increasing dietary diversity. Aquaculture households grew certain additional crops, possibly because of improved water supply on the farm in the form of ponds. Aquaculture households had more even distribution and higher diversity of key foods in their diets compared to non-aquaculture households, particularly a higher frequency of consumption of different fish species. Finally, aquaculture was a key predictor of food security, along with diversity in diets, incomes, and other demographic factors such as age and household size. Farming households that invest in aquaculture can increase their food and nutrition security by improving incomes, consuming more fish, and diversifying their crops—three key pathways to achieving food and nutrition security.

Development practitioners, policymakers and government programmes should look to promote aquaculture for smallholders. However, it should be realised that ponds can bring more benefits than just the cultivation of single fish species. Studies have shown that tilapias mixed with other wetland fish species in polyculture systems have improved nutritional diversity in homestead ponds [10, 94]. Productivity parameters in ponds can no doubt be improved in the region, however, this needs to be done in a manner that is both feasible and achievable for agricultural households, especially considering the crops already cultivated on the farm, including the role of off-farm nutrients (fertilizers and feed) that can boost productivity. The nuances in time, labour, and complex social and gender issues that may increase work burdens for women need to be critically factored into efforts at improving productivity. Fish farming in ponds can improve livelihoods, well-being, and food and nutrition security in a myriad of different ways. Quantifying the total yields of crops over different seasons as well as the share that are self-produced compared to the share of purchased foods would provide greater insight into the direct linkages between different crops, foods, dietary diversity and/or food and nutrition security. Understanding which foods are consumed when, and which foods, crops and livestock activities provide the most income would help to understand how aquaculture is placed within the farming system but also offer a better understanding of whether wealth status precedes aquaculture adoption or aquaculture adoption leads to wealth accumulation, or both. Further research in how ponds play a role in retaining water and improving water irrigation capabilities in the face of potential climate shocks should be urgently investigated.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s40066-023-00452-2.

Additional file 1: Appendix S1. Food items used in the FFQ to develop 12 food groups calculated in overall diet in last 28 days. **Appendix S2.** Fish species classification and groups used in the study. **Appendix S3.** Number of households (%) consuming foods in HDDS. **Appendix S4.** Average

daily rate (in past 28 days) of fish species consumed in households.
Appendix S5. Results of multilevel probit regression on HFIAS categories.

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Author contributions

Conceptualization: SG; SHT; Methodology: SG, AMK; Formal analysis and investigation: AMK; Writing—original draft preparation: AMK, SMC; Writing—review and editing: SG, SHT, AMK, DCL; JJ; ML; Funding acquisition: SHT; Resources: SG; SHT; AMK; Supervision: DCL; SHT.

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Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

Ethical clearance for the study was provided by the Directorate of Research and Graduate Studies, Humanities and Social Science Research Ethics Committee at the University of Zambia. Informed consent was obtained from each research participant prior to commencing the survey.

Consent for publication

All consent for publication from authors and participants has been given.

Competing interests

The authors declare that they have no competing interests.

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Publisher's Note

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Sven Genschick works at the Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH to support the sustainable development and integration of aquaculture into food systems. Before he joined GIZ, he worked as a scientist for WorldFish (CGIAR). He was stationed in both Malaysia and Zambia and supported research projects in various countries, but especially in sub-Saharan Africa. A major research focus was on the topic of 'nutrition-sensitive aquaculture' in the context of small-scale or rural production systems. Sven Genschick is a trained geographer with a PhD obtained at the Center for Development Research (ZEF, Bonn, Germany).

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