LUND UNIVERSITY

SCHOOL OF ECONOMICS AND MANAGEMENT

Master's Programme in Economic Growth, Population and Development

ECONOMIC DEVELOPMENT TRACK

More Fish, more *Mahasoa**?

A Quantitative Analysis of Food Security & Poverty Reduction in Rural Small-scale Aquaculture in Madagascar

Gianna Angermayr

gi3764an-s@student.lu.se / gianna.angermayr@bluewin.ch

Abstract The role of food-producing sectors such as agriculture and aquaculture in the development process is debated and while some consider industrial production to be the answer, others suggest that small-scale production can also make contributions to poverty reduction and food security. This thesis aims to shed light on these relationships by performing quantitative analyses of the small-scale freshwater aquaculture sector in six regions of Madagascar. By employing a multiple linear regression, the results of the first analysis indicate that the presence of extension services, the adoption of integrated production systems, and higher education levels are positively related to fish income generation. The binary logistic regression reveals that higher wealth levels, women in a decision-making position, fish consumption, and higher levels of education are positively associated with food security. Supporting the creation of extension services in the aquaculture sector and the development of linkages with the rest of the economy, increasing the adoption of integrated fish production systems, and investing in education to improve informed decision-making in the aquaculture sector and in households regarding fish consumption are the three main implications of the findings.

Keywords *Madagascar, Small-scale Aquaculture, Pond Aquaculture, Integrated Rice-Fish Farming, Community Well-being, Poverty Reduction, Food Security.*

Disclaimer The results and arguments of this thesis are the product of independent research. Although the data used for the quantitative analyses come from the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), the findings are not intended to reflect the position or opinions of GIZ and its staff but are attributable to the author.

Programme Code: EKHS22
Master's Thesis (15 credits ECTS)
26th of May 2023
Supervisor: Andrés Palacio
Examiner: Anna Tegunimataka
Word Count: 16'987

* Well-being in Malagasy.

Acknowledgments

I would like to thank my supervisor Andrés Palacio for his valuable feedback, but most of all for supporting my vision from day one and for being a trustworthy person during the thesis-writing process. I also thank Linda and Lukas from GIZ for giving me the opportunity to dive into this topic and for always being available for questions and clarifications.

Second, I would like to thank my friends and classmates in Lund for making the last two years so stimulating and memorable. A special thanks to Cecilia, Michele, Johannes, and Lea for staying by my side throughout this journey!

Finally, I would like to thank Lund University for the high quality of education, for the many insights I have gained along the way, and for the lifelong friendships I have been able to make.

And of course, I thank the people closest to me, León, Maria, Nina, and Alex, for their unconditional support!

Table of Contents

List of Tables

List of Figures

Glossary

AIC	Akaike Information Criterion.
APDRA	*Association Pisciculture et Développement Rural en Afrique tropicale humide.*
ASCLME	Agulhas and Somali Current Large Marine Ecosystems Project.
AU	African Union.
BE	Blue Economy.
BLUE	Best Linear Unbiased Estimator.
COFAD	Consultants for Fishery, Aquaculture and Regional Development.
EAA	Ecosystems Approach to Aquaculture.
FAO	Food and Agriculture Organization.
FIES	Food Insecurity Experience Scale.
GDP	Gross Domestic Product.
GIZ	*Deutsche Gesellschaft für Internationale Zusammenarbeit.*
GLS	Generalized Least Squares.
HDI	Human Development Index.
IAA	Integrated Agriculture-Aquaculture.
LDV	Limited Dependent Variable.
LIFD	Low-Income Food-Deficit.
MLE	Maximum Likelihood Estimation.
MLR	Multiple Linear Regression.
MPI	Multidimensional Poverty Index.
OLS	Ordinary Least Squares.
OPHI	Oxford Poverty and Human Development Initiative.
OR	Odds Ratio.
PADM	*Pêche et Aquaculture Durable à Madagascar.*

pH	Potential for Hydrogen.
PSAEP	*Programme Sectoriel Agriculture Élevage Pêche*.
RASAP	Regional Aquaculture Strategy and Action Plan.
SDGs	Sustainable Development Goals.
SMEs	Small- and Medium-scale Enterprises.
SNDAM	*Stratégie Nationale de l'Aquaculture à Madagascar*.
SSA	Sub-Saharan Africa.
TDE	*Tilapia de l'Est*.
UNDP	United Nations Development Programme.
VCA	Value-Chain Actors.
VIF	Variance Inflator Factor.
WLS	Weighted Least Squares.

1 Introduction

The fishing and aquaculture industries of Madagascar support around 1.5 million people, particularly the most vulnerable and remote communities, on the fourth largest Island in the world located close to the east coast of Southern Africa (World Bank 2020). The contribution of these sectors to development has been underestimated in national and international poverty reduction strategies, but since the strong growth rates of the global aquaculture sector in the last decades and a record-high in 2018, a renewed interest in its potential to contribute to sustainable development objectives has emerged (Cojocaru et al. 2022; Finegold 2009: 359). Food security and poverty reduction have always been central topics on the world development agenda, but the focus on smallholders and the recognition of the potential of small-scale agricultural and aquaculture production systems is relatively recent (Béné et al. 2016). This is particularly relevant for Madagascar, given that 80% of the population lives in rural areas and three-quarters work in the primary sector (World Bank 2023). Despite having suffered inconsistent growth cycles that are visible in the Malagasy population's low purchasing power and poorly developed transport infrastructure (Razafindrakoto, Roubaud & Wachsberger 2018: 22), the Island's low ranking in human and socio-economic development indexes points to a challenging development process. This is visible also in undernourishment and malnutrition trends of the population, specifically concerning the lacking intake of animal proteins which are often unavailable in the disconnected remote areas (GIZ 2022a). In this context, freshwater aquaculture has positive social and environmental attributes that make it an attractive entry point to tackle both poverty and food insecurity (Edwards 2000: 1). In other words, *"aquaculture can be a vehicle for improving livelihood and nutrition"* (Gonzalez Parrao et al. 2021: 5) by generating income for aquaculture farmers and increasing the availability of fish proteins to the food insecure population. Because research and practice-based evidence point to the linkages between rural small-scale aquaculture, poverty alleviation, and nutritional security, the two research questions that this thesis is going to answer are:

- **RQ1**: What are the key determinants of the aquaculture farmers' fish incomes in the six regions of interest in Madagascar?
- **RQ2**: What are the key determinants of food security levels among the population in the six regions of interest in Madagascar?

In other words, the purpose of this thesis is to investigate the factors associated with income generation from fish farming and to explore what factors predict food security, with a specific focus on fish as a source of nutritional value for consumer diets. To understand the relationships between small-scale aquaculture, fish, and human well-being, this thesis adopted a case study approach that is limited in scope, time, and geography. Indeed, the analyses are focusing on 6 of the 22 administrative regions of Madagascar and employ data that were collected at the micro-level in 2021. The first quantitative approach envisages determining the most important factors relevant to fish income generation by differentiating among three distinct production types, namely individual pond aquaculture, individual rice-fish aquaculture, and cooperative-based pond aquaculture. Similarly, the second cross-sectional analysis aims to understand whether fish consumption is relevant for food security levels in the areas of interest and, if so, what are the most important factors to consider when targeting food insecurity.

To date, research interested in these questions is slowly starting to take a more interdisciplinary approach given that aquatic biologists, economists, and health scientists alone have difficulties in understanding the benefits and drawbacks of aquaculture for communities (Edwards 2000: 1). Although there is consensus that aquaculture can act as an engine for economic development similar to the way agriculture can contribute to economic growth, the research frontier is stuck at the discussion of whether it is small-scale aquaculture or rather an industrial aquaculture that has more impact in creating human well-being, which is mostly due to the relatively weak evidence for the relationships supported by both proponents (Gonzalez Parrao et al. 2021). While the classic debate is focusing on the linkages that the two practices have with the rest of the economy, more critical theoretical perspectives question the definition of development and consider the need to think beyond the economy and take a more holistic approach. Indeed, it is not only about evaluating the contribution of aquaculture to economic growth but also to ecosystems conservation, livelihoods securitization, and resilience to shocks (Brugère et al. 2019; Soto, Aguilar-Manjarrez & Hishamunda 2008), particularly for a country that is frequently confronted with extreme weather events, such as the most recent Cyclone Freddy in the southern part of the Island. The duality between the contribution of industrial and small-scale aquaculture to inclusive development in the sector can therefore be inscribed in the much wider debate between blue growth and blue degrowth, two schools of thought proposing different pathways to sustainable development in the larger ocean- and water-based economy. Similar to other critical economic theories, the supremacy of economic growth over environmental externalities and unfair distributional outcomes are at the heart of the understanding of a successful development process (Campbell et al. 2021; Ertör & Hadjimichael 2020).

In this context, this thesis aims to study the relationships between small-scale aquaculture, income generation, and food security, to add to the existing knowledge about the potential of small-scale production for human development. Indeed, the evidence related to small-scale aquaculture is poor compared to the literature on smallholder agriculture, and there is still a knowledge gap when it comes to analyzing its linkages with poverty-related factors, food and nutritional outcomes, as well as gender dynamics (Béné et al. 2016; Gonzalez Parrao et al. 2021; Stevenson & Irz 2009). The contribution of this study to research results from asking classic questions that have been around for decades in the discipline of development economics and exploring the potential relationships through standard econometric methods that allow comparing the in-depth case study of Madagascar to other case studies. In addition, this study could shed light on some open questions in the field thanks to the use of a high-quality dataset that has never been used before to do similar investigations. Finally, this study contributes to overall research by enlarging knowledge in English literature about Madagascar, given that many studies included in this thesis are only available in the French language.

The rest of the thesis is structured as follows. The second chapter focuses on the theoretical framework, the literature review, and the case study to give an overview of the most important information needed to place the analyses into their context. The third chapter presents the research design of this thesis, including the data used, the methods selected, and the limitations of the study. Before concluding, chapter four presents the results and the robustness checks of the quantitative analyses, and discusses the findings in relation to previous research, academic theories, and the local context.

2 Background

The background chapter aims to present the relevant concepts related to the case study. The theoretical framework will first introduce (small-scale) aquaculture and place it within a wider discussion about economic development. The literature review will then discuss the relationships between small-scale aquaculture, poverty reduction and food security in rural areas. The final chapter will close with a presentation of Madagascar's economic trajectory since Independence, and it will give an overview of the aquaculture sector as well as a description of the case study of this thesis.

2.1 Theoretical Framework

I Freshwater Aquaculture

Freshwater aquaculture is the counterpart of seawater-based aquaculture and it involves the farming of fish in freshwater sources, such as rivers and lakes, or ponds and rice fields (Edwards 2000: 1). Particularly the latter require access to land and are often integrated into agricultural and livestock production systems (Lhoste, Baudoux & Vall 2009: 1575). Pond and integrated rice-fish farming are the oldest forms of aquatic animal production and contribute to more than 80% of total freshwater production (Lhoste, Baudoux & Vall 2009: 1575). Within this sector, there are several degrees of intensification. **Intensive and super-intensive** production systems are characterized by high productivity thanks to the adoption of formulated fish diets allowing high fish stocking densities. The supply of complete artificial feed is exogenous to the farm and their purchase generally makes up the biggest share of investments in aquaculture (Lhoste, Baudoux & Vall 2009: 1578; Soto, Aguilar-Manjarrez & Hishamunda 2008). **Semi-intensive** production systems have a lower stocking density and thus involve the occasional addition of supplementary feed produced *in situ* to complement the fish's natural diet. **Extensive** production systems rely entirely on the natural productivity of the water body and do therefore not require any additional input (Soto, Aguilar-Manjarrez & Hishamunda 2008).

Related to the different degrees of intensification, freshwater aquaculture mostly takes place in three different production sites. **Cage production** is usually an intensive system and occurs mostly in aquatic ecosystems that allow for the exchange of water with the surrounding environment, such as rivers, lakes, or artificial waterbodies (Soto, Aguilar-Manjarrez & Hishamunda 2008). **Pond aquaculture** can be semi-intensive or intensive and is the most widespread land-based aquaculture practice in rural areas. On one hand, static waterbodies have limited water exchange and therefore represent a suited environment for the composition of phytoplankton and other edible organisms, and they can naturally regulate oxygen and the potential for hydrogen (pH) of the water. On the other hand, with higher stocking densities in ponds, the addition of fertilizers and supplementary feed in the form of recycled nutrients from domestic farm waste increase productivity and regulate the water (Edwards 2000: 2; Lhoste, Baudoux & Vall 2009: 1595-1596). The use of additional nutrients depends also on whether producers farm their fish in monocultures or polycultures. For example, monocultures require rather high fish stocking densities and in some cases the addition of supplementary feed, whereas polycultures can lead to complementary use of the ponds' available nutrients. Although the literature suggests that secondary fish species can increase fish yield up to 40%, the potential of polyculture is debated, as it depends on the fish pairings and the work involved in sorting the different species at harvest time (Lhoste, Baudoux & Vall 2009: 1602). Finally, **integrated rice-fish farming** is a production system that goes back to ancient China and consists in breading and managing fish in irrigated or rainfed rice fields, either in rotational schemes or simultaneously. Fish refuges are linked to the fields in the form of trenches or ponds so that fishes can gather when the rice field is drained and producers can harvest rice and select the marketable sized fishes from there (Frei & Becker 2005). Rice-fish farming is an extensive production system given that it exploits the synergies between fish and plant: while rice plants provide fishes with weeds, pests, insects, and snails to eat, the fishes act as biological control agents of the rice plants and their manure fertilize the plants as well as the soil (Frei & Becker 2005). Therefore, integrated pest management and natural fertilization allow producers to reduce the use of chemical plant-protecting agents and the addition of complementary feed (Food and Agriculture Organization (FAO) 2019). The literature suggests that integrated rice-fish farming increases land productivity compared to rice and fish monocultures and that rice yields are greater compared to rice monocultures, although the evidence concerning the latter is mixed (Frei & Becker 2005).

Concerning the farmed fish, freshwater aquaculture is mostly composed of short food-chain species, such as carps and tilapias, that are usually herbivores or omnivores (Lhoste, Baudoux & Vall 2009: 1575). Freshwater species are dominated by *cyprinids* and *cichlids*. While common carp is the most widespread *cyprinids* species, given that it is farmed in 86 countries, Nile tilapia represents 72% of total *cichlids* production worldwide (Lhoste, Baudoux & Vall 2009: 1577), and both fish species are farmed by the Malagasy farmers of the case study. Grown **common carps** feed on zooplankton and insects: to do so, they dig through the ground at the bottom of the pond or field, and after retaining the digestible material they discard the rest, which often results in high water turbidity and the deterioration of the pond's dikes (Lhoste, Baudoux & Vall 2009: 1584). **Nile tilapias** on the other hand are phytoplankton-only eating fishes. Their peculiarity lies in their high rate of reproduction, which constrains farming in terms of over-population. For this reason, Nile tilapias are either farmed in polycultures with predator fishes eliminating the young fingerlings or in monosex cultures. However, a high level of technical knowledge is required for sexing[1], as farmers need to select them manually, or for adopting hormone treatments (Lhoste, Baudoux & Vall 2009: 1586-1587).

II Economic Development & Aquaculture

Aquaculture production has been developing in the last four decades and since it reached a record high in 2018 it is projected to supply half of the world's fish-based food by 2030 (Gonzalez Parrao et al. 2021). Aquaculture can play an important role in the development process of low-income countries, similar to the role played by the agricultural sector. Indeed, some scholars in development economics consider agricultural transformation to be the first step towards economic growth, the idea being that the change from subsistence farming to an industrial agricultural sector that releases labor to the urban industrial sectors after productivity improvements drives economic growth (Kuznets 1973; Lewis 1954). The green revolution that took off particularly in Asian countries is the example *par excellence* of an effective process of agricultural transformation, as it is considered to have contributed positively to growth, poverty reduction, and food security through technological revolutions in irrigation, improved seed, fertilizers and pesticides (Ahmed & Turchini 2021). Given that agriculture and aquaculture are both farming practices, the aquaculture sector could play a similar role. However, this possibility has not been as thoroughly explored in research or prioritized in growth strategies due to the lack of data on fisheries and aquaculture, which often encompass artisanal and subsistence production (Finegold 2009: 357).

Still, the rapid growth of the sector on the global scale has been termed the "**blue revolution**": according to Ahmed and Turchini (2021) between 1990 and 2018 global production increased by 600%, from 13 to 83 million tons. This has led to renewed interest in the aquaculture sector as a potential engine for economic growth (Ahmed & Turchini 2021). However, the impact of the blue revolution on the livelihoods of communities in developing countries remains contested. Indeed, it is considered that the success of large-scale industrial aquaculture having linkages with the rest of the economy is mostly evaluated in terms of tons of fish exported, therefore sharing the same negative environmental and social impacts of the green revolution (Ahmed & Turchini 2021;

[1] Sexing refers to the practice of selecting male fish populations.

Costa-Pierce 2008; FAO 2022). This strand of the literature considers that the stocking of high densities of aquatic animals at a commercial scale requires high levels of chemicals for disease control as well as fishmeal and fish oil sourced from marine capture fishing to feed omnivorous fish. Furthermore, automated processes pollute, production expansion destroys habitats, and the introduction of alien species reduce indigenous biodiversity, therefore being a burden to the environment (Ahmed & Turchini 2021; Finegold 2009: 363; Johnson 2007). The irony is that these communities are not the main actors harming the environment, yet they have to face the degradation of their ecosystems and livelihoods, thus exacerbating their vulnerability to poverty (Chen, De Bruyne & Bollempalli 2020). Moreover, besides reinforcing this poverty-environment nexus, intensive industrial aquaculture has also been denounced because large-scale aquaculture projects often displace small-scale farmers, they create only a small number of unskilled jobs, and they do not redistribute the gains to local communities (Ahmed & Turchini 2021; Burns et al. 2014). Furthermore, many question the contribution of the blue revolution to food security because trade reduces the amount of fish available for local consumption (Cojocaru et al. 2022; Finegold 2009: 359).

For these reasons, the international policy environment changed in the early 2010s, proposing an alternative path for aquaculture development as a social transformation that takes environmental impacts into account. The **Ecosystems Approach to Aquaculture** (EAA) emerged from discussions between the FAO and international aquaculture experts on how to move the sector towards greater sustainability and create positive linkages to society, thus becoming a cornerstone in international conservation and development strategies (Brugère et al. 2019; Soto, Aguilar-Manjarrez & Hishamunda 2008). More specifically, the EAA understands aquaculture within its wider socio-ecological ecosystem and therefore aims to address *"multiple needs and desires of society, without jeopardizing the options for future generations to benefit from the full range of goods and services provided by aquatic ecosystems"* (Finegold 2009: 364). In other words, the EAA aims to develop the aquaculture sector through an integrated approach that includes other relevant sectors and policies, with the goal of improving human well-being and equity for all stakeholders involved while respecting ecosystems functions, services, and resilience capacities (Hughes 2021). Although the guidelines do not give explicit importance to small-scale aquaculture, evidence has shown that most EAA has been implemented in the context of rural small-scale aquaculture practices using low-input methods, as well as extensive or semi-intensive technologies, and employing household labor (Brugère et al. 2019). This is not surprising given that subsistence, small- and medium-scale enterprises (SME) aquaculture employ over 41 million people worldwide (Edwards 2000: 1; Finegold 2009: 355; FAO 2022).

The EAA focusing on small-scale aquaculture is part of a wider narrative about economic growth in the blue economy (BE), which does not only encompass the aquaculture and fishery sectors, but other ocean- and water-related sectors, such as recreational services, commerce, and energy as well. The BE concept emerged from the Rio+20 Conference with the wish to combine the three pillars of sustainable development with aquatic environments and, although there is still no universally-agreed definition, can be described as the optimization of revenues from the sustainable use of aquatic resources and the minimization of ecosystems degradation and enhancement of social benefits (Ertör & Hadjimichael 2020). Voyer et al. (2018) described the BE through four functions, namely (1) the provision of natural capital, (2) a source of business opportunities, (3) a source of innovation, and (4) the securitization of small-scale fishing livelihoods. Similar to the debate between the blue revolution and EAA, the blue economy is often understood as a source of business and driver of innovation, rather than as the provider of ecosystem services or the root of local livelihoods. Indeed, growth strategies often focus on high-value sectors such as shipping, deep-sea mining, mass-tourism, or large-scale fisheries and aquaculture instead of supporting small- and medium-scale businesses in the aquaculture, fisheries, eco-tourism, or renewable energy sectors (Ertör & Hadjimichael 2020; Voyer et al. 2021). It is exactly in this context that blue degrowth scholars consider that there is the need to support alternative strategies that strengthen participatory community economies valuing aquatic ecosystems not only from an economic point of view (Ertör & Hadjimichael 2020). The EAA is therefore inscribed in this idea of reorienting the blue economy to blue communities, as suggested by Campbell et al. (2021), so that just and equitable governance is ensured, community well-being is created, ecosystems are managed and conserved locally, and natural capital and livelihoods are preserved. Finally, **Figure 1** sums up the current debates behind the role of small-scale aquaculture in the development process.

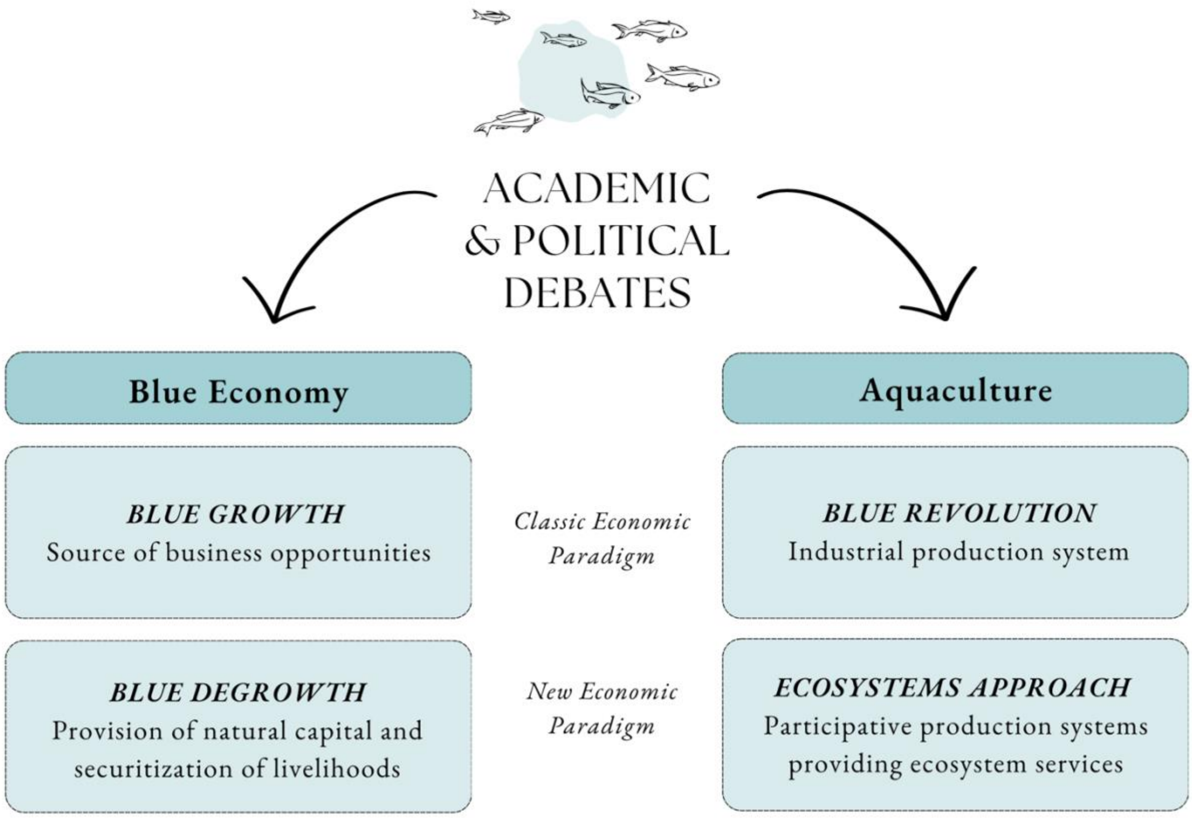


***Figure 1**: Placing small-scale aquaculture in the development process – Source: author's own computation.*

2.2 Literature Review

I Small-scale Aquaculture & Poverty Reduction

Poverty is a multi-faceted concept that can be defined in various ways. It is most widely referred to as *"whether households or individuals have enough resources or abilities to meet their needs"*, meaning that poverty also translates into insufficient outcomes related to health, nutrition, social relations, literacy, or self-confidence (World Bank 2005: 5). In this regard, vulnerability to poverty, or the risk of falling into poverty in the future, is an important notion to keep in mind. The global rise of the aquaculture sector has increased the interest in its potential to stimulate growth and therefore reduce poverty in developing countries, where fish production is mostly concentrated (Filipski & Belton 2018). However, there have been only a few studies that investigated the contribution of rural aquaculture to income generation and there is missing evidence of small-scale aquaculture reducing poverty directly (Stevenson & Irz 2009). The main problem is the lack of causal analyses and the difficulty of generalizing very diverse aquaculture practices and local contexts that differ in cultural norms and values determining who can farm, who can use new technologies, who is included in decision-making processes, who is responsible for labor or who can consume certain foods (Morgan et al. 2017; Stevenson & Irz 2009; Tuyen 2015). Although the discussions are ongoing, there is robust evidence that aquaculture can influence poverty-related outcomes and that these benefit particularly the poor (Stevenson & Irz 2009).

Gonzalez Parrao et al. (2021) consider that aquaculture development creates direct benefits to income and indirect benefits to poverty reduction and livelihoods. Concerning the former, **direct income links** are assumed to improve the efficiency of small- and medium-scale aquaculture production sites and their value chains, thus generating higher returns, and resulting in higher incomes (Gonzalez Parrao et al. 2021). However, Béné et al. (2016: 185) stress the importance of having access to urban markets as *"peri-urban fish farmers are more likely to generate higher incomes"*. Moreover, the literature about the poverty reduction potential of small-scale aquaculture nuances between different production practices given that some of them are more beneficial to raise farmers' incomes. For instance, polycultures have been associated with more positive impacts than monocultures, given that the successful combination of two complementary fish species has been found to improve fish yields between 14 and 35% depending on the fish species (Lhoste, Baudoux & Vall 2009: 1602). Another example is integrated production systems: according to Burns et al. (2014: 233) *"integrated farming systems were found to outperform the normal or commercial farming systems in all four dimensions […] food security, environmental functions, economic functions, and social functions"*. More specifically, integrated rice-fish culture has proven its high profitability and its potential to generate higher incomes compared to exclusive fish production given the two different sources of revenue (Frei & Becker 2005; Kawarazuka & Béné 2010).

Although the higher productivity of integrated systems is debated because of the lack of robust evidence to support this claim, it is generally considered that integrated agriculture-aquaculture (IAA) systems increase farm productivity, as the synergies between the two practices allow to produce more output on the same land surface (Dey et al. 2010; Stevenson & Irz 2009). Indeed, despite producing different foods, thanks to integrated resource management farmers can reduce production costs by avoiding the purchase of chemical fertilizers and pesticides (Dey et al. 2010). Moreover, by diversifying production, farmers diversify their income, therefore increasing their resilience to unexpected shocks and reducing their vulnerability to falling into poverty in the future. Nevertheless, IAA is not always a preferred option, as it involves high operational costs and risks due to the complexity of production and harvesting, and it is labor- and knowledge-intensive because of the synergistic interactions, which is often an obstacle for low-educated farmers (Frei & Becker 2005).

Despite the challenges, aquaculture also holds significant potential for pro-poor development in terms of increasing employment opportunities for the rest of the economy. The so-called

indirect income link is based on the idea that aquaculture development increasing profitability makes the entry into the sector for other producers attractive (Gonzalez Parrao et al. 2021). This would, in turn, create many low-skilled jobs in the rural economy that are accessible to the poor and that would ultimately increase rural wage rates and alleviate poverty in the long-term (Dey et al. 2010; Kawarazuka & Béné 2010; Stevenson & Irz 2009). Although it depends on the types of aquaculture farms and their requirements, this mechanism is recognized to work well for the aquaculture sector because it has proven to be more labor-intensive than other types of production practices on land, thus highlighting the complementarity of aquaculture development and employment generation (Cojocaru et al. 2022). It is however important to note that to enter the market some conditions need to be met: farmers need to have access to land, credit, and technical knowledge to open their businesses and know how to farm fish (Stevenson & Irz 2009). What has been pointed out by the literature is that because of these requirements, wealthier people with a minimum level of education are usually better-off adopting new practices or technologies, thus leaving out the poorest among them (Béné et al. 2016).

Another way aquaculture development can create employment in the economy is through up- and downstream sectoral linkages to other industries, although the evidence on the matter is mixed. The idea is that aquaculture development demands more supplying inputs (feed, fertilizers, hormones) and processing outputs (cleaning, sorting, descaling, filleting, etc.), thus creating additional employment opportunities (Stevenson & Irz 2009). However, the debate about these sectoral linkages is ongoing and differentiates between the *"small-scale narrative"* and the *"small- and medium enterprise narrative"* (Filipski & Belton 2018: 205–206). Indeed, it is considered that the indirect spillovers of SMEs to poverty reduction, resulting from business opportunities and employment generated on- and off-farm, are greater than the direct benefits, such as increasing the farmers' incomes, resulting from subsistence and small-scale fish farming (Brugère et al. 2019; Filipski & Belton 2018). However, it is also considered that small-scale and extensive aquaculture can effectively generate employment opportunities, particularly when associated with local ownership and integrated production practices thanks to the positive contribution to local employment and the optimized use of natural resources (Burns et al. 2014; Kaliba et al. 2007). In conclusion, there is the need to avoid generalizations when it comes to income and employment outcomes of aquaculture development, as there are gendered imbalances along different dimensions, such as the division of labor, the distribution of benefits, the access and control of assets and resources, which usually impact women negatively compared to their male counterparts (Gonzalez Parrao et al. 2021).

II Small-scale Aquaculture & Food Security

When it comes to the relationship between small-scale aquaculture and food security, the research output is very low compared to the literature on agriculture (Gonzalez Parrao et al. 2021). Nonetheless, although its impacts on nutritional status have not been thoroughly evaluated, small-scale aquaculture has generally been recognized as making important contributions to household food security and better quality consumption (Béné et al. 2016). According to the FAO (2006: 1), "*food security exists when all people, at all times, have physical and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life*". In other words, to ensure food security there need to be sufficient quantities of food (availability), foods need to be financially accessible (accessibility), they need to compose adequate and balanced diets (utilization), and people need to be able to access food at all times without being compromised by sudden shocks or cyclical events (stability) (FAO 2006). As can be inferred from the definition, food insecurity is not only about undernutrition but also about malnutrition and, while the former needs to be tackled with additional energy intake, the latter requires an adequate diet providing the missing nutrients (Kawarazuka & Béné 2010; Tacon & Metian 2018).

But how can fish help improve food security and reduce nutrient deficiencies? People in low-income food-deficit (LIFD) *"tend to depend essentially on carbohydrate-based diets for their nutritional intake"* (Kawarazuka & Béné 2010: 346) which are low in proteins and micronutrients. The most efficient way to consume important micronutrients is through animal proteins but given that their availability, affordability, and cultural acceptability are often limited they are not an option, particularly for the poor (Kawarazuka & Béné 2010). In this regard, fish has several advantages over other animal-sourced foods, as it is often more affordable and culturally preferred. This is also visible from the data, given that fish and fishery products already represent a major source of animal protein consumption in many LIFD countries in Asia and Africa (Finegold 2009: 360; Tacon & Metian 2018). Moreover, being rich in proteins, fatty acids, and micronutrients, fish consumption can overcome micronutrient deficiencies: this is true particularly for small fish species that are consumed whole, including bones, heads, and guts (Cojocaru et al. 2022; Kawarazuka & Béné 2010). However, it is important to keep in mind that the nutritional outcomes of aquaculture are context-dependent, as it depends on the socio-cultural dynamics of production and consumption determining whether fish consumption is desired (Morgan et al. 2017).

Kawarazuka and Béné (2010) theorize three impact pathways of aquaculture development on food security and nutrition. The **consumption pathway** consists of the direct contribution of aquaculture to fish intake by aquaculture farmers and their households. Although this linkage is debated, as many scholars did not find any difference in the amount consumed by fish-farming households compared to other households, the authors consider that there is strong evidence in research that aquaculture increases the fish consumption of producers (Béné et al. 2016; Kawarazuka & Béné 2010). Indeed, while on one hand there is evidence that farmers integrating ponds increased their household consumption of fish after the intervention, others suggest that the additional fish produced is rather sold on the market (Béné et al. 2016; Kawarazuka & Béné 2010). The **income pathway** is well-established in research and consists of the contribution of small-scale aquaculture development to higher incomes, therefore increasing the purchasing power of aquaculture farmers to buy other foods. In this way, the fish that is not directly consumed can be sold to generate a financial surplus to purchase lower-cost staple foods (Kawarazuka & Béné 2010). In this context, it is important to consider the **distribution pathway** which is about the role of women in securing nutritional outcomes. Indeed, the literature generally considers that women play an essential role in ensuring food security at the household level because they spend a higher proportion of the family income on food compared to men (Kawarazuka & Béné 2010).

On the macro-level, aquaculture development also increases the availability of fish in the market and therefore contributes to food security in the economy. The idea is that the additional fish makes it more accessible because prices in the market drop, thus improving the consumers' ability to purchase fish and other foods (Gonzalez Parrao et al. 2021; Stevenson & Irz 2009). This dynamic would increase the consumers' real incomes given that the demand-elasticity for fish is high, and would have a particularly important effect on the poor because they spend a relatively higher share of their income on food (Gonzalez Parrao et al. 2021; Stevenson & Irz 2009). However, this narrative is not proven in the literature, as other scholars consider that the scientific evidence is weak due to the heterogeneity of fish species sold in markets and because price effects are complex (Cojocaru et al. 2022; Kawarazuka & Béné 2010; Stevenson & Irz 2009).

To give a better idea of the complex relationships, **Figure 2** sums up the possible contribution of small-scale aquaculture to poverty reduction and food security by connecting the literature discussed in this chapter through a visual presentation.

The Small-scale Aquaculture, Poverty Reduction & Food Security Nexus[2]

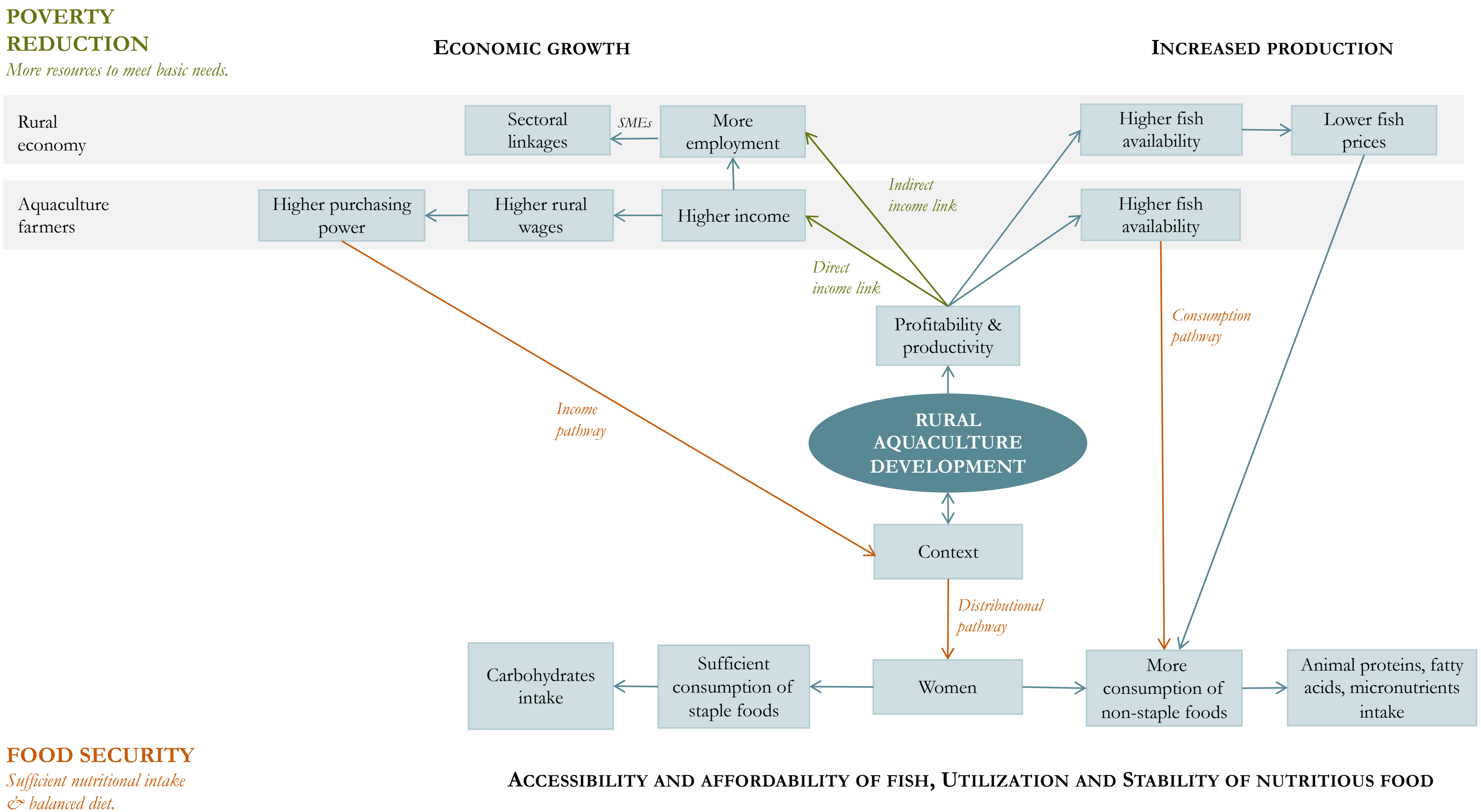


Figure 2: *Linkages between aquaculture development, poverty reduction, and food security – Source: author's own computation based on the literature.*

---

[2] The diagram does not aim to be comprehensive, as the literature review did not include findings related to health, climate and biodiversity, or behavioral economics for instance. Furthermore, the arrows do not indicate robust causal linkages, given that research is still debating on the different relationships.

2.3 Madagascar

I Economic Development & Poverty Profile

Madagascar is the fourth largest Island in the world and is located close to the African east coast in the Indian Ocean. According to Razafindrakoto, Roubaud, and Wachsberger (2018: 21–22) Madagascar's economic trajectory is characterized by an "enigma" and a "paradox" since it gained Independence from France in 1960. Indeed, the authors consider that while the past sixty years can be summed up by a recessionary trend that reduced the population's purchasing power by one-third between 1950 and 2015, the "Big Island" also experienced several periods of economic growth that were always interrupted by major political crises (Razafindrakoto, Roubaud & Wachsberger 2018: 22). These cycles were observed in the 1970s, the 1990s, and the 2000s, as well as in the 2010s and compute the Malagasy "mystery". This evolution is also visible in today's socio-economic development indicators, such as the Human Development Index (HDI), which ranked Madagascar 173rd of 191 countries in 2021 (United Nations Development Programme (UNDP) 2022). Even in comparison with the rest of Sub-Saharan Africa (SSA), Madagascar's Gross Domestic Product (GDP) increased only from 132 dollars per capita in 1960 to 402 dollars per capita in 2015, while the average of SSA's GDP per capita increased from 117 dollars to 1588 in the same period (Razafindrakoto, Roubaud & Wachsberger 2018: 21). Another symptom of this evolution is the rather under-developed infrastructure. Considering Madagascar's size, measuring approximately 587 km^2 with almost 29 million people[3], the 22 administrative regions are not well connected, neither by roads nor by railways (Rakotoambinima et al. 2009). Indeed, the road network is very small and becomes completely impassable after heavy rainfalls, and the railway network is practically inexistent, making economic development in remote areas extremely difficult (Rakotoambinima et al. 2009; Wiseman 2022).

The macroeconomic development and financial instability of the last decades have affected the Malagasy population's well-being, which is also visible in poverty measures. There are different ways to illustrate poverty trends, such as the share of people living under a poverty line (World Bank 2005). While international poverty lines are useful to make comparisons across space and over time, they are not always suited for all countries. On the other hand, national poverty lines are appropriate for a country analysis, but they do not give any information about the intensity of poverty (World Bank 2005). For this reason, the disaggregated poverty profile of Madagascar

[3] To give a comparison, Sweden, the largest country in northern Europe, measures 450 km^2 and hosts approximately 10.5 million people.

proposed here is based on the global **Multidimensional Poverty Index** (MPI) as it includes both the incidence and intensity of poverty (Oxford Poverty and Human Development Initiative (OPHI) 2021). The MPI is composed of the three equally weighted dimensions of health, education, and living standards, which are composed of 10 indicators (**Appendix A**).

According to the definition, a person is vulnerable to multidimensional poverty if they are deprived in one-third (33.33%) of the indicators, and living in severe poverty if they are deprived in 50-100% of the weighted indicators (OPHI 2021). Madagascar's national MPI measured 0.384 in 2018, placing it in the 104th position of 111, with 69.1% of the population being multidimensionally poor and with the average proportion of indicator deprivation equal to 55.6%, showing that a high percentage of the population is living in severe poverty (OPHI 2021). The MPI allows not only for the dimensional breakdown of poverty but also for sub-regional decompositions. This is particularly useful to assess regional inequalities and shape more informed local poverty reduction strategies. In the case of Madagascar, **Figure 3** illustrates the regional disaggregation of the MPI, showing that there is a large difference between the north and the south, which suffers from bad infrastructure and frequent weather events such as droughts or cyclones. More specifically, the Analamanga region, where the capital Antananarivo is located, and the northeast, where the vanilla and tourism sectors are booming, stand out from the rest of the country.

Furthermore, **Figure 4** shows the contributions of the ten indicators to the national, urban, and rural MPI. It can be noted that the indicator contributions are similar for urban and rural areas, as living standards contribute to half of the MPI, education to one-third, and health to 15-18%. Additionally, it is interesting to note that with 77% of people living in rural areas, they dominate the geographic distribution of the Malagasy population. Given that the high intensity of deprivation is similar in urban (50,72%) and rural areas (56,36%) (OPHI 2022), **Figure 4** reveals that severe multidimensional poverty is a problem in rural areas because of the high number of people they host.

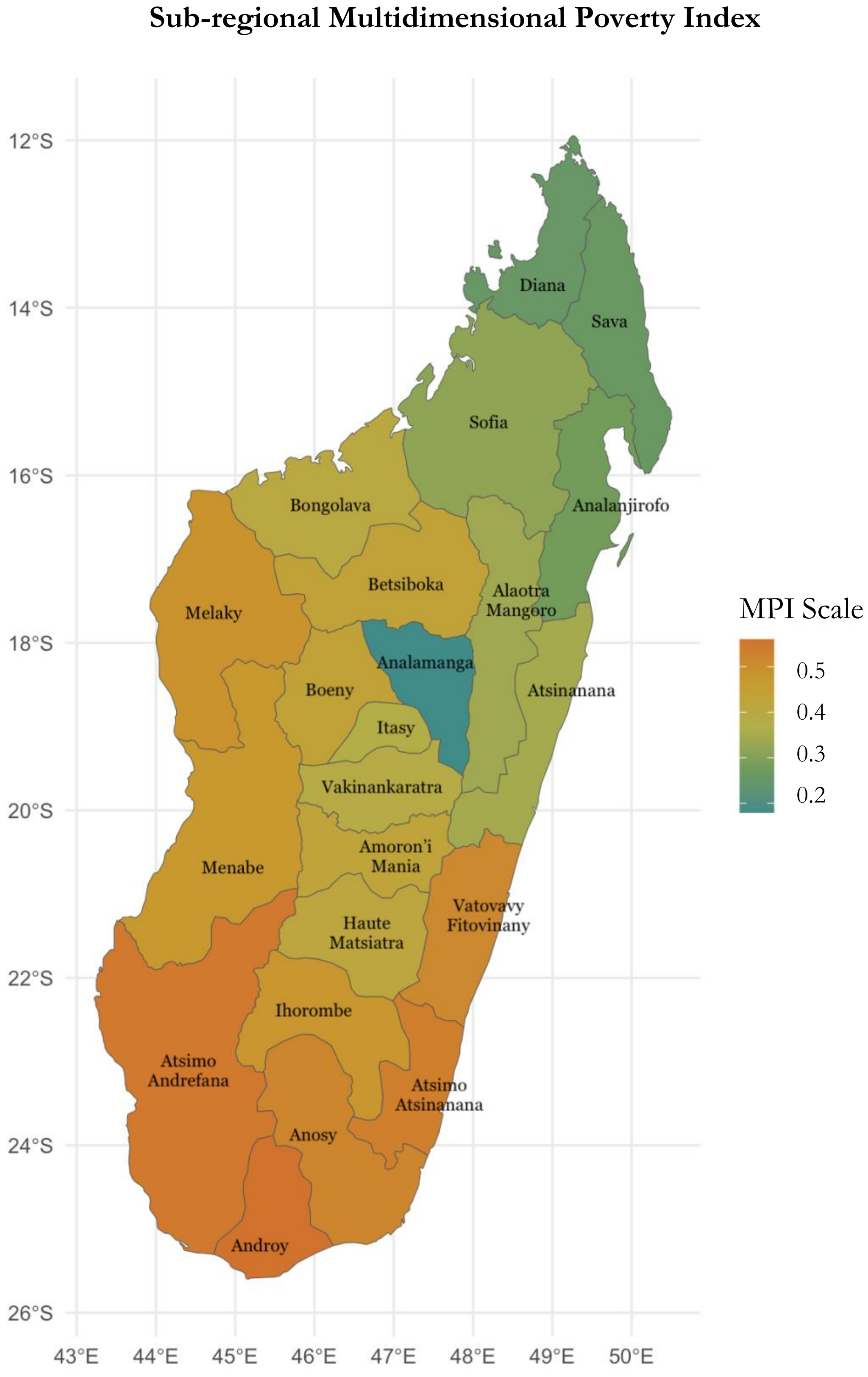
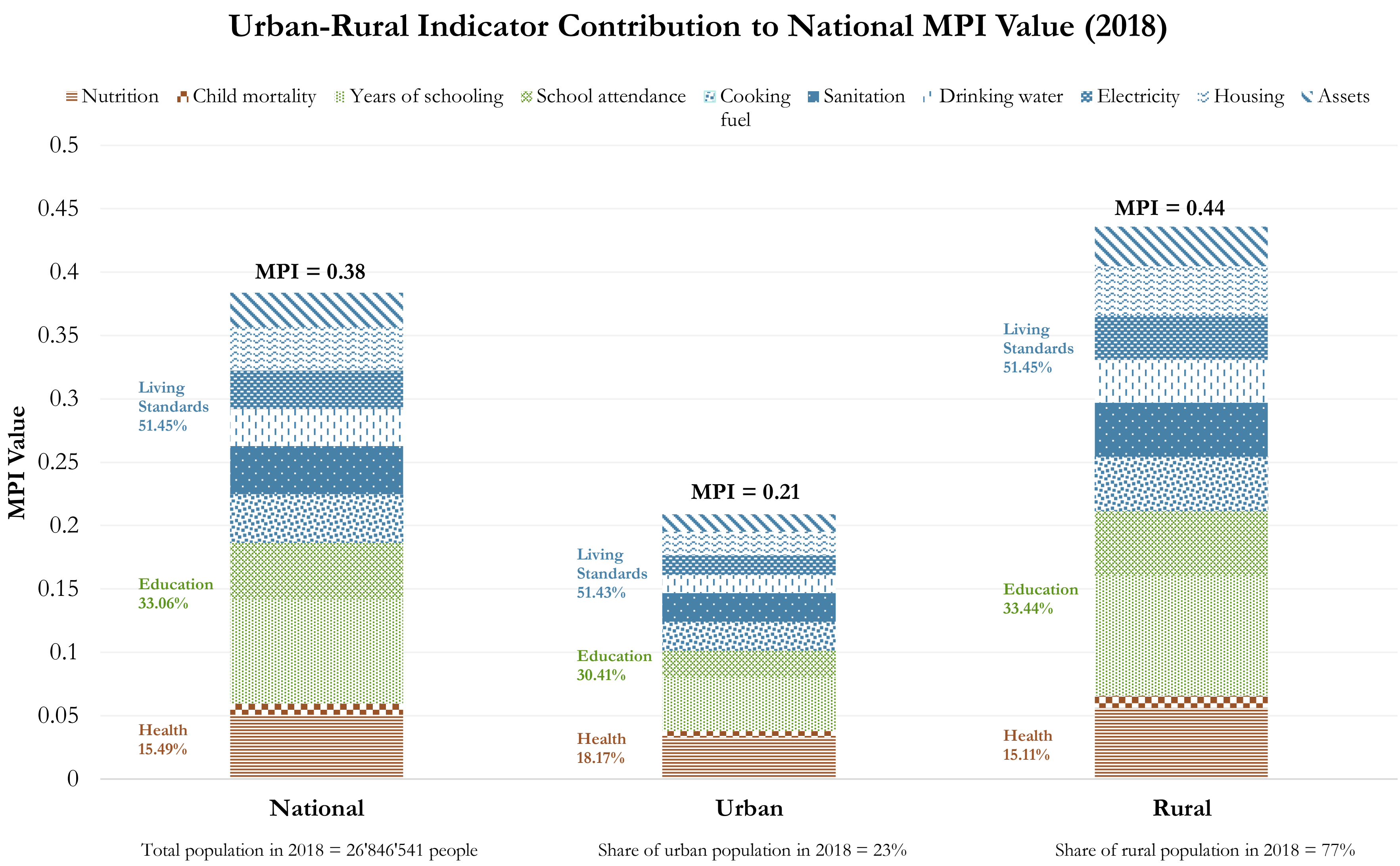


Figure 3: *National MPI mapping by subnational region – Source: author's own computation, adapted from OPHI (2021: 8).*

Figure 4: *Urban-rural indicator contribution to national MPI – Source: author's own computation with data from OPHI (2022).*



II Aquaculture in the Malagasy Economy

Compared to its neighbors Madagascar's fish production is very low, as its production volume is among the 16,7% not covered by the top five SSA producers (FAO 2022; Rakotoambinima et al. 2009). Nevertheless, the Malagasy fisheries and aquaculture sectors represented approximately 7% of the country's GDP with an annual production of 750 million dollars, and 6,6% of exports in 2018, thus playing a relatively important role in the country's economy (Djaoui & Hourtoule 2021; World Bank 2020). Indeed, Refaliarison (2023: 1) suggests that aquaculture *"is considered one of the key sectors of the country because of the contribution it makes to foreign exchange revenues […] and the part played by improving the incomes of smallholder fish farmers, the contribution to making fish available on local markets and the employment generated"*. Concerning the contribution to foreign exchange, Madagascar's mariculture sector, namely the farming of shrimps, sea cucumbers, and spirulina algae, is designed for the export market and developed strongly over the past ten years to become a vertically-integrated production system (Agulhas and Somali Current Large Marine Ecosystems Project (ASCLME) 2012; GIZ 2022a; FAO 2022; Refaliarison 2023). Related to this, Madagascar's mariculture production was among the top five in SSA (FAO 2022).

Concerning the contribution to the securitization of small-scale livelihoods, Madagascar's **inland aquaculture** is intended for self-consumption and oriented to local markets, making important contributions to the rural population's subsistence (GIZ 2022). This is particularly important considering that according to the latest data, 39,9% of children were stunted, 7,7% were wasted, and 23,4% were underweight in 2021 (USAID 2023).[4] Indeed, the sector is seen as central in reducing undernutrition and improving malnutrition in the country, particularly in the population-dense capital Antananarivo where coastal fish products are difficult to find and in rural areas where the share of consumption of fish is high, even more than suggested by national statistics (GIZ 2022a; Lhoste, Baudoux & Vall 2009: 1617; Rakotoambinima et al. 2009). Similar to other areas in the world, the freshwater aquaculture sector of Madagascar is based on extensive paddy fields-based production, semi-intensive pond production, and intensive cage production (ASCLME 2012; Refaliarison 2023). Of these, the most common is small-scale and subsistence pond and rice-fish aquaculture that employ traditional farming practices and use low-input technologies (GIZ 2022b).

Because of its importance, the Malagasy government has been prioritizing the sustainable development of the freshwater aquaculture sector by engaging in regional agreements and

[4] Based on a child's height and age, stunting measures chronic nutritional deficiency, wasting measures acute nutritional deficiency, and underweight combines the two measures.

producing national strategies. This is in line with SSA goals, as it is generally considered that the potential for aquaculture in the region is unfulfilled and should be supported through an adequate institutional environment (Finegold 2009: 363; FAO 2022). Indeed, despite supporting the Sustainable Development Goals (SDGs) that touch the aquaculture sector[5], Madagascar adhered to the African Union (AU) Agenda 2063 aiming to reinforce and modernize food systems, including the production, processing, value-chain, consumption, and disposal processes on the African continent (Commission de l'Union Africaine 2015; Joffre et al. 2023). More specifically, Madagascar adopted the Regional Aquaculture Strategy and Action Plan (RASAP) for 2016-2026. This strategy considers that aquaculture has important socio-economic potentials that are not yet exploited and it envisions that the Southern African Development Community (SADC) becomes a global leader in sustainable aquaculture production (Joffre et al. 2023; SADC 2016).

At the national level, the *"Lettre de la politique bleue"* as well as the *"Programme Sectoriel Agriculture Élevage Pêche"* (PSAEP) promote sustainable and resilient aquaculture development generating inclusive growth, reinforcing governance, strengthening public-private partnerships, and producing more accessible and affordable foods by 2025 (Joffre et al. 2023; Ministère des Ressources Halieutiques et de la Pêche 2015; République de Madagascar 2015). The government also adopted the *"Stratégie Nationale de l'Aquaculture à Madagascar"* (SNDAM) for the period 2021-2030 which aims to improve revenues for rural communities, create rural employment and increase rural food security through technological improvements, with a particular focus on inland aquaculture (Joffre et al. 2023; Ministère de l'Agriculture, de l'Élevage et de la Pêche 2020). It is therefore evident that while the Malagasy government is pushing for a blue revolution in the sector, it is aware that additional measures need to be taken to accompany small-scale producers in the transition.

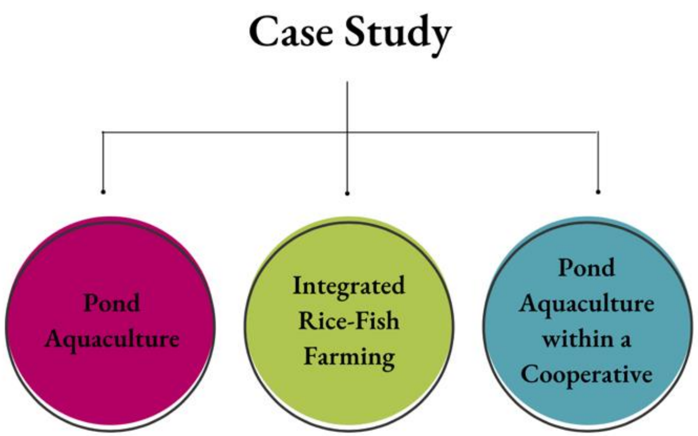
III Case Study

In line with the wider strategies adopted by the Malagasy government, the German Organization for International Cooperation (GIZ) is contributing to these objectives through the project *"Pêche et Aquaculture Durable à Madagascar"* (PADM). The project is under GIZ's Global Programme "Sustainable Fisheries and Aquaculture" (2016-2025) present in nine countries (GIZ 2022b). The program is part of the German Federal Ministry for Economic Cooperation and Development's special initiative "One World – No Hunger" aiming to eradicate poverty and hunger in 36 countries worldwide (Kleemann & Semrau 2022). The PADM project has been implemented between 2017 and 2023 under the tutelage of the Ministry of Fisheries and the Blue

[5] Such as eradicating poverty (SDG 1) and hunger (SDG 2), promoting economic growth (SDG 8) and sustainable infrastructure (SDG 9), and conserving ocean resources (SDG 14).

Economy of Madagascar (GIZ 2022b; Kleemann & Semrau 2022). Despite promoting national aquaculture strategies in line with the FAO guidelines on freshwater aquaculture, the objective of the project is to increase incomes and employment opportunities in the small-scale aquaculture value-chain, as well as increasing the fish supply from aquaculture to the food-insecure population (GIZ 2022b; Kleemann & Semrau 2022). To do so, GIZ is working with implementing partners, namely with the *Association Pisciculture et Développement Rural en Afrique tropicale humide* (APDRA) for rice-fish culture, *Consultants for Fishery, Aquaculture and Regional Development* (COFAD) for pond production in the Highlands, and *Norges Vel* and *Tilapia de l'Est* for pond aquaculture on the east coast (GIZ 2022b).

The case study selected for this thesis results from the PADM project given that the data used for the quantitative analyses were collected as part of the activities. More specifically, the case study includes six administrative regions of the country, namely Analamanga, Vakinankaratra, Itasy, Amoron'I Mania, and Haute Matsiatra in the Highlands and Atsinanana in the east coast, and is based on three different types of aquaculture production systems (Kleemann & Semrau 2022). In the Analamanga region containing the capital Antananarivo, the project accompanied pond aquaculture producers that employ a semi-intensive production system of common carps and Nile tilapias using additional on-farm produced nutrients (Desprez et al. 2023). In the regions of Vakinankaratra, Itasy, Amoron'I Mania, and Haute Matsiatra rice-fish farmers were accompanied in the context of the project. These aquaculture farmers only produced common carps through an extensive approach, as the nutrients present in the rice fields represent the biggest part of the fishes' diets (Bentz et al. 2023). Finally, in the Atsinanana region on the east coast, the project accompanied farmers producing Nile tilapias in ponds through the cooperative *Tilapia de l'Est* (TDE). As in Analamanga, these aquaculture producers adopted semi-intensive practices, but with the additional use of purchased formulated feed (Rafalimisy et al. 2023). The main differences between these practices that this study is going to exploit for the analysis in terms of profitability of the activity are the different degrees of productivity and intensification, as an extensive approach requires less additional inputs and therefore might reduce production costs, and the cooperative model that generates higher revenues through quantity discounts and improved access to markets (Desprez et al. 2023; Rafalimisy et al. 2023). The three different types of aquaculture production are summed up and illustrated in **Figure 5**.



	Pond Aquaculture	Integrated Rice-Fish Farming	Pond Aquaculture within a Cooperative
Region	(1) Analamanga	(2) Vakinanakaratra (3) Itasy (4) Haute Matsiatra (5) Amoron'I Mania	(6) Atsinanana
Production system	Semi-intensive	Extensive	Semi-intensive
Fish	Common carp Nile tilapia	Common carp	Nile tilapia
Operational goal	Subsistence and commercial aquaculture	Subsistence and semi-commercial aquaculture	Subsistence and commercial aquaculture
Productivity	Medium (766 kg/ha)	Medium-low (76-1215 kg/ha)	High (5970 kg/ha)

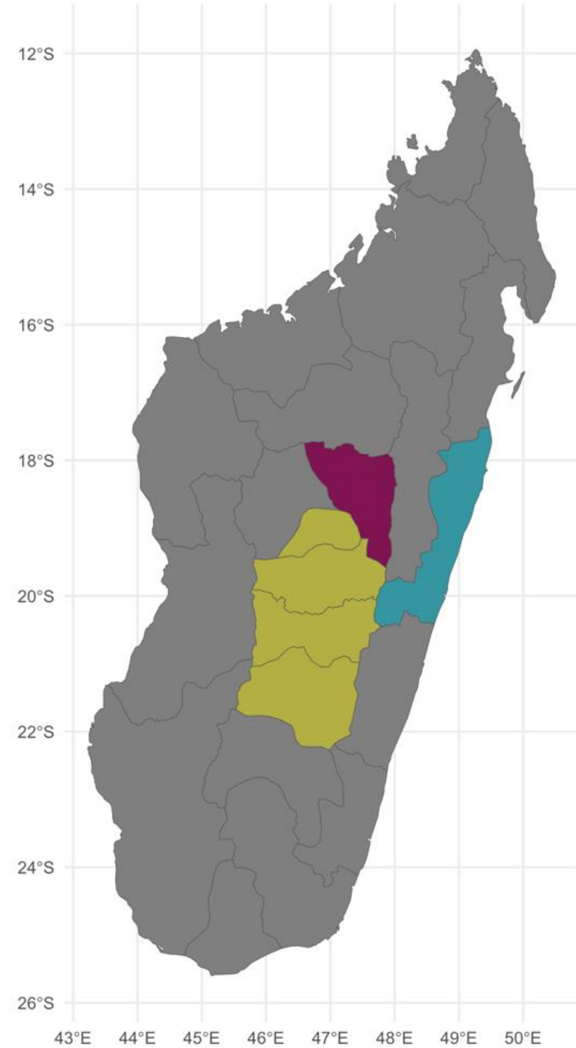


Figure 5*: Research case study – Source: author's own computation.*

3 Research Design

This chapter aims to go through the main methodological notions related to the quantitative analysis of the case study. First, the data will be introduced, and the process of data collection will be presented. Then, the main variables selected and developed that are included in the two econometric models will be specified. The third section will present the estimation methods used to answer the two research questions, namely the multiple linear regression and the binary logistic regression. Finally, the chapter will conclude with a discussion of the main limitations of the data, the methods, and the study.

3.1 Data

The data used for the analyses come from the monitoring and evaluation process of the PADM project. Together, the programme's steering unit, Madagascar-based team, and local consulting firms implemented the data collection process targeting fish farmers, value chain actors (VCA), and consumers in the six regions of interest (Kleemann & Semrau 2022). The process started with a survey in 2018 aiming to provide baseline values and develop target values for the project, and a midline survey took place in 2021 to monitor the progress toward the objectives. Given that the respondents of the two waves of surveys were not tracked over time, the analysis of this thesis involves only the midline data from the 2021 survey, resulting in a cross-sectional dataset. The sampling design involving the three types of respondents is based on different criteria: concerning consumers, the local teams conducted the surveys at the local markets and in restaurants in each of the six administrative areas on a random basis. The same applies to the interviewed VCA, which include food producers and vendors, fertilizer producers and distributors, wholesalers and retailers, fish shop and grocery store owners, manifold operators, restaurateurs and hoteliers, as well as service providers. Finally, the producers included in the surveys result from the master list of fish farmers beneficiaries of the project, namely pond producers in Analamanga and Atsinanana, and rice-fish producers in the Highlands except for the Analamanga region (Kleemann & Semrau 2022). After a pre-test in the field to get familiar with the process and evaluate the questionnaire, the data collection process was implemented by the local partners through the offline questionnaire platform Kobo Toolbox allowing them to fill out the forms even in the most remote areas and upload the retrieved information once internet connection is available. Before starting the surveys, the implementing partners carried out a courtesy visit to the local authorities to present the project and the objective of the surveys (Kleemann & Semrau 2022). The result of the 2021 data collection is a dataset with almost 2000 observations of the above-mentioned target groups. More specifically, for the two analyses of this thesis the determinants of fish income are based on the approximately 500 fish farmers that answered the questionnaires, and the determinants of food security are based on the 2000 consumers, VCA, and producers who took part in the surveys.

3.2 Variables & Hypotheses

I Determinants of Fish Income

To explore which factors influence income generation in the small-scale aquaculture sector of the six regions of interest in Madagascar, it was decided to use the total income derived from fish production for an aquaculture farmer in a year as the dependent variable of the model. This is possible because, as discussed in the literature review, poverty can be proxied by many different factors depending on what is investigated, and income measures are used often (World Bank 2005). Accordingly, the main variable of interest is the variable referring to the type of aquaculture producers: the categorical variable differentiates between individual pond producers, individual rice-fish farmers, and pond farmers producing in a cooperative system. As discussed in the theoretical framework, extensive and semi-intensive production systems have different degrees of intensity that need to be considered: on one hand IAA, such as rice-fish culture, has higher land productivity compared to pond aquaculture and can use the different factors of production more efficiently thanks to the integrated approach (Dey et al. 2010). On the other hand, IAA is a knowledge-intensive practice and labor productivity is not necessarily higher, thus not leading to higher fish yields and total income *per se* even though production costs are lower compared to a semi-intensive system (Frei & Becker 2005). Another distinction needs to be made between individual production and a cooperative economic model. Indeed, cooperatives provide extension services, such as lower input costs or better access to markets, that increase the profit margin per farmer (Rafalimisy et al. 2023).

In line with the findings in the literature, the analysis also includes several demographic and socio-economic control variables. For instance, age is associated with more farming experience and thus with potentially higher incomes, but after a certain age, older individuals become less productive thus reducing income per farmer (Assefa 2018; Gebre 2012). It is also considered that the gender of the household head and the size of the family influence household poverty, with women-headed families being poorer than those headed by men and with larger households being associated with higher poverty rates, particularly when the number of economically-dependent household members (dependency ratio) is higher (Iruo et al. 2018; Tuyen 2015; World Bank 2005). Concerning socio-economic factors influencing total income, the literature points to the importance of the level of education of the household head as well as of their farming experience, with higher education levels and more years of experience in fish farming being associated with a reduction of the poverty depth and an increase of total income (Iruo et al. 2018; Tuyen 2015). At the community level, another important factor is the available infrastructure: indeed, with good transport connections not only schools or hospitals are more easily reachable, but also markets are closer, allowing aquaculture farmers to have better access to the selling spots (Tuyen 2015).

Finally, the model also includes some variables related to the type of production. First, ownership of tangible goods and financial assets in general and ownership of farmland are considered to be positively related to aquaculture income generation because of greater income flow and no costs related to rental (Burns et al. 2014; Kaliba et al. 2007; Tuyen 2015; World Bank 2005). Second, polycultures are associated with higher incomes because research considers that fish yield can increase up to 40% species thanks to the complementary use of nutrients depending on the fish species (Lhoste, Baudoux & Vall 2009: 1586). Finally, extensive and semi-intensive aquaculture production systems require different feeding inputs translating into non-negligible production costs that could either drive the farmers' total income through increased production or become a burden due to too elevated costs (Burns et al. 2014; Frei & Becker 2005; Lhoste, Baudoux & Vall 2009: 1577). The overview of all these variables, their descriptions, as well as their expected relationship with total fish income is summed up in **Table 1** below.

***Table 1**: Variables included in the model estimating the determinants of fish income.*

	Variable	Coding	Description	Expected sign
Outcome Variable				
	Fish income	lnfish_income	Continuous variable indicating the aquaculture farmer's total income in Ariary (MGA) in a year.	
Independent Variables				
	Type of producer	type_producer	Categorical variable indicating whether the respondent is (1) a pond farmer, (2) a rice-fish farmer, or (3) part of a pond-based cooperative system.	(1) ref (2) ± (3) +
Demographic characteristics	Age of producer	age	Continuous variable indicating the age of the producer in years.	+
	Age squared	age_squared	Continuous variable measuring the square of the producers' age.	–
	Gender of producer	male	Dummy variable indicating whether the producer is a male (1) or a female (0).	+
	Household size	hh_size	Continuous variable indicating the number of people living in the household.	–
Socio-economic characteristics	Education of household head	hhhead_educ	Dummy variable indicating whether the household head went to secondary school or higher (1), or whether they only have a primary school degree or none at all (0).	+
	Farming experience	experience	Continuous variable indicating the number of years of experience of the aquaculture farmer.	+
	Market infrastructure	distance	Continuous variable indicating the walking distance in minutes from the closest selling point.	–
Production characteristics	Landowner	land_owner	Dummy variable indicating whether the aquaculture farmer owns the land (1) or not (0).	+
	Fish culture	polyculture	Dummy variable indicating whether the aquaculture farmer adopted a polyculture (1) or a monoculture (0).	+
	Fish feed costs	lnfeed_costs	Continuous variable indicating the aquaculture farmer's total costs in Ariary (MGA) in a year.	±

II Determinants of Food Security

To explore what the determinants of food security are in the six regions of interest and whether fish consumption contributes to this goal, the second model's dependent variable is a proxy for food security, namely the so-called Food Insecurity Experience Scale (FIES). The FIES is a subjective and widely accepted measure of food insecurity that includes eight questions (**Appendix B**) referring to different experiences related to food insecurity (FAO 2017). The score is based on the number of affirmative responses and the lower the score the more food secure is the respondent. In the analysis, a FIES score between 0-3 describes a food-secure individual, while a score of 4-8 characterizes a food-insecure person (FAO 2017). Also in this context, it is interesting to investigate carefully whether there are differences in food security levels when it comes to the different types of respondents. Indeed, although there is no consensus, some scholars suggest that individuals operating in the fish production sector, such as aquaculture farmers or value-chain actors, have facilitated access to fish compared to other consumers, particularly when extension services and networks are involved, which would increase fish consumption and improve food security levels (Assefa 2018; Gonzalez Parrao et al. 2021).

In addition, the analysis also includes several demographic and socio-economic variables to control for the explored linkages. For instance, the relationship between food security and age is considered to be ambiguous as adults are more food secure compared to children, but elderlies are more prone to be food insecure compared to younger individuals (Assefa 2018; Bashir, Schilizzi & Pandit 2012; Gebre 2012). Similarly, it is considered that the household's size is negatively related to food security, as the bigger the family, the higher the probability of the household being food insecure (Assefa 2018; Bashir, Schilizzi & Pandit 2012; Gebre 2012). When it comes to gender dynamics the evidence is mixed: while some scholars found that food security is worse in female-headed households, others found that in households in which females are in charge of the family income, a higher proportion is spent on food, and food security levels improve (Gebre 2012; Kawarazuka & Béné 2010). For this reason, both variables were included in the model. Concerning socio-economic factors, the findings related to the education level of the household level are evident: food insecurity is concentrated in the individuals and households that are relatively more illiterate, suggesting that education impacts positively the individual's ability to make well-informed decisions on food consumption (Assefa 2018; Gebre 2012). Asset possession and wealth are considered to be associated positively with food security outcomes, given that the possession of more financial means translates into potentially higher expenditures on food (Assefa 2018; Bashir, Schilizzi & Pandit 2012).

Finally, the model includes variables more specifically related to fish consumption to investigate whether fish is associated with higher levels of food security. First, the model includes a variable with information about the distance to the closest fish purchasing point given that evidence shows that improved food accessibility improves food security outcomes (Cojocaru et al. 2022; FAO 2017; World Bank 2005). Second, the frequency of consumption is included to account for the amount of fish consumed with the assumption that it is positively related to the food security status thanks to fish's nutritional value (Cojocaru et al. 2022; Kawarazuka & Béné 2010; Stevenson & Irz 2009). Third, the fish species consumed is included in the model too, to explore whether the consumption of fish produced in the local aquaculture market, such as carps and tilapias, is indeed associated with higher food security outcomes compared to fish coming from mariculture that is usually destinated to exports (FAO 2022; Refaliarison 2023). Lastly, food security outcomes are also closely related to the utilization of food through adequate and diverse diets. Given the importance of consuming fish including bones, heads, and interior parts for nutritional intake and thus for food security, the model includes this information to investigate whether these two factors are positively related (Cojocaru et al. 2022; Kawarazuka & Béné 2010). The summary of the variables and their expected signs can be found in **Table 2**.

Table 2*: Variables included in the model estimating the determinants of food security.*

	Variable	Coding	Description	Expected sign
Outcome Variable				
	Food security	fies	Dummy variable indicating whether the respondent is food secure (1), or food insecure (0).	
Independent Variables				
	Type of respondent	type_respondent	Categorical variable indicating whether the respondent is (1) a consumer, (2) a producer, or (3) a value-chain actor.	(1) ref (2) + (3) +
Demographic characteristics	Age of respondent	age	Continuous variable indicating the age of the respondent in years.	±
	Gender of household head	hhhead_gender	Dummy variable indicating whether the household head is a male (1) or a female (0).	–
	Who decides on food matters	hh_decide	Categorical variable indicating whether it is (1) the male, (2) the female, or (3) both together.	(1) ref (2) + (3) +
	Household size	hh_size	Continuous variable indicating the number of people living in the household.	–
Socio-economic characteristics	Education of household head	hhhead_educ	Dummy variable indicating whether the household head went to secondary school or higher (1), or whether they only have a primary school degree or none at all (0).	+
	Household wealth	hh_wealth	Dummy variable indicating whether the respondent perceives their household as better-off than the others (1), or not (0).	+
Fish consumption characteristics	Accessibility of fish	distance	Continuous variable indicating the walking distance in minutes from the closest fish purchasing point.	–
	Frequency of fish consumption	frequency	Dummy variable indicating whether the respondent consumes fish frequently (1), or not (0).	+
	Fish species consumed	fish_species	Categorical variable indicating whether the respondent consumed ocean fishes or other (1), carps (2), or tilapias (3).	(1) ref (2) + (3) +
	Consumption of whole fish	fish_whole	Dummy variable indicating whether the respondent consumes the whole fish (1), or not (0).	+

3.3 Estimation Methods

I Multiple Linear Regression

Poverty reduction outcomes are complex and influenced by many factors on the individual, household, and community levels. More specifically related to the case study, this research is interested in the determinants of income generation of fish farmers. To do so, an empirical model that can measure which factors are significantly related to fish income is needed. Therefore, and given the cross-sectional nature of the data, this study uses a multiple linear regression (MLR) to estimate the relationship between the independent variables and the outcome variable. On a practical level, a linear regression is appropriate because scientific research interested in similar questions has used the same approach to produce evidence (Tuyen 2015; World Bank 2005). **Model 1** below illustrates the relationship that is going to be estimated.

***Model 1**: Determinants of fish income*

$$
\begin{aligned}
ln(fish\_income)_i \\
&= \beta_0 + \beta_1 type\_producer_i + \beta_2 age_i + \beta_3 age_i^2 + \beta_4 male_i + \beta_5 hh\_size_i \\
&+ \beta_6 hhhead\_educ_i + \beta_7 experience_i + \beta_8 distance_i + \beta_9 land\_owner_i \\
&+ \beta_{10} polyculture_i + \beta_{11} ln(feed\_costs)_i \ + \varepsilon_i
\end{aligned}
$$

The final model is the result of the stepwise modeling approach that was used to optimize the model based on the gradual introduction of new variables. The results section presents the outcomes of the previous steps as well as the final model. Moreover, to further ensure its reliability, a series of econometric tests were carried out to test the model's goodness-of-fit and the underlying theoretical assumptions. The results of these tests can be found in **Appendix C** and are elaborated in the section covering the robustness checks of the model. Indeed, to use a MLR approach several assumptions need to hold: despite the requirement of a random sampling of the observations, the linearity in the parameters[6] of the model, the independence of the variables, also a homoskedastic distribution of the errors, multivariate normality, and the absence of multicollinearity are needed (Wooldridge 2015: 83–119). The formal tests reveal that the homoskedasticity and the normality assumptions are not met even after the non-linear transformation of the dependent variable with its natural logarithm and the deletion of outliers (Tuyen 2015). It can be noted, however, that the visual normality test suggests that the residuals could be considered "normal enough", given that real-world data most often do not follow a perfectly normal distribution.

[6] Note that this assumption is quite flexible, as it allows the dependent and independent variables to be logarithmic or square functions (Wooldridge 2015: 83).

For the analysis, this means that instead of using the ordinary least squares (OLS) method, the best unbiased linear estimator (BLUE) when all the assumptions are met, the estimation uses the weighted least squares (WLS) method, another special case of a generalized least squares (GLS) (Verbeek 2017: 102; Wooldridge 2015: 308). Contrary to OLS which gives the same weight to each observation, the WLS minimizes the weighted sum of squared residuals by giving less weight to observations with higher error variance (Verbeek 2017: 102; Wooldridge 2015: 311). In other words, the observations giving the most accurate information about the model parameters receive the greatest weights (Verbeek 2017: 102). The WLS is the most efficient estimator in the context of heteroskedasticity and the non-normality of the residuals only if the weights are correctly specified. In this case, the autocorrelation test that can be found in **Appendix C** supports the choice of the weights as the inverse of the error variance, as illustrated in equation (1):

$$w_i = \frac{1}{Var(\varepsilon_i)} = \frac{1}{\sigma_i^2} \tag{1}$$

II Binary Logistic Regression

Food security outcomes too are complex and depend on many individual-, household-, and community-level factors. Given the cross-sectional nature of the data and the limited dependent variable (LDV) of the model taking only two values, namely "food secure" and "food insecure", the study adopts a binary logistic regression to estimate the odds of being food secure according to the previously introduced predictor variables. Indeed, with a binary dependent variable a linear regression analysis is not appropriate because the predicted value of the numeric outcome cannot take any value between $-\infty$ and $+\infty$ like a continuous variable (Sommet & Morselli 2017). In a binary response model, the interest therefore lies in determining the response probability of a particular outcome based on the predictor variables. In other words, the main goal is to explain the effects of the predictor variables on the conditional probability that the outcome variable equals 1 (being food secure) (Sommet & Morselli 2017; Wooldridge 2015: 614). This function is represented by equation (2), where the left-hand side represents the probability that the outcome equals 1 and the right-hand side is the function predicting the probability through a maximum likelihood estimation (MLE), as required for the non-linear logistic model (Verbeek 2017: 220; Wooldridge 2015: 615).

$$P(Y_i = 1) = \frac{e^{\beta_0 + \beta_i x_i}}{1 + e^{\beta_0 + \beta_i x_i}} \overset{MLE}{\Longrightarrow} \hat{p} = \frac{e^{\hat{\beta}_0 + \hat{\beta}_i x_i}}{1 + e^{\hat{\beta}_0 + \hat{\beta}_i x_i}} \tag{2}$$

To avoid an additional log-transformation to interpret the results, the logit of the conditional probability that the outcome variable equals 1 over the probability that it equals 0 (the so-called logit of the odds) can be predicted with the logistic regression equation (3) below.

$$Logit(odds) = \frac{P(Y_i = 1)}{1 - P(Y_i = 1)} = \beta_0 + \beta_i x_i \tag{3}$$

Based on these conditions, the full model used to estimate the odds of being food secure (fies = 1) based on the predictor variables is as specified in **Model 2**:

***Model 2**: Determinants of food security*

$$\begin{aligned} logit(food\ secure) &= \beta_0 + \beta_1 type\_respondent_i + \beta_2 age_i + \beta_3 hhhead\_gender_i + \beta_4 hh\_decide_i \\ &+ \beta_5 hhhead\_size_i + \beta_6 hhhead\_educ_i + \beta_7 hh\_wealth_i + \beta_8 distance_i \\ &+ \beta_9 frequency_i + \beta_{10} fish\_species_i + \beta_{11} fish\_whole_i \end{aligned}$$

A multiple regression logit technique is the best fitting for this type of analysis, as it allows to obtain accurate predictions of the probabilities that the two possible outcomes occur. Furthermore, it has been used in several scientific publications investigating the determinants of food security (Bashir, Schilizzi & Pandit 2012). An additional advantage of using a logit model is the relatively flexible conditions needed for the model to predict the outcomes. Indeed, unlike linear regressions, logit regressions do not require a normal distribution or homoskedasticity of the residuals (Hua, Choi & Shi 2021). The main requirements are the presence of a categorical outcome variable, the independence of observations, and no perfect collinearity. Despite confirming the absence of multicollinearity, the tests in **Appendix D** and the stepwise-modeling approach of the results chapter show the goodness-of-fit of the final model, as will be discussed further in the robustness checks section.

3.4 Limitations

Although the dataset from the midline survey provides a satisfactory number of observations with nearly 2000 individuals, as well as a very broad set of questions that allow for various options to develop the necessary variables, some data limitations need to be acknowledged. First, the data were collected within the context of the PADM project that specifically targets regions in which freshwater aquaculture is already present or that are suited for aquaculture development. This raises the question of whether the data sample is representative of the population, given the likely presence of local characteristics in favor of small-scale rural aquaculture. For instance, in terms of the acceptability of aquaculture production for producers, market infrastructure or the knowledge about fish farming are probably more developed in these areas than in other regions of Madagascar. The same can be said for the importance of fish when it comes to dietary intake, as individuals in these regions might have the habit to consume fish as it is available on the markets and because they are more aware of the benefits of consuming it compared to other areas. Nevertheless, the dataset used for the analyses is considered to be reliable, as the sample should be a good representation of the population in the six target regions of this case study. Indeed, the sample design aimed to randomly survey different types of individuals that are linked to the fish markets, without being necessarily involved in the production processes (Kleemann & Semrau 2022).

The second shortcoming of the data structure is related to the absence of a longitudinal panel that covers the same individuals over time, as respondents were selected at random in both survey waves. In comparison to cross-sectional data, a panel dataset allows to estimate robust cause-effect relationships between the respondents' characteristics and their fish income (if applicable) and food security statuses over time. Nonetheless, with the available cross-sectional data constrained to the year 2021 and the availability of much information about the respondents, the analyses allow for the study of associations between the independent variables and the outcome variable for the determinants of fish income, and the prediction of the variables mostly implicated in a higher probability of respondents' being food secure for the logistic model. Therefore, the results of the analyses are considered to be representative of the six regions of interest in the period covered by the survey.

Next to data-specific limitations, there are also shortcomings related to the methods used for the analyses. Concerning the multiple linear regression, the assumptions that need to be met are very strict and are not all respected in the context of the analysis. Indeed, the normality and the homoskedasticity assumptions of the distribution of the errors are not fulfilled, thus questioning the power of the results (Backward 2012). However, this is not unusual for data coming from real-world data collection, as the reality is more complex and does not follow the simple linear relationships suggested by the model. The WLS estimation method is still the best approximation to reality based on the available data, given that the required manipulations have been carried out to account for the non-compliance with the MLR assumptions. Concerning the binary logistic regression, the results need to be analyzed carefully as well, given that compared to a continuous outcome variable a dummy dependent variable loses important information, making logistic regressions rather sensitive to specification errors (World Bank 2005). Moreover, as shown in **Appendix D** the predictive power of the model cannot be considered very large, as it predicts with only 64% accuracy. This is rather low compared to other similar analyses but is linked to the quality of the available data (Bashir, Schilizzi & Pandit 2012). The stepwise modeling specification that can be found in the results section shows that the final model used in the logistic analysis is the best one that could be developed with the available data.

Finally, concerning the general limitations of the study, it must be acknowledged that although the dataset provided a broad set of questions allowing to develop many variables that are considered key in the literature, other proxies related to health, psychology, climate, or biodiversity could not be constructed and included in the models. Despite these unobserved factors influencing the outcome variables for which the models cannot account, the econometric analyses can be considered to have a high degree of internal validity. Indeed, the case study is characterized by an in-depth understanding of the reality of the determinants of fish income for the different types of aquaculture producers and of food security for the population living in the six regions of interest in Madagascar (Creswell 2014: 43). Clearly, the detailed and context-specific findings are rather difficult to generalize across time and space, given that local characteristics always play important an important role. Nevertheless, external validity can be ensured thanks to the fact that the research questions that this study is investigating are rather classic in the field of development economics. Similarly, the quantitative methods adopted in this thesis are generally accepted in econometrics to conduct these types of analyses: several quantitative cross-sectional studies used linear regressions for continuous dependent variables and logistic regressions when the outcome variable was categorical or a dummy (Assefa 2018; Bashir, Schilizzi & Pandit 2012; Gebre 2012; Gonzalez Parrao et al. 2021; Iruo et al. 2018; Tuyen 2015), supporting the idea that the findings can be useful for the comparison with other in-depth quantitative case studies of rural small-scale aquaculture and its relationship with human well-being.

4 Results & Discussion

This chapter aims to present the results of the quantitative analyses and place them within a wider context. Given the two different types of analysis the section is split in two and first discusses the results of the determinants of fish income and then the findings related to the determinants of food security. Both sub-chapters follow the same structure: to begin, the descriptive results are displayed to give an overview of the samples' characteristics, then the empirical results and a review of the robustness checks of the final models are presented, and finally the findings are discussed according to previous research, academic theories, and information from the PADM project.

4.1 Determinants of Fish Income

I Descriptive Results

The sample is composed of a total of 492 observations. From **Table 3** it is visible that approximately 69% of fish farmers are involved in integrated rice-fish production, which is reasonable seen that this practice was targeted from the PADM project in four out of six regions. Accordingly, only one-third are involved in a semi-intensive production system. In terms of age, aquaculture farmers are generally in their productive age with the average being around 45 years. When it comes to gender dynamics, it is visible that aquaculture practices in the six regions are dominated by men, who cover more than 80% of the total sample, which is in line with worldwide trends in the aquaculture sector (Iruo et al. 2018). The household size distribution varies greatly between one person per household to 15 family members, highlighting that there are great differences among respondents. When it comes to education, **Table 3** shows that fish farmers in the area are generally educated, given that more than 65% have a secondary or higher-level degree. Concerning fish farming experience, the summary statistics reveals that there are some aquaculture farmers with almost a lifetime experience, but with a mean of approximately 7 and a median of 5, most fish farmers have only a moderate number of years of experience in the sector. When it comes to structural conditions related to fish farming, the distance from the closest selling point has a high degree of variability among producers, but **Table 3** shows that most are rather close with an average of 23 minutes walking distance, and a median of 10 minutes. With more than 93% of the total sample, it is also visible that almost all fish farmers own the land on which they engage in aquaculture production. More specifically related to the type of production, **Table 3** reveals that less than one-third of producers adopt a polyculture approach to production. Finally, concerning the two price measures of yearly net fish income and yearly fish feed costs, they were logged to normalize the high variability among fish producers. Indeed, fish income ranged between 20'000 and almost 44 million Ariary (MGA), while the total costs related to feed stretched from zero to more than 31'000 Ariary (MGA).

***Table 3**: Summary statistics of the determinants of fish income.*

Variable	Frequency	Percentage	Mean	Median	St. Dev	Min	Max
Fish income			13.4	13.26	1.5	9.9	17.6
Type of producer			-	-	-	-	-
Pond	117	23.8%					
Rice-fish	339	68.9%					
Cooperative	36	7.3%					
Age of producer			45.5	45	13.0	20	72
Age squared			168.8	99.04	174.2	0.002	678.5
Gender of producer			0.8	1	0.4	0	1
Male	398	80.9%					
Female	94	19.1%					
Household size			5.3	5	2.2	1	15
Education of household head			0.7	1	0.5	0	1
Primary or lower	171	34.8%					
Secondary or higher	321	65.2%					
Farming experience			7.3	5	7.0	1	41
Distance			23.4	10	31.6	0	180
Land ownership			0.9	1	0.2	0	1
Landowner	460	93.5%					
Otherwise	32	6.5%					
Fish culture			0.3	0	0.5	0	1
Polyculture	146	29.7%					
Monoculture	346	70.3%					
Fish feed costs			8.0	10.59	5.7	0	17.3

II Regression Outputs & Robustness Checks

Table 4 shows the results of the WLS estimation of the multiple linear regression, reporting the variables' coefficients, statistical significance levels, as well as other formal statistics. As can be seen in the table, the analysis was conducted in four steps, adding different groups of variables each time to ensure the reliability of the coefficients and significance levels. Models (2) to (4) gradually expand model (1) by adding demographic characteristics, socio-economic factors, and aquaculture production characteristics. Model (4) is therefore the final model concretely analyzed and discussed in the following section. The stepwise modeling approach indicates that upon adding additional independent variables to the model, the signs and significances of the variables previously included do not change significantly. The goodness-of-fit statistics in **Table 4** reveal that the proportion of the sample variation in fish income explained by the final model equals 52% (R-squared), and 51% when the R-squared is adjusted, remaining constant through the different steps of the models' specification, thus showing the robustness of the final model. Similarly, the residual standard errors remain small over the different models, and the F-statistics specifying whether the variables are jointly significant to explain the dependent variable remains significant at the 1% level between models (1) and (4).

To further ensure the robustness of the results several verification operations were carried out. First, the assumptions that are needed to conduct a multiple linear regression analysis were tested for the final model. **Appendices C2** and **C4** display the Durbin-Watson autocorrelation test and the Variance Inflator Factor (VIF) test for multicollinearity, clearly demonstrating that these two assumptions hold for model (4). Nevertheless, **Appendix C1** presents the Breusch-Pagan test of homoskedasticity of the errors, as well as a visual QQ-plot representation, showing that the homoskedasticity assumption does not hold for model (4). Similarly, **Appendix C3** presents the visual and formal tests for the normality assumption of the distribution of the errors, and particularly the result of the Shapiro-Wilk test reveals that the normality assumption is not given in model (4). Still, the line displayed in the QQ-plot roughly follows the 45° line despite some deviation in the extremes, suggesting that the residual's distributions can be considered close to following a normal distribution. Finally, an alternative model specification is presented in **Appendix C5** to check the robustness of model (4). **Table 13** shows that by replacing the dummy variable for the household head's education level with a 5-level categorical variable, the overall results do not significantly change. Despite pointing to the particular importance of education levels exceeding the secondary level, the sensitivity analysis provides further evidence for the goodness-of-fit of model (4).

***Table 4**: WLS regression output of the determinants of fish income.*

	Dependent variable: Fish income			
	(1)	(2)	(3)	(4)
Type of producer (ref = pond)				
Rice-fish	**-0.79***** (0.12)	**-0.80***** (0.12)	**-0.77***** (0.13)	**-0.45***** (0.12)
Cooperative	**2.48***** (0.16)	**2.53***** (0.17)	**2.67***** (0.18)	**2.31***** (0.20)
Age of producer		0.004 (0.004)	0.003 (0.004)	0.005 (0.004)
Age squared		-0.0003 (0.0003)	-0.0004 (0.0003)	-0.0001 (0.0003)
Male		**0.25*** (0.13)	**0.25*** (0.13)	**0.22*** (0.13)
Household size		0.01 (0.02)	0.01 (0.02)	-0.002 (0.02)
Education of household head			**0.30***** (0.11)	**0.32***** (0.11)
Farming experience			**0.02**** (0.01)	**0.02**** (0.01)
Distance			**-0.004**** (0.002)	**-0.003**** (0.002)
Landowner				-0.10 (0.20)
Polyculture				**0.33***** (0.11)
Fish feed costs				**0.09***** (0.01)
Constant	**13.78***** (0.10)	**13.44***** (0.26)	**13.21***** (0.29)	**12.21***** (0.34)
Observations	492	492	492	492
R^2	0.53	0.52	0.49	0.52
Adjusted R^2	0.53	0.51	0.48	0.51
Residual Std. Error	1.30 (df = 489)	1.31 (df = 485)	1.32 (df = 482)	1.33 (df = 479)
F Statistic	279.90*** (df = 2; 489)	86.95*** (df = 6; 485)	51.72*** (df = 9; 482)	38.60*** (df = 12; 479)
Note:				*p < 0.1; **p < 0.05; ***p < 0.01

III Interpretation & Discussion

Overall, eight of the twelve estimated parameters appear to be significantly related to the outcome variable. First, it is interesting to note that compared to being a pond aquaculture farmer, individuals involved in rice-fish farming earn on average 45%[7] less income derived from fish. This finding is not necessarily unexpected, but it needs contextualization. Indeed, on one hand the idea was that rice-fish culture improves farm productivity thanks to integrated resources management, and the fewer necessity of fish feed, fertilizers and pesticides, accumulates natural and social capital of rice-fish farmers and increases total incomes (Bentz et al. 2023; Dey et al. 2010; Edwards 2000: 1). On the other hand, being a sophisticated production system, integrated rice-fish culture can also involve relatively high operational costs and requires a certain level of skills, two characteristics that can hinder its adoption and that could translate into less profitability (Bentz et al. 2023; Frei & Becker 2005). More concretely related to the case study, the lower fish income could be explained by the fact that integrated rice-fish farmers face difficulties in commercializing their fish, mainly because of thefts and climatic shocks that impacted the yields (Bentz et al. 2023). In addition to this, the productivity of rice-fish aquaculture has a high degree of variability but with 76-1215 kg of fish per hectare it is generally low compared to the productivity of the other two production practices. However, a limitation of the analysis needs to be pointed out, as focusing on fish income is not a good evaluation of the economic benefits of adopting integrated rice-fish farming, given that no information about harvest quantities and income from rice production are included in the analysis. Given the two different income sources for aquaculture farmers, it is likely that the results would have looked different (Bentz et al. 2023; Finegold 2009: 359-360; Frei & Becker 2005).

When it comes to the finding concerning cooperative-based aquaculture compared to individual pond aquaculture, the 231% higher fish income suggests that being part of a cooperative is highly profitable. The reason is that the extension services provided by this economic system are very beneficial for production and commercialization purposes, as suggested by research in this field. The strong magnitude of the result can be explained by the global organization of *Tilapia de l'Est*'s value-chain that increases the profitability of production. Indeed, TDE is involved in fingerling production, technical skills support, entrepreneurial strategy development, and the improvement of commercialization processes (Rafalimisy et al. 2023). This approach not only

[7] The interpretation of the coefficients needs a transformation, given that fish income is logged. For log-lin relationships, one unit change in the independent variable changes the dependent variable by the explanatory variable's coefficient, multiplied by 100, and expressed in percentage (coefficient: $\beta_1 X$ > interpretation: $100 \times \beta_1\%$). For log-log relationships, which will be the case when interpreting the costs of fish feed, one unit change in the independent variable is associated with a change in the outcome variable by the explanatory variable's coefficient expressed in percentage (coefficient: $\beta_1 X$ > interpretation: $\beta_1\%$).

creates several advantages related to reduced costs and easier access to markets but also increases profitability thanks to the adoption of a semi-intensive production system based on formulated fish diets that increases productivity while respecting the farmers' socio-economic constraints (Rafalimisy et al. 2023). This finding suggests that the direct income link discussed in the literature review is present in this case study.

Closely related to production intensity, **Table 4** reveals that spending one Ariary more on fish feed is associated only with 0.09% higher fish income at the 1% level, indicating that the two variables are positively related, and that fish feed does not appear to be an important determinant of fish income. This is interesting because fish feed costs usually represent a large part of investments, with Lhoste et al. (2009: 1577) suggesting they cover more than 50% of total costs in intensive aquaculture. The hypothesis in this regard was not conclusive, as more feed costs could be associated with higher productivity and higher incomes, or with excessive costs that cannot be compensated with the income derived from fish (Burns et al. 2014; Edwards 2000: 2). The small magnitude of the coefficient is an indication that the benefits derived from adding complete diets are positive but not large, suggesting that the magic formula is to adopt the "right" quantity increasing productivity without having to face excessive costs. In the case of TDE, the technical production support probably contributes to a balanced use of fish feed for production, thus maximizing fish yields.

Another relevant factor to discuss is the adoption of polyculture to farm fish. Indeed, adopting a polyculture is associated with 33% higher fish income than producing in a monoculture, resulting in an important determinant of fish income. This is interesting because this topic is still debated in research, with some scholars suggesting up to 40% higher fish yields with polyculture, and others proposing no effect on fish yields (Frei & Becker 2005; Lhoste, Baudoux & Vall 2009: 1602). In this case study, the analysis suggests that adopting a polyculture is attractive, which is probably related to the synergistic characteristics of this production practice in terms of the complementarity of feeding regimes. Indeed, it is considered that the combination of Nile tilapias, a micro-herbivorous column feeder, with common carps, an omnivorous bottom feeder, can be very successful to increase fish yields (Frei & Becker 2005).

When it comes to the two structural characteristics of landownership and distance from the closest selling point, the regression results in **Table 4** have to be interpreted carefully. Indeed, concerning the former, it appears that the suggested sign of the variable is in line with previous findings, namely that farmers owning their land are associated with higher incomes (Burns et al. 2014; Kaliba et al. 2007; Tuyen 2015; World Bank 2005). However, the results are not significant, not allowing to make robust conclusions about the role of land ownership in this sample. A possible reason for the missing significance could be that the proportion of aquaculture farmers owning their land is very high (almost 94%), which could inflate the results by suggesting that ownership is not a relevant determinant of income in this case. Concerning the distance from the closest market, the results show that adding one more minute of walking distance is associated with 0.3% lower fish incomes. This result indicates that distance has the expected relationship with income, given that the higher the isolation, the more difficult the access to markets (Cojocaru et al. 2022; World Bank 2005). Nevertheless, it is a weak determinant of fish income, and the reason could be the selection bias of the data collection process, given that most aquaculture farmers surveyed had to be reached relatively easily, and are thus already well-connected to their corresponding markets.

Concerning socio-economic factors, education turns out to be an important determinant of fish income, being significant at the 1% level. Having a secondary degree or higher is associated with 32% higher fish income than individuals with only a primary school degree or none at all. This result is in line with previous research that found similar robust relationships (Iruo et al. 2018; Tuyen 2015). This finding suggests that educated households might tend to adopt improved fish farming techniques and make more informed decisions about business development because they understand their production processes better than uneducated farmers (Béné et al. 2016; Iruo et al. 2018). On the other hand, one additional year of experience is associated only with on average 2% higher fish incomes and is statistically significant at the 5% level. As expected, experience is positively related to income generation, similar to other findings, but the magnitude is rather low. However, this is nothing new, given that Iruo et al. (2018) found that more years of experience do not necessarily coincide with the adoption of more productive production systems, which are usually associated with higher incomes. Furthermore, the results suggest that there is not much difference between aquaculture farmers with much or little experience, maybe suggesting that the role played by partners, trainers, or the cooperative can compensate for the lack of experience of some farmers and contribute to the generation of high incomes.

When it comes to the demographic characteristics of the respondents, **Table 4** shows that only the gender of the respondent is statistically significant at the 10% level, with men being associated with 22% higher fish income. This is in line with most research and is supposed to be related to the fact that women face sharper conditions for employment in the aquaculture sector (Iruo et al. 2018; World Bank 2005). Indeed, without wanting to generalize, women are usually employed in less-profitable nodes of the fish production chain, they tend to receive lower returns and fewer benefits compared to men, and they face a larger degree of labor discrimination (Gonzalez Parrao et al. 2021; Iruo et al. 2018; World Bank 2005), which would explain the comparatively lower fish incomes. This finding implies that it is important to integrate women better into the production processes and adopt a gender focus when it comes to training and business development. Concerning the other important demographic variables age and age squared, **Table 4** shows that they are respectively positively and negatively related to the outcome variable, as expected (Assefa 2018; Gebre 2012). However, their magnitudes are low, and they are not statistically significant. This is probably related to the fact that with increasing age, the argument is that fish farming experience increases, thus leading to higher incomes. But given that years of experience do not appear as an important determinant of fish income, the relevance of age is not necessarily given. Similarly, the variable household size has the expected direction, with the negative sign suggesting that the larger the household, the lower the perceived income (Iruo et al. 2018). However, the result is not significant, meaning that there is no robust interpretation. The reason for this could be that this variable does not give information about the dependency ratio of the household (Tuyen 2015). This could indeed have given a more informative picture of the household situation, given that a large family with a high proportion of working members would not automatically be associated with lower incomes.

To conclude this analysis, the key **determinants of fish income** in this case study appear to be related to the **extension services** provided by the cooperative-based production system as they improve the profit margin of aquaculture farmers and support them in their production process. Furthermore, the fact of adopting a **fish polyculture** approach combining common carps and Nile tilapias resulted as a significant determinant of higher fish incomes, probably thanks to the synergistic interactions. Finally, fish incomes are positively related to the **education levels** of aquaculture farmers, with a higher degree being associated with a better understanding of production processes.

4.2 Determinants of Food Security

I Descriptive Results

The sample for the binary logistic regression is composed of a total of 1981 observations. Among these, slightly more than 60% are composed of consumers that are not involved in fish farming or are part of the value-chain. Respectively, fish farmers represent roughly 30% of the sample, and VCA less than 10%. The age of the respondents varies greatly, with the youngest aged 17 and the oldest being 83 years old. The mean and median ages are concentrated around 41-42 years, suggesting that the majority of the sample is in the productive age. Concerning household characteristics, **Table 5** shows that while males are the dominant household heads with more than

86% of the total sample, household decisions related to food encompass females (almost 50%), or both parents (43%), suggesting a rather gendered division of responsibilities within the household. Similar to the sample including only fish farmers, the household sizes vary between 1 and 15 members, but given that the mean and median are very close together most households are composed of no more than 5 individuals. Furthermore, with almost two-thirds having a secondary schooling level or higher, and one-third with primary or no education level, the sample is composed of generally well-educated respondents. When it comes to the self-perceived wealth status compared to other households, only 8% consider themselves to be better-off. Indeed, most respondents reported fitting in the average or lower wealth level of their area. Concerning structural conditions related to fish consumption, distance indicates that respondents suffer from a high degree of variability in their access to the closest fish selling point, given that while some live at the selling spot, others need up to 4 hours to be able to purchase fish. However, with a mean of around 20 minutes and a median of 10 minutes, most individuals have rather good access to fish products. **Table 5** also gives information about the frequency and type of fish consumption. First, it results that many respondents consume fish rather often, with more than 65% of the sample consuming fish on a weekly or daily basis. Second, the last fish species consumed by the surveyed individuals ranges between freshwater and seawater fish: indeed, around 30% of the fish consumed comes from the ocean, 48% are tilapias, and 20% are carps. Finally, the summary statistics in **Table 5** shows that most respondents consume the whole fish, including bones, heads, and guts, as approximately 20% consume only the valuable parts.

***Table 5**: Summary statistics of the determinants of food security.*

Variable	Frequency	Percentage	Mean	Median	St. Dev	Min	Max
Food security			0.6	1	0.5	0	1
Food insecure	869	43.9%					
Food secure	1112	56.1%					
Type of respondent			-	-	-	-	-
Consumer	1193	60.2%					
Fish farmer	611	30.8%					
VCA	177	8.9%					
Age of respondent			42	41	12.5	17	83
Gender of household head			0.1	0	0.3	0	1
Male	1712	86.4%					
Female	269	13.6%					
Who decides on food matters			-	-	-	-	-
Male	145	7.3%					
Female	984	49.7%					
Both	852	43%					
Household size			4.9	5	1.9	1	15
Education of household head			0.6	1	0.5	0	1
Primary or lower	698	35.2%					
Secondary or higher	1283	64.8%					
Household wealth			0.1	0	0.3	0	1
Poorer or same	1821	91.9%					
Better-off	160	8.1%					
Distance			19.7	10	26.9	0	240
Frequency			0.9	1	0.2	0	1
Rarely	680	34.3%					
Frequently	1310	65.7%					
Fish species			-	-	-	-	-
Ocean	623	31.4%					
Carps	406	20.5%					
Tilapias	952	48.1%					
Fish consumption			0.8	1	0.4	0	1
Parts	373	18.8%					
Whole	1608	81.2%					

II Regression Outputs & Robustness Checks

Table 6 shows the results of the binary logistic regression, reporting the variables' coefficients and odds ratios, the statistical significance levels, and other formal statistics. Also in this case, the analysis was conducted by adding different groups of variables in four steps. Models (2) to (4) expand model (1) with additional variables related to demographic characteristics, socio-economic factors, and fish consumption characteristics. The stepwise modeling approach indicates that upon the addition of further predictor variables their signs and significances do not deviate substantially from the previous ones, indicating that the final model is the best-fitting. This is confirmed by the comparative goodness-of-fit measures presented in **Table 6** suggesting that the variables included in the final model improve the previous ones. Indeed, the log-likelihood is a measure telling whether the tested models add more to the explanation of the outcome compared to a model restricted only to a constant, and the decreasing trend from model (1) to model (4) indicates that the final model fits the data best (Verbeek 2017: 221). Similarly, the decreasing values of the Akaike Information Criterion (AIC) confirm that the final model fits the data better compared to the previous ones, thus explaining the greatest amount of variation using the fewest possible independent variables. Moreover, the McFadden R-squared reveals that by extending the models, the additional variables capture important factors influencing food security outcomes (Verbeek 2017: 221), given that the value in model (4) is eight times higher than in model (1).

To further ensure the robustness of the analysis some tests were carried out. To make sure that the formal requirements hold, **Appendix D1** shows the VIF results proving that multicollinearity is not a problem in model (4). Concerning goodness-of-fit of the model there is no single approach, but a variety of ways to assess the fit of a logistic model against actual outcomes (Bashir, Schilizzi & Pandit 2012). **Appendix D2** presents the confusion matrix of model (4) that allows to calculate different measures of the predictive power of the final model to evaluate its performance. **Table 15** reveals that the model is not able to correctly classify all observations of the dependent variables, as the false positive and false negative represent a relatively large share of the total predicted values. This is also reflected in the calculation of the model accuracy, which reveals that the model correctly predicts only 64% of the observations. However, the predictive power of the model depends on the quality of the dataset and needs to be interpreted carefully because a high percentage does not necessarily equal a strong explanatory power (Wooldridge 2015: 618). Finally, the sensitivity analysis that can be found in **Appendix D3** confirms the same conclusion, given that the alternative specification of the "household head education level" variable from a dummy to a 5-level categorical variable, which is a strong predictor in terms of magnitude and significance, does not change the overall results significantly.

***Table 6**: Logistic regression output of the determinants of food security.*

	Dependent variable: FIES				
	(1)	(2)	(3)	(4)	Odds ratio
Type of respondent (ref = consumer)					
Fish farmer	0.26***	0.21**	0.12	0.07	1.07
	(0.10)	(0.11)	(0.11)	(0.12)	
VCA	**0.55*** **	**0.54*** **	**0.43** **	**0.33* **	**1.39**
	(0.17)	(0.17)	(0.17)	(0.18)	
Age of respondent		**0.01* **	**0.01** **	**0.01** **	**1.01**
		(0.004)	(0.004)	(0.004)	
Female as household head		**-0.56*** **	**-0.49*** **	**-0.45*** **	**0.64**
		(0.14)	(0.14)	(0.15)	
Who decides on food matters (ref = male)					
Female		**0.38** **	**0.37** **	**0.33* **	**1.39**
		(0.18)	(0.19)	(0.19)	
Both		0.21	0.18	0.09	1.09
		(0.18)	(0.19)	(0.19)	
Household size		-0.05*	-0.02	-0.02	0.98
		(0.03)	(0.03)	(0.03)	
Education of household head			**0.71*** **	**0.70*** **	**2.00**
			(0.10)	(0.10)	
Household wealth			**1.52*** **	**1.42*** **	**4.12**
			(0.24)	(0.24)	
Distance			-0.002	-0.002	1.00
			(0.002)	(0.002)	
Frequency				**0.48*** **	**1.62**
				(0.10)	
Fish species (ref = ocean)					
Carp				**0.74*** **	**2.11**
				(0.15)	
Tilapia				**0.31*** **	**1.36**
				(0.11)	
Consumption of whole fish				**-0.33** **	**0.72**
				(0.13)	
Constant	**0.12** **	**-0.13**	**-0.82*** **	**-1.04*** **	**0.35**
	(0.06)	(0.24)	(0.27)	(0.30)	
Observations	1981	1981	1981	1981	
Log Likelihood	-1350.78	-1339.15	-1277.72	-1255.58	
Akaike Inf. Crit.	2707.56	2694.30	2577.43	2541.17	
McFadden R squared	0.01 (df = 3)	0.01 (df = 8)	0.06 (df = 11)	0.08 (df = 15)	

Note: $^{*}p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.01$

III Interpretation & Discussion

Table 6 reveals that ten of the fourteen estimated variables are significant at least at the 10% level, thus being important predictors of food security. As discussed in the methods section, the binary logistic regression's interpretation is different from the one for linear regression results. Indeed, the coefficients only give information about the direction of the relationship with the binary outcome and their significance (Wooldridge 2015: 617-618). To say something about the magnitudes, the odds ratios need to be considered: they represent the ratio of the odds that the outcome will be positive (being food secure) given the predictor variables, compared to the odds that the same outcome occurs in the absence of the predictors (Torres-Reyna 2014).[8]

When it comes to the first predictor variable indicating the type of respondents, the results show that, despite the low magnitude, belonging to the group of aquaculture farmers is not a significant predictor of being food secure. The non-significance of the result could be because aquaculture farmers are a very heterogeneous group, as discussed in the results part of the determinants of fish income, which prevents from making general conclusions about the relationship between being a fish farmer and their food security status. Another interpretation of this result could be that the consumption pathway does not hold in this case study. The hypothesis was that fish farmers have easier access to fish compared to consumers and that they, therefore, consume relatively more fish and are associated with a better food security status (Assefa 2018; Gonzalez Parrao et al. 2021). However, this link is not proven in research, as other scholars consider that aquaculture farmers follow the income pathway like other individuals: they sell their products to generate income and buy additional staples or other foods (Béné et al. 2016; Gonzalez Parrao et al. 2021).

On the other hand, **Table 6** shows that belonging to VCA is significantly related to a positive outcome at the 10% level, with a 39% increase in the likelihood of being food secure compared to consumers. This result can be explained by the fact that jobs in the fish value-chain are generally more productive, higher value-added, and full-time jobs compared to fish farming, which is often an ancillary activity. Furthermore, when cross-checking the sample, it becomes evident that the respondents considering themselves as better-off compared to other households are often VCA. This strengthens the supposition that value-chain actors are associated with a better food security status because they are generally wealthier and can purchase high-quality and nutritious food (Gonzalez Parrao et al. 2021). Moreover, the results show that wealth is the predictor of food

[8] Concretely, this means that when the odds are larger than one, the value is read as (value – 1) increase in odds, and if it is smaller than one then it is read as (1 – value) decrease in odds (Torres-Reyna 2014).

security with the largest magnitude, as those that consider themselves to be better-off have a 312% increase in their likelihood of being food secure compared to those that believe to have the same or lower wealth level. This finding is significant at the 1% level and shows that the perception of an individual's economic position in society is associated with higher food security levels, as suggested by scientific research considering that asset possession and wealth are positively associated with food security (Assefa 2018; Bashir, Schilizzi & Pandit 2012; Gebre 2012).

At this point, it is interesting to look at the distributional pathway. When looking at who oversees the household, the results suggest that households headed by women have 36% less likelihood of being food secure compared to households headed by men, this finding being significant at the 1% level. This result is in line with previous research considering that men are more engaged in income-generating activities than women (Gebre 2012). However, another reason for this outcome could be related to the fact that female-headed households are not so because of choice, given that traditionally it is men who are in charge of the family, but because of necessity. The supposition is that female-headed households face unfavorable economic and social conditions influencing their food security status, such as being widows, separated, or divorced. When looking at who makes food-related decisions, the regression output reveals that when women make decisions independently, the likelihood of being food secure increases by 39% compared to when men are making them. Taking these decisions together does not result in any significant result, although the odds ratio suggests a positive relationship. This is in line with research that considers that a greater degree of control exercised by women over family income results in a higher proportion spent on food (Gonzalez Parrao et al. 2021; Kawarazuka & Béné 2010), thus highlighting the important role played by women in this regard.

In this context, the household size matters as well, given that the literature suggests that the larger the household, the likelier it is to be food insecure (Assefa 2018; Gebre 2012). Although the results point to this relationship, they are not significant, and a robust interpretation is not possible. Similar to the previous analysis, the dependency ratio would probably have given better information about the relationship with food security outcomes. When it comes to age, the results in **Table 6** suggest that one more year is associated with only a 1% increase in the likelihood of being food secure, confirming the idea that the relationship with food security is mixed: adults are more likely to be food secure compared to children, but elderlies are weaker and thus more prone to food insecurity (Assefa 2018; Gebre 2012). This finding is significant at the 5% level and suggests that age is not an important predictor of food security outcomes in this sample.

When it comes to socio-economic factors, an important predictor variable is education, given that when the household head has a secondary education level or higher, the likelihood of being food secure increases by 100% (at the 1% level of significance) compared to the individuals having only a primary education level or none at all. This finding is in line with previous research, as food insecurity has always been found to be concentrated in more illiterate individuals, suggesting that a higher level of education allows people to make well-informed decisions impacting food security positively (Assefa 2018; Bashir, Schilizzi & Pandit 2012; Gebre 2012).

Concerning fish consumption patterns, a high frequency of fish consumption, increases the likelihood of being food secure by 62% compared to individuals consuming fish only on a monthly or yearly basis. Being significant at the 1% level, the frequent consumption of fish appears as a significant predictor of food security. This finding insinuates that fish can contribute to positive food security levels, as suggested by the literature. Indeed, it is considered that fish provides consumers with high-quality proteins, fatty acids, and micronutrients that are usually missing in carbohydrate-based diets (Bashir, Schilizzi & Pandit 2012; Cojocaru et al. 2022; Kawarazuka & Béné 2010). However, the interpretation is not as straightforward, as the positive relationship could also be because individuals being better-off financially have the means to frequently consume fish, thus being associated with a higher nutritional status. It is evident that the relationships are complex and determined by many factors, but in either case, fish consumption seems to play a non-indifferent role in improving food security outcomes.

A similar carefulness in the interpretation is needed for the species and parts consumed. Indeed, concerning the former, the output in **Table 6** reveals that the consumption of a whole fish is associated at the 5% level with a decrease in the likelihood of being food secure by 28% compared to the individuals consuming only valuable parts of fish. This finding is unexpected, as scientific research considers that eating small whole fish greatly improves the micronutrient intake for consumers, thus supporting better food security outcomes (Kawarazuka & Béné, 2010). However, the message of these findings is probably rather that the food-insecure population consumes whole fishes because they cannot afford large fishes or valuable fish parts. This interpretation could also be in line with the findings related to the fish species consumed: consuming freshwater fish coming from local markets increases the likelihood of being food secure at the 1% level, compared to individuals consuming seawater fish species. Indeed, the consumption of carp increases the likelihood of being food secure by 111% and the consumption of tilapias increases it by 36% compared to ocean fish. On one hand, this could indicate that locally-produced fish contributes to food security, as previously discussed, but on the other, it could also signify the reverse: food-secure individuals can afford fresh and more expensive local fish, while the food-insecure population consumes the usually salted, dried and cheaper ocean fish (Cojocaru et al. 2022). This interpretation makes even more sense when it is considered that carps are the most expensive fish species in this sample, as they are traditionally consumed mostly for special occasions. Finally, contrary to the findings in research (FAO 2006; World Bank 2005), the results show that distance is neither significant nor presents any relevant magnitude. This is probably due as well to the fact that the data collection process involuntarily selected respondents that are well-connected, thus making proximity to markets an unimportant predictor variable of food security in the sample.

To conclude this analysis, the key **determinants of food security** in the population of the six selected regions of Madagascar are related to the relative **wealth** level of respondents, as financial means allow to access nutritious foods. At the same time, a high level of **education** is associated with improved food security outcomes thanks to better-informed individuals, and having **women deciding** on food expenditures also influences food security positively. Finally, although the directionality of the several factors is ambiguous, it seems that the frequent **consumption of fish** is associated with better nutritional outcomes.

5 Conclusion

Poverty reduction and food security have always been priorities on the global development agenda, but research is still inconclusive about the strategies to adopt. Particularly when it comes to food-producing sectors such as agriculture and aquaculture, their potential for contributing to development objectives is generally recognized, but the debate about whether it is more beneficial to focus on industrial-scale or small-scale production systems is still ongoing. In this context, this thesis aimed to shed light on these questions by focusing the analysis on the small-scale freshwater aquaculture sector in Madagascar. Indeed, to make effective policies tackling poverty and food insecurity, it is crucial to understand what factors can improve income generation in the aquaculture sector, and what factors are associated with better nutritional outcomes. By adopting a multiple linear regression, the purpose was on one hand (1) to investigate the determinants of the aquaculture farmers' fish incomes in six regions of Madagascar. On the other hand, the aim was (2) to explore what factors predict a successful food security outcome in the same regions by performing a binary logistic regression, with a specific focus on fish as a source of nutritional value for consumer diets.

Concerning the first research question, the quantitative analysis revealed that higher fish incomes can be generated by being part of a business model providing extension services that reduce costs and increase the profit margin. Moreover, farming fish in a polyculture allowing to take advantage of the synergistic interactions also appeared to be positively related to higher fish incomes. Finally, a higher education level also influenced income positively, as more knowledge translates into informed decisions about the farmers' production processes. Concerning the second research question, the results suggested that a positive food security status is related to the consumers' available income, given the strong relationship of food security with wealth. Furthermore, the role of women in making food-related decisions at the household level appeared as an important predictor for food security as well. Finally, fish consumption and education levels resulted as significant predictors of being food secure, suggesting that better knowledge about the nutritional benefits of fish and diets can influence food security outcomes positively.

There are three important policy implications resulting from these findings. First, there is the need to focus on supporting the development of cooperatives that help aquaculture farmers to have easier access to production inputs and markets, as well as technical support and training for aquaculture and business development. In addition, to ensure more disposable income for food expenditures, it is suggested to strengthen the linkages of aquaculture with the rest of the economy to create a positive spiral of income and employment generation. Second, aquaculture production should focus on integrated systems, such as fish polycultures, to take advantage of natural synergies in terms of feeding strategies and pest management and to reduce additional costs and environmental stresses. Finally, theoretical and practice-based education needs to be supported to ensure that aquaculture farmers can make informed decisions concerning their economic activities and develop the necessary knowledge to adopt the best production practice given their circumstances. Similarly, with education being a significant predictor of food security, strategies improving knowledge about food security and the role of fish in ensuring a healthy and balanced diet should be supported, no matter whether in schools or through awareness-raising campaigns. Particularly concerning this point, a specific focus should be on women, given that they face the sharpest labor market conditions in the aquaculture sector and play an essential role in household food security.

The findings of this thesis should be viewed as a starting point in the study of the relevant factors of fish income generation and food security in the context of rural small-scale aquaculture in the Malagasy Highlands and east coast. Although the empirical results are not exhaustive, they should be incorporated into future research. Indeed, more interdisciplinary research including agronomy, aquatic biology, economics, or health sciences should work together to assess the complex system of interlinkages among the different factors explored in these analyses. More concretely, gender dynamics and particularly the role played by women in the aquaculture sector need further investigation. In addition, more complete information is needed concerning integrated agriculture-aquaculture farming techniques, such as rice-fish culture, as one limitation of this thesis is the missing data about rice crops, which would probably have given another twist to the results. Moreover, it is important to expand this type of economic analysis to nutritional security focusing not only on the quantity of food consumed but on the quality of diets as well. Finally, the results of this thesis suffer from the same cause-effect limitations of many other research papers, highlighting the need to collect longitudinal data to ensure robust causal analyses.

In conclusion, despite the large potential for future research in this field, the findings of this thesis reveal the complexity of the small-scale freshwater aquaculture sector in Madagascar and highlight the importance of adopting a holistic approach to understanding its relationships with food security and poverty reduction. In other words, the results show that there are concrete reasons to believe that small-scale aquaculture has linkages with the rest of the rural economy and is therefore a suited pathway to promote socio-economic development.

References

Agulhas and Somali Current Large Marine Ecosystems Project (ASCLME). (2012). ASCLME National Marine Ecosystem Diagnostic Analysis: Madagascar, United Nations Development Programme.

Ahmed, N. & Turchini, G. M. (2021). The Evolution of the Blue-Green Revolution of Rice-Fish Cultivation for Sustainable Food Production, *Sustainability Science*, vol. 16, no. 4, pp. 1375–1390.

Assefa, B. A. (2018). Factors Influencing the Food Security of Smallholder Farmers in Madagascar, University of Minnesota.

Backward, C. (2012). Ordinary Least Squares Linear Regression: Flaws, Problems and Pitfalls, Available Online: https://lcn.people.uic.edu/classes/che205s17/docs/che205s17_reading_06c.pdf.

Bashir, M. K., Schilizzi, S. & Pandit, R. (2012). The Determinants of Rural Household Food Security in the Punjab, Pakistan: An Econometric Analysis.

Béné, C., Arthur, R., Norbury, H., Allison, E. H., Beveridge, M., Bush, S., Campling, L., Leschen, W., Little, D. & Squires, D. (2016). Contribution of Fisheries and Aquaculture to Food Security and Poverty Reduction: Assessing the Current Evidence, *World Development*, vol. 79, pp. 177–196.

Bentz, B., Randriampeno, T., Nantenaina Fanomezantsoa, P., Mandresilahatra, J., Nomentsoa Ramananjaona, J., Zafimandimby, E., Rafenomanjato, A., Maureaud, C. & Tiambahoaka, C. (2023). Rizipisciculture Sur Les Hautes Terres Malgaches: Manuel de Bonnes Pratiques, Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ).

Brugère, C., Aguilar-Manjarrez, J., Beveridge, M. C. & Soto, D. (2019). The Ecosystem Approach to Aquaculture: 10 Years on – A Critical Review and Consideration of Its Future Role in Blue Growth, *Reviews in Aquaculture*, vol. 11, no. 3, pp. 493–514.

Burns, T. E., Wade, J., Stephen, C. & Toews, L. (2014). A Scoping Analysis of Peer-Reviewed Literature about Linkages between Aquaculture and Determinants of Human Health, *EcoHealth*, vol. 11, pp. 227–240.

Campbell, L. M., Fairbanks, L., Murray, G., Stoll, J. S., D'Anna, L. & Bingham, J. (2021). From Blue Economy to Blue Communities: Reorienting Aquaculture Expansion for Community Wellbeing, *Marine Policy*, vol. 124, no. 104361.

Chen, S., De Bruyne, C. & Bollempalli, M. (2020). Blue Economy: Community Case Studies Addressing the Poverty–Environment Nexus in Ocean and Coastal Management, *Sustainability*, vol. 12, no. 4654.

Cojocaru, A. L., Liu, Y., Smith, M. D., Akpalu, W., Chávez, C., Dey, M. M., Dresdner, J., Kahui, V., Pincinato, R. B. & Tran, N. (2022). The "Seafood" System: Aquatic Foods, Food Security, and the Global South, *Review of Environmental Economics and Policy*, vol. 16, no. 2, pp. 306–326.

Commission de l'Union Africaine. (2015). Agenda 2063: L'Afrique Que Nous Voulons, Available Online: https://au.int/sites/default/files/documents/36204-doc-agenda2063_popular_version_fr.pdf.

Costa-Pierce, B. A. (2008). Epilogue: Aquaculture, Innovation and Social Transformation, *Aquaculture, Innovation, and Social Transformation*, vol. 17, pp. 315–326.

Creswell, J. W. (2014). Research Design: Qualitative, Quantitative and Mixed Methods Approaches, 4th edition.

Desprez, D., Rakotoambinina, S., Andriantsoa, M., Rakotoasimbola, L., Godard, L., Andriniaina, H., Randriarilala, F. & Rakotomavo, D. (2023). Production En Etang Dans La Région Analamanga: Manuel de Bonnes Pratiques, Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ).

Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ). (2022a). Sustainable Aquaculture in Madagascar – Global Programme Sustainable Fisheries and Aquaculture.

Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ). (2022b). Projet d'Aquaculture Durable à Madagascar (PADM) – Composante Du Programme Mondial « Pêche et Aquaculture Durable ».

Dey, M. M., Paraguas, F. J., Kambewa, P. & Pemsl, D. E. (2010). The Impact of Integrated Aquaculture–Agriculture on Small-scale Farms in Southern Malawi, *Agricultural Economics*, vol. 41, no. 1, pp. 67–79.

Djaoui, L. & Hourtoule, M. (2021). Madagascar 2021: L'Émergence Malagasy, Yearbook, LD Media Development, Available Online: https://edbm.mg/wp-content/uploads/2021/08/Yearbook-economique-Madagascar-2021.pdf.

Edwards, P. (2000). Aquaculture, Poverty Impacts and Livelihoods, Overseas Development Institute London.

Ertör, I. & Hadjimichael, M. (2020). Blue Degrowth and the Politics of the Sea: Rethinking the Blue Economy, *Sustainability Science*, vol. 15, no. 1, pp. 1–10.

Filipski, M. & Belton, B. (2018). Give a Man a Fishpond: Modeling the Impacts of Aquaculture in the Rural Economy, *World Development*, vol. 110, pp. 205–223.

Finegold, C. (2009). The Importance of Fisheries and Aquaculture to Development, The Royal Swedish Academy of Agriculture and Forestry, Available Online: https://digitalarchive.worldfishcenter.org/bitstream/handle/20.500.12348/1445/WF_2546.pdf?sequence=1&isAllowed=y.

Food and Agriculture Organization (FAO). (2006). Food Security, Policy Brief, Available Online:

https://www.fao.org/fileadmin/templates/faoitaly/documents/pdf/pdf_Food_Security_Cocept_Note.pdf.

Food and Agriculture Organization (FAO). (2017). The Food Insecurity Experience Scale: Measuring Food Insecurity through People's Experiences, Available Online: https://www.fao.org/publications/card/en/c/2c7ce182-b76d-40bb-9fbe-59ba3c8394fc/.

Food and Agriculture Organization (FAO). (2019). Scaling-Up Integrated Rice-Fish Systems: Tapping Ancient Chinese Know-How, Available Online: https://www.fao.org/3/i4289e/i4289e.pdf.

Food and Agriculture Organization (FAO). (2022). Regional Review on Status and Trends in Aquaculture Development in Sub-Saharan Africa (2020), no. 1232/4.

Frei, M. & Becker, K. (2005). Integrated Rice-fish Culture: Coupled Production Saves Resources, Natural Resources Forum, Wiley Online Library, vol. 29, pp. 135–143.

Gebre, G. G. (2012). Determinants of Food Insecurity among Households in Addis Ababa City, Ethiopia, *Interdisciplinary Description of Complex Systems: INDECS*, vol. 10, no. 2, pp. 159–173.

Gonzalez Parrao, C., Shisler, S., Moratti, M., Yavuz, C., Acharya, A., Eyers, J. & Snilstveit, B. (2021). Aquaculture for Improving Productivity, Income, Nutrition and Women's Empowerment in Low– and Middle–income Countries: A Systematic Review and Meta–analysis, *Campbell Systematic Reviews*, vol. 17, no. 4, pp. 1-95.

Hua, C., Choi, Y. & Shi, Q. (2021). Companion to BER 642: Advanced Regression Methods, vol. 31.

Hughes, A. D. (2021). Defining Nature-Based Solutions within the Blue Economy: The Example of Aquaculture, *Frontiers in Marine Science*, vol. 8, no. 711443.

Iruo, F. A., Onyeneke, R. U., Eze, C. C., Uwadoka, C. & Igberi, C. O. (2018). Economics of Smallholder Fish Farming to Poverty Alleviation in the Niger Delta Region of Nigeria, *Turkish journal of fisheries and aquatic sciences*, vol. 19, no. 4, pp. 313–329.

Joffre, O., Rovahasambarana Irajanahary Ekembahoaka, N., Loberline Ratiarisoa, D. & Borchert, P. (2023). Cadre Stratégique et Juridique de l'Aquaculture à Madagascar: Manuel de Bonnes Pratiques, Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ).

Johnson, R. (2007). The Ecosystem Approach to Aquaculture: An analysis of adaptive governance and management of small-scale coastal shrimp aquaculture in Thailand, Centre for Transdisciplinary Environmental Research, Stockholm University.

Kaliba, A. R., Ngugi, C. C., Mackambo, J. M., Osewe, K. O., Senkondo, E., Mnembuka, B. V. & Amisah, S. (2007). Potential Effect of Aquaculture Promotion on Poverty Reduction in Sub-Saharan Africa, *Aquaculture International*, vol. 15, pp. 445–459.

Kawarazuka, N. & Béné, C. (2010). Linking Small-Scale Fisheries and Aquaculture to Household

Nutritional Security: An Overview, *Food Security*, vol. 2, no. 4, pp. 343–357.

Kleemann, L. & Semrau, F. O. (2022). Unterstützung des Globalvorhabens Für Nachhaltige Fischerei und Aquakultur bei der Midline-Erhebung im Länderpaket Madagaskar, Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ).

Kuznets, S. (1973). Modern Economic Growth: Findings and Reflections, *The American economic review*, vol. 63, no. 3, pp. 247–258.

Lewis, W. A. (1954). Economic Development with Unlimited Supplies of Labour.

Lhoste, P., Baudoux, S. & Vall, E. (2009). Mémento de l'agronome, CIRAD.

Ministère de l'Agriculture, de l'Élevage et de la Pêche. (2020). Deuxième Projet de Gouvernance Des Pêches et de Croissance Partagée Du Sud-Ouest de l'Océan Indien (SWIOFisM) - Cridit IDA 59870 MG, Available Online: https://www.swiofish2.mg/wp-content/uploads/2020/05/AMI-N°01-2020-SNDA-opt.pdf.

Ministère des Ressources Halieutiques et de la Pêche. (2015). Lettre de Politique BLEUE: Pour Une Économie BLEUE, Valorisant Le Travail Des Pêcheurs et Aquaculteurs, Durabilisant La Création de Ses Richesses, et Prenant En Compte Le Bien Être Écologique Des Ressources Halieutiques, Available Online: https://faolex.fao.org/docs/pdf/mad163970.pdf.

Morgan, M., Terry, G., Rajaratnam, S. & Pant, J. (2017). Socio-cultural Dynamics Shaping the Potential of Aquaculture to Deliver Development Outcomes, *Reviews in Aquaculture*, vol. 9, no. 4, pp. 317–325.

Oxford Poverty and Human Development Initiative (OPHI). (2021). Global MPI Country Briefing 2021: Madagascar (Sub-Saharan Africa), Country Briefing October 2021, University of Oxford.

Oxford Poverty and Human Development Initiative (OPHI). (2022). Global MPI Data Tables 2022, Available Online: https://ophi.org.uk/multidimensional-poverty-index/data-tables-do-files/.

Rafalimisy, C. K., Monja, M. T., Ahitantsoa, F., Fuller, M., Mugaas, A. & Tønnesen, J. (2023). Production de Tilapia Du Nil (Oreochromis Niloticus) En Etang Dans La Région Atsinanana: Manuel de Bonnes Pratiques, Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ).

Rakotoambinima, S., Desprez, D., David, G., Bosc, P. & Le Roux, Y. (2009). Caractérisation des environnements écologiques et socio-économiques de la production piscicole continentale à Madagascar, *Les Cahiers d'Outre-Mer*, vol. 248, no. 4, pp. 471–488.

Razafindrakoto, M., Roubaud, F. & Wachsberger, J.-M. (2018). L'énigme et Le Paradoxe: Économie Politique de Madagascar, IRD éditions.

Refaliarison, J. (2023). National Aquaculture Sector Overview Madagascar, Rome: Fisheries and Aquaculture Division, Food and Agriculture Organization (FAO), Available Online:

https://www.fao.org/fishery/en/countrysector/naso_madagascar.

République de Madagascar. (2015). Programme Sectoriel Agriculture, Élevage, Pêche (PSAEP) et Plan National d'Investissement Agricole (PNIAEP) 2016-2020, Available Online: https://faolex.fao.org/docs/pdf/Mad169997.pdf.

Sommet, N. & Morselli, D. (2017). Keep Calm and Learn Multilevel Logistic Modeling: A Simplified Three-Step Procedure Using Stata, R, Mplus, and SPSS., *International Review of Social Psychology*, vol. 30, pp. 203–218.

Soto, D., Aguilar-Manjarrez, J. & Hishamunda, N. (2008). Building an Ecosystem Approach to Aquaculture. FAO/Universitat de Les Illes Balears Expert Workshop. 7-11 May 2007, Palma de Mallorca, Spain, Available Online: https://www.fao.org/3/i0339e/i0339e.pdf#page=125.

Southern African Development Community (SADC). (2016). SADC Regional Aquaculture Strategy and Action Plan (2016-2026), Available Online: https://faolex.fao.org/docs/pdf/sad212466.pdf.

Stevenson, J. R. & Irz, X. (2009). Is Aquaculture Development an Effective Tool for Poverty Alleviation? A Review of Theory and Evidence, *Cahiers Agricultures*, vol. 18, no. 2–3, pp. 292–299.

Tacon, A. G. & Metian, M. (2018). Food Matters: Fish, Income, and Food Supply – a Comparative Analysis, *Reviews in Fisheries Science & Aquaculture*, vol. 26, no. 1, pp. 15–28.

Torres-Reyna, O. (2014). Logit, Probit and Multinomial: Logit Models in R (v. 3.5).

Tuyen, T. Q. (2015). Socio-Economic Determinants of Household Income among Ethnic Minorities in the North-West Mountains, Vietnam, *Croatian Economic Survey*, vol. 17, no. 1, pp. 139–159.

United Nations Development Programme (UNDP). (2022). Human Development Index - Madagascar, Available Online: https://hdr.undp.org/data-center/specific-country-data#/countries/MDG.

USAID. (2023). STAT Compiler: The DHS Program, Available Online: https://www.statcompiler.com/en/.

Verbeek, M. (2017). A Guide to Modern Econometrics, 5th Edition, Wiley.

Voyer, M., Quirk, G., Farmery, A. K., Kajlich, L. & Warner, R. (2021). Launching a Blue Economy: Crucial First Steps in Designing a Contextually Sensitive and Coherent Approach, *Journal of Environmental Policy and Planning*, vol. 23, no. 3, pp. 345–362.

Voyer, M., Quirk, G., McIlgorm, A. & Azmi, K. (2018). Shades of Blue: What Do Competing Interpretations of the Blue Economy Mean for Oceans Governance?, *Journal of environmental policy & planning*, vol. 20, no. 5, pp. 595–616.

Wiseman, Y. (2022). Isolated Territories and Infrastructure Development: A Case for Land Transportation Investment in Madagascar, in *Interdisciplinary Approaches to the Future of*

Africa and Policy Development, IGI Global, pp. 78–97.

Wooldridge, J. M. (2015). Introductory Econometrics: A Modern Approach, Cengage learning.

World Bank. (2005). Introduction to Poverty Analysis, Washington DC, no. 90288, Available Online: http://documents.worldbank.org/curated/en/775871468331250546/Introduction-to-poverty-analysis.

World Bank. (2020). Madagascar: Balancing Conservation and Exploitation of Fisheries Resources, Available Online: https://www.worldbank.org/en/news/feature/2020/06/08/madagascar-balancing-conservation-and-exploitation-of-fisheries-resources.

World Bank. (2023). Employment in Agriculture (% of Total Employment) (Modeled ILO Estimate) – Madagascar, Available Online: https://data.worldbank.org/indicator/SL.AGR.EMPL.ZS?locations=MG.

Appendix A

***Table 7**: Indicators and questions of the Global MPI – Source: author's own computation, adapted from OPHI (2021).*

Dimension of Poverty	Indicator	Deprived if living in a household where…	SDG area	Weight
HEALTH	Nutrition	Any person under 70 years of age for whom there is nutritional information is undernourished.	SDG 2	1/6
	Child mortality	A child under 18 has died in the household in the five-year period preceding the survey.	SDG 3	1/6
EDUCATION	Years of schooling	No eligible household member has completed six years of schooling.	SDG 4	1/6
	School attendance	Any school-aged child is not attending school up to the age at which they would complete class 8.	SDG 4	1/6
LIVING STANDARDS	Cooking fuel	A household cooks using solid fuel, such as dung, agricultural crop, shrubs, wood, charcoal, or coal.	SDG 7	1/18
	Sanitation	The household has unimproved or no sanitation facility or it is improved but shared with other households.	SDG 6	1/18
	Drinking water	The household's source of drinking water is not safe or unsafe drinking water is a 30-minute walk or longer walk from home, roundtrip.	SDG 6	1/18
	Electricity	The household has not electricity.	SDG 7	1/18
	Housing	The household has inadequate housing materials in any of the three components: floor, roof, or walls.	SDG 11	1/18
	Assets	The household does not own more than one of these assets: radio, TV, telephone, computer, animal cart, bicycle, motorbike, or refrigerator, and does not own a car or truck.	SDG 1	1/18

Appendix B

Table 8: *English version of the FIES survey – Source: author's own computation, based on FAO (2017: 3).*

Q°	Standard Label	Food Insecurity Experience Scale Questions
1	Worried	During the last 12 MONTHS, was there a time when you were worried you would not have enough food to eat because of a lack of money or other resources?
2	Healthy	Still thinking about the last 12 months, was there a time when you were unable to eat healthy and nutritious food because of a lack of money or other resources?
3	Few Foods	Was there a time when you ate only a few kinds of foods because of a lack of money or other resources?
4	Skipped	Was there a time when you had to skip a meal because there was not enough money or other resources to get food?
5	Ate Less	Still thinking about the last 12 months, was there a time when you ate less than you thought you should because of a lack of money or other resources?
6	Ran Out	Was there a time when your household ran out of food because of a lack of money or other resources?
7	Hungry	Was there a time when you were hungry but did not eat because there was not enough money or other resources for food?
8	Whole Day	During the last 12 months, was there a time when you went without eating for a whole day because of a lack of money or other resources?

Appendix C

Appendix C includes all the relevant tests for the multiple linear regression model estimating the determinants of fish income.

C1 Homoskedasticity

The violation of the homoskedasticity assumption is visible in **Figure 6** because the variance is not constant across the residuals.

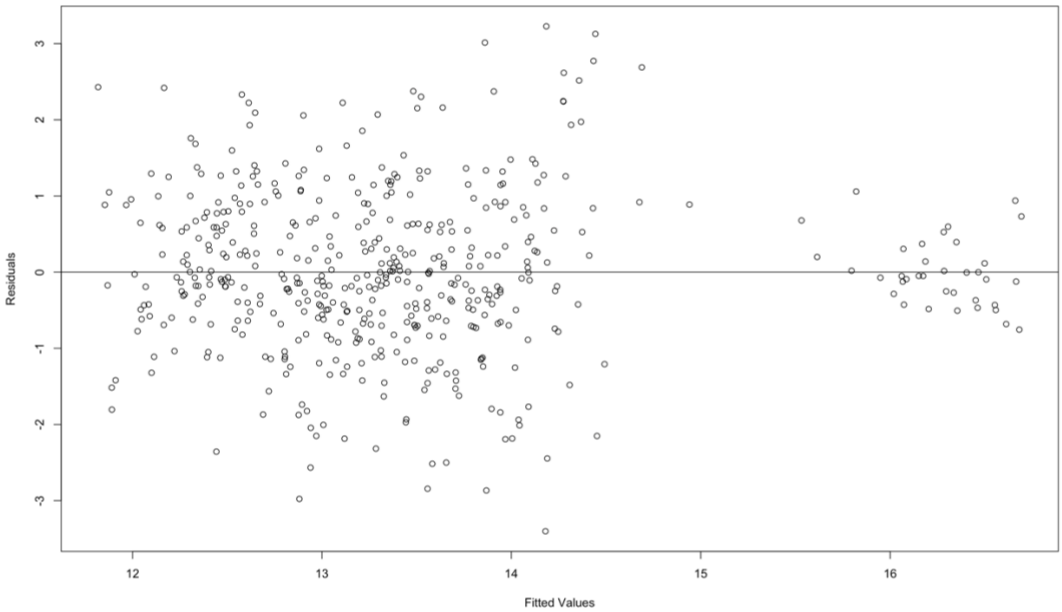


Figure 6: *Residual vs. fitted plot of the residuals of model (4) – Source: author's own computation.*

Moreover, the Breusch-Pagan test in **Table 9** reveals a p-value level that rejects the homoskedasticity assumption at the 5% level and concludes that there may be heteroskedasticity.

Table 9: *Studentized Breusch-Pagan test of model (4).*

	Data: model 4	
BP = 35.922	df = 12	p-value = 0.000
Null hypothesis (H0): homoskedasticity is present (the residuals are distributed with equal variance).		
Alternative Hypothesis (HA): heteroskedasticity is present (the residuals are distributed with equal variance).		

C2 Autocorrelation

The Durbin-Watson test statistic ranges between 0 and 4 and indicates that there is no autocorrelation if DW is equal to 2, as is the case in **Table 10** below. This means that the residuals in the linear regression are assumed to be independent of other error terms. In this case, the weights of the WLS estimator can correctly be specified as the inverse of the variance of the residuals.

***Table 10**: Durbin-Watson test of model (4).*

Data: model 4	
DW = 2.007	p-value = 0.527
Null hypothesis (H0): there is no correlation among the residuals. Alternative Hypothesis (HA): the residuals are autocorrelated.	

C3 Normality

The Shapiro-Wilk test in **Table 11** reveals a p-value level that rejects the null hypothesis assumption at the 5% level, indicating that the residuals may not be normally distributed. However, with large sample sizes, as is the case in the analysis, the Shapiro-Wilk test – which is sensitive to large samples – often concludes that the residuals are not normal, and it is better to check visually.

***Table 11**: Shapiro-Wilk normality test of model (4).*

Data: residuals of model 4 using WLS	
W = 0.992	p-value = 0.01
Null hypothesis (H0): the residuals are normally distributed. Alternative Hypothesis (HA): the residuals are not normally distributed.	

The QQ plot in **Figure 7** below shows us that the distribution of the residuals is following the straight 45-degree angle line in the middle, and that it has heavy tails in the extremities. This suggests that the errors are not following a normal distribution, thus violating the normality assumption. However, with real world data it is difficult to find perfectly normally distributed errors and they are usually considered "normal enough" if they roughly follow the line.

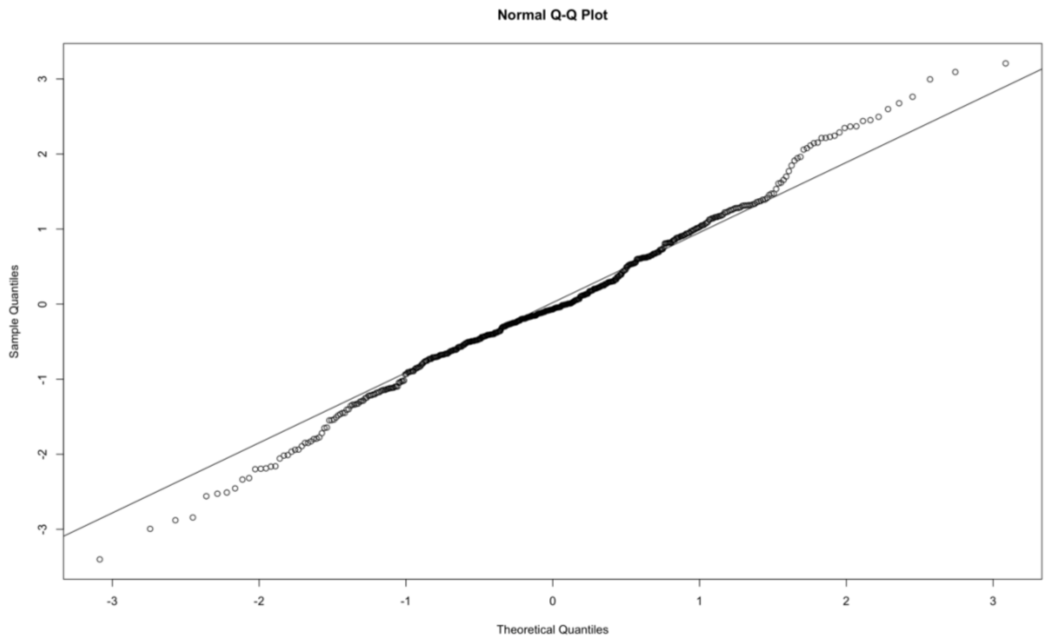


***Figure 7**: Sample vs. theoretical quantiles of model (4) – Source: author's own computation.*

C4 Multicollinearity

The multicollinearity test in **Table 12** shows that there is no risk of perfect collinearity among the variables, given that there are no values higher than 4 or 5 (moderately high according to the rule of thumb). For the variables age and age squared the multicollinearity problem was solved by standardizing age squared (subtracting the mean of age to every observation before squaring it).

***Table 12**: VIF test of model (4).*

	VIF
Type of producer: rice-fish	1.453
Type of producer: cooperative	1.466
Age of producer	1.160
Age squared	1.060
Male	1.052
Household size	1.059
Education of household head	1.083
Farming experience	1.203
Distance	1.031
Landowner	1.042
Polyculture	1.069
Fish feed costs	1.352

C5 Sensitivity Analysis

The sensitivity analysis that includes model (5) into the stepwise modeling presented in **Table 13** shows that the alternative specification of the education variable as a categorical variable does not change the results significantly, thus highlighting the robustness of the final model of the analysis, namely model (4).

***Table 13**: Sensitivity analysis.*

	Dependent variable: Fish income				
	(1)	(2)	(3)	(4)	(5)
Type of producer (ref = pond)					
Rice-fish	**-0.79*****	**-0.80*****	**-0.77*****	**-0.45*****	**-0.42*****
	(0.12)	(0.12)	(0.13)	(0.12)	(0.12)
Cooperative	**2.48*****	**2.53*****	**2.67*****	**2.31*****	**3.02*****
	(0.16)	(0.17)	(0.18)	(0.20)	(0.28)
Age of producer		0.004	0.003	0.005	0.01
		(0.004)	(0.004)	(0.004)	(0.004)
Age squared		-0.0003	-0.0004	-0.0001	-0.0002
		(0.0003)	(0.0003)	(0.0003)	(0.0003)
Male		**0.25***	**0.25***	**0.22***	**0.23***
		(0.13)	(0.13)	(0.13)	(0.12)
Household size		0.01	0.01	-0.002	0.002
		(0.02)	(0.02)	(0.02)	(0.02)
Education of household head			**0.30*****	**0.32*****	
			(0.11)	(0.11)	
Education of household head (ref = no)					
Primary					0.14
					(0.35)
Secondary					0.36
					(0.35)
More					**0.86****
					(0.37)
Other					0.48
					(0.45)
Farming experience			**0.02****	**0.02****	**0.02****
			(0.01)	(0.01)	(0.01)
Distance			**-0.004****	**-0.003****	**-0.003****
			(0.002)	(0.002)	(0.002)
Landowner				-0.10	-0.13
				(0.20)	(0.20)
Polyculture				**0.33*****	**0.34*****
				(0.11)	(0.11)
Fish feed costs				**0.09*****	**0.09*****
				(0.01)	(0.01)

Constant	**13.78*** **	**13.44*** **	**13.21*** **	**12.21*** **	**12.01*** **
	(0.10)	(0.26)	(0.29)	(0.34)	(0.47)
Observations	492	492	492	492	492
R^2	0.53	0.52	0.49	0.52	0.52
Adjusted R^2	0.53	0.51	0.48	0.51	0.50
Residual Std. Error	1.30 (df = 489)	1.31 (df = 485)	1.32 (df = 482)	1.33 (df = 479)	1.32 (df = 476)
F Statistic	279.90***	86.95***	51.72***	42.76***	33.94***
	(df = 2; 489)	(df = 6; 485)	(df = 9; 482)	(df = 12; 479)	(df = 15; 476)

Note: *p < 0.1; **p < 0.05; ***p < 0.01

Appendix D

Appendix D includes all the relevant tests for the binary logistic regression model estimating the determinants of food security.

D1 Multicollinearity

The multicollinearity test in **Table 14** shows that there is no risk of perfect collinearity among the variables, given that tall values are below 4-5, namely the threshold defined to consider multicollinearity as moderately high.

***Table 14**: VIF test of model (4).*

	VIF
Type of respondent: fish farmer	1.227
Type of respondent: VCA	1.073
Age of respondent	1.118
Gender of household head	1.120
Who decides on food matters: female	3.992
Who decides on food matters: both	3.906
Household size	1.079
Education of household head	1.076
Household wealth	1.027
Distance	1.055
Frequency	1.089
Fish species: carp	1.514
Fish species: tilapia	1.411
Consumption of whole fish	1.137

D2 Confusion Matrix

A confusion matrix is a test of the predictive performance of a classification model, in this case of a binary logistic regression. The idea is to evaluate the performance of the model in predicting the probability that the outcome variable truly occurs. With the confusion matrix in **Table 15**, it is thus possible to see to what extent the model predicts outcome 1 "food secure", and outcome 0 "food insecure" correctly: true positive (TP) and true negative (TN) are correctly specified observations.

***Table 15**: Confusion matrix of model (4).*

		Predicted Value	
		Negative (PN) fies = 0	Positive (PP) fies = 1
Actual Value	Negative (N) fies = 0	True negative (TN) 248	False positive (FP) 166
	Positive (P) fies = 1	False negative (FN) 277	True positive (TP) 513

With this table, it is then possible to compute several goodness-of-fit measures such as:

- **Model accuracy**: the number of samples correctly classified out of all samples present in the test set. In this case, accuracy equals 64%, which is not very large compared to other similar models. The opposite, namely the **model misclassification** rate equals 36%.
- **Model sensitivity** (true positive rate): the number of samples predicted correctly to be belonging to the positive class out of all the samples that belong to the positive class. In this case, sensitivity equals 76%, which is an acceptable result. The same can be done for the negatives: **model specificity** (true negative rate) equals only 47%, which again is rather low.
- **Model precision**: the number of samples belonging to the positive class out of all the samples that were predicted positive by the model. In this case, it equals 65%.

These different goodness-of-fit measures of the model reveal that its predictive power is not very elevated. Nevertheless, the stepwise modeling approach also shows that the final model is the best that could be developed with the available data.

D3 Sensitivity Analysis

The sensitivity analysis in **Table 16** shows that by replacing the education variable, which has a significantly strong effect in model (4), with a categorical predictor in model (5), the overall results do not significantly change, pointing to the robustness of the final model.

***Table 16**: Sensitivity analysis.*

	Dependent variable: FIES				
	(1)	(2)	(3)	(4)	(5)
Type of respondent (ref = consumer)					
Fish farmer	0.26***	0.21**	0.12	0.07	0.09
	(0.10)	(0.11)	(0.11)	(0.12)	(0.12)
VCA	**0.55*** **	**0.54*** **	**0.43** **	**0.33* **	**0.43** **
	(0.17)	(0.17)	(0.17)	(0.18)	(0.18)
Age of respondent		**0.01***	**0.01****	**0.01****	**0.01****
		(0.004)	(0.004)	(0.004)	(0.004)
Female as household head		**-0.56*****	**-0.49*****	**-0.45*****	**-0.44*****
		(0.14)	(0.14)	(0.15)	(0.15)
Who decides on food matters (ref = male)					
Female		**0.38****	**0.37****	**0.33***	**0.35***
		(0.18)	(0.19)	(0.19)	(0.19)
Both		0.21	0.18	0.09	0.12
		(0.18)	(0.19)	(0.19)	(0.19)
Household size		-0.05*	-0.02	-0.02	-0.02
		(0.03)	(0.03)	(0.03)	(0.03)
Education of household head			**0.71*****	**0.70*****	
			(0.10)	(0.10)	
Education of household head (ref = no)					
Primary					0.24
					(0.31)
Secondary					**0.72****
					(0.31)
More					**1.81*****
					(0.34)
Other					**0.88****
					(0.39)
Household wealth			**1.52*****	**1.42*****	**1.14*****
			(0.24)	(0.24)	(0.25)
Distance			-0.002	-0.002	-0.002
			(0.002)	(0.002)	(0.002)
Frequency				**0.48*****	**0.45*****
				(0.10)	(0.11)
Fish species (ref = ocean)					

Carp				**0.74*****	**0.75*****
				(0.15)	(0.15)
Tilapia				**0.31*****	**0.30*****
				(0.11)	(0.11)
Consumption of whole fish				**-0.33****	**-0.34*****
				(0.13)	(0.13)
Constant	**0.12****	**-0.13**	**-0.82*****	**-1.04*****	**-1.35*****
	(0.06)	(0.24)	(0.27)	(0.30)	(0.42)
Observations	1981	1981	1981	1981	1981
Log Likelihood	-1350.78	-1339.15	-1277.72	-1255.58	-1232.38
Akaike Inf. Crit.	2707.56	2694.30	2577.43	2541.17	2500.76
McFadden R squared	0.01 (df = 3)	0.01 (df = 8)	0.06 (df = 11)	0.08 (df = 15)	0.09 (df = 18)
Note:					*p < 0.1; **p < 0.05; ***p < 0.01