博士論文

A Study on the Linkages of Agriculture and Nutrition: Focusing on the Effects of Production Diversification, Market Access, and Climate Change in Central Madagascar

(農業と栄養の連環に関する研究：マダガスカル中央部における農業生産の多様化、市場へのアクセス、気候変動の効果に焦点をあてて)

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ABSTRACT

A Study on the Linkages of Agriculture and Nutrition: Focusing on the Effects of Production Diversification, Market Access, and Climate Change in Central Madagascar

By

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As the global community approaches the deadline for achieving zero hunger and addressing malnutrition, the urgent issue of the "triple-burden" nutrition crisis remains prevalent, particularly in developing countries. Despite low prevalence of obesity rates, the persistent challenges of undernutrition and hidden hunger are alarmingly high in rural areas of Sub-Saharan Africa (SSA). Paradoxically, despite the significant contribution of rural smallholder farmers to global food production, many of them suffer from malnutrition, leading to chronic undernutrition and micronutrient deficiencies in children. Bridging these critical dietary gaps in rural households is a pressing concern. While expanding production diversity is commonly assumed as a solution, the results are varied and context-specific. To tackle this challenge, understanding the intricate relationship between the food system and nutrition is thus crucial for improving human health outcomes.

This dissertation, titled "*A Study on the linkages of agriculture and nutrition: Focusing on the effects of production diversification, market access, and climate change in central Madagascar*", aims to investigate the interconnections between agricultural practices, livelihoods, and nutrition among smallholder farmers in SSA, specifically in Madagascar.

The first essay, "*Comparing Two Pathways: Agriculture to Child Health - Dietary Diversity and Micronutrient Intake in the Malagasy Highlands*," takes a dual approach to examine the relationships between agriculture, food/nutrition security, and child nutritional status. Using a three-year panel dataset, the study reveals a positive association between production diversity and both household dietary diversity, and children's weight. However, no significant relationship was found between the direct association household dietary diversity-children's weight. The analysis further highlights the significance of pulses as a key agricultural product, contributing to

increased energy and micronutrient intake, particularly zinc. Notably, higher zinc intake is linked to reduced undernutrition and stunting among preschool children. These findings underscore the importance of promoting zinc-rich foods and supporting their production as a viable strategy to enhance the nutritional well-being of disadvantaged communities.

The first essay of this study focuses on the significance of pulse production in augmenting energy and micronutrient intake, particularly highlighting the association of zinc intake with child nutritional status. While a strong association was observed between pulse production and improved nutrition, the study found a relatively weak link between plant-based food group production and child malnutrition through the market pathway.

Therefore, we propose that a shift in agricultural practices towards the cultivation of high-nutritional-value crops with commercial potential can offer dual benefits to impoverished rural households, promoting economic growth and improving access to affordable and nutrient-rich foods. Consequently, the second essay of this dissertation, titled "*Examining the Nexus of Vegetable Commercialization, Household Welfare, Nutrition, and Child Health: Evidence from Smallholder Producers in Central Madagascar*," delves into the identification of dynamic factors determining vegetable commercialization and the examination of the well-being and nutritional implications of vegetable production on vegetable growers. Using a three-year panel data, the study identifies several factors that hinder the commercialization of vegetables in central Madagascar: the age of the household head, availability of family labor and land, and changes in precipitation patterns. Results also indicate that households engaged in vegetable commercialization significantly experience increased monthly income, improved dietary diversity, and higher expenditures. Moreover, the study suggests a positive relationship between higher per-capita expenditures on non-food items, children's linear growth, and a reduced prevalence of stunting.

This second essay thus highlights the important welfare-enhancing and diet-diversifying role of market. However, a fundamental question remains: *Can the production of nutrient-rich foods provide a viable solution to address child malnutrition?*

This question serves as the impetus for the subsequent essay, which delves into alternative pathways linking "agricultural production - household food consumption - child malnutrition" by considering the role of more nutrient-dense sources. The third essay of this dissertation, entitled "*Animal-Sourced Foods and Early Childhood Nutrition: Panel Data Evidence in Central Madagascar*," aims to fill the existing gap in the literature regarding the relationship between Animal-Sourced Foods (ASF) production and child growth in developing countries. Despite the recognized significance of ASF as excellent sources of high-quality nutrient-rich foods, empirical studies examining this association, particularly those using a high frequency of longitudinal cohort data, are scarce. This essay seeks to contribute valuable insights and evidence from the context of central Madagascar, shedding light on the crucial link between ASF and early childhood nutrition. Using a comprehensive eight-round panel dataset from central Madagascar, a region with high stunting rates and low milk intake, the findings highlight that lagged milk production is significantly associated with improved HAZ and reduced stunting among children under 5 years old. Household-level factors such as increased frequency and probability of milk consumption play a key role in mediating this relationship. The results of this third essay thus emphasize the importance of dairy production in driving long-term growth improvements in children in central Madagascar.

Finally, while the previous essays have shed some light on the positive and negative associations between climate variability and nutrition, a deeper comprehension of these effects is still lacking. Specifically, examining the impact of changing rainfall patterns can uncover the true nutritional resilience of rain-dependent smallholder farmers. Hence, the following essay, titled "*Climate Conditions, Food Group Based-Nutrient Intake and Child Health in Tropical Climates: Evidence from Madagascar*," tries to disentangle the linkages between recent climatic conditions, child health outcomes, and diet quality in the central zones of Madagascar. Using a three-year panel dataset and climate data from Madagascar, the findings reveal a significant negative association between inadequate or excessive rainfall and key indicators such as child linear growth and the availability of nutrients from tuber consumption within households. Specifically, a curvilinear relationship is observed between rainfall during the rainy season and HAZ, with excessive rainfall levels detrimentally affecting children's health. The study also identifies a similar non-linear relationship between rainfall and the availability of calories, vitamin C, and especially protein from tubers. The reduction in these tuber-based nutrients subsequently influence child health outcomes. These findings emphasize the need for climate change-sensitive policies focusing on improving protein sources to combat child malnutrition in tropical regions.

These essays offer valuable insights into policy considerations that can significantly enhance the livelihoods and nutrition of impoverished smallholder farmers in Madagascar. Firstly, there is a need to prioritize the quantity and accessibility of specific food groups, namely pulse and tuber, tailored to targeted population segments, rather than solely focusing on maximizing cereal production. This approach can yield greater benefits in improving nutrition outcomes. Secondly, promoting the cultivation of commercially marketed crops, supported by well-functioning markets, is essential for diversifying agricultural production and enhancing farmers' economic prospects. Thirdly, recognizing the importance of ASF, particularly milk and dairy products, are crucial as they contribute significantly to improved nutrition and health outcomes. Implementing mechanisms to incentivize smallholder farmers and markets to invest in milk production can facilitate the adoption of healthier and sustainable dietary practices. Lastly, given the vulnerability of Madagascar's agricultural systems to climate change, transformative measures are imperative to build resilience and ensure a more secure nutrition landscape.

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"*The fear of the Lord is the beginning of knowledge…*" Prov 1, 7

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1 Introduction

1.1 Background of the study

Achieving Sustainable Development Goal 2, which aims to eradicate hunger and malnutrition, is a pressing global challenge, particularly in the context of Sub-Saharan Africa (SSA) (Giller, 2020; United Nations, 2022). The region is currently grappling with the “triple burden” of malnutrition, encompassing ongoing undernutrition, escalating obesity rates, and high prevalence of micronutrient deficiencies (Willet et al., 2019; FAO et al., 2021). Unfortunately, despite the collective efforts of international community, malnourishment rates in SSA have surged from 5.5 million to 30 million in the past decade. Consequently, over 3.5 million children under five succumb to insufficient food intake annually (Fanzo, 2012; Fraval, 2019). In 2020, approximately 800 million people worldwide experienced hunger, with SSA accounting for more than a third (34%) of the total (FAO et al., 2021). While the issue of overweight and obesity has yet to reach the rural areas of SSA, the region also suffers from hidden hunger, a form of malnutrition that affects individuals of all genders and ages and has less visible signs compared to malnutrition and hunger (Uchendu, 2018).

Hidden hunger, or micronutrient deficiency, remains a major public health concern in SSA (Lowe, 2021). Deficiencies in key minerals and vitamins are prevalent among approximately 1.5 to 2 billion people worldwide, with a disproportionate impact on the SSA region (WHO, 2006; Ritchie & Roser, 2017; Galani et al., 2020). Recent studies reveal that approximately 50% of preschool-aged children globally suffer from micronutrient deficiencies, with over 100 million living in SSA alone (Stevens et al., 2022). The consequences of these deficiencies can be severe and long-lasting, including anemia and impaired cognitive development resulting from iron deficiency, blindness from insufficient vitamin A, and stunted growth owing to zinc deficiency (WHO, 2020). Therefore, addressing the issue of micronutrient deficiency is critical to reducing the burden of malnutrition and improving the long-term health and development, and preventing stunted growth in children in SSA and around the world.

Stunting, caused by long-term and chronic malnutrition, remains a significant public health concern, particularly in low and middle-income countries (Quamme & Iversen, 2022). Globally, approximately 150 million children are affected by stunting, with SSA has an average prevalence of 41% among children under the age of five

(Black et al., 2013; Quamme & Iversen, 2022). The implications of stunting are irreversible and have far-reaching effects, including limited cognitive development, lower educational level affecting the economic growth in the long run (Babu et al., 2016). Despite UN efforts to halve stunting in children under 5 years of age, progress has been stalled, especially among smallholder farmers in rural areas who lacks the means to purchase nutritious diets to diversify within food groups (FAO et al., 2020, Herforth et al., 2020).

Climate change also poses a significant threat to global food security and nutrition, particularly in regions where rainfed agriculture is widely practiced (FAO et al., 2018; IFAD, 2021). Climate shocks, including altered precipitation patterns, have led to a decrease in agricultural yields and crop failures, resulting in food shortages, price increases, food insecurity, and child malnutrition (IPCC, 2013; Vogel et al., 2019; Thiede & Gray, 2020; IFAD, 2021; Randell et al., 2022; Schmitt et al., 2022). Moreover, the reduction in the nutritional value of staple crops such as rice due to increased atmospheric carbon dioxide levels is a growing concern that may worsen the issue of malnutrition (Zhu et al., 2018). As such, with millions of people predicted to be at risk of food insecurity, addressing the impact of climate change on food security and nutrition is crucial in ensuring sustainable development and reducing poverty (FAO et al., 2018).

Clearly, there is an urgent need for programs to alleviate micronutrient deficiencies, to reduce stunting in children, and to mitigate adverse climate impacts for farmers in rural areas. However, despite being responsible for producing much of the world's food, many smallholder farmers in SSA, paradoxically, still suffer from malnutrition due to various factors (FAO, 2014). These factors include (i) the consumption and production of less diverse and nutrient-poor diets in rural areas where subsistence farming is prevalent (IFAD, 2021; Khonje et al., 2022), (ii) the unaffordability of healthy diets (Fraval et al., 2019; FAO et al., 2020; GLOPAN, 2020; Herforth et al., 2020), and (iii) weak market connections that limit smallholder farmers' income and access to nutritious food (IFAD, 2021). Improving access to nutritious food, and enhancing market connections are thus crucial interventions needed to address malnutrition in the long-term, making food-based approaches such as fortification, crop biofortification, and dietary diversification increasingly important (Thompson & Amoroso, 2011; Jones, 2017a).

It is particularly assumed that increasing production diversity would enhance the nutritional outcomes among smallholder farmers, who constitute a large proportion of undernourished population (Burlingame & Dermini, 2012; Powell et al., 2015; Jones, 2017a; Jones, 2017b). This assumption is based on the notion that agricultural diversification can reduce income variability (Joshi et al., 2004; Headey et al., 2019; Chegere & Kauki, 2022; Haji, 2022) and improve household diet diversity (for example Jones et al., 2014; Hirvonen & Hoddinott, 2017; Muthini et al., 2020; Ogutu & Qaim, 2020; Sekabira & Nalunga, 2020), thereby improving nutrition in resource-constrained settings. However, recent empirical analysis and meta-analysis, including Sibhatu & Qaim (2018), Lovo & Veronesi (2019), Chegere & Stage (2020), Khonje et al. (2022) have provided little evidence to support this assumption. These studies suggest that increasing diversity in agricultural production may not always be a successful strategy to improve smallholder diets and overall nutrition.

The existing evidence on the link between production diversity and nutrition is inconclusive and context-specific (Sibhatu & Qaim, 2018). While some studies have found positive associations (Sibhatu et al., 2015; Fanzo, 2017), others have reported no significant associations (Sibhatu & Qaim, 2018) or even negative associations (Khonje et al., 2022). These studies often overlook the importance of differentiating the significance of each food group within agricultural production diversity, as some groups may only marginally improve or even undermine diet quality (Jones, 2017; Chegere and Stage, 2020; Mehraban and Ickowitz, 2021). Moreover, the debate surrounding whether to pursue a diverse set of crops or specialize in crop production for sale and purchase food remains unsettled among researchers (Jones et al., 2014; Shibatu et al., 2015; Jones, 2017; Shibatu and Qaim, 2018; Mulenga et al., 2021; Olabisi et al., 2021). Further research is necessary to gain a better understanding of the relationship between agricultural production diversity, dietary diversity, and nutrition outcomes and to identify effective interventions to enhance diet quality and nutrition outcomes in SSA.

1.2 Objectives and Hypotheses

The objective of this study is not merely to provide another case of link between agricultural production diversity and nutritional outcomes in a new context, but rather to shed a new light on the link by focusing on the contributions of each food group to micronutrient intake and by paying explicit attention to the role of market and the effects of climate change.

To achieve this, we aim to test the following hypotheses:

i. The association of household agricultural production and micronutrient intake is positive and significant through self-consumption in the case of foods whose market is missing (i.e. not always available in the market);

ii. The association of household agricultural production and household dietary diversity is positive and significant in the case of marketable foods through income generated by crop sales;

iii. Micronutrient intake, either by self-production or through market-based dietary diversification is potentially associated with better nutritional status of children and a stronger likelihood of reducing stunting;

iv. Insufficient and excessive rainfall in tropical developing countries negatively impact child health outcomes and the availability of calories and nutrients sourced from specific food groups within households.

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Chapter 2: Madagascar – African context and country profile

2 Madagascar and its context within the African continent

2.1 Country profile

Madagascar, located off the South-Eastern coast of the African continent, is the world's fifth largest island. The country is characterized by diverse soils and climates, with two predominant seasons: a dry and cold period and a wet and hot season. Moreover, Madagascar is prone to regular cyclones, further adding to its unique environmental dynamics (Otto et al., 2022). Presently, the estimated population of the country stands at 27.6 million, with projection indicating a rise to 34.2 million by the year 2030 (Population Reference Bureau, 2017; UNICEF, 2021). The population is predominantly youthful, with 41% under the age of 15, and is predominantly residing in rural areas (Population Reference Bureau, 2017). In rural settings, the average Malagasy woman has approximately 4.6 children (INSTAT & ICF, 2021). Moreover, Madagascar contends with a relatively high mortality rate, with a 75‰ risk of death before reaching the age of 5 (INSTAT & ICF, 2021). The country has witnessed a significant surge in poverty rates over the past decades, with around 80% of the population living on less than USD 2.15 a day (World Bank, 2023). Moreover, Madagascar's progress toward achieving the SDGs is ranked 153rd out of 157 (Sachs et al., 2017). Overall, Madagascar faces significant challenges including the high population growth, the pervasive poverty rates, and the arduous journey towards meeting global goals, which will require sustained efforts and targeted interventions.

2.2 The nutritional context of Madagascar

Despite the prevalent issue of malnutrition and pervasive hunger in SSA, there exist significant variations in the dietary composition sourced from food groups across countries within the region.

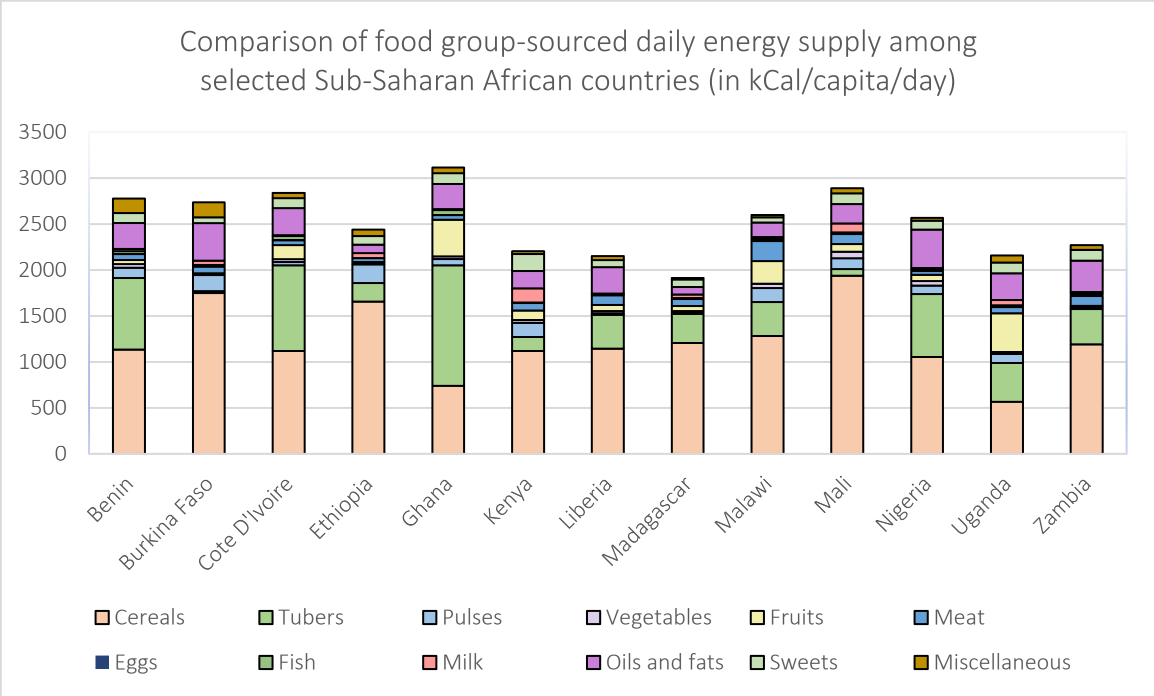

Fig. 2.1 Comparison of food group-sourced daily energy supply among selected Sub-Saharan African countries

Source: Calculated by Author based on data from FAOSTAT 2019 (2022)

Figure 2.1 presents a depiction of daily energy supply from diverse food groups in selected SSA countries. The total energy supply among populations showcases considerable diversity, with Ghanaians supplying the highest calorie of over 3,000 kCal/capita/day, while Madagascar records the lowest at less than 2,000 kCal/capita/day. Ethiopia, Kenya, Liberia, Uganda, and Zambia fall within the range of 2,000 – 2,500 kCal/capita/day, while Benin, Burkina Faso, and Malawi surpass 2,500 kCal/capita/day. Furthermore, the proportion of energy derived from distinct food groups demonstrates substantial variation. Cereals dominate the daily diet in Burkina Faso, Ethiopia, Madagascar, and Mali, whereas tubers constitute the primary food source in Ghana and Cote d'Ivoire. Pulses hold significance in Ethiopia, Burkina Faso, and Malawi, while vegetables are less prevalence across most countries. Fruit supply is prevalent in Ghana, Malawi, and Uganda, with Malawi additionally demonstrating a relatively substantial energy contribution from meat consumption. These findings underscore the necessity for further investigation into the roles of each food group's production within the agricultural sector of SSA to enhance their accessibility, given the observed diversity in daily caloric supply and energy sources across SSA countries.

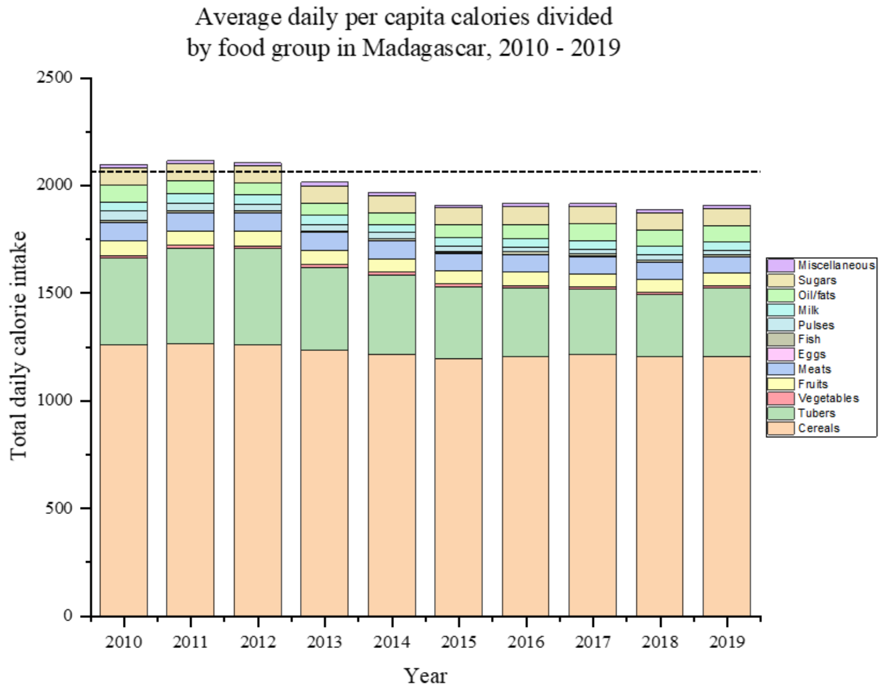

Fig. 2.2 Average daily per capita calories based on each food group in Madagascar from 2010 to 2019

<u>Source</u>: Calculated by Author based on data from FAOSTAT (2022)

Given the concerning malnutrition scenario in Madagascar relative to other countries in SSA, we try to elucidate the trajectory of daily energy supply among the Malagasy population over the past decade (Figure 2.2). Notably, from 2010 to 2019, there was a decline in overall calorie supply from 2,098 kCal/capita/day in 2010 to 1,909 kCal/capita/day in 2019, representing a daily deficit of approximately 190 calories. This indicates that the Malagasy diet has consistently fallen below the recommended daily calorie intake of 2,133 kCal/capita/day since 2013 – 2014, thus remaining inadequate. The contribution of cereals to daily caloric supply has remained steady, as have the other food groups except for tubers. The contribution of tuber showed a slight increase in 2011 – 2012, followed by a progressive decline until 2018, and a slight resurgence in 2019. These findings underscore the criticality of identifying and addressing the underlying factors contributing to the decline in calorie consumption in Madagascar.

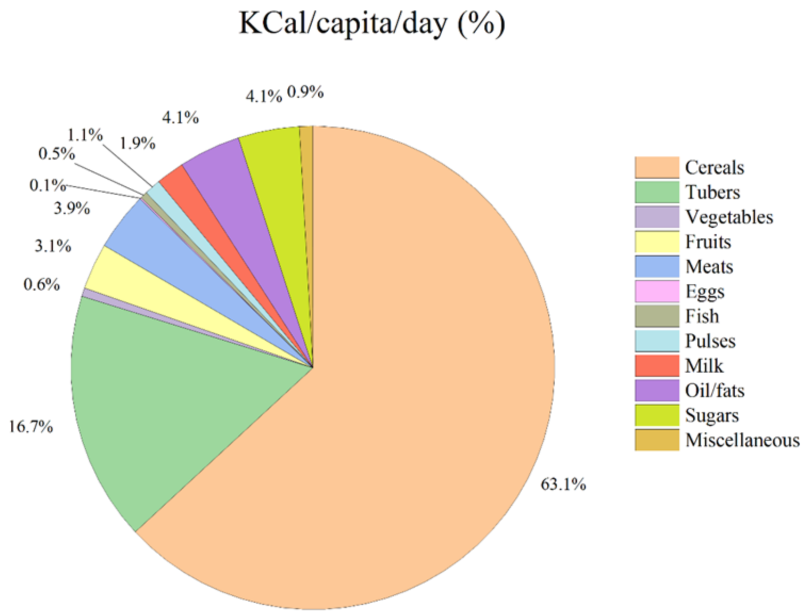

Fig. 2.3 Malagasy food supply in 2019

<u>Source</u>: Calculated by Author based on data from FAOSTAT (2022)

The nutritional supply of Madagascar in 2019 is visually represented in Figure 2.3. The pie-chart highlights the prevailing composition of the Malagasy diet, wherein cereals and tubers constitute a substantial proportion, collectively accounting for approximately 80% of the total calorie supply. In contrast, fruits and vegetables make up a mere 4% of the overall supply. Indeed, rice, as the primary staple food, occupies a central role in shaping the daily nutritional supply in Madagascar. ASF, which encompass meats, eggs, fish, and milk, account for about 7% of the total calorie supply. Pulses, on the other hand, make a modest 1% contribution, supplementing the dominant share of 93% derived from vegetable products. The observed food supply indicates the absence of a discernible nutrition transition in Madagascar, signaling the need for further investigation and intervention to foster diversified and balanced nutritional patterns.

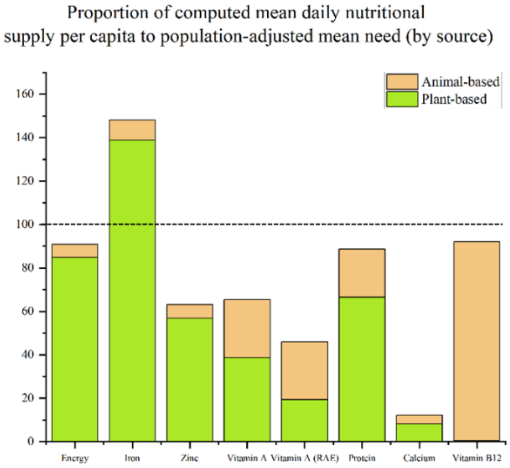

Fig. 2.4 Level of micronutrient intake based on the recommended daily nutritional supply

<u>Source</u>: Calculated by Author based on data from FAOSTAT (2022) and FAO/ INFOODS Food Composition table (2019)

By using the Food Composition Table from the FAO and referencing the 2019 food supply data, we have conducted estimation of the caloric and micronutrient supply within households in Madagascar. The outcomes, as depicted in Figure 2.4, indicate that these standard diets fall short in providing adequate levels of various macro and micronutrients, most notably zinc, vitamin A, and calcium, with the exception of iron. These findings align with the observations reported by Shiratori and Nishide (2018). Notably, plant-based foods assume a pivotal role as the primary source of calories, iron, and protein, whereas ASF serve as the main source of vitamin A and B12. The lack of dietary diversity and nutrient-dense food intake in Malagasy households may have contributed to the observed deficiencies in both macro and micronutrients.

Considering the significant reliance on cereal-based dietary patterns, the prevailing unbalanced nutritional profile, and the identified deficiencies in macro and micronutrients, a comprehensive assessment of the health status of children in Madagascar becomes imperative. This evaluation warrants particular attention to child stunting, a prevalent consequence of chronic malnutrition.

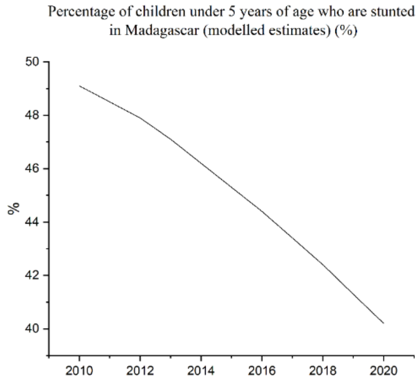

Fig. 2.5 Percentage of children under 5 years of age who are stunted in Madagascar (%)

<u>Source</u>: Calculated by Author based on data from FAOSTAT (2022)

Figure 2.5 shows the evolution of the percentage of child stunting over the last decades. While there has been substantial progress, the level of stunting remains alarmingly high, reaching 41% in 2020. National statistics indicate that a staggering 2 in 5 children suffer from acute malnutrition, among which 13% endure severe acute malnutrition. Stunting prevalence increases rapidly with age, starting at 25% in the first 6 months, escalating to 30% in children aged 9-11 months, and peaking at 46% among those aged 36 – 47 months. Furthermore, the prevalence of stunting is more pronounced among rural children compared to their urban counterparts (INSTAT & ICF, 2021). At the regional level, the prevalence of stunting stands at 44% in Antananarivo (Center), 21.7% in Diana (North), 35% in Menabe (West), and 37.6% in Atsinanana (East). Particularly, the Vakinankaratra region has the highest burden of chronic malnutrition, accounting for 52% of children under 5 (INSTAT & ICF, 2021). Thus, this region stands out as a compelling area of study due to its disproportionately high prevalence of stunting, making it an ideal context for exploring the intricate relationships between agricultural production, household food consumption, and child nutritional outcomes.

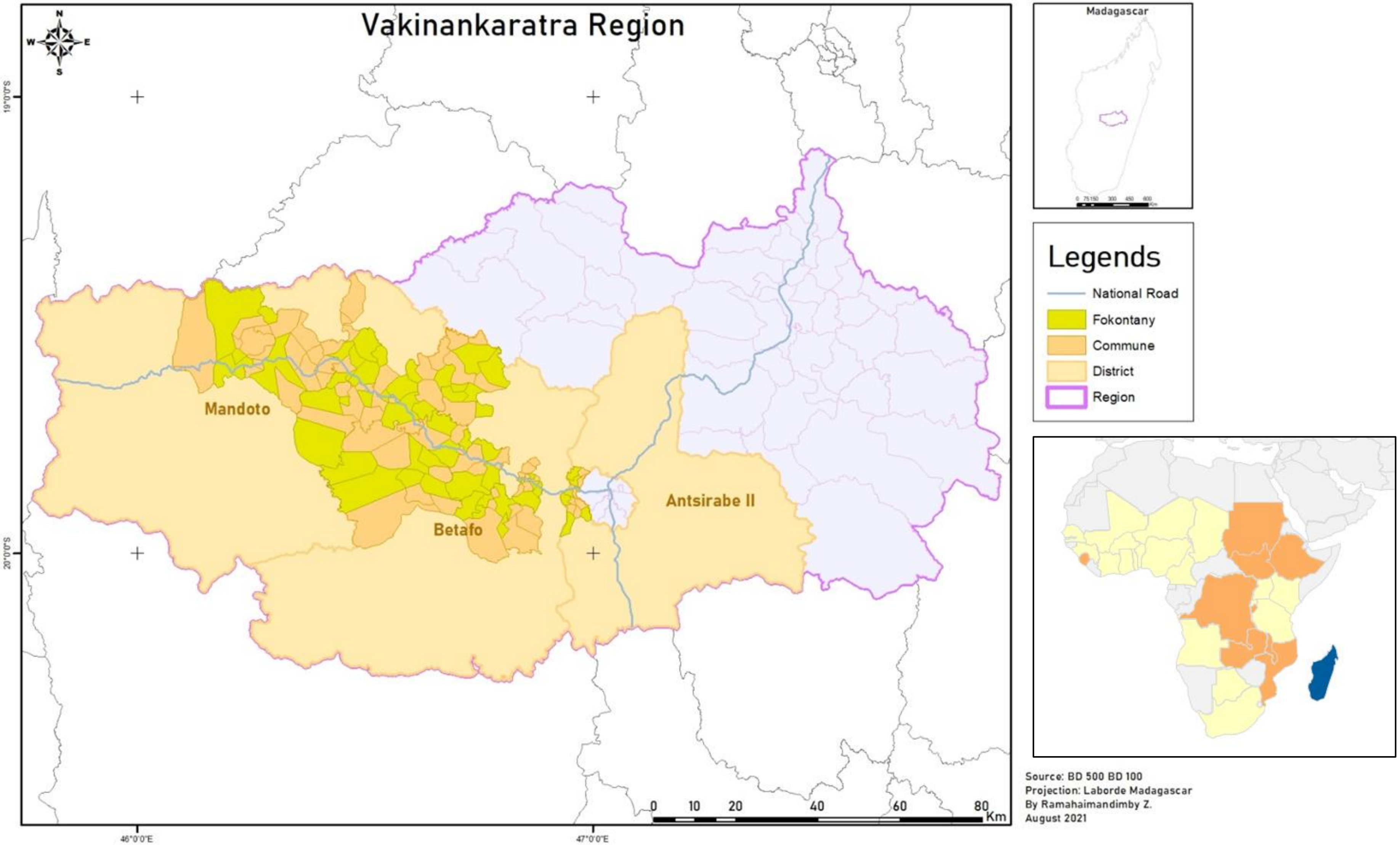

Fig. 2.6 Vakinankaratra region

2.3 Study site

2.3.1 *Vakinankaratra's agricultural and dairy potential*

Figure 2.6 depicts the Vakinankaratra region, nestled within the central highlands of Madagascar, comprising 7 districts, of which two are urban (Antsirabe I and Ambatolampy) and five rural (Antanifotsy, Faratsiho, Antsirabe II, Betafo, and Mandoto). Renowned as one of the most agriculturally productive areas in the country, the region witnesses the cultivation of lowland rice by over 80% of farmers and upland rice by nearly half of them (CREAM, 2013; Ozaki & Sakurai, 2020). Cereal production covers 63% of the region's total area, with rice dominating 48% of the cultivated land (Sourisseau et al., 2016). Nevertheless, rapid population growth has engendered land scarcity, necessitating intensified cropping systems and agricultural diversification to secure livelihoods (Minten & Zeller, 2017). Consequently, smallholder farmers have shifted their focus toward labor- and capital-intensive farming systems, namely vegetables, which hold considerable income-generating potential (Manguin-Salomon & Rakotonirainy, 2012). In addition, the region benefits from favorable climatic conditions, fostering intensive farming practices, earning it the nickname of "market gardening per excellence" (Minten & Zeller, 2017). Moreover, the Vakinankaratra region is located within the "dairy triangle", serving as a primary hub for milk production in Madagascar (Penot et al., 2016). In 2008, the Vakinankaratra region contributed 80% of the total milk production in the country (World Bank, 2011), though underwent major reorganization in the aftermath of the socio-politico-economic crisis in 2009 (Penot et al., 2016; Droy et al., 2018). Finally, the geographical position of the region provides the area with significant benefits in terms of access to domestic and urban markets (CREAM, 2013).

2.3.2 *Study area and data*

To investigate the relationship between "agriculture production – household food consumption – child nutritional outcomes", data was collected from three rural districts in the region of Vakinankaratra, namely Antsirabe II, Betafo, and Mandoto. Data collection spanned a period of eight waves, commencing from June 2018 and concluding in July 2021, effectively capturing the critical seasons of food consumption, including the lean season

(January to April), post-rice harvest period (May to August), and pre-lean season (September to December). Surveys were carried out once in 2018, thrice in 2019, twice in 2020 and twice in 2021 (Table 2.1.). From a total of 60 villages in selected districts of the region, ten lowland rice farmers were randomly selected at the time of the baseline survey and interviewed repeatedly for subsequent surveys. Collected data encompassed a comprehensive household questionnaire with modules that covered various topics, including household characteristics, agricultural production, income sources, food and non-food expenditures, detailed food consumption with 7-day and 24-h recall periods, and anthropometric measurements of available individuals. Precipitation data was obtained from the GIOVANNI tool, which provides a high-resolution satellite-derived imagery (Huffman et al., 2019).

Table 2.2. presents a comprehensive overview of the descriptive statistics derived from the combined data across all eight waves. The mean household size of 4.71 indicates a prevalence of relatively large households in the sample. With respect to the composition of household members, the share of preschool children is 11%, the share of schooling children is 24%, and the share of old members is 11%. This suggests that there is a comparatively similar proportion of young children as well as older individuals within the households. The proportion of working women (26%) underscores the important role of women in the labor force. Regarding land endowment, the average number of lowland plots is 1.42, with the majority of households (78%) possessing other plots in addition to lowland plots. Additionally, over half (57%) of households have upland plots, indicating a diverse portfolio of land holdings. The low proportion of households renting plots (5%) indicates that most households own the land they cultivate. In terms of irrigation, the average percentage of irrigated parcels is 23%, suggesting that irrigation is not a widespread practice among households in the sample. The average number of days household lasts went to the market is 3.51 days, indicating infrequent market visits. Finally, the mean Total Livestock Unit (TLU) of 1.05 reveal relatively low levels of livestock ownership among the households.

The three districts exhibit both similarities and differences. In terms of average household size, Antsirabe II has the smallest size (3.76), while Betafo has the largest (4.87). The proportion of preschool children is relatively similar in Antsirabe II and Betafo (8% and 10%, respectively), but higher in Mandoto (12%). Betafo has the highest share of schooling children (26%), while Antsirabe II has the lowest (15%). When considering the presence of older members, Antsirabe II has the highest share (22%), while Betafo and Mandoto have approximately the same share (10%).

With regard to land endowment, Betafo stands out with the highest number of lowland plots per household (1.49), suggesting a greater concentration of lowland agricultural activities. Mandoto has the highest share of upland plots (69%), while Antsirabe II has the lowest (39%). The proportion of households renting plots is lowest in Antsirabe II (2%), while Mandoto has the lowest share of irrigated parcels (18%).

In terms of household assets, Mandoto has the highest farm asset per capita at 73 148 MGA[1] (equivalent to USD 17), while Betafo has the lowest at 51 230 MGA (equivalent to USD 11), indicating potentially lower levels of agricultural investment and asset accumulation.

In terms of market activities, the approximate number of days households went to the market is lowest in Antsirabe II, with an average of 2.30 days prior to the survey. This implies more frequent market visits compared to the other districts, potentially driven by different market access and economic dynamics.

Overall, while Antsirabe II, Betafo, and Mandoto share some similarities in terms of demographic and land characteristics, there are notable differences among them.

[1] MGA stands for Malagasy Ariary, 1 MGA is equivalent to 0.00023 USD as of September 22th, 2022.

Table 2.1 Survey rounds

Waves	Year	Month	Timing of the survey	Total months covered	Note	Used in this study?
1	2018	June - July	Post rice-harvest	6	Baseline survey	Yes
2	2019	February - March	Lean period	6		Yes
3	2019	May - June	Post rice-harvest	5		Yes
4	2019	October - November	Pre-lean period	4		Yes
5	2020	February - March	Lean period	4		Yes
(6)	2020	(June - July)	Post rice-harvest		(Cancelled)	-
6	2020	October - November	Pre-lean period	8		Yes
7	2021	February - March	Lean period	4		Yes
8	2021	July - August	Post rice-harvest	5		Yes

Source: Author (2022)

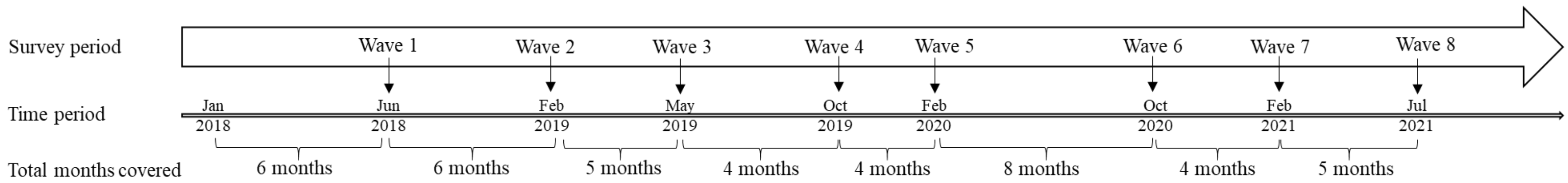

Table 2.2 Summary statistics

Variables	Pooled		Antsirabe 2		Betafo		Mandoto	
	Mean	sd	Mean	sd	Mean	sd	Mean	sd
Household characteristics								
Household size	4.71	1.95	3.76	1.77	4.87	1.96	4.75	1.92
Share of preschool children	0.11	0.15	0.08	0.14	0.10	0.14	0.12	0.15
Share of schooling children	0.24	0.20	0.15	0.18	0.26	0.20	0.24	0.20
Share of old members	0.11	0.24	0.22	0.36	0.10	0.22	0.09	0.23
Share of working woman	0.26	0.16	0.27	0.23	0.26	0.15	0.27	0.15
Parcel characteristics								
Number total of lowland plots	1.42	1.07	1.35	1.28	1.49	1.10	1.34	0.95
Have any upland plots (Yes=1)	0.57	0.49	0.39	0.49	0.53	0.50	0.69	0.46
Have any other plots (Yes=1)	0.78	0.42	0.79	0.40	0.77	0.42	0.79	0.41
Renting any plot (Yes=1)	0.05	0.22	0.02	0.15	0.05	0.22	0.06	0.23
Percentage of irrigated parcel	0.23	0.25	0.22	0.23	0.27	0.27	0.18	0.22
Last day to markets	3.51	2.27	3.21	2.47	3.41	2.30	3.73	2.15
Household assets								
TLU	1.05	0.87	1.08	0.77	1.11	0.86	0.96	0.91
Farm asset per capita (in MGA[1])	60918.99	153057.30	65552.95	136891.90	51230.88	141524.60	73148.76	171031.60
Home asset per capita (in MGA[1])	68118.12	252815.70	111310.90	169044.90	65685.76	323642.00	59250.44	127707.60
Observations	4429		441		2325		1663	

Notes: Observations from all eight surveys were pooled. [1]MGA stands for Malagasy Ariary. [1]MGA = 0.00023 USD as of September 22nd, 2022.

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Chapter 3: Comparison of Two Pathways Linking Agriculture to Child Health: Dietary Diversity and Micronutrient Intake in the Malagasy Highlands

Abstract

Rising micronutrient deficiencies pose a significant threat to the well-being of preschool-aged children, especially in vulnerable communities like disadvantaged farmers in Madagascar. The lack of effective interventions to improve their nutritional status further exacerbates this issue. In light of this, a comprehensive study was conducted to investigate the complex relationship between agriculture, food/nutrition security, and the nutritional status of children, using a dual approach (the dietary diversity and the micronutrient intake approach). To unravel the intricate connections, a three-year panel dataset was used. The results of the study provide compelling evidence supporting the link between production diversity and dietary diversity, emphasizing its positive association with children's weight. Furthermore, the study sheds light on specific agricultural products that have a significant influence on child nutritional outcomes. It reveals that the production of pulses has a direct association with increased energy and micronutrient intake, particularly zinc intake, among household. Another noteworthy finding from the study is the positive correlation between zinc intake and the reduction of undernourished and stunted children. Zinc, an essential micronutrient, thus plays a vital role in child growth and development. By emphasizing the importance of zinc-rich foods and supporting its production, policymakers can work towards mitigating the nutritional challenges faced by these vulnerable populations, ultimately contributing to the well-being and development of preschool-aged children.

Key words: pulse production；zinc intake; child nutritional status; Madagascar

3 Comparison of Two Pathways Linking Agriculture to Child Health: Dietary Diversity and Micronutrient Intake in the Malagasy Highlands

3.1 Introduction

"Hidden hunger" or "micronutrient malnutrition" has exacerbated the problem of food security in SSA and has remained a silent obstacle for preschool children. In particular, micronutrient deficiency is a major contributor to premature death and cognitive disablement. This deficiency is prevalent among children in the central highlands of Madagascar, with a high prevalence of stunting (59.9%), wasting (6.0%) and underweight (40.1%)[2] (INSTAT and UNICEF, 2019). However, effective interventions to address their micronutrient status are still unclear (Campos et al., 2019). Hence, understanding the link between agriculture and improved nutritional outcomes for children is of strategic importance.

Research linking agriculture and nutrition has recently gained much attention for its global importance. Specifically, agricultural diversification is often recommended for its contribution to dietary diversification, which in turn is associated with improved nutritional status of individuals. However, no common understanding has been reached regarding its impact on dietary diversity (Khonje et al., 2022; Sibhatu and Qaim, 2018). At the same time, supporting evidence indicating a link between dietary diversity and nutrient adequacy among children in developing countries has so far been inconclusive (Arimond and Ruel, 2004; Sié et al., 2018). More recent studies have analyzed the relationship between agricultural diversification - household diets - and child nutritional outcomes (Bühler et al., 2018; Chegere and Stage, 2020). Their findings suggest that production diversification significantly increases dietary diversity; yet, the latter explains only to a negligible extent the state of malnutrition among children.

To date, nearly all studies in this area contend that dietary diversity score can serve as a reliable proxy of dietary quality containing a range of micronutrients essential to the body (Arimond and Ruel, 2004). However, as a summary indicator, its appropriateness is often of concern (Jones, 2017).

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[2] These figures are of Vakinankaratra region, one of the regions belonging to the central highlands of Madagascar. Our study site is located in this region. Note that stunting rate is the highest in this region among 22 regions in Madagascar, whose average rate of child stunting is 41.6% (INSTAT and UNICEF, 2019). This is one of the reasons why we choose this study site.

That is, a diverse diet could:

(i) be devoid of important micronutrients (Chegere and Stage, 2020);

(ii) hide important variations in nutrient intakes (Jones, 2017);

(iii) mask the heterogeneous effect of each food group (Chegere and Stage, 2020);

(iv) obscure underlying pathways with limited understanding of the influence of subsistence and market-based production; and

(v) conceal the role of micronutrient intakes in improving a child's nutritional status.

With respect to (i) and (ii), the burden of collecting data on every micronutrient consumed leaves this area unexplored. Only one study has addressed the agriculture - food security- nutrition nexus from the perspective of micronutrient intake (Sekabira and Nalunga, 2020). However, the study does not investigate the role of food groups and their importance to human health. About (iii), only one study has analyzed the estimation of nutrient intakes by specifying food groups (Chegere and Stage, 2020). Yet, the study fails to assess the extensive role of each food group on micronutrient intake. As for (iv), although a handful of studies have distinguished the subsistence and income-generating pathways, they have not explicitly differentiated the impact of each food group (Muthini et al., 2020; Sekabira and Nalunga, 2020). Finally (v) implies the use of dietary diversity scores obscures the important role of caloric and micronutrient intake on child growth. Yet, limited studies have used the calorie and micronutrient intake measurements to assess the nutritional status of children thus far. Hence, there is an overall lack of empirical analyses to elucidate mediating pathways between the agriculture - food security - nutrition nexus. The present study aims to address these important gaps. The purpose is to unravel the link between agriculture, food/nutrition security, and child nutrition to formulate an effective intervention to address micronutrient deficiencies in children.

This study offers a more comprehensive contribution to the growing literature on agriculture - food security and food security - nutrition by taking three novel approaches. First, we use a twofold approach (the dietary diversity and the micronutrient intake approach) to trace the micronutrient intake pathway. Second, we single out the contribution of each food group on both dietary diversity and micronutrient intake to uncover their specific roles and to capture the heterogeneous linkage through both subsistence and market pathways. Third, we explore the association of diet quality in terms of calorie and micronutrient intake with child nutritional status.

The rest of the paper is organized as follows. Section 3.2 elucidates the conceptual framework that underpins the study. Section 3.3 provides an overview of the data collection process and outlines the analytical framework used in the analysis. In Section 3.4, we present the findings of our study and engage in detailed discussions. Finally, Section 3.5 offers concluding remarks to summarize the key insights and implications of our research.

3.2 Conceptual framework

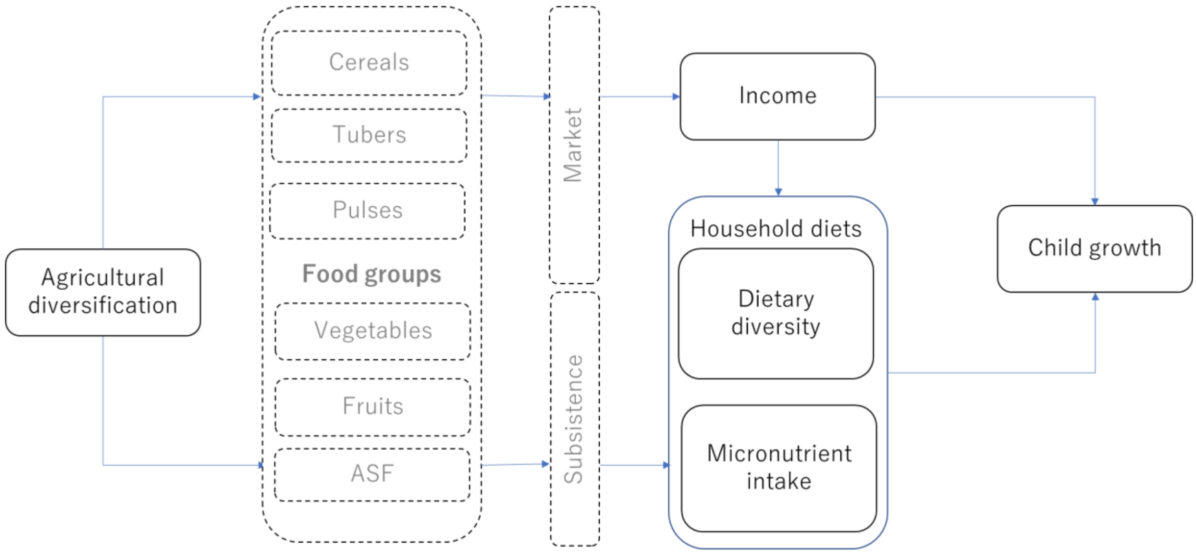

Fig. 3.1 Linkage between agricultural diversification and child nutritional status

Figure 3.1 represents the possible linkage between "agricultural diversification – household diets – child growth". Diversification of production is well known for its several benefits for smallholder farmers, including its potential to (i) manage risk by smoothing household incomes (Joshi et al., 2004) and (ii) influence household diet diversity (Jones et al., 2014). Empirical studies have demonstrated that agricultural diversification is associated with household nutrition in resource-constrained settings, mainly through two important pathways: (i) by generating income (Headey et al., 2019; Chegere & Kauki, 2022; Haji, 2022) and (ii) by improving the diversity and quality of household diets (for example Hirvonen & Hoddinott, 2017; Muthini et al., 2020; Ogutu & Qaim, 2020; Sekabira &

Nalunga, 2020). However, a meta-analysis by Sibhatu & Qaim (2018) concluded that there is little evidence to support the assumption that increasing diversity in agricultural production provides a successful strategy to improve smallholder diets and nutrition in most cases, which is further supported by other recent studies with their implications for child health (Lovo & Veronesi, 2019; Chegere & Stage, 2020).

Producing diverse foods then does not necessarily translate into a high-quality diverse diet that provides the adequate energy and nutrients needed for children's health. One issue that empirical research typically overlooks is the significance of each food group comprising the agricultural production diversity (Jones, 2017; Chegere & Stage, 2020). Indeed, some food groups may be more beneficial for market-oriented production, while others are for subsistence. A lack of differentiation between them may consequently negate or have the opposite effect on food security.

ASF, including milk, meat, and eggs, also have an important influence in the nutritional outcomes of children (Grace et al., 2018). ASF are dense in essential macronutrients (protein and fatty acids) and micronutrients (zinc, calcium, Vitamin A and B12), all of which are vital for growth and development, especially during the first two years of life (Randolph et al., 2007; Grace et al., 2018). Milk, in particular, has been found to stimulate growth factors, namely insulin-like growth factor (IGF), in children (Dror and Allen, 2011). Therefore, the need of a continuous and appropriate levels of ASF intake is necessary as it takes time for the nutritional benefits of these foods to have an effect on child growth, as well as any potential confounding factors that may affect the relationship between food consumption and growth (Grace et al., 2018).

Thus, by examining the role of each food group, this study attempts to pinpoint some of the reasons for the equivocal results of studies on the association between agricultural diversity production and nutritional outcomes.

3.3 Data, variables and descriptive statistics

3.3.1 *Data*

This study uses an original panel dataset produced from household surveys conducted in January/February

2019, in January/February 2020, and in January/February 2021 as part of SATREPS[3] project in which the authors participated. Each survey covers a total of 600 lowland rice producing households randomly selected from 60 villages in 3 out of 7 districts of the Vakinankaratra region in Madagascar. The surveys were implemented in the middle of rainy season, or the leanest season, and collected detailed information about agricultural activities and income in the previous dry season as well as household current situation at the time of interview including household-level food consumption (7-day recall) from home production and market purchases, household characteristics and individual-level anthropometric measures and characteristics. It is worth noting that the stock of produced food is the lowest in the lean season, and it concerns most of the food groups. After eliminating the cases with incomplete data, we construct an unbalanced panel dataset of 1624 household-observations, including households that appear at least twice across the three waves. For the panel data setting, we also include 229 child-observations under the age of 5 years, who were measured at least twice across the three waves.

3.3.2 Variables

3.3.2.1 Outcome variables

a. Household diet quality

The household dietary quality is assessed by household dietary diversification and micronutrient components in the diet. We use two indicators for household dietary diversification: Household Dietary Richness Score (HDRS), and Household Dietary Diversity Score (HDDS).

HDRS is a quantitative measure used to evaluate the nutritional diversity and quality of the diet within a household, serving as an indicator of the adequacy and variety of food consumption. This scoring system incorporates raw count of any food crops and animal products consumed by the household. To do so, we analyze the types of foods consumed by the household using 7-day period dietary recall. A higher HDRS implies a more diverse

[3] SATREPS stands for Science and Technology Research Partnership for Sustainable Development

and nutritious diet, signifying superior nutritional quality within the household.

Similarly, HDDS is a quantitative measure used to assess the variety and breadth of food consumption within a household, providing an indication of dietary diversity and quality. This scoring system is based on the inclusion of different food groups that represent distinct nutritional categories, such as cereals, tubers, pulses, fruits, vegetables, milk and dairy products, meat, fish, egg, fats/oils, sweets, and other miscellaneous items. Each food group is assigned a score, typically binary (0 or 1), based on whether any food from that group is consumed by household members during the 7-day recall period. The scores for all food groups are then summed to calculate the HDDS, with a higher score indicating a greater range of foods consumed and therefore greater dietary diversity within the household (Kennedy, Ballard & Dop, 2013).

The micronutrient components, namely Iron, Zinc, and Vitamin A, as well as calorie intake, are derived from the food consumption based on the 7-day recall data. Portion sizes consumed by the households are recorded and subsequently converted into standardized measurements. By referencing the food composition tables, specifically the FAO (2020) dataset, appropriate nutrient values are assigned to each food item. The intake of micronutrients is calculated by multiplying the consumed amounts by the respective nutrient values. We then aggregate the micronutrient values across the 7-day recall period for each household to enable estimation of the overall micronutrient intake within a household.

In our analysis, we use the calorie and micronutrient intake per Adult-Male Equivalent (AE). An AE is a metric that allows for the direct comparison of food or energy intakes across households of different sizes and compositions by accounting for the household's characteristics. Micronutrient intake per AE thus represents the adjusted intake of micronutrients considering variations in energy needs among individuals, ensuring accurate comparisons within the household. In our analysis, we use a table provided by Sununtnasuk (2013), based on USAID project, to derive our adult-equivalent factor. To scale it to the energy and micronutrient intake of the household, we multiply the micronutrient intake of the household by the corresponding AE factor. This method enables us to standardize the assessment of micronutrient adequacy across individuals.

b. Child nutritional status

The second category of outcome variables are the indicators of child nutritional status. These variables are based on the anthropometric measurements of children aged 6 to 60 months. Anthropometric measurements provide critical indicators for assessing child nutritional status, enabling the calculation of Height-for-Age Z-score (HAZ), Weight-for-Age Z-score (WAZ), and Weight-for-Height Z-score (WHZ). These scores are derived from the child's anthropometric data, including height, weight, and age, and are commonly used to evaluate growth and nutritional adequacy (WHO, 2021). The HAZ reflects linear growth and indicates chronic malnutrition or stunting, with negative scores indicating below-average height-for-age. We measure stunting as indicated by low HAZ (HAZ <-2) (ibid.). WAZ captures overall nutritional status and helps identify acute malnutrition or underweight, where negative scores indicate below-average weight-for-age. We also capture a child being underweight as having a low WAZ (WAZ < - 2) (ibid.). WHZ, on the other hand, focuses on acute nutritional status and identifies wasting, with negative scores indicating below-average weight-for-height. Wasting indicates a child characterized by a low WHZ (WHZ <-2) (ibid.). In our analysis, we define an additional variable to account for all of the above chronic indicators, namely, child undernutrition status. An undernourished child is assigned a score of 1 if he/she is either stunted, wasted or underweight, and 0 otherwise.

3.3.2.2 Independent variables

a. Main explanatory variables

Two explanatory variables are used as indicators of production diversity within a household. First, we use the Agricultural Richness Score (ARS) as an indicator of agricultural diversity production by the household. The ARS is calculated based on the count of different food crops and animal products produced by the household, consistent with the approaches used by Sibhatu & Qaim (2018) and Chegere & Stage (2020). Our analysis focuses on the agricultural production during the dry season preceding the survey, specifically emphasizing the pre-lean period. While acknowledging that the ARS does not account for the proportional allocation of land to each crop, previous research by Chegere & Stage (2020) highlights its strong association with the Household Dietary Richness Score (HDRS) if they are closely related. Second, we use the Agricultural Diversity Score (ADS) which is a measure of a food-group based agricultural diversity production at the household level. The ADS is calculated based on the count of different food groups produced by the household, following the classification of the 12 food groups used in the HDDS. However, it is important to note that households may produce only a limited number of food groups, while obtaining others from the market. In the subsequent analysis of this study, this scoring system allows for the identification of specific food groups that potentially contribute to a higher nutritional quality within the household[4].

b. Control variables

In our regression analysis, we account for various factors at both the household and child levels that are deemed significant in our study. At the household level, we include variables such as household size, the proportion of preschool and schooling children, the proportion of elderly individuals, and the proportion of working women. Additionally, we consider plot characteristics, including the number of lowland rice plots, ownership of upland rice plots, presence of other gardening plots, and rented-in plots. To capture household affluence, we control for per-capita farm and non-farm assets. Other controls encompass water availability in the dry season, last time to visit the market, per capita Tropical-Livestock Unit (TLU), and yearly rainfall[5] preceding the survey. At the child level, we include four additional variables: the age of the children in months (including its squared term), a binary variable indicating school attendance, and another binary variable indicating whether the child was sick during the survey period. By incorporating these comprehensive control variables, we ensure robustness and account for potential confounding factors in our analysis.

[4] During the three surveys, 54% of sample households produced at least one of the 8 food groups: cereals (23%), tubers (23%), pulses (5%), vegetables (12%), milk (8%), egg (6%), meat (4%), and other food groups (grass and artemezia) (1%). There was no household producing 5 food groups, namely fish, fruit, sugar, oil, or other miscellaneous foods such as tea. Therefore, we consider only 8 food groups for ADS. Also please note that 43% of sample households produced nothing because it is in the dry season.

[5] Our climatic data is derived from the Integrated Multi-satellitE Retrievals (IMERG) for Global Precipitation Mission (GPM). This data source offers half-hourly global precipitation data, providing a spatial resolution of 0.1º or 10km*10km (Huffman et al., 2020).

3.3.3 *Analytical Framework*

First, we examine the linkage of production diversity (ARS and ADS respectively) with household dietary quality (diversification as well as micronutrient components) and child nutritional status using household and child fixed effects (FE) models, respectively.

The estimates for drivers of household food consumption information are obtained using the following model:

$$y_{ht} = \beta_1 D_{ht} + \beta_2 X_{ht} + \beta_3 (V_h * T_t) + \beta_4 T_t + \beta_5 V_h + \tau_h + \varepsilon_{ht} \quad (3.1)$$

where y_{ht} represents household dietary diversification, calorie and micronutrient intake, D_{ht} is the crop diversification as described by ARS and ADS. X_{ht} is vector of the household characteristics, asset endowment or capital variables. We also include the village (*V*), time (*T*), and village-time interactions (*V*T*) to control for temporal and spatial differences in biophysical conditions, access to infrastructure, policy changes, etc. that are not possibly captured by the other covariates. τ_h and ε_{ht} are the household-specific fixed effects and the error term, respectively. In Equation 3.1., we estimate the regression using FE model clustering at household level.

At the child level, we use the following model to investigate the association between the agricultural production diversity on child nutritional outcomes:

$$y_{cht} = \alpha_1 D_{ht} + \alpha_2 C_{ct} + \alpha_3 X_{ht} + \alpha_4 (V_h * T_t) + \alpha_5 T_t + \alpha_6 V_h + \tau_c + \varepsilon_{cht} \quad (3.2)$$

where y_{cht} represents nutritional outcomes of a child *c* of household h at time *t*. D_{ht} is the crop diversification as described by ARS and ADS. C_{ct} is a vector of child characteristics. X_{ht} is vector of the household characteristics, asset endowment or capital variables. We also include the village (*V*), time (*T*), and village-time interactions (*V*T*). τ_c and ε_{cht} are the child-specific fixed effects and the error term, respectively. In Equation 3.2., we estimate the regression using FE model clustering at child level.

Third, using the same model as in Equation 3.1, we disaggregate foods produced into food groups and investigate the linkage of the production of each food group with household dietary quality. In this analysis, we consider two sources of foods for consumption, market purchase and self-production, and respectively investigate their association with dietary diversity as well as micronutrient intakes[6]. The relationship between household dietary diversification, micronutrient intake and food group produced is represented using the following model:

$$y_{ht} = \alpha_1 FG_{ht}^1 + \alpha_2 FG_{ht}^2 + \alpha_3 FG_{ht}^3 + \alpha_4 FG_{ht}^4 + \alpha_5 FG_{ht}^5 + \alpha_6 FG_{ht}^6 + \alpha_7 FG_{ht}^7 + \beta_2 X_{ht} + \beta_3 (V_h * T_t) + \beta_4 T_t + \beta_5 V_h + \tau_h + \varepsilon_{ht} \quad (3.3)$$

where y_{ht} represents household dietary diversification, calorie and micronutrient intake. FG_{ht}^{1-7} represent each food group comprising the ADS, namely cereal, tuber, pulse, vegetable, milk, egg and meat[7]. The other variables are similar to the ones described in Equation 3.1.

Fourth analysis is for the latter half of the linkage, namely between food consumption and child nutritional status. We use the model as in Equation 3.2. but as explanatory variables, we use the household dietary quality variables, namely HDRS or HDRS, and calorie and micronutrient intake from the market and subsistence pathways. Their associations with child nutritional status are estimated by a FE linear model, clustered at child level.

3.4 Results

3.4.1 *Descriptive Statistics*

Table 3.1 presents the summary statistics of outcome variables for the pooled sample. Based on a 7-day recall period, the average household consumes 11.38 food items, which is composed of 8.07 food groups, indicating a shortage of 4 food groups. Table 3.1. also indicates that approximately 75% of the consumed food groups are acquired from the market sources. Furthermore, we provide insights into the qualitative aspects of household food security, focusing on energy and essential micronutrient intakes, which are converted into AE. The findings reveal an average energy intake of approximately 2,645 kCal/AE/day. The household's average iron intake stands at 16.22 mg/AE/day, while zinc intake is 9.55 mg/AE/day, and vitamin A intake is 1083.80 µg/AE/day. It is worth noting that

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[6] Within the same food group, a household can consume both self-produced foods and market-purchased foods. We treat them as different kinds of foods and analyze their contributions to dietary quality separately.
[7] For the purpose of the disaggregation analysis, we use only 7 specific food groups, excluding the "other food groups" category, due to the relatively low proportion of households producing such groups.

the intake of zinc and iron falls below the recommended levels for adult males, while calorie intake and vitamin A appear to be sufficient[8]. Moreover, more than 60% of calorie intake is sourced from the household's own production. Both the market and own production make virtually an equal contribution to the iron supply. In the case of zinc, there is a slightly higher contribution from own production, while the majority of vitamin A intake is acquired from the market.

The second set of outcome variables in our study focuses on the nutritional status of children. Our analysis reveals that nearly 60 percent of children in the sampled households suffer from stunting, approximately 20 percent experience wasting, and over 40 percent are classified as underweight[9]. Among these indicators, stunting presents the most concerning average score of -2.34, falling below the stunting threshold of -2. Furthermore, when considering any of the three conditions (stunted, wasted, or underweight), they collectively account for over 70 percent of the observed child cases.

Table 3.2 provides a summary of the mean values for the explanatory and control variables used in our analysis. The key explanatory variables examined are the ARS and ADS, with average values of 0.90 and 0.83, respectively. The control variables are categorized into different groups encompassing household characteristics, parcel characteristics, household status, water availability in the dry season, market orientation, and other relevant factors. On average, households consist of 4.73 members, with a proportion of preschool children (under 5 years old) at 11%, schooling children (5-15 years old) at 24%, elderly members (above 60 years old) at 11%, and working women (between 15 and 60 years old) at 27%. One household possesses 1.62 lowland plots on average. Additionally, approximately 60% of households own at least one upland rice plot, 90% own other types of plots, and 5% rented additional plots during the survey period.

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[8] They are 2,133 Kcal/day, 17.5 mg/day for iron, 12 mg/day for zinc, and 900 µg/day for vitamin A.

[9] These figures are not the same as those from INSTAT and UNICEF (2019) given in Section 3.1, particularly about the wasting. Although we cannot provide evidence, we consider that the difference should come from the fact that the INSTAT and UNICEF data covered the whole Vakinankaratra region including urban area and were collected after harvest period, while our data were only from rural area and collected during lean period. Since wasting reflects acute malnutrition in a short period, seasonality matters.

Table 3.1 Summary statistics of outcome variables

Variables	Obs.	Mean	Std.	Min.	Max.
Outcome variables: Household dietary quality (7-day recall)					
Household Dietary Richness Score	*1624*	11.38	3.36	3	26
From market	*1624*	7.75	3.20	2	21
From subsistence	*1624*	3.59	2.28	0	16
Household Dietary Diversity Score	*1624*	8.07	1.41	3	12
From market	*1624*	6.45	1.75	2	11
From subsistence	*1624*	2.44	1.36	0	7
Energy (Kcal/AE/day)	*1624*	2645.02	1175.51	553.0	14493.01
From market	*1624*	1047.28	1164.58	0	8240.98
From subsistence	*1624*	1598.70	1137.28	0	14493.01
Fer (mg/AE/day)	*1624*	16.22	9.88	2.2	100.79
From market	*1624*	8.67	8.77	0	89.19
From subsistence	*1624*	7.56	6.49	0	73.03
Zinc (mg/AE/day)	*1624*	9.55	5.10	1.6	84.22
From market	*1624*	4.22	4.22	0	27.93
From subsistence	*1624*	5.34	4.28	0	79.47
Vitamin A (μg/AE/day)	*1624*	1083.80	1320.16	0	12460.34
From market	*1624*	805.19	1246.80	0	12232.75
From subsistence	*1624*	279.89	513.13	0	4939.06
Outcome variables: Child nutrition					
HAZ	*229*	-2.34	1.60	-5.76	2.63
Stunted	*229*	0.58	0.49	0	1
WHZ	*229*	-0.66	2.05	-6.7	8.57
Wasted	*229*	0.20	0.40	0	1
WAZ	*229*	-1.79	1.39	-5.28	2.33
Underweight	*229*	0.42	0.50	0	1
Undernourished	*229*	0.70	0.46	0	1

Notes: Observations from all the surveys were pooled. Mean values are displayed with standard deviations (Std).

Only a small fraction of households (20%) has access to plots that are irrigated during the dry season. The average per-capita TLU is 0.25, while the average per-capita home value is 58,790 MGA (equivalent to USD 13), and the average per-capita farm value is 63,509 MGA (equivalent to USD 14.6). Rainfall during the rainy season is approximately 1467 mm for annual precipitation. In terms of child characteristics, the average age is 34.84 months, 7% of children have started attending school, and 4% were reported as sick during the survey.

Table 3.2 Summary statistics of socioeconomic characteristics

Variables	*Obs.*	Mean	Std.	Min.	Max.
Main explanatory variables					
Agricultural Richness Score (ARS)	*1624*	0.90	1.04	0	8
Agricultural Diversity Score (ADS)	*1624*	0.83	0.92	0	6
Control variables					
Household characteristics					
Household size	*1624*	4.73	1.93	1	13
Share of preschool children	*1624*	0.11	0.15	0	0.75
Share of schooling children	*1624*	0.24	0.20	0	0.85
Share of old members	*1624*	0.11	0.24	0	1
Share of working woman	*1624*	0.27	0.16	0	1
Parcel characteristics					
Number of plots used for lowland rice	*1624*	1.62	0.99	0	10
Possession of upland rice (Yes=1)	*1624*	0.61	0.49	0	1
Possession of other plots (Yes=1)	*1624*	0.90	0.30	0	1
Rented-in plots (Yes=1)	*1624*	0.05	0.22	0	1
Household status					
Home value per capita (MGA[1])	*1624*	58790.62	149033.50	0	2062000
Farm value per capita (MGA[1])	*1624*	63509.96	168494.10	0	2075000
Water availability in dry season	*1624*	0.20	0.24	0	1
Market orientation (last day to market)	*1624*	3.67	2.27	0	30
Tropical Livestock Unit (per-capita)	*1624*	0.25	0.27	0	2.54
Yearly rainfall[2]	*36*	1467.52	145.43	1186.76	1770.28
Child-level variables					
Age in months	*229*	34.84	15.37	6	60
School attendance	*229*	0.07	0.25	0	1
Sick (Yes=1)	*229*	0.04	0.20	0	1

Notes: Observations from all the surveys were pooled. Mean values are displayed with standard deviations (Std). [1]MGA stands for Malagasy Ariary. 1MGA is equivalent to USD 0.00023 as of September 2022. [2] We use 36 rainfall grids that cover the study area to match our geolocation data, which are specific to each household.

3.4.2 *Empirical results*

3.4.2.1 *The association between agricultural production diversity, household dietary diversity and dietary quality*

Table 3.3 provides the outcomes of panel regression models that investigate the relationship between agricultural production diversity and both household dietary diversity and dietary quality. To examine these associations, separate regressions are conducted for two sets of outcome variables: (i) household dietary diversity, measured by HDRS and HDDS; and (ii) calorie and micronutrient intake, specifically Iron, Zinc, and Vitamin A. Generally, the findings reveal that agricultural production diversity show a positive and statistically significant correlation with both HDRS and HDDS. However, there is no significant association observed between agricultural production diversity and calorie or micronutrient intake.

The findings in Column [1] of Table 3.3 show a significant positive association between ARS and HDRS at a significance level of 1%. The estimated marginal effect of 0.42 indicates that increasing agricultural production by two additional types of food items leads to a corresponding increase of one food item in dietary richness. Moreover, Column [2] presents the results of the association between ADS, a score based on food-group diversity, and HDRS, indicating a significant and positive association. The estimated marginal effect of 0.50 for ADS suggests that expanding agricultural production by two more food groups would result in an increase of one food item in dietary richness. Moreover, Columns [3] and [4] show significant associations between both agricultural production diversity scores and HDDS. The estimated marginal effects for both ARS and ADS are 0.12 and 0.15, respectively, indicating that agricultural diversity would need to expand by nine different species to elevate dietary diversity by one food group. These results thus highlight that increasing agricultural diversity within specific food groups has a greater influence on dietary richness compared to increasing the number of crop species. However, it is important to recognize that it is inherently difficult for households to achieve such expansion, necessitating choices and prioritization of certain food groups over others.

Table 3.3 Association of agricultural production diversity, household dietary diversity and micronutrient intake (fixed-effect linear regression)

Variables	HDRS		HDDS		Log of energy (kCal/AE/day)		Log of Fe (mg/AE/day)		Log of Zn (mg/AE/day)		Log of Vitamin A (µg/AE/day)	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
ARS	0.42***		0.12***		-0.012		0.013		-0.014		0.051	
	(0.087)		(0.042)		(0.014)		(0.015)		(0.013)		(0.035)	
ADS		0.50***		0.15***		-0.0064		0.023		-0.011		0.053
		(0.098)		(0.048)		(0.016)		(0.018)		(0.016)		(0.042)
Household characteristics	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Household Fixed-effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Village*year	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Village dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Within R-sq	0.535	0.536	0.350	0.351	0.282	0.282	0.473	0.474	0.428	0.427	0.589	0.589
adj. R-sq	0.494	0.495	0.292	0.294	0.219	0.218	0.427	0.427	0.377	0.377	0.552	0.552
Observations	1624	1624	1624	1624	1624	1624	1624	1624	1624	1624	1624	1624

Notes: These are FE estimates. We control for household variables as those described in Table 3.2. We also control household fixed-effects, interaction term between village and year dummies, village dummies. Standard errors in parentheses are clustered at household level; * p<0.10 ** p<0.05 *** p<0.01

In Columns [5] to [12] of Table 3.3, we observe that neither ARS nor ADS has a significant relationship with energy and micronutrient intakes. The large insignificant results imply that heterogeneity as to how to diversify food production may mask the potential contribution of specific food groups to the overall intake of micronutrients. All our results are consistent considering the pooled OLS regression (see Table A3.1 in Appendix).

3.4.2.2 *The association between agricultural production diversity and child nutritional outcomes*

Table 3.4 presents the findings on the relationship between agricultural production diversity and child nutritional outcomes. In Columns [1] to [4], we examine the marginal effects of household agricultural production diversity on the HAZ and the prevalence of stunting among children. The results reveal that neither ARS nor ADS shows a statistically significant association with the linear growth of children. One potential explanation for the lack of statistical significance could be the insufficient presence of crucial micronutrients within the diverse diets (Chegere & Stage, 2020).

Moving to Columns [5] to [8], we explore the potential association of agricultural production diversity on the WHZ and the likelihood of wasting among children. The results indicate that both ARS and ADS have a positive and statistically significant association with the WHZ, indicating that diversified agricultural production positively influences children's weight relative to their height. Results indicate that expanding agricultural production by one additional type is associated with an average increase of 0.64 in the WHZ at a significance level of 5%. However, no significant association is observed between agricultural production diversity and the binary variable of wasting status. Since wasting serves as an indicator of acute malnutrition, reflecting recent and severe weight loss, the findings suggest that recent diversified agricultural production significantly improves the WHZ within a shorter time period. This finding may offer an explanation for the elevated prevalence of wasting observed in our study area compared to regional statistics (6% versus 20%).

In Columns [9] to [12] of Table 3.4, we examine the relationship between agricultural production diversity and the WAZ of children, as well as their underweight status. Across all regression models for these outcome variables, consistent associations are observed for both ARS and ADS.

Table 3.4 Association of agricultural production diversity on child nutritional outcomes (fixed-effect linear regression)

Variables	HAZ		Stunted		WHZ		Wasted		WAZ		Underweight		Undernourishment	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
ARS	0.30		-0.062		0.64**		-0.015		0.59***		-0.15***		-0.0032	
	(0.19)		(0.083)		(0.26)		(0.052)		(0.15)		(0.054)		(0.075)	
ADS		0.33		-0.094		0.74***		-0.034		0.66***		-0.18***		-0.030
		(0.21)		(0.090)		(0.25)		(0.054)		(0.15)		(0.060)		(0.079)
Child characteristics	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Household characteristics	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Child Fixed-effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Village*year	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Village dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R-sq	0.764	0.763	0.681	0.685	0.766	0.769	0.758	0.759	0.741	0.745	0.747	0.753	0.681	0.681
adj. R-sq	0.628	0.628	0.499	0.505	0.633	0.636	0.619	0.621	0.593	0.599	0.603	0.612	0.498	0.499
Observations	229	229	229	229	229	229	229	229	229	229	229	229	229	229

Notes: These are FE estimates. We control for household variables and child characteristics as those described in Table 3.2. We also control child fixed-effects, interaction term between village and year dummies, village dummies. Standard errors in parentheses are clustered at child level; * p<0.10 ** p<0.05 *** p<0.01

Results reveal that the addition of a single crop species to the household's agricultural production diversity is significantly and positively associated with an approximate 0.6 increase in the WAZ at a significance level of 1%. This implies a substantial reduction in the prevalence of underweight status, ranging from around 15% for children aged 6 to 60 months.

Moving to Columns [13] and [14], we investigate the association between agricultural production diversity and the status of being undernourished. Results indicate no significant association between agricultural production diversity and undernourishment.

Taken together, the findings highlight the relationship between agricultural production diversity and child nutritional status, particularly emphasizing the influence of recent agricultural production on children's weight, which is more susceptible to short-term hunger and nutritional fluctuations.

3.4.2.3 The association between each food group and household dietary quality

Table 3.5 presents the findings obtained from disaggregating the agricultural production diversity into distinct groups to explore their individual contributions to household dietary quality. In Columns [1] and [3], we focus on the association of each food group on dietary diversification under the influence of market. We observe that only egg and milk production have a positive and significant effect on the 7-day dietary scores. These products, being primarily sold in the market to generate cash income, may contribute to food consumption diversity through the indirect pathway.

Conversely, we investigate the direct linkage, or dietary diversification through own-production, in Columns [2] and [4]. Here, we find that the production of egg and pulses significantly increases both HDRS and HDDS based on the 7-day recall. Additionally, tuber production presents a significant influence on HDDS through the same route.

The second half of Table 3.5 focuses on the results pertaining to calorie and micronutrient intakes, specifically presented in Columns [5] to [12]. In particular, our analysis reveals a remarkable and statistically significant association between tuber and pulse production and the intake of key micronutrients, including iron, zinc, as well as calorie intake through the pathway of own production. However, pulse production presents not only significantly higher estimates than tuber production, but also is solely significantly associated with the vitamin A intake. Since the outcome variables are measured in logarithm, we can interpret our results in percentage change. The findings thus demonstrate that cultivating crops within the pulse food group in dry season is significantly associated with a substantial increase in daily calorie intake by approximately 65%. Similarly, for each unit increase in pulse production, daily iron intake significantly rises by approximately 41%, daily zinc intake by 26%, and daily vitamin A intake by 77%. On the other hand, cultivating crops within the tuber food group in dry season is significantly associated with a substantial increase in calorie intake by approximately 52%, iron intake by 18%, and zinc intake by 10%. It is important to note that the contribution to household zinc intake is about three times higher for pulse production than for tuber production, at the 5% and 10% significance level, respectively. Thus, pulse production consistently presents the highest estimates among the various agricultural production categories, emphasizing its prominent role in enhancing household micronutrient intake.

With regards to other food groups, cereal production also demonstrates a negative association with calorie and two crucial micronutrient intakes sourced from the market: zinc and iron. Similarly, our analysis uncovers a noteworthy significant and positive association between cereal production and zinc intake through subsistence, albeit with relatively smaller estimates. Additionally, egg groups are positively associated with calorie and vitamin A intake through subsistence, and negatively associated with iron intake from the market within households. These findings indicate that cereal production may impede farmers to procure nutrient-rich foods from the market, whereas households engaged in egg production may tend to enhance dietary diversity by purchasing foods with lower nutrient density. Furthermore, the lack of a significant association between vegetable/ meat production and energy or micronutrient intake suggest a limited contribution of both food groups to household calorie and micronutrient intake.

All our results are robust considering the Pooled OLS regression (see Table A3.2 in Appendix). Hence, the findings in Table 3.5 imply that dietary diversity indicators may (i) miss out on important micronutrients; (ii) mask important variations in nutrient intakes; (iii) conceal the heterogeneous linkage of specific food groups; and (iv) mask the underlying pathway of micronutrient sources.

Table 3.5 Association between individual food groups on dietary diversity and micronutrient intake of household (fixed-effect linear model)

Variables	HDRS		HDDS		Log of energy intake		Log of iron intake		Log of zinc intake		Log of VitA intake	
	Foods bought in the market	Food own produced	Foods bought in the market	Food own produced	Foods bought in the market	Food own produced	Foods bought in the market	Food own produced	Foods bought in the market	Food own produced	Foods bought in the market	Food own produced
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(9)	(10)
Cereal	0.068	0.20	-0.052	0.083	-0.43***	0.24	-0.16**	0.060	-0.21***	0.13**	0.14	-0.026
	(0.21)	(0.16)	(0.13)	(0.098)	(0.099)	(0.17)	(0.063)	(0.068)	(0.061)	(0.059)	(0.14)	(0.16)
Tuber	0.014	0.22	-0.077	0.19**	0.0091	0.52***	0.012	0.18***	-0.017	0.10*	0.0079	0.12
	(0.20)	(0.15)	(0.12)	(0.093)	(0.078)	(0.17)	(0.054)	(0.068)	(0.049)	(0.055)	(0.13)	(0.15)
Pulse	-0.51	1.13***	-0.16	0.61***	-0.26	0.65**	-0.17*	0.41***	-0.12	0.26**	-0.51*	0.77***
	(0.34)	(0.28)	(0.19)	(0.18)	(0.17)	(0.29)	(0.094)	(0.12)	(0.088)	(0.11)	(0.28)	(0.29)
Vegetable	0.032	-0.12	-0.015	-0.13	-0.0091	0.0096	-0.0021	-0.0077	-0.0051	-0.017	0.089	0.049
	(0.29)	(0.24)	(0.17)	(0.15)	(0.11)	(0.24)	(0.063)	(0.095)	(0.061)	(0.077)	(0.17)	(0.25)
Egg	0.75**	0.72***	0.60***	0.56***	-0.12	0.71***	-0.21*	0.23*	-0.17	0.11	-0.14	0.92***
	(0.35)	(0.23)	(0.22)	(0.15)	(0.16)	(0.24)	(0.11)	(0.12)	(0.11)	(0.095)	(0.20)	(0.34)
Milk	0.99***	0.54	0.40**	0.16	-0.044	0.070	-0.029	-0.019	-0.035	0.018	0.014	-0.34
	(0.36)	(0.35)	(0.20)	(0.18)	(0.14)	(0.26)	(0.087)	(0.12)	(0.083)	(0.094)	(0.24)	(0.30)
Meat	0.17	0.058	-0.062	-0.00081	0.0019	0.011	0.12	0.091	0.051	-0.022	-0.099	0.17
	(0.50)	(0.37)	(0.22)	(0.22)	(0.18)	(0.30)	(0.11)	(0.15)	(0.10)	(0.12)	(0.31)	(0.40)
Household characteristics	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Household Fixed-effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Village*year	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Village dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Within R-sq	0.265	0.480	0.237	0.415	0.291	0.425	0.340	0.494	0.291	0.409	0.424	0.477
adj. R-sq	0.197	0.432	0.166	0.361	0.225	0.372	0.279	0.447	0.225	0.354	0.370	0.428
Observations	1624	1624	1624	1624	1624	1624	1624	1624	1624	1624	1624	1624

Notes: These are FE estimates. We control for household variables as those described in Table 3.2. We also control household fixed-effects, interaction term between village and year dummies, village dummies. Standard errors in parentheses are clustered at household level; * p<0.10 ** p<0.05 *** p<0.01

3.4.2.4 *Diet quality and child nutrition outcomes*

In Table 3.6, we present the findings derived from a FE linear model that examines the relationship between household dietary diversification, micronutrient intake, and child nutritional outcomes. Overall, our results reveal no significant association between HDRS and HDDS, assessed over a 7-day recall period, with the various child nutritional outcomes. These results suggest that, within our study area, a diversified diet does not necessarily exert a direct influence on the health status of children.

We further examine the relationship between energy and micronutrient intake (specifically zinc, iron, and vitamin A), sourced either from the market or through own production, on the nutritional status of children within the same regression framework. These variables are measured in logarithms. Among all the variables of interests, results indicate a consistent and significant association between zinc intake from subsistence and both the HAZ and the prevalence of stunting among children. In fact, the biggest and the only positive association with HAZ is from zinc intake through the indirect pathway. Columns [1] to [4] reveal that with a 10% increase in zinc intake from the subsistence pathway, the HAZ increases by approximately 0.22, and the likelihood of stunting is reduced by around 7%, respectively. This result is in line with a recent study conducted in Uganda (Amondo et al., 2023) reporting that zinc supply had also the biggest contribution in increased HAZ over caloric, protein and iron supply, despite the limitations in estimating all nutrients collectively. Moreover, our results show that zinc intake from subsistence shows a negative and statistically significant association with the likelihood of children being underweight and undernourished, as shown in Columns [11] to [14]. Specifically, for every 10% increase in daily zinc intake from the subsistence route, there is a reduction in the likelihood of underweight and undernourishment status ranging from 5.5% and 5%, respectively. We also observe that zinc intake from the indirect pathway significantly and negatively influence the likelihood of being stunted and undernourished, not HAZ, WAZ and underweight status, suggesting the important role of zinc in improving child chronic malnutrition overall.

Additionally, we observe that energy intake from both sources significantly and negatively influences linear growth and positively the prevalence of stunting among children, while not affecting the likelihood of being undernourished.

Table 3.6 Association between household dietary quality and child's nutritional status

Variables	HAZ		Stunted		WHZ		Wasted		WAZ		Underweight		Undernourished	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
HDRS	-0.054		0.040		0.13		-0.040		0.059		0.029		-0.0015	
	(0.074)		(0.034)		(0.15)		(0.042)		(0.082)		(0.032)		(0.030)	
HDDS		-0.17		0.056		-0.084		-0.022		-0.11		0.047		0.026
		(0.14)		(0.061)		(0.24)		(0.063)		(0.14)		(0.060)		(0.064)
Log of energy intake from market	-1.17***	-1.22***	0.43**	0.41***	0.34	0.085	-0.072	-0.031	-0.43	-0.61	0.19	0.18	0.23	0.25
	(0.40)	(0.37)	(0.16)	(0.16)	(0.69)	(0.67)	(0.16)	(0.15)	(0.41)	(0.39)	(0.15)	(0.15)	(0.17)	(0.16)
Log of energy intake from subsistence	-0.51*	-0.47*	0.22***	0.20***	0.14	0.083	-0.066	-0.047	-0.27*	-0.29*	0.17**	0.15**	0.060	0.059
	(0.28)	(0.26)	(0.062)	(0.061)	(0.40)	(0.39)	(0.071)	(0.068)	(0.16)	(0.16)	(0.077)	(0.076)	(0.055)	(0.054)
Log of iron intake from market	0.89	0.93	0.51	0.56	2.17	2.64	0.10	0.017	1.94*	2.23**	-0.72	-0.69	0.66**	0.62*
	(1.02)	(0.96)	(0.35)	(0.37)	(1.87)	(1.90)	(0.34)	(0.33)	(0.99)	(1.01)	(0.44)	(0.45)	(0.32)	(0.33)
Log of iron intake from subsistence	-1.01	-0.94	0.40	0.37	1.81	1.73	-0.082	-0.051	0.61	0.59	-0.049	-0.077	0.38	0.38
	(0.70)	(0.69)	(0.27)	(0.28)	(1.14)	(1.13)	(0.20)	(0.19)	(0.55)	(0.56)	(0.18)	(0.17)	(0.24)	(0.24)
Log of zinc intake from market	1.14	1.24	-1.02**	-1.06**	-2.84	-2.86	-0.13	-0.11	-1.22	-1.19	0.52	0.49	-1.20**	-1.21**
	(1.25)	(1.22)	(0.47)	(0.48)	(2.16)	(2.19)	(0.47)	(0.48)	(1.35)	(1.30)	(0.60)	(0.61)	(0.48)	(0.48)
Log of zinc intake from subsistence	2.53***	2.45***	-0.82***	-0.75***	-0.51	-0.26	0.23	0.16	1.22	1.34*	-0.68**	-0.63**	-0.53*	-0.54**
	(0.85)	(0.79)	(0.28)	(0.26)	(1.56)	(1.44)	(0.28)	(0.24)	(0.77)	(0.71)	(0.29)	(0.27)	(0.28)	(0.27)
Log of vitamin A from market	-0.15	-0.17	0.0072	0.013	-0.14	-0.17	0.046	0.046	-0.16	-0.19	0.077*	0.082*	0.018	0.023
	(0.14)	(0.15)	(0.047)	(0.050)	(0.23)	(0.26)	(0.041)	(0.047)	(0.13)	(0.14)	(0.043)	(0.047)	(0.041)	(0.044)
Log of vitamin A from subsistence	0.21	0.17	-0.14***	-0.12**	-0.67**	-0.67**	-0.0055	-0.017	-0.26*	-0.27*	-0.025	-0.010	-0.086*	-0.081
	(0.20)	(0.19)	(0.054)	(0.059)	(0.32)	(0.31)	(0.054)	(0.057)	(0.15)	(0.14)	(0.049)	(0.049)	(0.048)	(0.050)
Child characteristics	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Household characteristics	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Child Fixed-effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Village*year	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Village dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Within R-sq	0.857	0.859	0.787	0.785	0.797	0.794	0.801	0.794	0.822	0.822	0.820	0.820	0.748	0.749
adj. R-sq	0.754	0.758	0.635	0.631	0.651	0.646	0.658	0.647	0.695	0.696	0.692	0.691	0.567	0.569
Observations	229	229	229	229	229	229	229	229	229	229	229	229	229	229

Notes: These are FE estimates. We control for household variables and child characteristics as those described in Table 2. We also control child fixed-effects, interaction term between village and year dummies, village dummies. Standard errors in parentheses are clustered at child level; * p<0.10 ** p<0.05 *** p<0.01

One plausible explanation for this result could be the disproportionate consumption of cereals as it may not sufficiently contribute to micronutrient intake, as evidenced in Table 3.5.

Overall, our results underscore the importance of achieving adequate micronutrient intake, particularly through the direct pathway, as reflected by zinc intake, in significantly reducing the risk of stunting and undernourishment among children. Hence, the finding (v) displays the role of micronutrient intakes, in this case zinc, in improving stunting in children and reducing the probability of being undernourished in children.

It is worth noting that since small children do not necessarily consume the same food as adults, the observed associations are considered to be due to the household's awareness about nutrition, but may be partially attributed to pulse production. Moreover, even though we acknowledge that the two linkages are not joined, the result tends to seemingly show the associative link between pulse production – zinc intake – and child nutritional status. To further probe the robustness of our analysis, we run one additional regression at the child level. We use the different food groups produced by the household as explanatory variables. Results are presented in Table A3. Results show positive significant associations between pulse production and HAZ, WAZ, while there is no significant association with the stunting status. Tuber production indicates no association with any of the child nutritional outcomes. From these results, we may conclude that agricultural diversity production is particularly associated with reduced child stunting via zinc supplied by pulse production.

3.5 Conclusion

This study aims to examine the relationship between farm production diversity and food diversity, specifically focusing on micronutrient intake, as well as the association between food diversity/micronutrient intake and child nutritional status. Through the use of panel regression models, our findings provide evidence of a positive link between production diversity and dietary diversity through both direct (own consumption) and indirect (market purchase) linkages. Moreover, this study underscores the significance of assessing the pathway of micronutrient intake and disaggregating production diversity into distinct food groups. Furthermore, this study supports a positive and significant association between certain food group and calorie and micronutrient intake through the subsistence route, particularly pulse production. These findings thus highlight the potential benefits of promoting the production of micronutrient-rich crops, such as pulses, particularly during periods of low agricultural productivity (see Table A3.4 in Appendix for the current proportion of household producing pulse).

At the child level, our model emphasizes the critical role of increased zinc intake from subsistence sources in improving overall child nutritional status, reducing the prevalence of stunting, underweight, and undernourishment status. These findings underscore the significance of targeted interventions to enhance nutritional outcomes within households. Such measures have the potential to improve the nutritional well-being of children and contribute to broader efforts aimed at addressing malnutrition.

However, it is important to acknowledge certain limitations of this study. First, the number of children under 5 years of age is limited in the sample, hence generalization of the results may belie the regional figure. Second, the food consumption data are from a household consumption survey and are not based on an individual level. Further research is warranted to investigate the roles of other food groups and their implications on child nutritional outcomes through alternative pathways.

This study has important policy implications for Madagascar and for other low- and middle-income countries. Firstly, policymakers should prioritize investments in research and development to enhance crop productivity, especially pulse, and resilience. This can be achieved through breeding programs that focus on developing high-yielding and nutrient-rich pulse varieties. Additionally, policymakers should support the dissemination of improved agricultural practices, such as proper crop rotation and integrated pest management, to maximize pulse production, especially during the dry season. Furthermore, policymakers should invest in nutrition education programs that specifically promote the consumption of pulses, emphasizing their nutritional benefits and demonstrating ways to incorporate pulses into daily diets. Such programs can target caregivers, schools, and healthcare providers, creating awareness about the importance of diverse and nutrient-rich diets for child growth and development.

By implementing these specific policy implications, policymakers can contribute to the promotion of pulse production, increase their consumption, and ultimately reduce stunting rates, leading to improved child health and nutrition outcomes.

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APPENDICES

Table A 3.1 Association between agricultural production diversity on dietary diversity of the household (Pooled OLS regression)

Variables	HDRS		HDDS		Energy (kCal/AE)		Fe (mg/AE)		Zn (mg/AE)		Vitamin A (ug/AE)	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Agricultural Richness Score	0.27***		0.11***		0.0039		0.012		-0.0035		0.016	
	(0.074)		(0.035)		(0.0099)		(0.010)		(0.0088)		(0.024)	
Agricultural Diversity Score		0.33***		0.15***		0.011		0.021*		0.00099		0.024
		(0.086)		(0.041)		(0.011)		(0.012)		(0.010)		(0.028)
Household characteristics	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Village*year	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Village dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Within R-sq	0.594	0.595	0.445	0.446	0.401	0.402	0.531	0.532	0.504	0.504	0.620	0.620
adj. R-sq	0.540	0.541	0.371	0.373	0.321	0.322	0.469	0.469	0.438	0.438	0.569	0.569
Observations	1624	1624	1624	1624	1624	1624	1624	1624	1624	1624	1624	1624

Notes: These are estimates from the pooled OLS regression. We control for household variables as those described in Table 3.2. We also control interaction term between village and year dummies, village dummies. Clustered standard errors in parentheses; * p<0.10 ** p<0.05 *** p<0.01

Table A 3.2 Association between individual food group production and dietary diversity and micronutrient intake of household (Pooled OLS regression)

Variables	HDRS		HDDS		Log of energy intake		Log of iron intake		Log of zinc intake		Log of VitA intake	
	Foods bought in the market	Food own produced	Foods bought in the market	Food own produced	Foods bought in the market	Food own produced	Foods bought in the market	Food own produced	Foods bought in the market	Food own produced	Foods bought in the market	Food own produced
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(9)	(10)
Cereal	0.013	0.11	-0.047	0.12	-0.45***	0.47***	-0.19***	0.10**	-0.24***	0.20***	0.075	-0.020
	(0.17)	(0.14)	(0.10)	(0.082)	(0.084)	(0.13)	(0.050)	(0.052)	(0.047)	(0.047)	(0.10)	(0.14)
Tuber	-0.22	0.29**	-0.15	0.22***	-0.013	0.37***	-0.039	0.16***	-0.048	0.10**	-0.16	0.26**
	(0.17)	(0.13)	(0.096)	(0.080)	(0.059)	(0.13)	(0.043)	(0.052)	(0.039)	(0.042)	(0.10)	(0.13)
Pulse	-0.67**	0.71***	-0.35*	0.51***	-0.37**	0.82***	-0.17**	0.36***	-0.16**	0.26***	-0.33	0.45*
	(0.30)	(0.24)	(0.18)	(0.16)	(0.17)	(0.24)	(0.077)	(0.096)	(0.068)	(0.080)	(0.22)	(0.26)
Vegetable	0.14	-0.31*	0.089	-0.26**	0.039	-0.12	0.0089	-0.042	0.0083	-0.064	0.13	0.034
	(0.26)	(0.18)	(0.14)	(0.11)	(0.080)	(0.19)	(0.050)	(0.069)	(0.046)	(0.056)	(0.14)	(0.20)
Egg	1.05***	0.92***	0.73***	0.67***	-0.11	0.69***	-0.11	0.30***	-0.13	0.18**	0.38***	0.58***
	(0.28)	(0.19)	(0.15)	(0.12)	(0.12)	(0.19)	(0.081)	(0.088)	(0.082)	(0.078)	(0.14)	(0.20)
Milk	0.69**	0.35	0.32**	0.12	0.047	0.13	0.060	-0.020	0.041	0.0068	0.25	-0.021
	(0.29)	(0.27)	(0.14)	(0.13)	(0.100)	(0.19)	(0.065)	(0.086)	(0.060)	(0.070)	(0.16)	(0.23)
Meat	1.03**	-1.53***	0.35	-0.67***	0.22	-0.92***	0.31***	-0.35**	0.19**	-0.32***	0.52**	-1.10***
	(0.48)	(0.36)	(0.23)	(0.21)	(0.18)	(0.32)	(0.11)	(0.14)	(0.094)	(0.11)	(0.26)	(0.38)
Household characteristics	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Village*year	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Village dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R-sq	0.522	0.456	0.458	0.410	0.321	0.406	0.371	0.479	0.348	0.435	0.441	0.485
adj. R-sq	0.456	0.381	0.383	0.328	0.227	0.324	0.284	0.407	0.258	0.357	0.364	0.414
Observations	1624	1624	1624	1624	1624	1624	1624	1624	1624	1624	1624	1624

Notes: These are estimates from the pooled OLS regression. We control for household variables as those described in Table 3.2. We also control interaction term between village and year dummies, village dummies. Clustered standard errors in parentheses; * p<0.10 ** p<0.05 *** p<0.01

Table A 3.3 Association between household food group production with child nutritional status

Variables	HAZ	Stunted	WHZ	Wasted	WAZ	Underweight	Undernourished
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Cereal	0.082	0.0010	1.27**	-0.16	0.63**	-0.21	-0.021
	(0.36)	(0.16)	(0.57)	(0.17)	(0.31)	(0.15)	(0.15)
Tuber	-0.18	-0.015	-0.81	0.26	-0.48	0.19	0.19
	(0.56)	(0.21)	(0.76)	(0.16)	(0.32)	(0.12)	(0.20)
Pulse	2.53***	-0.11	1.35	0.0051	2.68***	-0.46**	-0.12
	(0.66)	(0.28)	(1.24)	(0.26)	(0.64)	(0.23)	(0.27)
Vegetable	0.069	-0.27	1.18*	-0.059	0.68**	-0.40***	-0.095
	(0.53)	(0.25)	(0.64)	(0.16)	(0.30)	(0.13)	(0.21)
Egg	-1.00	0.32	2.73***	-0.38	1.20***	0.011	0.11
	(0.61)	(0.38)	(0.79)	(0.26)	(0.38)	(0.17)	(0.29)
Milk	-2.36*	-0.048	2.06	-0.32	-1.03	-1.30***	-0.21
	(1.22)	(0.69)	(2.04)	(0.38)	(0.91)	(0.38)	(0.68)
Meat	0.60	-0.27	0.016	-0.18	-0.25	-0.73**	-0.55
	(1.23)	(0.43)	(1.42)	(0.30)	(1.27)	(0.31)	(0.39)
Child characteristics	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Household characteristics	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Child Fixed-effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Village*year	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Village dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Within R-sq	0.844	0.716	0.807	0.798	0.848	0.830	0.714
adj. R-sq	0.736	0.520	0.674	0.660	0.743	0.713	0.517
Observations	229	229	229	229	229	229	229

Notes: These are FE estimates. We control for household variables and child characteristics as those described in Table 2. We also control child fixed-effects, interaction term between village and year dummies, village dummies. Standard errors in parentheses are clustered at child level; * p<0.10 ** p<0.05 *** p<0.01

Table A 3.4 Detailed descriptive statistics of each type of pulse produced in each wave

Wave	Obs.	Pulse	Frequency
Wave 1	*515*	54	10%
Wave 2	*557*	10	2%
Wave 3	*552*	14	3%
Household Observations	*1624*	*78*	5%
Wave 1	*59*	11	19%
Wave 2	*94*	2	2%
Wave 3	*76*	4	5%
Child Observations	*229*	*17*	7%

Notes: Observations in the first panel show the total number and proportion of household producing pulse. Observations in the second panel show the total number and proportion of households having at least one child aged 6 to 60 months producing pulse.

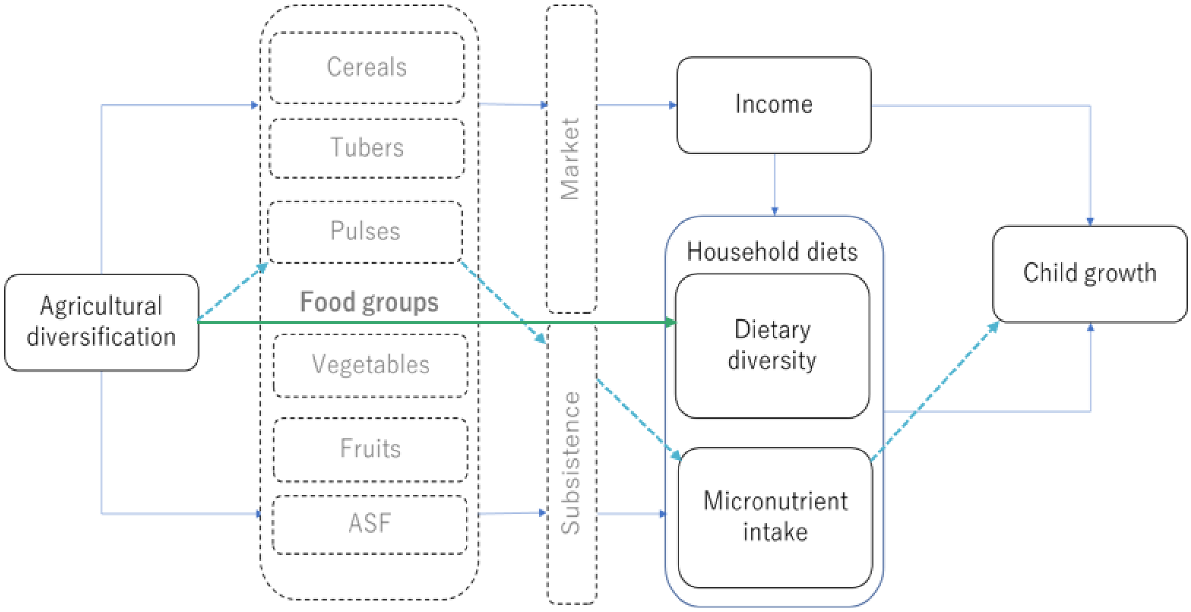

Fig. A 3.1 Linkage between agricultural diversification and child nutritional status, with a focus on Micronutrient pathways

Chapter 4: Examining the Nexus of Vegetable Commercialization, Household Welfare, Nutrition, and Child Health: Evidence from Smallholder Producers in Central Madagascar

Abstract

This study traces the possible effect of commercializing vegetable on household income, nutrition and child health outcomes. Using a three-year panel data from central Madagascar, this study offers a comprehensive insight by (i) examining the dynamic factors that significantly influence smallholders' participation in the commercialization of vegetable crops; by (ii) investigating whether commercializing vegetable increase household income and expenditures, and diversify their diets; and by (iii) exploring the possible underlying pathways between commercial vegetable farming and the reduced prevalence of stunting in preschool children. Our findings highlight the critical role of household head's age, family labor and land availability, and altered precipitations as key dynamic factors impeding the commercialization of vegetables in central Madagascar. Moreover, results indicate that the more a household engaged in vegetable commercialization increase their monthly per Adult-Male Equivalent of total value of vegetables, the more they enhance their income, improve their dietary diversity, and increase their expenditures. Finally, we provide evidence of possible pathway indicating that higher per-capita expenditures on non-food items are positively correlated with linear growth and a reduced prevalence of stunting among children aged 6 to 47 months. This study thus underscores the importance of addressing barriers to the vegetable commercialization to harness the economic and nutritional potential for smallholder farmers and ultimately to combat child malnutrition.

Key words: vegetable production, commercialization, welfare, child nutritional outcomes, Madagascar

4 Examining the Nexus of Vegetable Commercialization, Household Welfare, Nutrition, and Child Health: Evidence from Smallholder Producers in Central Madagascar

4.1 Introduction

The reduction of poverty and hunger in Sub-Saharan Africa (SSA) is a key focus of the Sustainable Development Goals (SDGs) (Lucas et al., 2019). In SSA countries, a significant proportion of individuals living in poverty, approximately 85%, reside in rural areas where poverty rates are more than three times higher compared to urban areas, mainly due to their dependence on agriculture (Willis, 2019; Minten & Barrett, 2008). Among the population, children under the age of five are particularly susceptible to extreme poverty and malnutrition, which can have detrimental effects on their physical and cognitive development (Babu et al., 2016). Despite international efforts to enhance food production in SSA, poverty and malnutrition persist as substantial barriers to sustainable development (IFPRI-Global Nutrition Report, 2015; WHO, 2021).

The predominant food system in many African countries centers around major staple crops such as rice, maize, and tubers, which often lack essential minerals and vitamins necessary for human health (Afari-Sefa et al., 2012). Moreover, despite some staples such as rice not being the most cost-effective carbohydrate staple available, impoverished farmers tend to allocate a significant portion of their income to these expensive products, which perpetuates their cycle of poverty, as is the case in Madagascar (Farris, Misyak, O'Keefe, VanSicklin, & Porton, 2019). To address these nutrient-related challenges, it becomes imperative to explore solutions that promote the diversification of food group production, focusing on specific crops rich in nutrients (Jones, 2017; Bachewe & Minten, 2023). Furthermore, access to fundamental daily necessities including firewood, charcoal, and other daily commodities is still of critical importance for survival in low-income countries. Yet, some of those daily necessities pose serious environmental, social, economic, and health implications (Ritchie et al., 2020). There is thus a pressing challenge toward finding appropriate solutions to address the prevailing malnutrition and poverty patterns in SSA.

The production of high-value and nutrient-rich food groups such as vegetables can bring multiple benefits to low-income countries (Schreinemachers et al., 2018). However, there is limited understanding regarding these non-staple sectors in the context of African continent (Bachewe & Minten, 2023). Thus, this study aims to investigate the association of commercializing vegetables on income enhancement and nutrient diversification, and its possible association with child health in the central highlands of Madagascar using panel data from the years 2018 to 2020. Madagascar serves as an ideal research setting for several reasons. Firstly, poverty and malnutrition are widespread issues throughout the country (WorldBank, 2018; WorldBank, 2019). The majority of Malagasy households reside in rural areas and rely heavily on rice cultivation (Minten & Zeller, 2017). Malagasy farmers also spend nearly 60% of their income to purchase rice for which they consume approximately 140 kg of milled rice per capita annually, which is one of the highest figures worldwide (Minten & Barrett, 2008; Smith et al., 2016; Golden et al., 2019). As a result of this prevalence of cereal-based diets, achieving the recommended daily nutrient intake remains a challenging goal for rural farmers (Afari-Sefa et al., 2012). Secondly, due to population growth and limited land availability, shifts in agricultural production practices are underway (Sourisseau et al., 2016). These dynamics require not only the intensification of agricultural systems but also the diversification of income sources. This entails the adoption of more labor- and capital-intensive farming practices, resulting in the emergence of vegetable production in the central regions of Madagascar (Minten & Zeller, 2017). Finally, there is a growing interest from private sector markets and large-scale agro-industries in sourcing vegetables and exporting them from the region (Bellemare & Novak, 2017). In fact, vegetable production offers substantially higher profits per hectare compared to rice production (Joosten et al., 2015). However, despite its tremendous potential to improve the welfare and nutrition of smallholder farmers and enhance household dietary diversity (Lotter et al., 2014; Mphafi et al., 2019), the potential benefits of vegetable production in SSA, particularly in Madagascar, have been largely overlooked.

Despite the recognized significance of market-oriented vegetable farming in generating income for smallholder farmers, there is a limited body of research that has explored the effects of vegetable production on household income, expenditures, and food security, offering insights into its potential benefits. Specifically, promoting market participation among smallholder farmers has been advocated to enhance income (Joshi et al., 2006; Birthal et al., 2013; Barrett, 2008; Shibatu et al., 2015; Emana et al., 2015; Muriithi & Matz, 2015; Krause et al., 2019), and nutrition at the household level (Zanello et al., 2019; Krause et al., 2019). Conversely, several studies have provided evidence of the nutrition-enhancing effects of agricultural commercialization and vegetable production, although the findings are not yet conclusive (Carletto et al., 2017; Odendo et al., 2023). Nevertheless, vegetable commercialization is regarded as a crucial component of the development process (Muriithi & Matz, 2015; FAO, 2017; Sibhatu & Qaim, 2017). Therefore, prioritizing vegetable production as a sub-sector of agriculture can contribute to poverty reduction (Joshi & Piya, 2021).

In this study, we aim to contribute to the existing literature on vegetable production by (i) investigating dynamic factors determining the adoption of commercial vegetable production and (ii) examining the effect of commercializing vegetable on household income, expenditures and food security. Despite the focus of most studies on factors determining market participation (e.g. Mulenga et al., 2021; Adepoju et al., 2015; Onoja et al., 2013; Bellemare & Barrett, 2006), limited studies concentrated on factors that facilitate or hinder the adoption of commercial vegetable farming have been explored to date (e.g. Joshi & Piya, 2021; Aliyi et al., 2021; Megerssa et al., 2020). Fewer studies examined the dynamics of farmers' participation in the commercialization of vegetables (Muriithi et al., 2014). Other strand of studies has also investigated the effects of vegetable commercialization on income and food security (Muriithi & Matz, 2015; Krause et al., 2019). Yet, only a handful of them (i) investigated the effect of vegetable commercialization on food and non-food expenditures separately; and (ii) considered the associated benefits on child chronic malnutrition, a pressing issue in low-income countries.

The contribution of this paper are thus manifolds. First, this paper uses a panel data approach to investigate the determinants of vegetable production, including dynamic factors that influence households' engagement in commercial market activities. Secondly, it adopts a nuanced perspective by analyzing heterogeneous effects of vegetable production, distinguishing between less market-oriented households and those with a stronger market orientation. Thirdly, this study addresses a significant gap in the literature by investigating the potential mechanisms underlying the effect of vegetable commercialization on child health tracing a possible novel pathway. Fourthly, the study focuses on the understudied country of Madagascar, where child stunting is a significant challenge, particularly in the central regions (INSTAT & ICF, 2021).

This study provides empirical evidence on the significant influence of various dynamic factors on vegetable commercialization. These factors include the age of the household head, with older household heads being less engaged in vegetable markets; family labor and land availability, implying the labor and capital-intensive of vegetable farming practices; as well as climate change-related factors, specifically changes in precipitation patterns. Additionally, among households involved in vegetable production, those with a stronger market orientation experience significant improvements in dietary diversity scores, income, and expenditures as their per-AE total value of vegetable production increases. In particular, the degree of commercial market-orientation is positively associated with increased household expenditures on both food and non-food items, with the latter significantly linked to positive outcomes in child HAZ and a reduction in the prevalence of child stunting among children aged 6 to 47 months. These findings carry important policy implications.

The remainder of this paper is organized as follows. Section 4.2 presents the context of vegetable production in our study area. Section 4.3 describes the data used for this study, and Section 4.4 presents the estimation strategy, section 4.5 presents the results. Finally, Section 4.6 concludes with a discussion of the results and outlook.

4.2 Vegetable production in central Madagascar

Central Madagascar is known for its significant vegetable production, with various studies highlighting its importance (e.g. Minten et al., 1997; Manguin-Salomon & Rakotonirainy, 2012; Rakotoarisoa & Bélières, 2016; Sourisseau et al., 2016; Minten & Zeller, 2017). The region thus presents several prospects for vegetable production. Firstly, private sector markets show increasing interest in beans, onions, and potatoes, while larger agro-industries are gradually exploring opportunities to export vegetables from this area (Bellemare & Novak, 2017). Small-scale farmers, operating on plots ranging from 1 to 10 ares, commonly grow vegetables for local consumption and supply the surplus to the local market, especially during the off-season. Moreover, commercial vegetable producers, who cultivate on a relatively larger scale of 10 to 30 ares, often belong to farmer-led organizations. There are also larger farms that operate on more than 30 ares to several hectares, which are highly integrated into the market and may be involved in other activities related to the sector, such as supplying inputs (Sourisseau et al., 2016). Secondly, the region benefits from cost-effective and well-managed peri-urban diversified cropping systems, enabling it to meet the growing demand for vegetables in urban areas. Despite the prevalent socioeconomic challenges and persistent rural poverty and malnutrition in Madagascar, the Vakinankaratra region possesses significant resources, particularly in horticultural production, and plays a crucial role in the lives of rural farmers (Rakotoarisoa & Bélières, 2016). However, existing limitations prevent small-scale farmers from fully capitalizing on the emerging opportunities in vegetable production.

In our study area, there are various factors that influence farmers' decisions to engage in vegetable production, despite its potential for profitability and labor-intensive nature (Razakamiaramanana et al., 2009). One of the main constraints on adopting vegetable production is the lack of irrigation systems and available land resources (Minten & Zeller, 2017). The maintenance and repair of irrigation channels have been neglected by the state, leading to the unpreparedness of water users' associations to undertake the necessary work. As a result, many irrigation schemes are non-functional, and rice fields no longer receive adequate water, particularly after the lowland rice harvest. To ensure successful vegetable adoption, it is crucial to provide irrigation during the dry season, as a consistent water supply improves yield, quality, and uniformity, especially for leafy vegetables, thereby enhancing profitability and market potential (Razakamiaramanana et al., 2009). Furthermore, the limited availability of land resources poses a significant obstacle to vegetable production adoption (Minten & Zeller, 2017). Land ownership is primarily based on inheritance, resulting in younger generations inheriting negligible land sizes, especially for lowland rice fields. Additionally, the inaccessibility of affordable inputs like improved seeds, chemical fertilizers, and pesticides further hinders the adoption of vegetable production in the region, despite their potential to enhance yield and profit (Manguin-Salomon & Rakotonirainy, 2012). Overall, the vegetable sector in central Madagascar presents both opportunities and challenges.

4.3 Data

To show empirical evidence of the effect of vegetable production on the household's livelihoods, 60 villages were randomly selected from 13 communes spread over 3 districts in the Vakinankaratra region of Madagascar. Ten households that grew lowland rice were randomly selected from each village for the survey. As a result, the initial number of sample households were 600. We repeatedly conduct survey among the same households to form a three-year panel data used for this study. The data capture yearly agricultural activities from the years 2018 to 2020. Collected data include household characteristics, agricultural practices, expenditure on food and non-food items, and food consumption information for the month and the week prior to the interview. With an attrition rate of 10% along with incomplete data, 1624 household-observations are retained for the first part of the analysis dealing with the factors determining vegetable production. For the second part, we only consider vegetable growers, which account for 421 household-observations. Among the 421 households, 355 are considered as "market-oriented vegetable growers" and 66 are considered as "less market-oriented non-vegetable growers" for the binary setting. At the child-level, we use 229 child-observations in a panel data setting. For all the analysis, we use panel data as it has advantages of disentangling pathways more convincingly (Baker & Antilla-Hughes, 2020) (see Table A4.1 in Appendix).

4.3.1 Outcome variables

At the household level, the main outcomes of interest are the diet diversification of a household, represented by Household Dietary Diversity Score (HDDS), micronutrient-sensitive HDDS (MsHDDS), and the per-capita income, proxied by per-capita total expenditures, as well as the disaggregate forms of expenditures, namely per-capita monthly expenditures on food items[10], non-food items[11], and non-food major items[12].

Table 4.1. presents the descriptive statistics of the outcome variables. We distinguish HDDS according to their sources, either from market or subsistence. On average, household consume 8 foods groups, 6 of which are sourced from the market while about 2 are from own production. We add another indicator of HDDS which is the MsHDDS. MsHDDS splits the group of "sub-vegetables" in the HDDS into dark green leafy vegetables, vitamin A-rich (red/ orange/ yellow) vegetables, and other vegetables; the group of fruits into vitamin A-rich and other fruits;

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[10] Food items comprise basic foods such as sugar, oil, condensed milk, tea, coffee, biscuits, soft and alcohol drinks, baby foods, tobacco and other items.
[11] Non-food items comprise basic commodities such as candles, battery, petrol for lamp, charcoal, firewood, soap, matches, personal care goods and other items.
[12] Non-food major items include clothes, administrative fees, health expenditures, insurance fees, cultural event costs, annual education fee, and other costs and fees.

and the group of meat into red meat and white meat (mainly poultry). A total of 16 different food groups are used for the MsHDDS, rather than the 12 groups used for the HDDS. This disaggregation serves to better account for the large differences in the bioavailable micronutrient contents between these groups and the combination of these food groups in meals (Mazunda et al., 2018). On average, 7 food groups are from the market while 4 are from the subsistence pathway for this scoring system.

With respect to the per-capita total expenditure (proxied for income), on a monthly basis, household spends on average 17,108 MGA (equivalent to USD 3.93). Approximately 7,000 MGA (equivalent to USD 1.5) is monthly spent on non-food items, and about 5,000 MGA (equivalent to USD 1) serve to purchase food and non-food major items.

Table 4.1 Descriptive statistics of outcome variables for household level data

Outcome variables	Obs	Mean	Std.Dev.	Min	Max
Household Dietary Diversity					
Household Dietary Diversity Score (market)	*1624*	6.45	1.75	2	11
Household Dietary Diversity Score (subsistence)	*1624*	2.44	1.36	0	7
Micronutrient-sensitive HDDS (market)	*1624*	7.54	2.94	2	19
Micronutrient-sensitive HDDS (subsistence)	*1624*	3.69	2.34	0	15
Food expenditures per capita					
Total expenditures (in MGA[4])	*1624*	17108.74	22138.27	1414.29	511050.00
Expenditures on food items[1] (in MGA[4])	*1624*	4783.72	3892.93	266.67	50266.67
Expenditures on non-food items[2] (in MGA[4])	*1624*	7227.23	9398.15	162.50	141688.90
Expenditures on non-food major items[3] (in MGA[4])	*1624*	5097.79	15142.50	0.00	363472.20

Notes: Observations from all three-year surveys were pooled. [1]Food items include sugar, oil, condensed milk, drinks and other foods. [2]Non-foor items include soaps, electricity, matches, rent, and others. [3]Non-food major items include clothes, health expenditures, educational fees, and other costs. [4]MGA stands for Malagasy Ariary. 1 MGA = USD 0.00023 as of September 22nd, 2022.

At the child level, we consider a variable capturing the long-term chronic malnutrition of children, which is often represented by the child HAZ (Table 4.2). On average, children in our study area are prevalently chronically malnourished, with HAZ of -2.34 where stunting is represented by nearly 60% of them.

Table 4.2 Descriptive statistics of outcome and explanatory variables for child level data

Panel sample	Obs	Mean	Std.Dev.	Min	Max
Outcome variables					
HAZ	*229*	-2.34	1.60	-5.76	2.63
Stunted (Yes=1)	*229*	0.58	0.49	0	1

*Notes: O*bservations from the three-year surveys were pooled.

4.3.2 *Variables of interest and control variables*

Table 4.3 summarizes the descriptive statistics of both our variable of interests and control variables at the household, district, and child-level. With regard to our variable of interest, households produce an average of about 2230 MGA (USD 0.5) in monthly revenue per AE of vegetable production. The socio-economic characteristics of the households indicate that nearly 90% are male-headed. The average age is 47 years old, with about 5 years of schooling. More than half have the ability to understand French, which is the spoken language from the colonialism period, and is still practiced in administrative and institutional systems. The average household size comprises 4.73 people of which, on average, 11% were preschool children, 24% schooling children, 11% elderly members, and 27% were women at the working age of 15 to 60 years old. On average, each household in our study possesses 1.62 lowland plots, 61% of households own at least one upland rice plot, 90% own other types of plots., and 5% rented-in additional plots. Access to irrigated plots during the dry season is reported among only 20% of households. The average per-capita Tropical Livestock Unit (TLU) is estimated to be 0.25. Regarding asset values, the average per-capita home value is found to be 58,790 MGA (equivalent to USD 13), while the average per-capita farm value is 63,509 MGA (equivalent to USD 14.6). The average annual precipitation[13] is approximately 1467 mm. The average number of days household last visited the market was 3.6 days. Household also diversified into 1.8 different crops, excluding vegetables. 9%, 53%, and 38% lives in Antsirabe 2, Betafo and Mandoto, respectively. In terms of child characteristics, the average age is determined to be 34.84 months, with 7% of children reported as attending school and 4% experiencing illness during the survey period.

[13] Precipitation data was obtained from the GIOVANNI tool, which provides a high-resolution satellite-derived imagery (Huffman et al., 2019).

Table 4.3 Summary statistics

Variables	Pooled				
	Obs	Mean	Std.	Min.	Max.
Explanatory variables					
Total value per AE of vegetable production	*1624*	2231	12182	0.00	390126
Control variables					
Household-level variables					
Household head characteristics					
Age	*1624*	47.74	14.01	19	92
Sex (Male=1)	*1624*	0.88	0.32	0	1
Both parents	*1624*	0.85	0.36	0	1
Ability in French	*1624*	0.64	0.48	0	1
Last education (years)	*1624*	5.30	3.70	0	19
Household characteristics					
Household size	*1624*	4.73	1.93	1	13.00
Share of preschool children	*1624*	0.11	0.15	0	0.75
Share of schooling children	*1624*	0.24	0.20	0	0.86
Share of old members	*1624*	0.11	0.24	0	1
Share of working woman	*1624*	0.27	0.16	0	1
Parcel characteristics					
Total number of lowland plots	*1624*	1.62	0.99	0	10
Have any upland plots (Yes=1)	*1624*	0.61	0.49	0	1
Have any other plots (Yes=1)	*1624*	0.90	0.30	0	1
Renting any plot (Yes=1)	*1624*	0.05	0.22	0	1
Percentage of irrigated parcel	*1624*	0.20	0.24	0	1
Last day to markets	*1624*	3.67	2.27	0	30
Crop diversification	*1624*	1.84	0.85	0	5
Household assets					
TLU (per capita)	*1624*	0.25	0.27	0	2.54
Farm asset per capita (in MGA[1])	*1624*	58790.62	149033.50	0	2075000
Non-farm asset per capita (in MGA[1])	*1624*	63509.96	168494.10	0	2062000
Rainfall (mm)	*1624*	1467.52	145.43	1186.76	1770.28
District-level variables					
Altitude (m)	*1624*	1236.89	238.19	763.13	1717.83
Antsirabe 2	*1624*	0.09	0.29	0	1
Betafo	*1624*	0.53	0.50	0	1
Mandoto	*1624*	0.38	0.49	0	1
Child-level variables					
Age in months	*229*	34.84	15.37	6	60
School attendance (Yes=1)	*229*	0.07	0.25	0	1
Sick (Yes=1)	*229*	0.04	0.20	0	1

Notes: Observations from all seven surveys were pooled. [1]MGA stands for Malagasy Ariary. 1 MGA = 0.00023 USD as of September 22nd, 2022.

4.3.3 *Empirical strategy*

4.3.3.1 *Determinants of smallholder commercial vegetable production*

To determine the various socio-economic factors that play important roles in the adoption of commercial vegetable production, we use the multinomial logit (MNL) model in the context of panel data. Vegetable production in general is driven by underlying personal characteristics, some of which are unobserved. Our variable of interests is 0 if the household does not produce any vegetables, 1 if they produce vegetable but do not sell any part to the market, and 2 if they produce vegetable and sell some portion or the entire produces to the market. In our analysis, we use random effects to account for unobserved characteristics of the unobserved characteristics of the households. This methodology allows us to separate the error terms resulting from factors within households and factors that vary between households (StataCorp, 2023). We further check for conditional fixed-effects[14] to highlight the dynamic factors engaging farmers to commercial vegetable uptake while controlling for household-specific time-invariant variables.

4.3.3.2 *Association of vegetable commercialization on nutrition, household income and expenditures*

In this section, specifically, among vegetable growers, we estimate the association between vegetable market participation and nutrition, income and food expenditure using the following linear equation:

$$y_{ht} = \beta_1(D_{ht} * T_{ht}) + \beta_2 T_{ht} + \beta_3 D_{ht} + \beta_4 X_{ht} + \beta_6(V_h * T_t) + \beta_7 T_t + \beta_8 V_h + \tau_h + \varepsilon_{ht} \qquad (4.1)$$

where y_{ht} represents the outcome variables: household dietary diversification, household income (proxied by per-capita total expenditures[15]), and food and non-food expenditures. D_{ht} is the per-capita total value of vegetable production per Adult-Male Equivalent (AE), and T_{ht} is dummy for market participation. T_{ht} takes the

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[14] The conditional fixed-effects estimator offers several benefits. It allows for correlations between unobservable factors and covariates, eliminating the need to make distributional assumptions about the heterogeneity term. This, in turn, helps mitigate the incidental parameters problem to some degree (StataCorp, 2023).
[15] Household expenditure data is often favored in numerous studies over income data due to its lower susceptibility to seasonal and yearly fluctuations, resulting in reduced measurement errors (Deaton, 1991).

value of 1 if the household has sold some portion or all their produces to the market, or 0 otherwise. $(D_{ht} * T_{ht})$ is the interaction term between the per-capita total value of vegetable production per AE and market participation. β_1 is thus our coefficient of interest, representing the simple effect of vegetable commercialization depending on the total amount produced. X_{ht} is vector of the household characteristics, asset endowment or capital variables. We also include the village (*V*), time (*T*), and village-time interactions (*V*T*) to control for temporal and spatial differences in biophysical conditions, access to infrastructure, policy changes, etc. that are not possibly captured by the other covariates. τ_h and ε_{ht} are the household-specific fixed effects and the error term, respectively. We estimate the regression using FE model clustering at household level.

4.3.3.3 *Association of nutrition, household income and expenditures on child health*

At the child level, we use the following model to investigate the association between nutrition, household income and expenditures on child nutritional outcomes:

$$y_{cht} = \alpha_1 CM_{ht} + \alpha_2 C_{ct} + \alpha_3 X_{ht} + \alpha_4 (V_h * T_t) + \alpha_5 T_t + \alpha_6 V_h + \tau_c + \varepsilon_{cht} \qquad (4.2.)$$

where y_{cht} represents nutritional outcomes of a child *c* of household h at time *t*. CM_{ht} or Channel Mechanism is the HDDS, household income and expenditures. C_{ct} is a vector of child characteristics. X_{ht} is vector of the household characteristics, asset endowment or capital variables. We also include the village (*V*), time (*T*), and village-time interactions (*V*T*). τ_c and ε_{cht} are the child-specific fixed effects and the error term, respectively. In Equation 4.2., we estimate the regression using FE model clustering at child level.

4.4 Results

4.4.1 *The determinants of vegetable production*

Table 4.4 presents the estimation results of a random and fixed-effect MNL model for vegetable production. The study classifies households involved in vegetable cultivation into two distinct categories: (i) less market-oriented households (first group) and market-oriented households (second group), in comparison to the control group comprising non-vegetable growers.

Using the random-effects estimator, results reveal several statistically significant variables. Four variables show strong associations with the first group, representing less market-oriented households. Firstly, a male-headed household demonstrates a significant positive effect on the likelihood of engaging solely in subsistence vegetable production. Secondly, literacy in the French language among household heads negatively correlates with the inclination towards less market-oriented households, implying that households with lower levels of education are more inclined to cultivate vegetables for personal consumption. Thirdly, the results suggest that higher altitudes of household locations are positively associated with the adoption of vegetable production for subsistence purposes. Lastly, the ownership of an upland-rice plot significantly contributes to vegetable cultivation for personal consumption.

In the case of market-oriented vegetable growers, firstly, the analysis indicates a significant correlation between the age of the household head and vegetable adoption, as well as its squared term. This suggests that younger and elderly farmers are less inclined to engage in vegetable cultivation due to potential lack of experience and physical strength, respectively. Secondly, the likelihood of vegetable production is closely tied to the characteristics of the household land endowment. Owning additional lowland plots and plots for gardening purposes demonstrate a positive and significant association with vegetable production. Furthermore, access to irrigation, particularly during the dry season, significantly enhances the odds of commercial vegetable cultivation at the household level. More importantly, annual precipitation plays a pivotal role, with both insufficient and excessive rainfall impeding vegetable production for commercialization. Thirdly, the variable "altitude" also demonstrates a connection to vegetable cultivation, potentially reflecting the influence of specific environmental factors on the decision to cultivate vegetables. Additionally, the distance from the nearest market (proxied by the number of days since the household's last visit to a market) shows a negative correlation with vegetable adoption. This outcome can be explained by the significance of markets and access to agricultural inputs. Lastly, the location of Antsirabe 2 is found to be less conducive to commercial vegetable farming, suggesting that district-specific characteristics either hinder vegetable producers or indicate the prevalence of alternative agricultural practices. In summary, considering the RE estimation, commercial vegetable production is predominantly undertaken by middle-aged household heads, requires available plots, relies heavily on rainfall and irrigation systems, and is practiced by households in close proximity to markets.

We now use the conditional FE estimator instead of the RE estimator to fit our model. time-invariant variables are assimilated into the fixed effects component, enabling us to focus on factors that exhibit variation or dynamics over time (StataCorp, 2023). The second part of Table 4.4 presents the results of the FE model. Results show no significant variables that are associated with less-market oriented vegetable growers. However, few variables are found to be significantly associated with the likelihood of being market-oriented vegetable growers. Significant association is observed for variables such as household head's age. This is similar to the results from RE. This finding suggests that as household heads are getting older, they are more likely to exit form commercializing vegetables. This finding is in line with the study of Muriithi et al. (2016). Conversely, younger household heads are reluctant into engaging into commercializing vegetables. Two new variables emerge to be significant, which is the share of preschool and schooling children. Some explanations might be driven by the necessity to generate more income for the expenses of the preschool children and the availability of more labor from the schooling children. Land endowment remained statistically significant for both possession of other plots ("positive") and the rented-in plots ("negative"). Most importantly, climate change-related factors including altered precipitations are associated with the adoption of commercial vegetable production following an inverse-U relationship, implying that insufficient and excessive rainfall decrease the likelihood of producing vegetable for commercial purpose.

4.4.2 *Association between the two categories of vegetable producers (less market-oriented and market-oriented) and household food consumption and income*

For the subsequent analysis, our focus is specifically on vegetable producers as we aim to examine the potential influence of commercialization. To achieve this, we create a binary variable to identify vegetable producers who engage in selling all or a portion of their produce in the market (categorized as market-oriented vegetable producers, assigned a value of 1), and those who solely rely on subsistence farming without selling any produce in

Table 4.4 Determinants of vegetable production

Variables	Random-effects				Fixed-effects			
	Less-market oriented		Market-oriented vegetable		Less-market oriented		Market-oriented vegetable	
	Coef.	S.D.	Coef.	S.D.	Coef.	S.D.	Coef.	S.D.
Sex (Male=1)	1.45*	(0.84)	-0.48	(0.53)	33.5	(33260.5)	-1.59	(2.63)
Age	-0.0078	(0.076)	0.19***	(0.068)	-1.28	(0.94)	0.72*	(0.38)
Age in squared term	0.00015	(0.00072)	-0.0019***	(0.00070)	0.014	(0.0092)	-0.0062*	(0.0037)
Both parents still present	-0.30	(0.63)	0.35	(0.49)	-14.5	(593.7)	0.32	(1.85)
French ability	-0.63*	(0.36)	-0.11	(0.25)	-13.6	(1370.4)	-2.24	(3.80)
Educational level in years	-0.036	(0.049)	0.013	(0.031)	3.37	(16946.8)	0.14	(0.64)
Household size	-0.099	(0.12)	-0.018	(0.092)	-0.48	(0.41)	0.10	(0.19)
Share of preschool children	-0.94	(1.67)	-0.39	(0.92)	4.84	(5.75)	4.66**	(2.21)
Share of schooling children	-0.11	(1.13)	-0.15	(0.78)	-0.37	(4.81)	3.32*	(1.71)
Share of old members	-0.64	(1.26)	0.088	(0.78)	-2.03	(4.74)	1.03	(2.29)
Share of working woman	1.00	(1.41)	-1.04	(0.83)	-2.52	(3.86)	1.55	(1.64)
Total number of lowland plots	0.085	(0.17)	0.22**	(0.11)	-0.57	(0.72)	0.46	(0.30)
Have any upland plots (Yes=1)	0.50*	(0.31)	0.17	(0.20)	-0.055	(0.70)	0.27	(0.34)
Have any other plots (Yes=1)	-0.040	(0.46)	0.65*	(0.36)	0.17	(0.81)	0.97*	(0.52)
Renting any plot (Yes=1)	-0.30	(0.80)	-1.00**	(0.50)	1.63	(1.37)	-1.75*	(0.96)
Percentage of irrigated parcel	-1.19	(0.93)	1.81***	(0.41)	-1.03	(1.79)	0.78	(0.72)
TLU per-capita	0.085	(0.60)	0.67	(0.45)	1.54	(2.33)	1.11	(0.99)
Natural log of farm asset per capita	-0.027	(0.24)	-0.29*	(0.18)	-0.17	(1.08)	-0.35	(0.53)
Natural log of non-farm asset per capita	-0.050	(0.21)	0.14	(0.19)	0.13	(1.07)	0.48	(0.49)
Number of days last visited market	-0.054	(0.054)	-0.11***	(0.041)	-0.11	(0.12)	0.019	(0.052)
Annual rainfall	-0.058	(0.046)	0.079***	(0.021)	-0.032	(0.090)	0.15**	(0.058)
Annual rainfall in squared term	0.000018	(0.000015)	-0.000028***	(0.0000070)	0.000014	(0.000028)	-0.000046**	(0.000018)
Altitude (m)	0.0046***	(0.0011)	0.0058***	(0.00098)	-	-	-	-
Betafo								
Antsirabe 2	0.61	(0.80)	-1.90**	(0.91)	-	-	-	-
Mandoto	0.81	(0.65)	0.33	(0.48)	-	-	-	-
Year dummies	Yes		Yes		Yes		Yes	
Interaction district-year	Yes		Yes		Yes		Yes	
Observations	66		355		66		355	

Notes: Standard errors in parentheses are clustered at household level. *** p<0.01 ** p<0.05 * p<0.10

the market (categorized as less-oriented vegetable producers, assigned a value of 0). We also introduce an interaction term between this binary variable and the per-capita total value of vegetable production per AE to assess the influence of market engagement.

Table 4.5 presents the findings on the association between vegetable production and household dietary diversification. Our analysis reveals a positive and statistically significant relationship between the interaction of being a market-oriented household and the total value of vegetable production, and the HDDS and MsHDDS derived from market sources. This indicates that the association of producing vegetables for the market on household dietary diversification is contingent on the per-AE total value of vegetable production. In other words, as market-oriented households increase their per-AE vegetable production value on a monthly basis, they experience an improvement in their dietary diversity scores. To further examine whether this relationship is driven by an underlying income-enhancing effect, we explore the association between vegetable production and household per-capita income, which is approximated by total per-capita expenditures.

Table 4.5 Marginal effect of vegetable production on household dietary diversity (fixed-effect linear model)

Variables	HDDS		MsHDDS	
	Market	Subsistence	Market	Subsistence
	(1)	(2)	(3)	(4)
Interaction between market-oriented households and log of total value of vegetable production	0.82*	0.093	1.31*	-0.65
	(0.46)	(0.39)	(0.76)	(0.64)
Market-oriented households (Yes=1)	-5.03	-0.76	-8.59*	4.18
	(3.15)	(2.88)	(5.19)	(4.70)
Log of total value of vegetable production per AE	-0.70*	-0.0012	-1.21*	0.64
	(0.37)	(0.34)	(0.62)	(0.52)
Other control variables	Yes	Yes	Yes	Yes
Household fixed-effects	Yes	Yes	Yes	Yes
Interaction village-year dummies	Yes	Yes	Yes	Yes
Year dummies	Yes	Yes	Yes	Yes
Within R-squared	0.616	0.608	0.603	0.626
Adj. R-sq	0.510	0.500	0.493	0.522
Observations	421	421	421	421

Notes: These are marginal effects from FE linear model estimates, with standard errors in parentheses, clustered at household level. Control variables are as described in Table 4.3. without controlling for district-level and child-level variables. *** p<0.01 ** p<0.05 * p<0.10

Table 4.6 presents the findings on the relationship between vegetable production, market access, household income, and expenditure patterns. The interaction terms show a positive and statistically significant association with per-capita income, implying that an increase in the per-AE monthly value of vegetable production is associated with a higher income for market-oriented households. This suggests that the income benefit of higher vegetable production differs between the two groups, with the income gap widening as the per-capita value of vegetable production increases. After disaggregating the per-capita expenditures, we also observe a positive and significant association between food and non-food expenditures at 1% significance level and the interaction term of per-capita total value of vegetable production and market-oriented households. This result suggests that the effect of being part of market-oriented households on food and non-food expenditures depends on the increased per-AE total value of vegetable production. In other words, the more the households produce for the market, the more they increase their income and expenditures on food and non-food items.

Table 4.6 Marginal effect of vegetable production on household per-capita income (fixed-effect linear model)

Variables	Log of expenditures			
	Total	Food	Non-food items	Non-food major items
	(1)	(2)	(3)	(4)
Interaction between market-oriented households and log of total value of vegetable production	0.16***	0.16***	0.14***	0.18
	(0.051)	(0.057)	(0.046)	(0.13)
Market-oriented households (Yes=1)	-1.09***	-1.24***	-0.94***	-1.33
	(0.35)	(0.42)	(0.32)	(0.94)
Log of total value of vegetable production per AE	-0.16***	-0.16***	-0.14***	-0.19*
	(0.044)	(0.051)	(0.041)	(0.12)
Other control variables	Yes	Yes	Yes	Yes
Household fixed-effects	Yes	Yes	Yes	Yes
Interaction village-year dummies	Yes	Yes	Yes	Yes
Year dummies	Yes	Yes	Yes	Yes
Within R-squared	0.984	0.978	0.969	0.706
Adj. R-sq	0.979	0.972	0.961	0.625
Observations	421	421	421	421

Notes: These are marginal effects from FE linear model estimates, with standard errors in parentheses, clustered at household level. Control variables are as described in Table 4.3. without controlling for district-level and child-level variables. *** p<0.01 ** p<0.05 * p<0.10

4.4.3 *Association between per-capita household income and child nutritional outcomes*

This section explores the association between per-capita total expenditure and child nutritional status. The findings, presented in Table 4.7, are derived from a FE linear regression model that explores the association of aggregated per-capita income and disaggregated per-capita expenditures and child health.

Column [1] and [2] reveal no statistically significant correlation between HAZ and stunting status in children aged 6 – 60 months with neither household income nor dietary diversity score. However, upon disaggregating the per-capita total expenditures, in Column [3], a noteworthy relationship emerges between per-capita non-food expenditures and child linear growth, reaching statistical significance at the 10% level. In particular, a 10% increase in per-capita non-food expenditures is associated with a HAZ increase of approximately 0.28 S.D.

The second part of our analysis exclude children older than 48 months to highlight the association of household expenditures and younger children. We observe two important findings. First, the significant association of HDDS from subsistence, which we found to be insignificantly associated with vegetable commercialization, and child HAZ ("positive association") and stunting status ("negative association"). Second, another important finding is the positive and significant association between monthly per-capita non-food items expenditures and child HAZ, and the negative and significant association with stunting rates at 1% significance level. Since the expenditures are measured in logarithms, our results imply that increasing monthly per-capita expenditure on non-food items by 10% would result in increasing child HAZ to 0.55 S.D. and reduce child stunting by nearly 2%. Overall, our findings suggest that increasing monthly total revenue from vegetable production affect child nutritional status through the pathway of increased expenditures of non-food items.

Table 4.7 Association between household income and HAZ and stunting status of children aged 6 - 60 months and 6 - 47 months

Variables	**6 - 60 months**				**6 - 47 months**			
	HAZ	Stunted	HAZ	Stunted	HAZ	Stunted	HAZ	Stunted
	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
HDDS (market)	0.0027	0.048	0.016	0.043	0.078	-0.031	0.12	-0.043
	(0.16)	(0.069)	(0.16)	(0.073)	(0.14)	(0.055)	(0.13)	(0.054)
HDDS (subsistence)	0.10	0.028	0.076	0.031	0.35	-0.16*	0.68*	-0.37**
	(0.18)	(0.068)	(0.20)	(0.070)	(0.27)	(0.095)	(0.39)	(0.14)
Log of per-capita total expenditure	1.11	-0.40			0.46	0.39		
	(1.21)	(0.53)			(1.79)	(0.83)		
Log of per-capita food expenditure			-0.31	-0.027			-1.38	1.24**
			(1.41)	(0.62)			(1.40)	(0.57)
Log of per-capita non-food expenditure			2.86*	-0.54			5.54***	-2.00***
			(1.46)	(0.50)			(1.90)	(0.66)
Log of per-capita non-food major items expenditure			-0.22	0.059			-0.063	-0.21
			(0.43)	(0.17)			(0.59)	(0.26)
Child variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Child fixed-effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Household variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Interaction village-year	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	229	229	229	229	175	175	175	175

Notes: These are FE estimates. Standard errors, clustered at child level, are in parentheses. Control variables are as described in Table 4.3. without controlling for household-head characteristics, and district-level variables. *** p<0.01 ** p<0.05 * p<0.10

4.5 Conclusion

This study aims to examine the dynamic factors influencing commercial vegetable production and their potential implications for the welfare and nutritional well-being of smallholder farmers. The results of the analysis indicate that, according to the FE estimator, no statistically significant variables were associated with the category of less market-oriented households. In contrast, market-oriented households were characterized by factors such as age, plot characteristics, and optimal rainfall conditions. Furthermore, the study reveals no significant differences in diet diversification and overall individual income between vegetable producers and non-vegetable producers.

However, among vegetable producers, those involved in marketing their produce displayed a higher likelihood of experiencing rapid income growth, which corresponded to an increased total value of vegetable production compared to less market-oriented households. Additionally, the findings indicate that an increase in the per-capita total value of vegetable production significantly contributes to higher per-capita food and non-food expenditures among market-oriented households. Ultimately, the latter was found to influence child nutritional outcomes.

To fully leverage the underlying economic and nutritional significance of commercial vegetable production, it is imperative to prioritize interventions that enhance crop commercialization. Specifically, implementing comprehensive training programs tailored to the needs of farmers and implementing targeted initiatives to overcome existing barriers that impede vegetable market access are highly recommended. Such interventions hold the potential to not only improve the overall welfare and nutritional well-being of smallholder farmers but also foster the adoption of sustainable agricultural practices. Importantly, these efforts will play a crucial role in combating child malnutrition, ensuring long-term positive outcomes for both farmers and the broader community.

Hitherto, the implementation of vegetable-related strategies is not current policy priorities in the region yet hold high potential in smallholders' nutritional wellbeing; however, policies that strongly emphasize production of staple crops such as rice, cassava or maize do not help in this context. Thus, more efforts are needed to increase the diversity of crops especially its diversification toward commercial vegetable production that might be additional agricultural strategies to improve nutrition and it must receive much more attention from development agencies to harness its impact on household’s welfare. These policies should further include addressing barriers constraining vegetable market access, and improving irrigation system in the study area. Because vegetables are rich in micronutrient, the main role for vegetable production is to fight macro and micronutrient deficiencies; the impact of vegetable production on the household diets were supported from the findings, however, their nutritional effects within the household more importantly on the children are not straightforward. Thus, it is clear that future research should emphasize on the impact of vegetable production on a more individual basis.

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APPENDICES

Table A 4.1 Detailed descriptive statistics of each type of vegetables produced in each wave

Wave	Obs.	Vegetables	Frequency	Vegetables	Frequency
Wave 1	*515*	137	27%	114	22%
Wave 2	*557*	141	25%	119	21%
Wave 3	*552*	143	26%	122	22%
Household Observations	*1624*	*421*	26%	*355*	22%
Wave 1	*59*	11	19%	11	19%
Wave 2	*94*	27	29%	22	23%
Wave 3	*76*	15	20%	13	17%
Child Observations	*229*	*53*	23%	*46*	20%

Notes: Observations in the first panel show the total number and proportion of household producing vegetables and commercialized vegetables. Observations in the second panel show the total number and proportion of households having at least one child aged 6 to 60 months producing vegetable and commercialized vegetables.

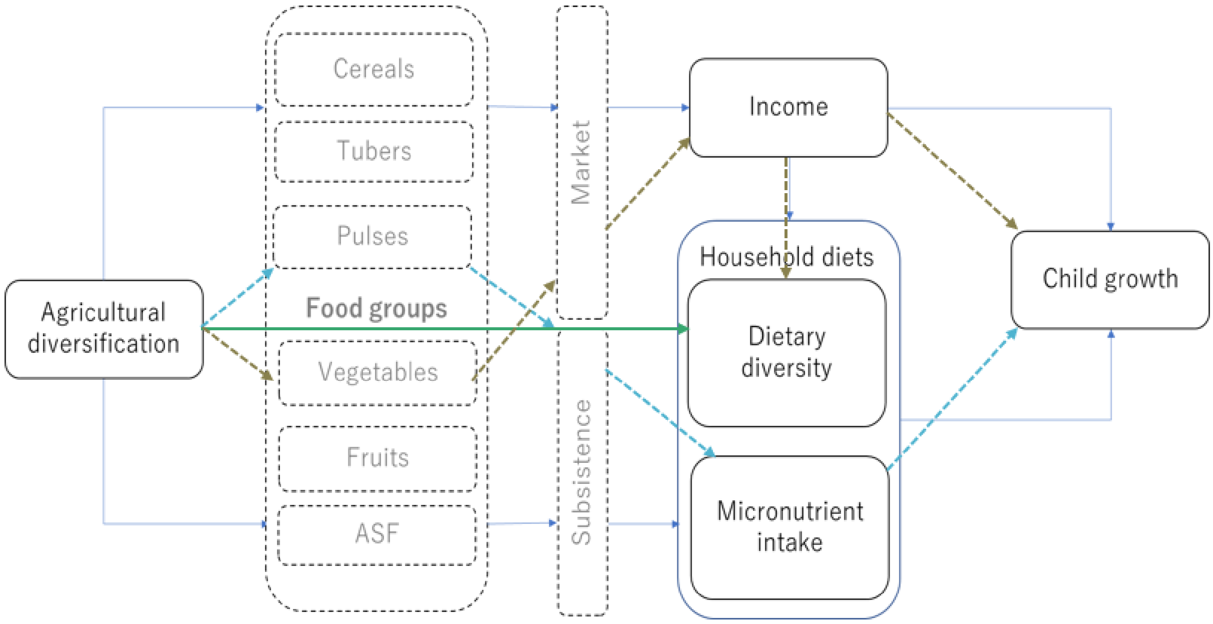

Fig. A 4.1 Linkage between agricultural diversification and child nutritional status, with a focus on Micronutrient pathways, and Vegetable Commercialization

Chapter 5: Animal-Sourced Foods Production and Early Childhood Nutrition: Panel Data Evidence in Central Madagascar

Abstract

Renewed interest in the significance of Animal-Sourced Foods (ASF) in addressing a variety of health issues in developing countries, most notably stunted growth in children, has arisen recently. Although ASF products constitute an important source of proteins and essential nutrients for young children, empirical evidence on the relationship between ASF production and child growth is limited, especially studies using a longitudinal cohort. We go one step further and contribute to the existing literature by unveiling the multiple causal mechanisms between ASF production and child health, and by including lagged indicators of ASF at the individual level. We investigate this topic with the advantage of an eight-round panel dataset from the central zones of Madagascar, a region with relatively poor milk intake and high stunting rates. Findings indicate that only lagged milk production is positively and significantly associated with the height-for-age (HAZ) scores and stunting of children under 5 years of age. The possible transmission channels at the household level are sustained frequency, probability of milk consumption, and improved welfare, suggesting that production of milk and dairy products is an important driver of long-term growth gains among children in central Madagascar.

Key words: animal-sourced foods; milk production; HAZ; lagged analysis; Madagascar

5 Animal-Sourced Foods Production and Early Childhood Nutrition: Panel Data Evidence in Central Madagascar

5.1 Introduction

Notwithstanding some real progress in reducing malnutrition globally, the Sustainable Development Goals (SDGs) aim of providing healthy diets for all by 2030 remains an ambitious objective for both affluent and poor population segments (FAO and WHO, 2019). In high-income countries, concerns have been raised about the perceived negative impact of Animal-Sourced Foods (ASF) production on human health, the environment, and animal welfare (Poore and Nemecek, 2018; Willet et al., 2019). This worldwide controversy has prompted international organizations to advocate for increased consumption of plant-based foods while proposing a dietary shift toward less ASF consumption on a global scale (Herforth et al., 2019; Willet et al., 2019; Adesogan et al., 2020). However, recent evidence reveals that this approach may not be optimal for the African and South Asian regions, where low-income households in rural areas primarily rely on energy-rich but nutrient-poor staple foods, with limited access to nutrient-dense options such as pulses, milk, meat, or eggs (Hirvonen et al., 2019; Henchion et al., 2021).

Within Sub-Saharan Africa (SSA), despite the substantial involvement of the rural population in agricultural activities, a pervasive issue of malnutrition persists (FAO et al., 2021). Malnutrition, in turn, is argued to be caused by a lack of nutrient-rich meals, which supply multiple bioavailable nutrients missing in the cereal-based diets (FAO et al., 2019). The usual diet of more than 60 percent of rural households involved in farming is heavy on starchy carbohydrates (IFAD, 2021). Concurrently, malnutrition remains a pressing public health concern, inflicting enduring detrimental effects on children. Stunting, affecting an estimated 149.2 million children under the age of five (22.2 percent) in 2020, emerges in early life, particularly within the first 1,000 days (WHO, 2021). This emphasizes the critical significance of optimal nutrition during a child's initial thousand days of development.

Nearly all studies attempting to address child malnutrition investigate the link between agriculture production, diet, and nutrition among smallholder farmers in developing countries (Sibhatu & Qaim, 2018). A longstanding yet debated policy recommendation promotes agricultural diversification as a means to enhance farmers' income, foster nutritional diversity, and encourage commercialization, contrasting specialization (Waha et al., 2018; Tesfaye, 2022). Nonetheless, despite some studies supporting the positive nutritional outcomes associated with dietary diversification, recent critical reviews underscore the limited effectiveness of these agricultural approaches in terms of quality and nutrient enhancement (Jones, 2017; Sibhatu & Qaim, 2018). This viewpoint is further supported by recent study, indicating that focusing solely on dietary diversity indicators may obscure the distinct contributions of individual food items in increasing nutrient intake needed for improving children's nutrition security (Heeman et al., 2022). According to WHO (2014), specific food groups, particularly ASF products, are among the best available sources of high-quality nutrient-rich foods crucial for children's optimal growth and development. ASF products not only supply the necessary calories but also deliver essential nutrients essential for realizing human developmental potential. Remarkably, ASF products constitute the only readily available sources of these nutrients (Adesogan et al., 2020).

Despite the fact that the benefits of such nutrient-dense food intake have been thoroughly assessed in the existing literature, there is a concerning lack of scientific evidence with consistent conclusions on the association between ASF production and child nutrition (Grace et al., 2018; Iannotti et al., 2021). From the consumption perspective, Iannotti et al. (2017) conducted a randomized controlled trial (RCT) in Ecuador and found that daily egg consumption for children is significantly associated with a 50 percent reduction in stunting. However, these findings did not align with those from Malawi, where different geography and dietary patterns, particularly high fish consumption, may have diminished the nutritional relevance of eggs (Stewart et al., 2019). In addition, a comprehensive analysis of Demographic and Health Survey data from 49 countries revealed a strong negative correlation between indices of ASF consumption and stunting (Headey et al., 2018). Another systematic review and meta-analysis of 62 controlled trials comprising over 30,000 participants across 5 continents found that ASF supplementation improves birth weight, and child weight, but has a less consistent association with the height-for-age scores (HAZ) (Pimpin et al., 2019). A more recent systematic review identified inconsistent associations between ASF consumption and stunting, length/height, weight, and other child growth parameters (Shapiro et al., 2019). Their study also concluded that the association between ASF and child nutritional outcomes was largely insignificant, suggesting that the highly heterogeneous results could be attributed to variations in study design (Shapiro et al., 2019). Moreover, nearly all existing studies are observational cross-sectional studies, restricting the potential for detecting causal or lagged effects (Hoddinott et al., 2015; Grace et al., 2018; Shapiro et al., 2019). The sole research to assess the relationship between ASF intake and stunting in a longitudinal setting was conducted by Zaharia et al. (2021) using data from Nepal, Bangladesh, and Uganda. The study found that lagged and contemporaneous ASF intakes were positively associated with linear growth in children, highlighting the need for continuous ASF intake to enhance child growth. However, the study's narrow focus on consumption-nutrition nexus overlooked household-level ASF production, as well as possible underlying mechanisms. It is important to note that the study had several limitations, including a narrow focus on food consumed by children using a short 24-hour recall period and the use of different survey time periods that were less frequent[16] (Zaharia et al., 2021). From the production side, another line of research highlights a positive link between milk production, child HAZ, and improvement in children's diet (Choudhury and Headey, 2018; Miller et al., 2022). However, most did not include lagged analysis, leaving a crucial gap in understanding long-term effects. Overall, existing studies (i) are largely cross-sectional in nature, (ii) provide inconsistent findings, (iii) warrant further analysis using lagged variables, and (iv) necessitate the inclusion of multiple survey periods to account for potential seasonal variations.

Using data from rural Madagascar, the current study aims to fill these gaps and contributes to the literature by highlighting the association of past and current ASF production with child nutritional outcomes in the central areas of the country, specifically in the Vakinankaratra region. Madagascar serves as an ideal setting for examining how increased ASF production affects child nutrition for the following reasons. First, Madagascar is a country where agriculture is the primary source of income for 70 percent of the population with all participants in our study engaged in rice cultivation and some involved in off-farm activities (FAOSTAT, 2019a). Moreover, as the study area is located in rainfed agricultural zones, seasonal and annual fluctuations in agricultural production and food prices are very high. Second, according to FAOSTAT (2019b), cereals and tubers account for 80 percent of the calorie supply among

[16] The datasets used in the paper are unbalanced panels consisting of three annual surveys in Nepal (2014-2016), three bi-annual surveys in Bangladesh (2016-2017), and three biennial surveys in Uganda (2012-2016).

Malagasy farmers, with plant-based foods accounting for 93 percent of total calorie supply, while ASF products account for only 7 percent. This persistent dietary imbalance underscores the relevance of investigating the subject within Malagasy households. Third, Madagascar ranks third globally in hunger and malnutrition rates according to the 2020 Global Hunger Index (GHI) scores and holds the top position among conflict-free countries in SSA. Finally, official statistics report that two out of five children experience chronic malnutrition in Madagascar, with high stunting prevalence of 46 percent among children aged 36 to 47 months. Stunting rates are also likely to be higher in rural areas compared to urban areas, with 41 percent versus 36 percent, respectively. Moreover, the Vakinankaratra region experiences particularly severe stunting, affecting over half of preschoolers (INSTAT & ICF, 2021).

This study thus contributes to the literature linking ASF production to nutrition in several novel ways. First, while most studies use cross-sectional data, this study is one of the first papers to use multiple rounds (high frequency) of panel data, thereby eliminating endogeneity emanating from unobserved, time-invariant factors that may be correlated with both ASF production and food and nutrition outcomes with a better control of seasonality. Second, unlike previous studies that primarily focused on either the household or individual level, this study considers the interplay between ASF production and nutrition at both levels, providing a more comprehensive understanding of the relationship. Thirdly, the study delves into the underlying mechanisms through which ASF production influences stunting, specifically investigating two key pathways: self-consumption and income generation. This approach sheds light on the potential drivers of the observed associations. Fourthly, this study incorporates important methodological considerations often overlooked in the literature, including the use of lagged analysis and the control of various survey periods. These factors enhance the rigor and validity of the findings. Finally, while most studies in this area have been conducted in regions and countries where milk consumption is common, this study focuses on Madagascar, a country characterized by relatively low milk intake. Overall, by adopting these particular approaches and examining the specificities of ASF production in Madagascar, this study contributes significantly to the understanding of the complex dynamics between ASF production and nutrition outcomes.

The remainder of this paper is structured as follows. Section 5.2 establishes the conceptual framework, providing a theoretical basis for the study. In Section 5.3, the empirical strategy used in this study is outlined. Section 5.4 introduces the variables used in the analysis. Subsequently, Section 5.5 presents the descriptive results and main findings derived from the empirical analysis. Section 5.6 concludes the paper by summarizing the key insights and providing implications for policy-making.

5.2 Conceptual framework

This study adopts a child health production function framework of a farm household, motivated by Hoddinott et al. (2015):

$$H_{cht} = f(N_{ht}, N_{ht-1}, C_{cht}, X_{ht}, \tau_{ch}) \quad (5.1)$$

where H_{cht} represents the health of child c of household h at time t; N_{ht} denotes food intake of household h at time t, and N_{ht-1} represents the same food intake in the previous period. Here, child's current health status depends not only on current food intake, but also past food intake. C_{cht} is a vector for exogenous variables that may directly affect child health, including factors such as sex, age, and other child-related variables. X_{ht} represents household characteristics at time t; while τ_{ch} represents unobserved variables related to child health endowment. In the case of perfect market, N_{ht} does not depend on household's food production. However, due to the absence or imperfections of markets, as observed in the context of Madagascar (Barrett, 1997), household production decisions and its consumption decisions are not separable (Singh et al., 1986). Thus, household-level agricultural production plays an important role in determining the nutritional status of children, and hence food intake in Equation (5.1) can be replaced by food production as below.

$$H_{cht} = f(F_{ht}, F_{ht-1}, C_{cht}, X_{ht}, \tau_{ch}) \quad (5.2)$$

where F_{ht} and F_{ht-1} represent food production of household h in t and t-1 respectively.

In the framework presented by Hoddinott et al. (2015), the association between dairy cow ownership and child health was investigated using cross-sectional data. However, in our specific study area, there is a need to address the potential endogeneity arising from other unobserved time-invariant factors, including preferences, cultural norms (Ribeli & Pfister, 2022), and maternal knowledge (Rakotomanana et al., 2020). To address for these potential cofounders, we estimate the proposed model using panel data methods, which help mitigate biases associated with unobserved variables that remain constant over time. Moreover, the model can be improved by using high-frequency panel data to better control for seasonality effects.

5.3 Empirical strategy

The third equation assesses the association between ASF production and child growth indicators:

$$y_{cht} = \beta_1 F_{ht} + \beta_2 F_{ht-1} + \gamma_1 M_t + \gamma_2 (V_h * T_t) + \gamma_3 C_{cht} + \gamma_4 X_{ht} + \gamma_5 Z_{gt} + \gamma_6 T_t + \tau_{ch} + \varepsilon_{cht} \qquad (5.3)$$

where c is an index for the child, h for the household, t for time (survey wave), and g for rainfall grid. y_{cht} represents the child nutritional outcomes in household h at time t, a continuous variable. We consider two types of child growth variable: HAZ and a binary variable taking 1 if the child is stunted (HAZ<-2) or 0 otherwise. D_{ht} and D_{ht-1} are the respective total value per Adult-Male equivalent[17] (AE) for the contemporaneous and lagged ASF production in natural logarithm[18] on a monthly average. β_1 and β_2 are the respective coefficients of interest that denote the association between both the contemporaneous and lagged ASF production and child growth. Furthermore, we control for M_t, which is the number of months covered by each survey. We also consider $(V_h * T_t)$, which is the interaction terms between village dummies and time dummies to control for time-variant factors such as changes in infrastructure, institutional conditions, and prices at the village level. C and X are vectors for child and household characteristics, respectively. Z indicates the rainfall variability or the statistical z-scores within the survey period at the grid level[19]. Time dummies (T_t) are introduced to control for potentially omitted variables that are time specific and common to all the study sites but not observed in the data set, for example the pandemic of COVID-19. τ_{ch} and ε_{cht} are the child-specific fixed effects and the error term, respectively. To investigate the possible association between ASF production and child nutritional growth, we estimate a child fixed-effects (FE)

[17] Adult-Male Equivalent is obtained from a table provided by USAID (Sununtnasuk, 2013).
[18] To be explained in section 5.4
[19] To be explained in section 5.4

model with standard errors clustered at the child level.

In order to investigate potential pathways from ASF production to food consumption at the household level, the following regression model is specified:

$$y_{ht} = \beta_1 F_{ht} + \gamma_1 M_t + \gamma_2 (V_h * T_t) + \gamma_3 X_{ht} + \gamma_4 Z_{gt} + \gamma_5 T_t + a_h + v_{ht} \quad (5.4)$$

where h represents the household, t for time (survey wave), and g for rainfall grid. The dependent variable, y_{ht}, is either household food consumption or the monthly household income per-capita. The household food consumption is captured by food consumption frequency of each food group in a week and a binary dummy variable taking 1 if the food group is consumed in a week or 0 otherwise. The household income per capita is proxied by per-capita expenditures. D_{ht} is a variable representing the monthly average of the total value per AE of ASF produced by the household during the survey period. *X* is a vector of observed household characteristics. a_h and v_{ht} are the household-specific fixed effects and the idiosyncratic error term, respectively. The interaction term, and other control variables are the same as in Equation (5.3). Equation (5.4) is estimated using a household FE model with standard errors clustered at household level.

5.4 Data variables

5.4.1 *Household survey and rainfall data*

This study uses an eight-wave panel dataset encompassing critical seasons from June 2018 to July 2021. The study area, situated in the Vakinankaratra region of the central regions of Madagascar, experience distinct agricultural seasons, including the lean season (January to April), post-rice harvest period (May to August), and pre-lean season (September to December). Surveys were carried out once in 2018 (baseline), three times in 2019, twice in 2020, and twice in 2021. The baseline survey solely provided lagged data on ASF production for the subsequent survey in this study. At the beginning of the baseline survey, ten lowland rice growers were randomly selected from 60 villages in three of the seven districts in the region, and a total of 600 households were repeatedly interviewed in each wave of the survey. Only households appearing in at least two surveys were included in the analysis, resulting in an unbalanced panel data set of 3915 household-observations with a moderate attrition rate of 10 percent of the initially selected households. Data collection included comprehensive assessment of agricultural activities, monthly food and non-food expenditures, and a 7-day recall questionnaire on food consumption. Additionally, health-related information at the individual level was recorded, including anthropometric measurements of children aged 6 to 60 months, serving as proxies for their nutritional status. Of course, not all households had young children, such that the total number of measured child-observations was 984. The child sample for the panel analysis consisted of 802 observations, considering only those children appearing in at least two surveys. Precipitation data was obtained from the GIOVANNI[20] tool (Huffman et al., 2019), offering high-resolution satellite-derived data on global daily precipitation from June 2000 to September 2021. The z-scores[21] were calculated by comparing the total rainfall quantities (in mm) received during each survey period to the long-term mean for the corresponding time period.

5.4.2 *Explanatory variables*

For our variables of interest, we use a continuous variable that indicates the total value per AE of ASF production on a monthly average[22]. We further disaggregate this variable based on specific ASF product types, including milk, eggs, meat, and poultry. We thus consider one alternative set of specifications, which is the physical amount per AE of ASF production on a monthly average for each ASF type. To capture the variability in ASF production, we collect data by recalling the quantities of ASF produced each month as reported in the survey. In our analysis, both the total value and physical amount per AE are transformed using logarithms[23].

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[20] Giovanni is an acronym for the Geospatial Interactive Online Visualization ANd aNalysis Infrastructure. Data were accessed on September 8th, 2021 and available at https://giovanni.gsfc.nasa.gov/giovanni/

[21] Z-scores are defined by the following formula: $z_{gt} = \frac{X_{gt} - \bar{X}_{gt}}{\sigma_{gt}}$ where X_{gt} is calculated by summing the monthly total rainfall recorded in an enumeration area g for all months covered by the survey period t, $\bar{X}_{gt}$ and σ_{gt} are respectively the 2000-2021 rainfall average and standard deviation (SD) for enumeration area g during the months covered by the respective survey period t.

[22] Fish farming was not included due to the small number of fish farmers.

[23] While addressing zero values poses a challenge, using a logarithmic transformation offers the advantage of interpreting the explanatory variables as percentage changes. First, we use ln (x+1), a method introduced by MaCurdy and Pencavel (1986). To ensure the robustness of our findings, we also explore the Inverse-Hyperbolic

5.4.3 *Outcomes measures*

In this study, two distinct categories of outcome variables are evaluated: (i) child nutritional status and (ii) household food consumption information to address the potential underlying mechanisms.

5.4.3.1 *Child nutritional status*

Child nutritional outcomes in this study are assessed using two indicators: HAZ and stunting. These indicators are derived from anthropometric measurements of children aged 6 to 60 months. Stunting is represented by a binary variable, indicating low height-for-age based on z-scores calculated relative to the standard median obtained from WHO reference populations (WHO, 2006).

5.4.3.2 *Household food consumption and expenditures*

a. Consumption frequency in each food group

The first category of food consumption variables in this study pertains to the frequency of consumption of specific food groups by any member of the household in the seven days preceding the interview. For this specific category of variables, we focus on 7 major food groups including *staples, tubers, pulses, vegetables, fruits, meat-eggs-fish, and milk and dairy products*. Meat, eggs, and fish are put in one group of "*meat-eggs-fish*", instead of three groups, because the questionnaire design did not allow us to deal with them separately. We omit the group of *oils and fats, sweets* and *miscellaneous* as their consumption remains almost constant. This measure captures the number of days each food group is consumed, ranging from 0 to 7. It is important to note that the question related to these variables was not included until wave 3 (May - June 2019), resulting in the exclusion of wave 2 from the initial regression analysis on these variables. As a result, the sample size for the analysis was reduced to 3373 households.

Sine (IHS) transformation of x. This transformation behaves similarly to a logarithm and allows us to retain observations with zero values (Bellemare et al., 2013). The formula for the IHS transformation is represented by: $IHS(x) = \ln{(x + (x^2 + 1)^2)}$.

b. Binary variables for consumption of each food group

The second category of food consumption variables in this study consists of binary variables indicating the consumption of specific food groups. These variables are derived from the food groups used to calculate the Household Dietary Diversity Score (HDDS)[24], excluding oils and fats, sweets, and miscellaneous. Instead of combining them all together to a HDDS, we maintain each food group as a separate variable. This approach allows us to highlight the percentage of households consuming each specific food group. Since we can disaggregate the "*meat-eggs-fish*" category, we now consider nine variables instead of seven. These variables are represented by the group of *staples, tubers; pulses; vegetables; fruits; meat; eggs; fish; milk and dairy products*. Each of these is a binary dummy variable, taking the value of 0 if there was no consumption and 1 if any food from the respective group was consumed in the last 7 days prior to the interview.

c. Household consumption aggregate

The third category of food consumption related variables in our study is the household consumption aggregate. We use this variable as a summary measure of living standards, which is an important component of household welfare (Deaton & Zaidi, 2002). To further examine the relationship, we disaggregate this variable into separate categories of food, non-food consumption, and other major items. We calculate the monthly per-capita consumption aggregate by dividing the total amount by the number of household sizes and transform into a logarithmic form.

5.4.3.3 Control variables

To comprehensively examine the association between ASF production and child nutrition, we control for important household- and geographic-level factors. Specifically, we consider important household characteristics

[24] Household dietary diversity Score (HDDS) is a qualitative indicator of food intake that reflects household access to a variety of foods. This indicator is based on adding up 12 food groups including: staples, tubers; pulses; vegetables; fruits; meat; eggs; fish; milk and dairy products, oils and fats, sweets, and miscellaneous (spice, condiments and beverages) (Kennedy, Ballard & Dop, 2013).

such as household size, the proportion of preschool children, school-going children, elderly members, and working women. Furthermore, we incorporate plot-related attributes, including the overall count of lowland plots, ownership of upland or other plots, and engagement in plot rental. To capture market dynamics, we introduce a variable reflecting the duration since the household's most recent market visit. Recognizing the influence of household wealth on both food consumption and child nutrition, we incorporate two proxy variables such as farm and non-farm assets. Lastly, we include variables linked to crop diversification and precipitation, factors known to influence the subject under investigation.

5.5 Empirical results

5.5.1 *Descriptive statistics*

Table 5.1 presents the summary statistics for the child growth outcomes based on the panel data. After excluding children with biologically implausible values (HAZ<-6 or HAZ>6), the results show that stunting in children aged 6 to 60 months is prevalent in the highland zones of Madagascar with nearly 60 percent of children stunted. The mean HAZ of -2.34 further indicates the severity of the issue. The average age of children in the sample is 35 months, with 6 percent already attending school and 4 percent reporting illness during the survey period.

Table 5.1 Descriptive statistics of outcome and explanatory variables for child level data

Panel sample	Obs	Mean	Std.Dev.	Min	Max
Outcome variables					
Stunted (Yes = 1)	*802*	0.59	0.49	0	1
HAZ	*802*	-2.34	1.68	-6	3.86
Explanatory variables					
Age in months	*802*	34.93	15.68	6	60
School attendance (Yes = 1)	*802*	0.06	0.24	0	1
Sick (Yes = 1)	*802*	0.04	0.21	0	1

Notes: Observations from all the seven surveys were pooled.

Figure 5.1 visually depicts the distribution of HAZ, providing a comprehensive representation of the alarming prevalence of stunting in the central highlands of Madagascar.

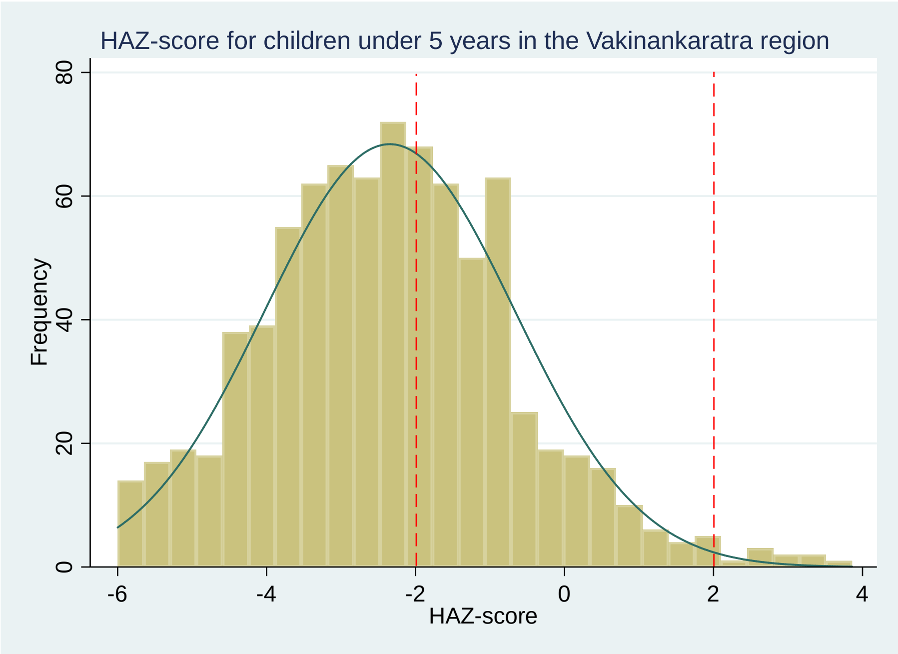

Fig. 5.1 HAZ distribution for children under 5 years. The vertical bar represents measured data, the solid line represents the expected distribution of z-scores, and the dashed line represents ± 2 standard deviations.

Table 5.2 presents the summary statistics for the outcome variables, providing insights into the consumption patterns of different food groups over a seven-day period. Staples and vegetables emerge as the most frequently consumed food groups, with households consuming them for more than 5 days on average. Tubers follow closely, with an average consumption frequency of 4.17 days. In contrast, meats, fish, and eggs exhibit relatively lower consumption frequencies, with households consuming them for approximately 2.60 days per week. Pulses and fruits are consumed for 1.94 and 1.43 days respectively during the 7-day recall period. Notably, milk and dairy products have the lowest consumption rates, with households reporting consumption for only 0.66 days per week on average.

When considering a binary response for each food group or whether the household consumed at least one item within a food group during the 7-day recall period, almost all the households reported consuming staples and vegetables at least once. Pulses, fish, and tubers are also popular, being consumed by more than 70 percent of households. Meats, milk and dairy products are among the least consumed food groups, with only about 39 and 17 percent of households respectively. And only 4 percent of household observations reported egg consumption.

In terms of household consumption aggregate, indicative of household welfare, the average monthly per capita consumption aggregate is relatively low. On average, households spend around 65,329 Malagasy Ariary (MGA) per capita per month, which is equivalent to less than USD 15[25].

Table 5.2 Descriptive statistics of outcome variables for household level data

Outcome variables	Obs[1]	Mean	Std.Dev.	Min	Max
Consumption frequency during the last 7 days					
Staples (days)	*3373*	6.98	0.29	0	7
Tubers (days)	*3373*	4.17	2.74	0	7
Pulses (days)	*3373*	1.94	1.53	0	7
Vegetables (days)	*3373*	5.02	1.54	0	7
Fruits (days)	*3373*	1.43	1.87	0	7
Meats/ eggs/ fish (days)	*3373*	2.60	1.69	0	7
Milk and Dairy Products (days)	*3373*	0.66	1.64	0	7
Consumption of food group during the last 7 days					
Staples (Yes=1)	*3915*	1.00	0.03	0	1
Tubers (Yes=1)	*3915*	0.78	0.41	0	1
Pulses (Yes=1)	*3915*	0.78	0.41	0	1
Vegetables (Yes=1)	*3915*	0.99	0.09	0	1
Fruits (Yes=1)	*3915*	0.49	0.50	0	1
Meats (Yes=1)	*3915*	0.39	0.49	0	1
Fish last (Yes=1)	*3915*	0.77	0.42	0	1
Egg last (Yes=1)	*3915*	0.04	0.19	0	1
Milk and Dairy Products (Yes=1)	*3915*	0.17	0.38	0	1
Food expenditures per capita					
Household consumption aggregate (in MGA[2])	*3915*	65329	43000	8200	577027
Expenditures on food consumption (in MGA[2])	*3915*	49987	26582	4120	269800
Expenditures on non-food consumption (in MGA[2])	*3915*	8503	11226	0	174625
Expenditures on non-food major items[3] (in MGA[2])	*3915*	6839	20216	0	426333

Notes: Observations from all the seven surveys were pooled. [1]The smaller sampling size is due to the information on frequency only being available in waves 3 to 8, not in wave 2. [2]MGA stands for Malagasy Ariary. 1 MGA = 0.00023 USD as of September 22nd, 2022. [3]Major items include health insurance costs, travel expenses, clothing, and other fees.

Table 5.3 presents the summary statistics of both the main explanatory variables of our interest and control variables. With regard to our variables of interest, households produce an average monthly value per AE of 11,500 MGA (equivalent to USD 2.6) for ASF products. This production level corresponds to an approximate monthly production of 2.24 liters of milk, 0.09 egg (unit), 0.07 kilograms of meat, and 0.74 poultry (unit) per AE per month.

[25] 1 MGA is equivalent to 0.00023 USD as of September 22nd, 2022

Table 5.3 Descriptive statistics of explanatory variables for household level data

Variables	Obs	Mean	Std.	Min	Max
Main explanatory variables of our interest					
Total value per AE of ASF production[1] (in MGA[7])	*3915*	11500	33057	0	59779
Amount per AE of milk production[1](in liter)	*3915*	2.24	12.13	0	217
Amount per AE of egg production[1](in unit)	*3915*	0.09	1.09	0	51
Amount per AE of meat production[1](in kg)	*3915*	0.07	0.77	0	17
Amount per AE of poultry production[1](in unit)	*3915*	0.74	3.10	0	139
Control variables					
Household characteristics					
Household size	*3915*	4.71	1.95	1	14
Share of preschool children	*3915*	0.18	0.20	0	1
Share of schooling children	*3915*	0.26	0.21	0	1
Share of old members	*3915*	0.11	0.24	0	1
Share of working woman	*3915*	0.26	0.16	0	1
Plot characteristics					
Total number of lowland plots	*3915*	1.42	1.07	0	10
Have any upland plots (Yes=1)	*3915*	0.57	0.49	0	1
Have any other plots (Yes=1)	*3915*	0.78	0.42	0	1
Renting any plot (Yes=1)	*3915*	0.05	0.22	0	1
Percentage of irrigated plots	*3915*	0.23	0.25	0	1
Last day to markets	*3915*	3.51	2.27	0	30
Household assets					
Cow ownership[2] (Yes = 1)	*3915*	0.30	0.46	0	1
Chicken ownership[3] (Yes = 1)	*3915*	0.84	0.37	0	1
Other livestock[4] (Yes = 1)	*3915*	0.82	0.39	0	1
Farm asset per capita[5] (in MGA[7])	*3915*	60769	15279	0	20750
Non-farm asset per capita[6] (in MGA[7])	*3915*	68219	25250	0	11800
Crop diversification[8]	*3915*	0.87	0.85	0	5.00
Total month covered during each survey	*3915*	5.13	1.35	4	8.00
Rainfall variability (z-scores)	*3915*	-0.51	0.66	-1.63	0.81

Notes: Observations from all the seven surveys were pooled. [1]per Adult-Male Equivalent (AE) produced on a monthly average. [2]Some cows were probably not producing milk at the time of the survey as, according to the questionnaire, these include cows that have previously or currently had offspring. [3]The high percentage is due to the inclusion of all types of chicken (chick, hens, and rooster). [4]Most cattle are used as riding or draft animals; hence, they are rarely marketed. [5]Farm asset is defined as the total value of all the farm equipment such as hand hoe, carts, and other equipment. [6]Non-farm asset is defined as the total value of all the house items such as beds, bicycles, TV, and other assets. We note that none of the household owns a refrigerator. [7]MGA stands for Malagasy Ariary. 1 MGA = 0.00023 USD as of September 22nd, 2022. [8]Crop diversification represents the number of food groups produced by the household, namely cereal, tuber, pulse, vegetable, fruit and others (grass, artemisia).

With respect to the control variables, the average household size is 4.71 individuals. Among the household members, preschool children, school-aged children, elderly members, and working women account for an average of 18, 26, 11, and 26 percent, respectively. On average, each household possesses 1.42 lowland plots. About 57 percent of households own at least one upland plot, while 78 percent own other types of plots such as gardens, and 5 percent engage in rented-in plot. The percentage of irrigated lowland plots are about 23 percent. We also include binary variables for household owning cow, meat-producing animals (bulls, heifer, calves, goat, sheep, and pigs), and chicken, which represent 30 percent, 82 percent, and 84 percent of all households, respectively. The per capita values of farm and non-farm assets amount to approximately 61,000 MGA (equivalent to USD 14.03) and 68,000 MGA (equivalent to USD 15.64), respectively. The model also controls for crop diversification, which represents the number of food groups produced by the household, including cereals, tubers, pulses, vegetables, and fruits. On average, households produced one out of the five food groups. Finally, in terms of our climatic variable, we control for the rainfall variability. Assuming a normal distribution, a z-score of 0 implies that the data point value is equal to the mean. However, we observe that the average z-scores across all the waves is -0.51, indicating a smaller precipitation during the survey period than the twenty-year mean.

5.5.2 *Association of ASF production with child nutritional status*

Table 5.4 presents the FE estimates examining the relationship between lagged and contemporaneous production of each type of ASF product and child nutritional status. The analysis focuses on two nutritional outcomes: HAZ and stunting status of children. Columns [1] to [4] present the results for children aged 6 to 60 months, while Columns [5] and [6] specifically examine the sub-category of children aged 6 to 47 months[26].

First, the independent variables used are the aggregated lagged and contemporaneous value per AE of total

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[26] In our analysis, we opted to exclude the oldest children, aged 48-60 months, due to the small differences observed between households that owned cows and those that did not (see Appendix Fig A5.2). In addition, since the panel spans several years, some of the older children might have received milk during the 0-23 month period if milk production persisted. However, this might not hold true for the oldest children, whether they received milk or not during their younger years.

ASF production, measured in natural logarithm of the monthly average. In Columns [1] and [2] of Table 5.4, the corresponding results show no significant association between ASF production and the nutritional outcomes. To further investigate, we disaggregate the previous variable based on the physical amount of ASF produced per AE, also measured in natural logarithm on a monthly average. In Columns [3] and [4] of Table 5.4, we observe that only lagged milk production shows a significant association with HAZ-scores ("positive") and the binary variable for stunting ("negative"). Specifically, results indicate that a 50 percent increase in the physical amount per AE of milk production in the previous period is significantly associated with an increase in HAZ-score by about 0.17 (0.43 x ln [1.5]; 99% C.I: 0.17, 0.69) and a decrease in stunting by 0.04 (-0.098 x ln [1.5]; 95% C.I: -0.16, -0.03).

To probe the robustness, we use the IHS transformation as an alternative to the simple log(x+1) transformation. Results show similar findings. Specifically, for every 50 percent increase in the physical amount per AE of milk production on a monthly average in the previous survey, the HAZ-score increases by about 0.15 (0.37 x ln [1.5]; 99% C.I: 0.15, 0.59), and stunting prevalence decreases by 0.03 (-0.08 x ln [1.5]; 99% C.I: -0.14, -0.02) (see Appendix Table A5.1).

Conversely, we observe that contemporaneous egg production is negatively associated with HAZ in all specifications, but does not show a significant association with stunting status. One possible explanation might be related to cultural beliefs surrounding egg consumption, particularly considering the specific context of our study area in Madagascar (Ribeli & Pfister, 2022). Another possible explanation may lie in the dietary habits of households, whereby the consumption of eggs, primarily in combination with rice, may lead to a limited inclusion of other food items, resulting in reduced dietary diversity.

In Columns [5] and [6], results present the association between the physical amount of ASF production and child nutritional status, with a specific focus on excluding children aged 6 - 47 months of age. The results indicate that a 50 percent increase in the physical amount per AE of milk production during the previous survey period is associated with an approximate increase of 0.19 (0.40 x ln [1.5]; 99% C.I: 0.20, 0.69) in the HAZ-score and a decrease of 0.04 (-0.09 x ln [1.5]; 95% C.I: -0.16, -0.02) in the prevalence of stunting.

Table 5.4: Association between exposure to lagged and contemporaneous ASF production and HAZ-score and stunting status of children (fixed-effects)

	6 - 60 months				6 - 47 months	
Column	(1)	(2)	(3)	(4)	(5)	(6)
Dep. Variables	HAZ	Stunted	HAZ	Stunted	HAZ	Stunted
Ind. Variables	Total amount per AE		Log of physical amount per AE		Log of physical amount per AE	
Total amount of ASF	-0.016	-0.00014				
	(0.017)	(0.0066)				
Lagged total amount of ASF	0.0050	-0.0018				
	(0.017)	(0.0058)				
Milk amount			0.13	-0.061	0.30*	-0.059
			(0.16)	(0.037)	(0.18)	(0.050)
Egg amount			-0.63**	0.14	-0.56**	0.12
			(0.29)	(0.11)	(0.28)	(0.13)
Meat amount			0.25	-0.032	-0.39	0.21
			(0.63)	(0.12)	(0.90)	(0.26)
Poultry amount			0.059	-0.033	0.011	-0.041
			(0.14)	(0.057)	(0.21)	(0.095)
Lagged milk amount			0.43***	-0.098***	0.47***	-0.11**
			(0.13)	(0.036)	(0.12)	(0.044)
Lagged egg amount			-0.12	-0.0093	-0.059	-0.081
			(0.28)	(0.13)	(0.34)	(0.17)
Lagged meat amount			-0.87	0.48	-2.52	0.73*
			(1.70)	(0.30)	(2.35)	(0.44)
Lagged poultry amount			-0.14	0.047	-0.58***	0.11
			(0.15)	(0.057)	(0.20)	(0.078)
Controlled variables	Yes	Yes	Yes	Yes	Yes	Yes
Observations	802	802	802	802	593	593

Notes: These are FE linear model estimates with standard errors in parentheses, clustered at child level. *** p<0.01 ** p<0.05 * p<0.10. Control variables are child characteristics (age, age squared, school attendance, sickness), household characteristics, plot characteristics, last day to markets, household assets, total month covered by the survey, rainfall variability, survey dummies, child fixed-effects, and the interaction term between village and survey dummies. Columns [1] and [2] used aggregated total value per Adult-Equivalent (AE) in natural logarithm. Columns [3] and [4] used physical amount of production per AE for each ASF production in natural logarithm: liter for milk, unit for egg, kilogram for meat, and unit for poultry. Columns [5] and [6] used physical amount of production per AE for children aged 6 - 47 months. ASF stands for Animal-Sourced Foods. HAZ represents the height-for-age of children. Stunting is defined by an HAZ-score <-2. Lag lengths are based on the time interval between each survey, as shown in Table 2.1.

Moreover, in order to explore the temporal dynamics of the association between milk production and child nutritional status, we conduct regressions using two-lag models (see Appendix Table A5.2). The results consistently support the significant association between lagged milk production and child health outcomes. However, when considering variables with a two-lag structure, no significant associations were found, particularly in relation to stunting prevalence, but a positive association between contemporaneous egg production and stunting status.

Overall, these results provide insight into a potential pathway by which ASF production, specifically milk production, is linked to child nutritional outcomes. The results indicate a discernible inclination towards the subsistence pathway, highlighting the importance of further analysis at the household level to gain a deeper understanding of this mechanism.

5.5.3 *Association between ASF production with household food consumption*

In this section, we aim to examine the potential mechanisms through which exposure to ASF production at the household level may influence child nutritional outcomes. Specifically, we explore the pathways of self-consumption and income generation. To shed light on these underlying mechanisms, we use various consumption-related variables as dependent variables, including food consumption frequency, binary variables for the consumption of specific food groups, and the monthly per-capita consumption aggregate of the household. We present a summary of the results for these dependent variables in Table 5.5. To conduct this analysis, we directly use the physical amount of ASF production per AE, specifically milk, eggs, meat, and poultry, as explanatory variables.

Using the panel data FE model, the findings in Table 5.5 reveal several significant associations with our variables of interest. Given the significant relationship between child health and milk production identified in the child-level analysis, we place particular emphasis on this variable at the household level. In Panel [A], Column [7] of Table 5.5 demonstrates a statistically significant and positive association between the physical amount of milk production per AE and the frequency of milk consumption. Results suggest that an increase in 50 percent in physical amount of monthly average milk production per AE of is associated with an average increase of 0.22 days per week in milk consumption (0.56 x ln [1.5]; 99% C.I: 0.41, 0.71).

Next, we delve into examining the extent to which ASF production correlates with the consumption of individual food groups during the week preceding the survey. The estimation results are presented in Panel [B] of Table 5.5. According to Column [9], results suggest that a 50 percent increase in the physical amount of monthly average milk production per AE is associated with a 0.045 increase in the likelihood of milk consumption (0.11 x ln [1.5]; 99% C.I: 0.09, 0.14). Moreover, the analysis reveals that milk production is significantly and positively associated with both the frequency and the likelihood of consuming vegetables at 10 percent statistical significance level. One possible explanation is that, although wealth level is controlled for by household assets, a possible link is that a rich household can own/produce milk and buy vegetable.

Table 5.6 reports the association between the physical amount of ASF production per AE and per capita household consumption aggregate. The results show that there is a positive and significant association with per-capita household consumption aggregate and milk production. According to Column [1], results suggest that a 50 percent increase in the physical amount of monthly average milk production per AE is associated with a 0.01 increase in the monthly per-capita consumption aggregate of the household (0.025 x ln [1.5]; 95% C.I: 0.004, 0.05). However, when investigating the disaggregated household consumption, results reveal significant and positive associations between the quantity of milk produced per AE and food consumption and non-food major items. Hence, milk production significantly enhances household welfare by promoting increased food consumption and the acquisition of major items.

Table 5.4 Summary table of the association between ASF production and household food consumption (fixed-effect linear model)

Panel A: Number of days in a week at least one item in a food group has been consumed in a household	(1) Staples	(2) Tubers	(3) Pulses	(4) Vegetables	(5) Fruits	(6) Meat-Fish-Egg	(7) Milk
Milk amount	0.023	-0.053	-0.060	0.089*	0.019	-0.019	0.56***
	(0.018)	(0.060)	(0.038)	(0.047)	(0.057)	(0.044)	(0.075)
Egg amount	0.020	-0.21	0.00038	-0.16	0.054	0.061	0.16
	(0.027)	(0.17)	(0.13)	(0.14)	(0.19)	(0.13)	(0.18)
Meat amount	0.026	0.028	0.11	0.043	0.20	-0.16	0.20
	(0.057)	(0.16)	(0.11)	(0.11)	(0.14)	(0.14)	(0.13)
Poultry amount	-0.014	0.046	0.024	0.12**	0.013	0.0076	0.016
	(0.016)	(0.083)	(0.055)	(0.051)	(0.068)	(0.052)	(0.056)

Panel B: Whether the household has consumed at least one item in the food group in the previous week	(1) Staples	(2) Tubers	(3) Pulses	(4) Vegetables	(5) Fruits	(6) Meat	(7) Fish	(8) Egg	(9) Milk
Milk amount	-0.00017	-0.00043	-0.011	0.0023*	-0.0075	0.0080	-0.0090	0.0022	0.11***
	(0.00028)	(0.011)	(0.010)	(0.0014)	(0.012)	(0.014)	(0.014)	(0.0066)	(0.013)
Egg amount	0.0011	0.012	0.0023	0.0016	0.093***	-0.062	0.15***	0.033	0.018
	(0.0023)	(0.041)	(0.033)	(0.0051)	(0.036)	(0.038)	(0.047)	(0.029)	(0.033)
Meat amount	0.0015	0.059*	0.029	-0.0059	-0.039	0.051	-0.070**	0.011	-0.0078
	(0.0014)	(0.032)	(0.025)	(0.0048)	(0.031)	(0.038)	(0.034)	(0.026)	(0.031)
Poultry amount	-0.0011	0.015	-0.010	-0.00062	0.0084	-0.025*	-0.011	0.0095	0.013
	(0.0017)	(0.015)	(0.014)	(0.0028)	(0.016)	(0.015)	(0.016)	(0.0083)	(0.013)

Notes: These are FE linear model estimates with standard errors in parentheses, clustered at household level. *** p<0.01 ** p<0.05 * p<0.10. In this table, we only show the estimates of our variables of interest (log of physical amount of production per AE of each ASF). For each model in each panel, we control for household characteristics, parcel characteristics, household assets, and rainfall variability as described in Table 3. We additionally control for survey dummies, and the interaction terms between village and survey dummies. Panel A also do not distinguish the consumption frequency of meat-fish-egg but rather combined them into one variable, which is not the case for Panel B. The observations in Panel A and B are 3373 and 3915, respectively. The smaller sampling size in Panel A is due to the information on frequency only being available in waves 3 to 8, not in wave 2.

Table 5.5: Marginal effects of contemporaneous ASF production on household expenditures (fixed-effect linear model)

Variables	(1)	(2)	(3)	(4)
	Consumption aggregate			
	Total	Foods	Non-foods	Major items
Milk amount	0.025**	0.016*	0.0088	0.065**
	(0.011)	(0.0088)	(0.0084)	(0.032)
Egg amount	-0.020	0.019	-0.024	0.093
	(0.029)	(0.033)	(0.021)	(0.11)
Meat amount	-0.022	-0.019	-0.041**	0.073
	(0.022)	(0.020)	(0.020)	(0.12)
Poultry amount	0.0084	0.0031	0.0071	0.039
	(0.011)	(0.011)	(0.010)	(0.042)
Household variables	Yes	Yes	Yes	Yes
Rainfall variability	Yes	Yes	Yes	Yes
Total months covered	Yes	Yes	Yes	Yes
Survey dummies	Yes	Yes	Yes	Yes
Interaction village-year	Yes	Yes	Yes	Yes
Within R-sq	0.399	0.392	0.919	0.357
adj. R-sq	0.335	0.328	0.911	0.289
Observations	3915	3915	3915	3915

Notes: These are FE linear model estimates, with standard errors in parentheses, clustered at household level. *** p<0.01 ** p<0.05 * p<0.10. Explanatory variables are the log of physical amount of each ASF production per AE. We control for other variables which are not being shown here. Those control variables include household characteristics, parcel characteristics, household assets, and last day to market.

5.6 Discussions and policy implications

This study uses high-frequency panel data to examine the relationship between ASF production and child nutritional outcomes in the central highlands of Madagascar. Our estimations using the eight-wave panel data enable us to assess child growth dynamics controlling for child fixed effect, which is an advantage over standard regression approaches relying on cross-sectional or short panel data. Our findings demonstrate a positive and significant association between lagged milk production and child nutritional outcomes in our study area. Specifically, our results indicate that an increase in the physical quantity of dairy produced per AE leads to enhanced child growth indicators, as reflected in higher HAZ and a reduced prevalence of stunting among children aged 6 to 60 months. The mechanism underlying this relationship suggests that as households increase their dairy production, the frequency and probability of milk consumption principally through self-consumption rise, thereby contributing to improved child nutritional outcomes. These results highlight the crucial role of sustained milk production and increased milk consumption in fostering long-term growth benefits for children.

Despite the valuable insights provided by this study, it is important to acknowledge several limitations. Firstly, having data on individual dietary intake would have strengthened the robustness of our findings. Secondly, the inability to comprehensively control for all potential confounding factors and identify suitable instruments limits our ability to establish causal relationships. Thirdly, given the relatively low uptake of ASF production by households, we were unable to examine the association between ASF production and child outcomes across different age groups, warranting further investigation. Lastly, it is important to acknowledge that our results are region-specific and may not be generalizable to other contexts, yet they contribute to supporting the external validity of the findings pertaining to dairy production.

To facilitate the formulation of substantive policy recommendations, an in-depth comprehension of Madagascar's historical backdrop is imperative. The country has faced significant challenges, particularly the socio-economic-political crisis in 2009. This crisis had profound implications for the country's economic landscape, resulting in international economic sanctions, the withdrawal of economic aid, the collapse of the main agro-industrial company, and the closure of numerous milk collection centers that used to receive over 50 percent of the fresh milk produced in the region (Penot et al., 2016). The Vakinankaratra region, in particular, experienced pronounced effects due to the last two repercussions. In response to these challenging circumstances, many milk producers were forced to reduce production costs by decreasing the number of dairy cows or producing their own feed (Penot et al., 2016). Long-term effects were observed in terms of reduced access to technical support and artificial insemination straws, negatively impacting dairy cow production capacity. Moreover, services providing guidance on feeding and hygiene practices, especially in remote areas, were severely affected (Droy & Rasolofo, 2018; Penot et al., 2016). Despite the emergence of small and private operators in recent years, the region has yet to fully recover from the aftermath of the crisis. It is worth noting however that even before the onset of this “milk crisis”, the stunting rate in the region had already reached an alarming level of approximately 60 percent (INSTAT & ICF, 2010).

The findings of this study emphasize the critical need for tangible policy interventions to address the challenges surrounding milk production and its possible influence on reducing stunting in central Madagascar and other areas with potential for dairy production. Based on the existing milk production literature, several policy recommendations can be proposed. One specific policy with potential for impactful change is to encourage local farmers to actively engage in milk production for nutrition or school feeding programs, drawing inspiration from successful initiatives implemented elsewhere. A similar strategy has been effectively used in Thailand, where dairy was incorporated into school feeding programs to promote child nutrition and simultaneously support dairy farmers by providing a reliable market (Heaver & Kachondam, 2002). By adopting a comparable approach, the Vakinankaratra region can leverage the benefits of local milk production, ensuring a steady supply of nutrient-rich milk for children while simultaneously empowering farmers to improve their livelihoods.

Furthermore, it is crucial to invest in the revitalization of the dairy value chain by re-establishing milk collection centers (Van Campernhout et al., 2022; Bélières & Lançon, 2020), implementing modern and efficient production practices (Minten et al., 2020), and promoting quality control measures (Minten et al., 2022). Strengthening linkages between milk producers, processors, and distributors can enhance the efficiency and reliability of the milk supply chain, contributing to increased production and accessibility of milk. Moreover, efforts should be made to integrate smallholder farmers into the formal dairy sector, providing them with training, resources, and opportunities for collective action to enhance their productivity and income (Bélières & Lançon, 2020).

In parallel, a comprehensive approach is required that considers the broader livelihoods of smallholder farmers, their resilience mechanisms, and the nutritional support needed for children (Penot et al., 2016). This includes supporting diversified farming systems that integrate livestock rearing with crop production, promoting sustainable feed management practices, and ensuring access to veterinary services for the well-being of dairy cattle. Additionally, awareness campaigns and educational programs should be implemented to enhance knowledge and understanding of the importance of milk and dairy consumption for child nutrition.

Ultimately, the successful implementation of these policy recommendations hinges upon strong collaborations between the government, development agencies, local communities, and other stakeholders. To ensure their effectiveness, a comprehensive framework encompassing ongoing monitoring, evaluation, and adaptive management strategies must be adopted. This framework will facilitate the systematic assessment of intervention outcomes, identification of obstacles, and iterative refinement of policies. By embracing these evidence-based policy actions, Madagascar can make significant strides in improving milk production, reducing stunting, and fostering sustainable and inclusive agricultural development for the betterment of its population.

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APPENDICES

Table A 5.1 Association between exposure to lagged and contemporaneous ASF production and HAZ and stunting status of children (fixed-effects)

	6 - 60 months		**6 - 47 months**	
Column	(1)	(2)	(3)	(4)
Dep. Variables	HAZ	Stunted	HAZ	Stunted
Ind. Variables	IHS of physical amount		IHS of physical amount	
Milk amount	0.11	-0.048	0.25*	-0.048
	(0.13)	(0.031)	(0.15)	(0.043)
Egg amount	-0.47**	0.096	-0.41*	0.084
	(0.22)	(0.088)	(0.22)	(0.10)
Meat amount	0.19	-0.026	-0.32	0.17
	(0.50)	(0.098)	(0.72)	(0.21)
Poultry amount	0.045	-0.022	0.0075	-0.028
	(0.11)	(0.044)	(0.16)	(0.073)
Lagged milk amount	0.37***	-0.082***	0.40***	-0.093**
	(0.11)	(0.030)	(0.10)	(0.037)
Lagged egg amount	-0.090	-0.012	-0.026	-0.071
	(0.22)	(0.10)	(0.27)	(0.13)
Lagged meat amount	-0.68	0.37	-1.92	0.57*
	(1.30)	(0.23)	(1.81)	(0.34)
Lagged poultry amount	-0.11	0.036	-0.45***	0.087
	(0.12)	(0.045)	(0.15)	(0.060)
Controlled variables	Yes	Yes	Yes	Yes
Observations	802	802	593	593

Notes: These are FE linear model estimates with standard errors in parentheses, clustered at child level. *** p<0.01 ** p<0.05 * p<0.10. Control variables used in Table A1 are child characteristics (age, age squared, school attendance, sickness), household characteristics, plot characteristics, last day to markets, household assets, total month covered by the survey, rainfall variability, survey dummies, child fixed-effects, and the interaction term between village and survey dummies. Column [1] to [4] used physical amount per Adult-Equivalent (AE) in natural logarithm using the IHS transformation: liter for milk, unit for egg, kilogram for meat, and unit for poultry. Column [1] and [2] display results for children aged 6 to 60 months and Column [3] and [4] for children aged 6 - 47 months. HAZ represents the height-for-age of children. Stunting is defined by an HAZ <-2. Lag lengths are based on the time interval between each survey, as shown in Table 2.1.

Table A 5.2 Association between exposure to two lagged, lagged and contemporaneous ASF production and HAZ and stunting status of children (fixed-effects)

	6 - 60 months		**6 - 47 months**	
Column	(1)	(2)	(3)	(4)
Dep. Variables	HAZ	Stunted	HAZ	Stunted
Ind. Variables	Log of physical amount per AE		Log of physical amount per AE	
Milk amount (0 lag)	0.11	-0.089	0.27	-0.077
	(0.15)	(0.055)	(0.24)	(0.094)
Egg amount (0 lag)	-1.02***	0.23*	-1.19**	0.32*
	(0.31)	(0.13)	(0.47)	(0.18)
Meat amount (0 lag)	1.37*	0.034	-4.85*	0.97
	(0.74)	(0.20)	(2.87)	(1.37)
Poultry amount (0 lag)	0.19	-0.057	0.27	-0.11
	(0.14)	(0.063)	(0.21)	(0.10)
Lagged milk amount (1 lag)	0.37**	-0.13**	0.62***	-0.18**
	(0.18)	(0.058)	(0.22)	(0.080)
Lagged egg amount (1 lag)	-0.25	-0.012	-0.61	0.069
	(0.34)	(0.15)	(0.57)	(0.24)
Lagged meat amount (1 lag)	-0.17	0.57	-5.71***	1.20
	(1.38)	(0.35)	(1.63)	(1.15)
Lagged poultry amount (1 lag)	-0.00031	0.020	-0.43**	0.13
	(0.14)	(0.067)	(0.19)	(0.086)
Lagged milk amount (2 lags)	0.0061	-0.0069	0.025	0.0057
	(0.092)	(0.051)	(0.13)	(0.062)
Lagged egg amount (2 lags)	-0.35	0.0057	-0.51	0.028
	(0.33)	(0.15)	(0.33)	(0.18)
Lagged meat amount (2 lags)	0.26	0.19	-6.13**	1.19
	(0.46)	(0.16)	(2.49)	(1.14)
Lagged poultry amount (2 lags)	0.26*	-0.069	0.13	0.016
	(0.16)	(0.063)	(0.21)	(0.083)
Controlled variables	Yes	Yes	Yes	Yes
Observations	678	678	492	492

Notes: These are FE linear model estimates with standard errors in parentheses, clustered at child level. *** p<0.01 ** p<0.05 * p<0.10. Control variables used in Table A2 are child characteristics (age, age squared, school attendance, sickness), household characteristics, plot characteristics, last day to markets, household assets, total month covered by the survey, rainfall variability, survey dummies, child fixed-effects, and the interaction term between village and survey dummies. Explanatory variables are the log of physical amount of each ASF production per AE. Column [1] to [4] used physical amount per Adult-Equivalent (AE) in natural logarithm: liter for milk, unit for egg, kilogram for meat, and unit for poultry. Column [1] and [2] display results for children aged 6 to 60 months and Column [3] and [4] for children aged 6 - 47 months.

Table A5.3: Detailed descriptive statistics of each type of ASF products produced in each wave

Wave	Obs.	Milk[1]	Frequency	Egg[1]	Frequency	Meat[1]	Frequency	Poultry[1]	Frequency
Wave 2	*533*	30	6%	38	7%	14	3%	208	39%
Wave 3	*580*	51	9%	38	7%	3	1%	150	26%
Wave 4	*572*	47	8%	33	6%	0	0%	249	44%
Wave 5	*558*	31	6%	5	1%	39	7%	239	43%
Wave 6	*559*	44	8%	29	5%	10	2%	275	49%
Wave 7	*557*	40	7%	32	6%	2	0%	290	52%
Wave 8	*556*	38	7%	24	4%	2	0%	285	51%
Household Observations	*3915*	*281*	7%	*199*	5%	*70*	2%	*1696*	*43%*
Wave 2	*104*	1	1%	14	13%	4	4%	35	34%
Wave 3	*121*	8	7%	15	12%	2	2%	34	28%
Wave 4	*119*	8	7%	20	17%	0	0%	62	52%
Wave 5	*119*	6	5%	0	0%	7	6%	53	45%
Wave 6	*113*	7	6%	13	12%	4	4%	54	48%
Wave 7	*106*	8	8%	8	8%	0	0%	53	50%
Wave 8	*120*	6	5%	10	8%	0	0%	58	48%
Child Observations	*802*	*44*	5%	*80*	10%	*17*	2%	*349*	*44%*

Notes: Observations in the first panel show the total number and [1]proportion of household producing milk, egg, meat, and poultry. For instance, in wave 2, 6% of the total household (533) produced milk. Observations in the second panel show the total number and proportion of households having at least one child aged 6 to 60 months producing milk, egg, frequency, and poultry. For instance, 5% of children belong to households producing milk in wave 8.

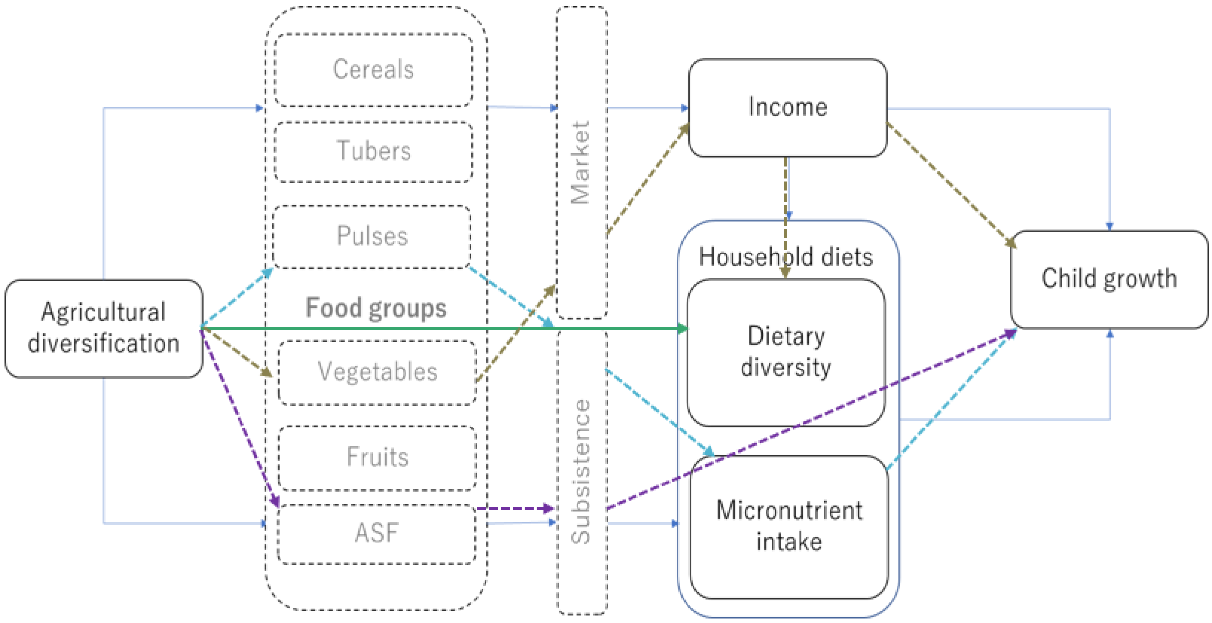


Fig. A 5.1 Linkage between agricultural diversification and child nutritional status, with a focus on Micronutrient pathways, Vegetable Commercialization, and Animal-Sourced Food Production

Chapter 6: Climate Conditions, Food Group Based-Nutrient Intake and Child Health in Tropical Climates: Evidence from Madagascar

Abstract

This study investigates the effects of recent rainfall conditions on child health outcomes and household food-group based consumption in developing countries, with a specific focus on the vulnerable context of tropical countries. By using a recent three-year wave household panel dataset in combination with high-resolution climate data from Madagascar, we explore the implications of climatic conditions on the socioeconomic status, diets, and food security of agriculturally dependent, economically disadvantaged farmers. Our findings reveal a significant negative relationship between insufficient and excessive rainfall and key indicators such as child linear growth and the availability of calories and nutrients sourced from tubers within households. In particular, a curvilinear association is observed between rainfall during the rainy season and height-for-age scores (HAZ), with rainfall levels surpassing 1280 mm found to have detrimental effects on children's health. We further investigate the underlying mechanisms at the household level and observe a similar non-linear association between rainfall and the availability of calories, protein, and vitamin C provided by tuber consumption. The reduced supply of these essential nutrients subsequently influences child health indicators. A 10% increase in protein supplied by tubers (namely cassava) corresponds to a HAZ increase of approximately 0.10 Standard Deviations (SD) and reduces the likelihood of stunting by 3%. Hence, climate change-sensitive policies toward tuber production should be prioritized in the fight against child malnutrition in tropical climates.

Key words: Nutrition, tropical countries, child stunting, protein, cassava

6 Climate Conditions, Food Group Based-Nutrient Intake and Child Health in Tropical Climates: Evidence from Madagascar

6.1 Introduction

The African continent has confronted substantial challenges stemming from the effects of climate change, precipitating profound disruptions in both agricultural and societal systems (World Food Programme, 2019). Of particular concern are the shifts in precipitation patterns resulting from climate variability, which have yielded detrimental consequences for agricultural productivity (Vogel et al., 2019), crop yields (Schmitt et al., 2022), livestock mortality rates (Morton, 2007), and the livelihoods of smallholder farmers (Brückner & Ciccone, 2011), thereby exacerbating vulnerabilities associated with food insecurity (Randell et al., 2022; World Food Programme, 2019). Consequently, the agricultural sector shoulders the onus of the economic repercussions of climate change, further accentuating health disparities, especially among individuals residing in environmentally strained conditions with limited adaptive capacities and mitigation resources (Mank et al., 2021; Le & Nguyen, 2021; Bennett & Friel, 2014). Moreover, climate experts anticipate that future temperature increments on a global scale, alongside unpredictable precipitation patterns, portend a significant threat to the subsistence farmers of Sub-Saharan Africa (SSA), whose reliance on rainfall remains pivotal to their sustenance (IPCC, 2022).

The intensifying frequency of extreme weather events has amplified the probability of agricultural households facing production shocks, subsequently influencing their farming practices and dietary choices (IPCC, 2022). These shocks can impede households' capacity to sustain their livelihoods and overall well-being (Tanner et al., 2015). Empirical studies have shed light on the adoption of informal strategies by smallholder farmers, including crop diversification (Makate et al., 2023), livestock diversification (Ngigi et al., 2021), and adjustments in agricultural inputs (Jagnani et al., 2020), as mechanisms to mitigate climate risks. These strategies have showcased promising outcomes in enhancing farmers' resilience and diminishing vulnerability to climate-induced shocks. However, it is imperative to acknowledge that financial constraints faced by resource-constrained farmers may inadvertently engender unintended consequences for household members.

The risk mitigation strategies and adaptive measures adopted by farmers bear direct implications for the well-being of vulnerable populations, with a particular focus on children (Amondo et al., 2021; Thiede & Gray, 2020; Grace et al., 2012). Amidst declining agricultural productivity, smallholder farmers may necessitate adjustments in their food sources and dietary practices (Brown et al., 2014). The implications of these adaptations are of paramount importance for children, as they may lead to a transition towards less nutritious and less diverse dietary patterns (Melaku et al., 2018). However, children under the age of five are particularly susceptible to nutritional deficiencies, which can have lasting consequences for their cognitive development, overall health, and long-term socioeconomic prospects (Thiede & Gray, 2020; Alderman et al., 2006). This predicament assumes heightened significance in tropical nations, where climate seasonality exerts a profound influence on rural lives and livelihoods.

The livelihoods of smallholder farmers in tropical regions are inherently shaped by the dynamics of seasonality, characterized by cyclical shifts in production and income (Emediegwu & Ubabukoh, 2023; Ellis, 2000). Notably, seasonal rainfall patterns play a pivotal role in disrupting agricultural systems, as farmers base their actions on this critical determinant (World Food Programme, 2019). The interplay of climate change-induced income shocks, credit constraints, and price fluctuations further exacerbates vulnerabilities within household livelihoods (Kakpo et al., 2022; Brückner & Ciccone, 2011). Moreover, climate-related shocks pose tangible threats to smallholder farmers who heavily depend on a singular rainy season for crop cultivation and livestock rearing (Nébié et al., 2021). Considering the seasonality of these challenges, household responses to weather fluctuations are likely to yield cumulative impacts on household nutrition and child health (Mank et al., 2021). Thus, acquiring a comprehensive understanding of the influence of seasonal rainfall on farmers' dietary patterns and its subsequent implications for child health is crucial, fostering the development of tailored mitigation strategies (Hoddinott et al., 2013).

The relationship between climate change and nutrition has recently gained significant attention; however, there remains a dearth of research on the climate-nutrition nexus, particularly in the tropical regions of SSA (Phalkey et al., 2015). This knowledge gap is particularly evident in countries of the Southwest Indian Ocean, such as Madagascar, Mozambique, Malawi, and Zimbabwe, which confront heightened vulnerability to tropical storms and heavy rainfall, exacerbating poverty and food insecurity (Otto et al., 2022). These challenges have been further compounded by the COVID-19 pandemic, projected to exacerbate the situation to critical levels (Otto et al., 2022).

While numerous studies have explored the linkages between climatic conditions, household nutritional outcomes, and food security in SSA (e.g., Randell et al., 2022; van der Merwe et al., 2022; Amondo et al., 2021; Cooper et al., 2019), research specifically focusing on tropical countries remains scarce, highlighting the imperative for further investigations in these vulnerable regions.

This study aims to address the existing research gap by investigating the influence of recent rainy seasons on child nutrition and health in Madagascar, while also exploring potential household-level pathways. Previous studies have provided evidence of the association between severe droughts and child stunting in various African countries, including Kenya (Grace et al., 2012), Uganda (Amondo et al., 2023), Tanzania (van der Merwe et al., 2022), Ethiopia (Dimitrova, 2021; Randell et al., 2020; Bahru et al., 2019), and Burkina Faso (Yeboah et al., 2022). While literature exists on the climate change-nutrition relationship in specific tropical regions such as Zimbabwe (Jouzi et al., 2023), Mozambique (Cunguara et al., 2011), and Malawi (Makate et al., 2023), these studies have primarily focused on spatial heterogeneity, nonfarm income, and crop diversification, respectively. Furthermore, limited attention has been given to investigating the long-term effects of climate change on child health outcomes. For instance, van der Merwe et al. (2022) found that increased rainfall in the preceding three years is associated with reduced levels of stunting. Their study builds upon prior research, particularly the work of Cooper et al. (2019), which highlighted the delayed impact of precipitation on child health outcomes. Additionally, other studies have identified indirect effects of precipitation on stunting, mediated by factors such as water scarcity (Myers & Bernstein, 2011), poor road infrastructure (Hirvonen et al., 2020), reduced agricultural production (Trinh et al., 2021), and diminished dietary quality (Amondo et al., 2023). None of the cited studies have comprehensively explored the specific underlying mechanisms of food group-related dietary quality, despite its growing importance in the field of nutrition (Chegere & Stage, 2020; Jones, 2017). Given the limited literature on the climate-nutrition nexus in tropical countries, there is a clear need for empirical studies that incorporate (i) the consideration of long-term precipitation effects and (ii) the identification of possible mechanisms related to food group-based dietary quality. Thus, this study offers a comprehensive understanding of the effects of climate change on stunting by examining its association on household food consumption in tropical countries.

This paper makes three significant contributions to the existing literature. Firstly, it offers a pioneering and comprehensive examination of the influence of precipitation on child health in tropical countries within SSA. These regions are characterized by frequent and intense extreme weather events, including floods, droughts, and tropical storms. Secondly, our study takes a multi-dimensional approach by exploring various channel pathways at the household level, specifically analyzing the consumption shares of different food groups and investigating the relationship between food group-based nutrient supply pathways and child health. To the best of my knowledge, no previous study has thoroughly examined these food group-based pathways. This approach provides a more nuanced understanding of the mechanisms through which precipitation affects child health outcomes. Lastly, our research incorporates a sufficient time lag between rainfall and child health, using recently collected data to ensure the accuracy and relevance of our findings.

This study focuses on the examination of recent rainfall patterns and their implications for child stunting and household dietary quality in rural areas of central Madagascar. The choice of this region is motivated by several key factors. Firstly, central Madagascar exhibits alarmingly high rates of child stunting, surpassing 50% of the population, highlighting the urgent need for research and intervention in this area (INSTAT & IFC, 2021). Secondly, the country itself ranks among the top five globally in terms of vulnerability to climate change, as evidenced by the 2018 Climate Risk Index (Eckestein et al., 2019). Lastly, given that approximately 80% of the population relies on the agricultural sector for their livelihoods and food security, understanding the impact of climate change on this sector is of paramount importance. Indeed, the majority of agricultural workers in central Madagascar are smallholder farmers who depend heavily on rainfall and possess limited resources and adaptive capacity. Consequently, they are particularly vulnerable to the adverse effects of droughts or excessive precipitation (Otto et al., 2022; Harvey et al., 2014). By focusing on this region, we aim to shed light on the intricate relationship between rainfall patterns, child stunting, and dietary quality in the context of a highly vulnerable and agriculturally dependent population.

Our study contributes valuable evidence regarding the impact of rainfall on child health outcomes. Specifically, we observe detrimental effects on child health resulting from both insufficient and excessive rainfall. At the household level, our analysis uncovers significant non-linear relationships between rainfall patterns and the consumption of a specific food group, namely tubers. Furthermore, we investigate the crucial role of tuber-based nutrients, including calorie, protein, and vitamin C, in mitigating stunting and enhancing the linear growth of preschool children. We found that increase in calorie, protein, and vitamin C supplied by tubers, namely cassava, increase HAZ and reduce the probability of stunting in preschool children. These novel findings provide important insights into the underlying mechanisms linking rainfall, tuber consumption, and child health outcomes. Our study thus contributes to the existing literature by elucidating the pathways through which rainfall influences child health and highlighting the significance of tuber-based nutrients in addressing child stunting.

The subsequent sections of this paper are outlined as follows. Section 6.2 offers a comprehensive overview of the study region, including its key characteristics, and presents the dataset along with descriptive statistics. In Section 6.3, we elucidate the empirical approach employed in our analysis. Moving forward, Section 6.4 presents the empirical results derived from our study. Finally, in Section 6.5, we conclude our study by discussing the policy implications arising from our findings.

6.2 Materials and Methods

6.2.1 *Study country and characteristics*

Madagascar boasts a diverse array of hydroclimates, influenced by prevailing trade winds that mold its precipitation patterns (Oldeman, 1990). This results in distinct zones characterized by heavy rainfall along the East coast, frequent cyclones in the North, intermittent rainfall from anticyclonic fronts in the South, and a drier climate along the West coast. In particular, there exists significant variation in annual precipitation across different regions, with levels ranging from as low as 350 mm in the Southwest to as high as 4000 mm along the East Coast (Randriamarolaza et al., 2022). The country showcases a semi-arid to arid climate in its southwestern regions, a tropical climate along the eastern coast, and moderate temperature and moisture regimes in its central highlands (GIZ, 2020).

Madagascar’s climate can be characterized as tropical, with distinct wet and dry seasons. Specifically, the Vakinankaratra region, situated on a high plateau at elevations ranging from 800 to 1500 meters above sea level, displays unique climatic characteristics. Compared to other parts of the country, this region experiences relatively cooler temperatures and receives the majority of its rainfall during the wet season, spanning from November to April (Sourisseau et al., 2016). This unimodal precipitation regime significantly shapes the agricultural and environmental conditions of the Vakinankaratra region, playing a pivotal role in the livelihoods and socio-economic activities of its inhabitants (Sourisseau et al., 2016).

6.2.2 Data

6.2.2.1 Household and individual level data

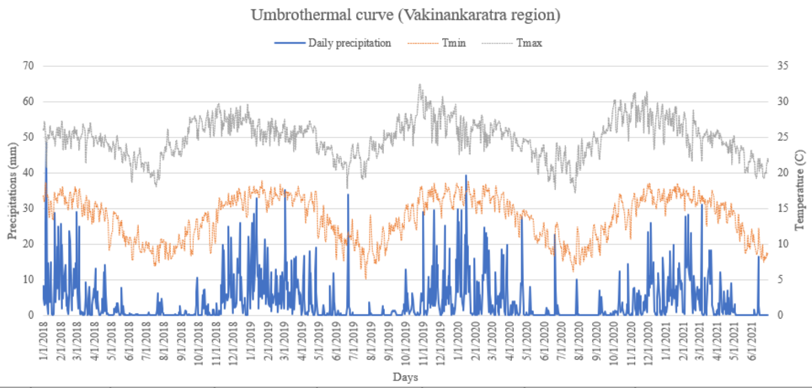
To understand the relationship between seasonal rainfall and child health outcomes in Madagascar, we link recent field survey data to gridded precipitation data. Our analysis draws on a panel dataset spanning three waves, covering the years 2018, 2019, and 2020. Specifically, data were collected in the highland zones of Madagascar in the Vakinankaratra region. Sample households were randomly selected at two levels, namely the district and village. Firstly, we ensured the even distribution of 60 villages across three districts in the region. Subsequently, we randomly selected 10 lowland-rice growers from each of the 60 villages. Initially selected households were then repeatedly interviewed to form our panel. We observe nearly 10% of attrition rate from the initial selection. In this study, we use unbalanced data comprising households with complete data, encompassing those households that were interviewed at least twice. The total number of household-observations used in this study amounts to 1624. At the child level, we have 229 observations covering all three waves, including children who were measured at least twice. Each wave encompasses modules on household composition and demographics, food consumption, detailed agricultural production, assets, and expenditures. Data also contain detailed anthropometric measurement of the children, household socioeconomic information, and geographic coordinates of the sampling clusters.

6.2.2.2 Climate related data

The climatic data used in this study is derived from the Integrated Multi-satellitE Retrievals (IMERG) for

Global Precipitation Mission (GPM). This data source provides half-hourly global precipitation data with a spatial resolution of 0.1º or 10km x 10km (Huffman et al., 2020). Recent studies have demonstrated the superior accuracy of the IMERG product in terms of gridded precipitation data, particularly at the monthly and daily levels in northern Madagascar, surpassing other Gridded Precipitation Products (Ramahaimandimby et al., 2022). While its detection capabilities for excessive rainfall (>100 mm/day) are slightly less precise, the IMERG product remains a reliable source of information for regions of the island with lower rainfall, given the absence of a comparable study in the central highlands. To merge the climatic data with our survey data, we use the GPS-referenced households in our survey, associating them with each grid in the climate data, and covers 36 grids in total. This allows us to integrate the daily accumulated precipitation and temperature data with our household- and child-level information, enabling a comprehensive analysis of the relationship between climate variables and child health outcomes.

Figure 6.1 depicts the distribution of the daily precipitation, minimum and maximum temperature during a three-year period. We use a panel dataset encompassing three consecutive years, denoted by observations (1) and (2) for the first year, (3) and (4) for the second year, and (5) and (6) for the third year. Data collection for the first year (2018) took place in January/February 2019, for the second year (2019) in February 2020, and for the third year (2020) in February 2021. Each year consists of two distinct seasons, namely a dry season (D.S) and a rainy season (R.S). The average rainfall in 2018, 2019, and 2020 are 1532.7 mm, 1594.4 mm, and 1278.7 mm respectively.



Covered survey period	(1)	(2)	(3)	(4)	(5)	(6)	
Survey period			↔		↔		↔
Season	R.S	D.S	R.S	D.S	R.S	D.S	

Notes: a) Covered survey period: (1) and (2) constitute the precipitation for the first year, (3) and (4) the second year, and (5) and (6) for the third year. b) Survey period: the first survey took place in January and February 2019, the second survey in February 2020, and the third survey in 2021. c) Season: One year is constituted by one Rainy Season (R.S) and one Dry Season (D.S)

Fig. 6.1 Stylized timeline of data collection period, covered month, daily precipitation, and daily minimum and maximum temperature (Source: Author, 2022 based on data from Huffman et al., 2020)

6.2.3 *Outcome variables*

6.2.3.1 *Child level*

Child health outcome variables were derived at the individual level using anthropometric measurements. Height-for-age z-scores (HAZ) were calculated, taking into account age, sex, and height of the children. These z-scores provide a measure of how many standard deviations the child's height is below or above the median of the WHO child growth standard (WHO, 2019). To ensure data integrity, HAZ values exceeding 6 or below -6 were excluded from the sample. Additionally, we created two binary indicators for child linear growth, classifying children as stunted (<-2) or severely stunted (<-3).

The prevalence of stunting exceeding 30 percent in a specific location is considered a public health concern according to the World Health Organization (WHO, 2019). However, our analysis of the pooled sample presented in Table 6.1 reveals that approximately 58 percent of children aged 6 to 60 months in our study area are classified as stunted, with 35 percent showing severe stunting. The mean HAZ falls below the threshold of -2, indicating a high prevalence of stunting in the sampled household.

Table 6.1 Descriptive statistics of outcome and explanatory variables for child level data

Outcome variables	Mean	Std.Dev.	Min.	Max.
	(1)	(2)	(3)	(4)
HAZ	-2.34	1.60	-5.76	2.63
Stunted (HAZ < -2)	0.58	0.49	0	1
Severely stunted (HAZ < -3)	0.35	0.48	0	1
Number of observations	*229*			

Notes: Observations are pooled from the three year-waves.

6.2.3.2 *Household level*

Table 6.2 presents a comprehensive overview of food consumption and dietary quality among households in our sample.

Table 6.2 Descriptive statistics of outcome variables for household level data

Outcome variables	Consumption shares		Energy[1] (kCal/AE/day)		Protein[1] (mg/AE/day)		Vitamin C[1] (µg/AE/day)	
	Mean	Std.Dev.	Mean	Std.Dev.	Mean	Std.Dev.	Mean	Std.Dev.
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Rice	0.39	0.11	1566.98	620.46	28.27	11.19	0	0
Cereal	0.02	0.03	203.82	425.31	5.50	12.04	3.06	14.45
Tuber	0.06	0.05	346.22	517.92	3.50	4.60	47.88	67.86
Pulse	0.04	0.03	222.43	188.12	13.75	11.93	0.97	1.47
Vegetable	0.06	0.03	49.03	57.88	3.22	3.26	41.17	32.95
Fruit	0.01	0.01	37.26	95.93	0.47	0.86	12.95	45.03
Meat	0.07	0.08	52.00	76.40	4.96	6.76	0.19	0.34
Fish	0.03	0.03	29.74	34.91	2.12	2.65	1.43	2.78
Milk	0.00	0.02	8.04	51.73	0.62	4.44	0.10	0.74
Egg	0.00	0.00	0.90	5.37	0.08	0.47	0	0
Observations	1624	1624	1624	1624	1624	1624	1624	1624

Notes: Observations are pooled from three waves. [1]These variables represent the daily intake per Adult-Male Equivalent (AE).

The "Consumption shares" section of this study provides valuable insights into the relative monetary contribution of specific food groups towards overall food expenditure. This standardized price ratios are used to facilitate cross-village comparisons of food prices, irrespective of currency. Notably, rice emerges as the dominant component in household diets, with a mean share of 39%. Following rice, meat, vegetables, and tubers hold respective mean shares of 7%, 6%, and 6%. The combined average shares of cereals, fruits, and fish amount to approximately 10%, while milk and eggs make up negligible shares. In the "Energy" section, we examine the per-Adult-Male-Equivalent (AE) daily calorie intake of households. Once again, rice takes the lead, contributing nearly 70% of the daily calorie intake. Tuber (346 kCal), pulses (222 kCal), and other cereals (203 kCal) also make notable contributions. The remaining food groups provide less than 200 kCal on a daily basis. Protein supply analysis reveals that rice (28.27 mg) and pulses (13.75 mg) are the primary sources for households. Finally, regarding vitamin C[27],

[27] We selected vitamin C due to its property to affect children's height and height-for-age index, in addition to

our descriptive analysis indicates that tubers are the main source, providing 47.88 µg/day. Vegetables (41.17 µg/day) and fruits (12.95 µg/day) follow as significant contributors, while rice does not contribute to vitamin C intake.

6.2.4 *Variables of interest*

Table 6.3 presents the key explanatory and control variables used in our analysis. Our primary variable of interest is the cumulative rainfall experienced during the preceding rainy season, spanning from November to April. The significance of these climatic conditions during the rainy season cannot be overstated, particularly in tropical regions where rural households heavily rely on rain-fed agricultural systems. The performance of crops and livestock production, and consequently the attainment of food security, are intricately intertwined with these climatic dynamics (Randell et al., 2022). In particular, the average precipitation levels observed across all three waves during the rainy season amount to 1295 mm, with an annual precipitation of approximately 1467 mm.

6.2.5 *Control variables*

To comprehensively address the multifaceted nature of our study, we control for a wide array of control variables at both the household and child levels. At the household level, our analysis takes into account critical factors such as household size, the proportion of preschool children (aged <= 5 years), the proportion of schooling children (aged > 5 - 15 years), the proportion of elderly members (aged > 60 years), and the proportion of working women (women aged 15 to 60 years). Moreover, we consider farm and home asset per capita to control for household's affluence. To capture nutrition-related aspects, we introduce the number of days elapsed since the household's last visit to the market, which offers valuable insights into their dietary patterns. Furthermore, we account for specific household parcel characteristics, including the number of lowland-rice, upland-rice, other, and rented-in plots, as well as the percentage of irrigated parcels and the level of crop diversification. At the child level, we include variables such as the age of the children and two binary indicators to ascertain their school attendance

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Zinc and other micronutrients (Purnamaningrum et al., 2019) and health status during the interview.

Table 6.3 Descriptive statistics of explanatory variables for household level data

Variables	Obs	Mean	Std. Dev.	Min.	Max.
Main explanatory variables					
Total yearly precipitation (mm)	*1624*	1467.52	145.43	1186.76	1770.28
Total precipitation in rainy season (mm)	*1624*	1295.28	128.63	1080.33	1576.31
Household level variables					
Household characteristics					
Household size	*1624*	4.73	1.93	1	13
Share of preschool children	*1624*	0.11	0.15	0	1
Share of schooling children	*1624*	0.24	0.20	0	1
Share of old members	*1624*	0.11	0.24	0	1
Share of working woman	*1624*	0.27	0.16	0	1
Farm asset per capita (in MGA[1])	*1624*	58790.62	149033.50	0	2075000
Home asset per capita (in MGA[1])	*1624*	63509.96	168494.10	0	2062000
Nutrition-related variables					
Last day to the market	*1624*	3.67	2.27	0	30
Parcel characteristics					
Number of lowland-rice plots	*1624*	1.62	0.99	0	10
Number of upland-rice plots	*1624*	0.61	0.49	0	1
Number of other plots	*1624*	0.90	0.30	0	1
Number of rented plots	*1624*	0.05	0.22	0	1
Percentage of irrigated parcel	*1624*	0.20	0.24	0	1
Crop diversification[2]	*1624*	1.84	0.82	0	5
Child level variables					
Age in months	*229*	34.84	15.37	6	60
School attendance (Yes = 1)	*229*	0.07	0.25	0	1
Sick (Yes=1)	*229*	0.04	0.20	0	1

Notes: Observations from both waves are pooled. [1]MGA stands for Malagasy Ariary. 1 MGA = 0.00023 USD as of March 16th, 2023. [2]Crop diversification represents the number of food groups produced by the household, including cereals, tubers, pulses, vegetables and other food groups (grass and artemezia).

6.3 Estimation strategy

6.3.1 *Association between precipitation and HAZ*

To explore the potential link between child HAZ and precipitation, we present Figure 6.2, which illustrates the total precipitation in the preceding year (A), rainy season (B), and dry season (C) on the x-axis, and the HAZ of children aged 6 to 60 months on the y-axis. The first plot reveals a non-linear association between annual rainfall and child HAZ, exhibiting an inverted U-shaped pattern. Notably, this non-linear relationship becomes more pronounced when considering the most recently completed rainy season as the x-axis (Panel B). During this specific season, as precipitation levels increase, child HAZ initially demonstrate improvement up to a certain threshold. However, beyond this threshold (at approximately 1280 mm), higher levels of precipitation actually hinder linear growth in children. Our regression models thus incorporate a squared term to capture the curvilinear nature of the relationship.

(A) (B) (C)

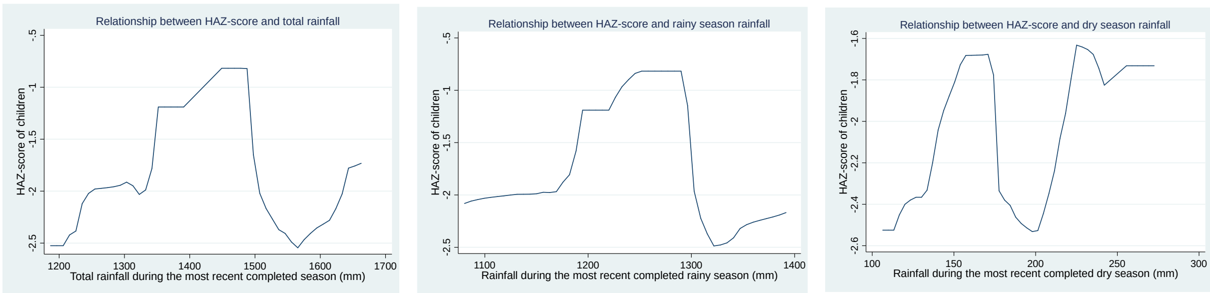

Fig. 6.2 Relationship between HAZ of children aged 6 to 60 months and the total rainfall during the most recent completed rainy and dry season (A), during the most recent completed rainy season (B), and during the most recent completed dry season (C)

6.3.2 Regression models

Given the limitations of controlled experimental data and instrumental variables, panel data analysis offers a robust and efficient approach for estimating the effects of rainy season precipitation on children's nutritional status. By using panel FE estimation, we can effectively address potential biases arising from unobserved time-invariant factors. First, we assess the effect of precipitation directly on child health outcomes. At the child level, the model takes the following form:

$$y_{cht} = \alpha_1 R_{gt}^{RS} + \alpha_2 R_{gt}^{RS^2} + \beta_1 (V_h * T_t) + \beta_2 T_t + \iota Z_{cht} + \kappa X_{ht} + \tau_c + \varepsilon_{cht} \quad (6.1)$$

where *c* is an index for the child, h for the household, g for the rainfall grid, and *t* for year. y_{cht} represents the child nutritional outcomes in household h at time *t*. Those variables are represented by HAZ and the binary dummies of a child being stunted or severely stunted. R_{gt}^{RS} represents the total amount of precipitation recorded during the most recently completed rainy season. $R_{gt}^{RS^2}$ is the total amount of precipitation in the previous rainy season in squared term. It is worth noting that our survey was conducted 10 months[28] after the completion of the rainy season, giving us ample time to account for potential delayed implications for child health (Cooper et al., 2019). $V_h * T_t$ indicate the interaction term between the village and year dummies. *Z* and *X* are vectors for child and household characteristics, respectively. τ_c and ε_{cht} are the child-specific fixed effects and the error term, respectively. To investigate the possible association between seasonal rainfall and child nutritional growth, we estimate a FE model with standard errors clustered at the child level.

Second, we estimate multiple regressions in order to establish the possible channel mechanisms at the household level using the following regression:

$$CM_{ht} = \beta_1 R_{gt} + \beta_2 R_{gt}^2 + \Upsilon_1(V_h * T_t) + \Upsilon_2 T_t + \delta X_{ht} + \tau_h + \varepsilon_{ht} \quad (6.2)$$

where CM_{ht} (*Channel Mechanism*) represents the groups of outcome variables described in Table 6.2, including the consumption shares, calorie, protein, and vitamin C supplied by different food groups. For this regression, we use the annual precipitation (*R*) due to the probable association of both wet and dry seasons with crop production. The other variables are similar to Equation 6.1. For Equation 6.2, we estimate a FE model with standard errors clustered at the household level.

6.4 Empirical results and discussions

6.4.1 *Marginal effect of precipitation on child health outcomes*

Table 6.4 presents the marginal effects of previous yearly precipitation and rainy season precipitation on HAZ and stunting status (stunted and severely stunted) of children in rural Madagascar. We conduct two regression analyses, progressively introducing control variables. The results are presented in three panels, labeled A, B, and C.

Panel A reveals a positive and significant association between total yearly rainfall and both HAZ, but no

[28] Specifically, the timeframe under consideration spans from April of the previous year leading up to the survey period in February.

significant effect on both stunting-related variables. Moving to Panel B, we focus specifically on the most recently completed rainy season's rainfall and examine its marginal effect on child nutritional outcomes. Interestingly, the estimates in Panel B are nearly doubled compared to the previous results, underscoring the heightened vulnerability of food security during this period. In Panel C, we introduce a squared term of the most recent rainy season. Column (1) of Panel C demonstrates an inverted U-shaped relationship between rainy season rainfall and HAZ, even without controlling for other variables. Upon accounting for factors that may influence child growth and development, such as household socioeconomic status and village-year interactions, the relationship between rainfall and HAZ remains significant (Column [3] of Panel C). Specifically, the relationship indicates a negative trend at low rainfall levels, turns positive at moderate levels, and becomes negative again at high levels. We identify the turning point of this relationship to be around 1280 mm of rainy season rainfall. Similar patterns are observed for severely stunted children, but not for stunted children. In Column [9] of Panel C, we find that initially, increasing precipitation significantly reduces the likelihood of severe stunting in children. However, when total rainfall surpasses 1222 mm, the likelihood of severe stunting increases. Some possible explanations may be that low levels of rainfall may contribute to water scarcity and poor agricultural productivity, leading to malnutrition and severe stunting in children. Conversely, excessive rainfall can result in flooding and water-borne diseases, negatively impacting child health. However, we could not find any significance on stunted for the subgroup of children aged 6 to 47 months (see Table A6.1 in Appendix), nor for the temperature, except for HAZ (see Table A6.2 in Appendix).

6.4.2 *Robustness check at the child-level*

To ensure the robustness of our findings, we conduct additional analyses by estimating one alternative model (see Table A6.3 in Appendix). We explore an alternative specification for climate shock exposures, specifically rainfall variability. We compare these measures to all rainy seasons within the enumeration area from 2000 to 2020. We also control for the yearly temperature. We find that the results remain consistent with our main models for both rainfall variability and temperature conditions.

Table 6.4 Marginal effects of the most recent completed yearly and rainy season on nutritional status of children aged 6 - 60 months (fixed-effects linear model)

	HAZ		Stunted (HAZ < -2)		Severely stunted (HAZ < -3)	
***Panel A:** Marginal effect of the annual rainfall (mm) on HAZ and stunting*						
	(1)	(2)	(3)	(4)	(5)	(6)
Annual rainfall	-0.00065	0.10***	0.0000022	-0.0075	0.00013	-0.011
	(0.00063)	(0.034)	(0.00020)	(0.015)	(0.00021)	(0.013)
***Panel B:** Marginal effect of the most recent completed rainy season (mm) on HAZ and stunting in rainy season*						
	(1)	(2)	(3)	(4)	(5)	(6)
Total rainfall in rainy season	-0.0016**	0.21***	0.00015	-0.015	0.00032	-0.023
	(0.00074)	(0.068)	(0.00023)	(0.030)	(0.00023)	(0.027)
***Panel C**: Marginal effect of the most recent completed rainy season (mm) and its squared term on HAZ and stunting*						
	(1)	(2)	(3)	(4)	(5)	(6)
Total rainfall in rainy season	0.089**	1.82***	-0.015	-0.22	-0.015	-0.31*
	(0.036)	(0.43)	(0.013)	(0.19)	(0.013)	(0.16)
Total rainfall in rainy season in squared term	-0.000036**	-0.00071***	0.0000061	0.000088	0.0000063	0.00013**
	(0.000014)	(0.00016)	(0.0000050)	(0.000072)	(0.0000051)	(0.000061)
Interaction village-survey	No	Yes	No	Yes	No	Yes
Survey dummies	No	Yes	No	Yes	No	Yes
Household characteristics	No	Yes	No	Yes	No	Yes
Child characteristics	No	Yes	No	Yes	No	Yes
Observations	229	229	229	229	229	229

Notes: *** p<0.01 ** p<0.05 * p<0.10. All standard errors are clustered at child level. In Columns [1]-[3]-[5], we do not control for any variables. In Columns [2]-[4]-[6], we control for year-village dummies, survey dummies, household-level and child-level variables as in Table 6.3.

These additional analyses underscore the need for further investigation at the household level to enhance our understanding of the underlying pathways contributing to the observed relationships.

6.4.3 *Marginal effect of annual precipitation on household food group-related consumption*

In this section, we explore the potential mechanisms by which rainfall indirectly influences child health outcomes at the household level, focusing on the consumption of specific food groups. Table 6.5 presents the marginal effects of yearly precipitation and its squared term on household's consumption shares of different food groups, as well as daily food group-based caloric, protein and vitamin C intake.

Our findings reveal a non-linear relationship between rainfall and the share of some specific food groups. Specifically, we observe that low levels of rainfall are associated with reduced consumption shares of tubers, namely cassava (see Table A6.5 in Appendix). As rainfall levels increase, the share of tuber consumption initially peaks and then declines at higher rainfall levels. This relationship was however inconsistent when considering temperature conditions and the yearly rainfall variability as independent variables (see Table A6.4, Panel A in Appendix).

Furthermore, we observe the same inverse U-shaped relationship between the calorie and other micronutrient supplied by tubers, namely protein and vitamin C, and the annual rainfall, indicating that both low and high levels of rainfall increase the likelihood of households consuming them. Results are robust with the use of alternative explanatory variables (see Table A6.4, Panel B, C, and D in Appendix). One plausible explanation for the observed decline in the proportion of cassava consumption in central Madagascar could be attributed to the projected negative trend in cassava yield. In fact, under various climate change scenario, with climate projections predicting a potential decline in annual precipitation of up to 114 mm by 2080 in Madagascar, there is a heightened risk of more frequent and severe dry and wet spells. These climatic changes can have detrimental consequences on agricultural productivity, with cassava yield projected to decline by approximately 3% by 2080 (GIZ, 2020). While the full impact of climate change on cassava consumption may become more apparent in 2050, our findings already suggest that climate change has already contributed to a reduction in cassava-sourced nutrient consumption in central Madagascar, possibly influenced by the observed decline in cassava yield.

Table 6.5 Marginal effect of annual rainfall and its squared term on consumption share and micronutrient supply from each food group

***Panel A**: Consumption shares*	Rice	Cereal	Tuber	Pulse	Vegetable	Fruit	Meat	Fish	Egg	Milk
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Annual rainfall	-0.00057	-0.0015	0.0098**	-0.00097	0.0019	0.0013	-0.0011	0.0015	-0.000062	0.00042
	(0.0057)	(0.0015)	(0.0044)	(0.0014)	(0.0020)	(0.0010)	(0.0027)	(0.0031)	(0.00012)	(0.00057)
Annual rainfall in squared term	-0.00000017	0.00000043	-0.0000031**	0.00000052	-0.00000056	-0.00000040	0.00000044	-0.00000031	0.000000016	-0.00000016
	(0.0000017)	(0.00000044)	(0.0000014)	(0.00000040)	(0.00000062)	(0.00000032)	(0.00000086)	(0.00000097)	(0.000000033)	(0.00000015)
***Panel B**: Energy (kCal/AE/day)*	Rice	Cereal	Tuber	Pulse	Vegetable	Fruit	Meat	Fish	Egg	Milk
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Annual rainfall	-17.4	28.7	24.6**	6.25	3.14	2.63	-5.17	-0.23	1.40	0.070
	(26.7)	(21.3)	(10.6)	(10.0)	(2.97)	(3.48)	(5.43)	(1.72)	(0.90)	(0.14)
Annual rainfall in squared term	0.0036	-0.0096	-0.0071**	-0.00075	-0.00092	-0.00090	0.0017	-0.0000076	-0.00040	-0.000019
	(0.0084)	(0.0065)	(0.0032)	(0.0032)	(0.00092)	(0.0011)	(0.0017)	(0.00053)	(0.00027)	(0.000044)
***Panel C:** Protein (mg/AE/day)*	Rice	Cereal	Tuber	Pulse	Vegetable	Fruit	Meat	Fish	Egg	Milk
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Annual rainfall	-0.31	1.40	0.20**	0.30	0.25***	0.0054	-0.54	-0.0062	0.12	0.0061
	(0.48)	(0.94)	(0.096)	(0.55)	(0.098)	(0.050)	(0.35)	(0.26)	(0.075)	(0.013)
Annual rainfall in squared term	0.000065	-0.00046	-0.000057**	-0.000017	-0.000077**	-0.0000046	0.00018	-0.0000045	-0.000035	-0.0000017
	(0.00015)	(0.00029)	(0.000029)	(0.00017)	(0.000030)	(0.000015)	(0.00011)	(0.000082)	(0.000023)	(0.0000039)
***Panel D**: Vit C (μg/AE/day)*	Rice	Cereal	Tuber	Pulse	Vegetable	Fruit	Meat	Fish	Egg	Milk
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Annual rainfall	0	0.0079	2.91**	-0.039	3.43*	-0.42	0.013	0.0063	0.019	0
	(.)	(0.46)	(1.37)	(0.038)	(2.07)	(3.42)	(0.021)	(0.071)	(0.012)	(.)
Annual rainfall in squared term	0	0.0000054	-0.00084**	0.000018*	-0.0011*	-0.00015	-0.0000045	-0.0000044	-0.0000054	0
	(.)	(0.00014)	(0.00041)	(0.000011)	(0.00065)	(0.00098)	(0.0000067)	(0.000021)	(0.0000036)	(.)

Notes: For each regression in each panel, we control for household variables as described in Table 6.3. We also control for the year dummies, interaction term between year dummies and village dummies, and household fixed-effects. Standard errors in parentheses are clustered at household level; * p<0.10 ** p<0.05 *** p<0.01

6.4.4 *Association between potential mechanism and child nutritional outcomes*

To find whether there is a link between household food group consumption and child health, we conducted additional analyses. Specifically, we ran regressions using consumption shares, calorie, protein and vitamin C of each food group as explanatory variables of child nutritional outcomes (HAZ and stunting status). Overall, we observe a consistent association between calorie, protein, and vitamin C supplied by the tuber group and the increased child linear growth and reduction in stunting.

Table 6.6 presents the estimated associations between the consumption of different food groups and child health outcomes. Our findings indicate a positive and statistically significant relationship between the HAZ and the intake of protein and vitamin C from the tuber group. However, no significant association was observed with the consumption shares of tubers. This aligns with the insignificance of rainfall variability when controlling for temperature conditions, unlike the other specifications. Energy, protein, and vitamin C are measured in logarithms, implying that a 10% increase in the intake of these nutrients supplied by tubers is associated with a significant increase in HAZ by approximately 0.05, 0.12, and 0.07 SD, respectively. Similarly, protein provided by tubers indicates a negative and significant association with the likelihood of stunting in children at the 5% significance level. For instance, for every 10% increase in protein intake sourced from tubers, the prevalence of stunting decreases by approximately 3%, which is three times greater than the effect of tuber-sourced calories. Therefore, we can conclude that the protein content in tubers, specifically cassava, is the most predictive factor for child growth[29].

A study conducted in Tanzania by Nicodemas et al. (2019) reported no significant association between cassava consumption patterns and the prevalence of stunting. In addition, another study by Nungo et al. (2012) conducted in Kenya highlighted the cassava consumption was not associated with child nutritional status, but rather serves to cushion hunger. In Madagascar, insufficient utilization of cassava as a source of energy fails to ensure food security for farmers as risk-coping strategy (Rakotosamimanana et al., 2014).

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[29] Cassava is also rich in calcium, thiamine, riboflavin and niacin (Nicodemas et al., 2019). We also tested for each of them at both household and child level, but they present inconsistent results as is the case for tuber consumption shares.

Table 6.6 Possible pathways connecting rainfall to nutritional status outcomes in children aged 6 - 60 months (fixed-effects linear model)

Dependent variables	HAZ				Stunted (HAZ < -2)				Severely stunted (HAZ < -3)			
Independent variables	Share	Energy	Protein	VitC	Share	Energy	Protein	VitC	Share	Energy	Protein	VitC
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Log of rice	-0.34	-0.18	-0.50	0	1.55	0.14	0.20	0	-0.010	-0.27	-0.19	0
	(3.92)	(0.86)	(0.83)	(.)	(1.38)	(0.23)	(0.23)	(.)	(1.47)	(0.26)	(0.25)	(.)
Log of cereal	14.9	0.048	0.11	-0.28	-2.70	-0.021	-0.048	-0.023	-4.99**	-0.041	-0.086	0.31*
	(9.15)	(0.089)	(0.20)	(0.59)	(3.13)	(0.022)	(0.045)	(0.20)	(2.11)	(0.029)	(0.064)	(0.17)
Log of tuber	-3.80	0.50***	1.20***	0.68**	1.94	-0.098*	-0.28**	-0.18*	0.094	-0.064	-0.15	-0.076
	(4.93)	(0.14)	(0.40)	(0.29)	(2.83)	(0.058)	(0.13)	(0.095)	(2.75)	(0.064)	(0.16)	(0.13)
Log of pulse	-4.51	0.13	0.15	-0.56	2.57	0.0071	0.0068	0.097	2.21	-0.065*	-0.10	-0.32
	(11.0)	(0.11)	(0.25)	(0.48)	(3.63)	(0.039)	(0.078)	(0.19)	(2.87)	(0.036)	(0.075)	(0.20)
Log of vegetable	6.44	0.33	0.48	0.30	-1.99	-0.13	-0.23*	-0.20	-1.27	0.0081	0.12	0.12
	(5.55)	(0.31)	(0.43)	(0.33)	(2.03)	(0.086)	(0.12)	(0.13)	(1.90)	(0.076)	(0.13)	(0.13)
Log of fruit	-23.0	-0.24**	-1.12*	-0.16	7.41	0.10***	0.55***	0.12***	6.90	0.033	0.31*	0.083*
	(18.3)	(0.10)	(0.58)	(0.17)	(6.55)	(0.032)	(0.17)	(0.041)	(4.37)	(0.033)	(0.16)	(0.042)
Log of meat	0.054	-0.015	0.012	-0.75	1.35	0.039	0.037	0.60**	-0.12	0.012	0.012	0.0084
	(3.98)	(0.087)	(0.18)	(1.12)	(1.54)	(0.039)	(0.066)	(0.27)	(1.65)	(0.032)	(0.057)	(0.35)
Log of fish	-5.30	0.12	0.20	-0.79	0.49	0.030	0.030	0.26	5.20	-0.053	-0.095	0.076
	(9.09)	(0.19)	(0.31)	(0.84)	(3.42)	(0.080)	(0.12)	(0.30)	(3.18)	(0.078)	(0.12)	(0.28)
Interaction village-survey	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Survey dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Household characteristics	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Child characteristics	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	229	229	229	229	229	229	229	229	229	229	229	229

Notes: In each regression, we control for child and household characteristics as described in Table 6.3. We also control for survey dummies, and the interaction terms between village and survey dummies. All standard errors are clustered at child level. *** p<0.01 ** p<0.05 * p<0.10. Dependent variables are HAZ, and two dummies of stunting status of children. Independent variables are Log of consumption shares of each food group in Columns [1]-[5]-[9], log of daily calorie intake per AE in Columns [2]-[6]-[10], log of daily protein intake per AE in Columns [3]-[7]-[11], and log of daily vitamin C intake in Columns [4]-[8]-[12]. Moreover, due to the small contribution of both milk and egg in household daily food intake, we did not include them in the regressions.

In the context of this study, the link between cassava consumption and child nutritional status could be explained by the reverse impact of rainfall on pulse production. More precisely, when there is insufficient (or excessive) rainfall, households tend to prioritize the cultivation of pulses, which represent the third primary source of protein after rice and cereals. In these situations, households are compelled to rely on pulses for a significant portion of their food intake (and hence protein) instead of tubers, which constitute the second most consumed crop (See Table A 6.6 in Appendix).

6.5 Discussions and policy implications

This study investigated the association between recent rainfall and child stunting, by highlighting the household-level possible pathways in the central highlands of Madagascar, a region with high dependence on subsistence-based and rain-fed agriculture. While many studies have examined the linkages between climatic conditions and stunting in SSA, few have been conducted in tropical countries which are prone to frequent drought or flooding, and fewer has focused on a food group-related nutrient supply.

At the child-level, results indicate that there is an inverted-U shaped relationship between the linear growth of children and the cumulative rainfall in the previous rainy season. Insufficient and excessive rainfall thus pose an impediment for preschool children in central Madagascar. In other words, greater precipitation is positively associated with child nutritional outcomes but only to a certain threshold. This turning point may have important implications for public health policy. In areas where rainfall is consistently below this threshold, interventions aimed at improving access to water and promoting sustainable agriculture may be effective in reducing the prevalence of stunting. In areas where rainfall is consistently above this threshold, interventions aimed at improving sanitation and preventing water-borne diseases may be more effective.

By exploring the possible mechanisms at the household level, we found that the non-linear relationship between annual precipitation and household food consumption, namely tuber consumption, was maintained. While increased rainy season precipitation is positively associated with these indicators, the relationship only holds up to a certain threshold, beyond which it becomes negative. The findings that the annual precipitation is both beneficial and detrimental for multiple indicators suggests that drought and excessive rainfall do influence dietary quality and food security sourced from the tuber category. Moreover, our results support the association between tuber-supplied nutrients, namely cassava, and child nutritional outcomes. Cassava can, to some extent, alleviate stunting in children due to its efficient production of calorie, vitamin C, and most importantly, protein. However, despite its inherent resilience to harsh environmental conditions, our results reveal that the availability and nutritional quality of tuber-related nutrients are significantly influenced by changes in precipitation patterns in central Madagascar.

Based on our results, several climate adaptation strategies can be implemented to combat the adverse effects of climate change on stunting and protein-rich crop production in central Madagascar. Firstly, since some food groups were likely to be consumed at low levels of rainfall, encouraging farmers to diversify their crops as well as promoting drought-tolerant and nutrient-enhanced crops can help the negative impact of droughts and floods. Secondly, awareness campaigns and educational programs can be implemented to promote the nutritional benefits of protein-rich crops and encourage its inclusion in balanced diets for children. Thirdly, with the future projections of more extreme dry and wet periods, the construction of small-scale water storage systems and the establishment of irrigation systems, can increase water availability during dry periods and reduce waterlogging during floods.

Subsequent research endeavors should delve into the intricate pathways that establish a definitive connection between protein-rich crop production (or consumption) and child nutritional status.

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APPENDICES

Table A 6.1 Marginal effects of the most recent completed rainy season on nutritional status of children aged 6 - 47 months (fixed-effects linear model)

	HAZ		Stunted (HAZ-score < -2)		Severely stunted (HAZ-score < -3)	
	(1)	(2)	(3)	(4)	(5)	(6)
Total rainfall in rainy season	0.12**	0.31	-0.027	0.12	-0.016	0.27
	(0.046)	(0.81)	(0.016)	(0.32)	(0.016)	(0.17)
Total rainfall in rainy season in squared term	-0.000048**	-0.000072	0.000011	-0.000051	0.0000066	-0.00010*
	(0.000018)	(0.00027)	(0.0000065)	(0.00010)	(0.0000063)	(0.000055)
Interaction village-survey	No	Yes	No	Yes	No	Yes
Survey dummies	No	Yes	No	Yes	No	Yes
Household characteristics	No	Yes	No	Yes	No	Yes
Child characteristics	No	Yes	No	Yes	No	Yes
Observations	229	229	229	229	229	229

Notes: *** p<0.01 ** p<0.05 * p<0.10. All standard errors are clustered at child level. In Column [1]-[3]-[5], we do not control for any variables. In Column [2]-[4]-[6], we control for year-village dummies, survey dummies, household-level and child-level variables as in Table 6.3.

Table A 6.2 Marginal effects of the average temperature on nutritional status of children aged 6 - 60 months (fixed-effects linear model)

	HAZ		Stunted (HAZ-score < -2)		Severely stunted (HAZ-score < -3)	
	(1)	(2)	(3)	(4)	(5)	(6)
Average temperature	0.28	-0.81***	-0.082	0.058	-0.10	0.088
	(0.29)	(0.26)	(0.056)	(0.11)	(0.063)	(0.10)
Interaction village-survey	No	Yes	No	Yes	No	Yes
Survey dummies	No	Yes	No	Yes	No	Yes
Household characteristics	No	Yes	No	Yes	No	Yes
Child characteristics	No	Yes	No	Yes	No	Yes
Observations	229	229	229	229	229	229

Notes: *** p<0.01 ** p<0.05 * p<0.10. All standard errors are clustered at child level. In Column [1]-[3]-[5], we do not control for any variables. In Column [2]-[4]-[6], we control for year-village dummies, survey dummies, household-level and child-level variables as in Table 6.3.

Table A 6.3 Marginal effects of rainfall variability on nutritional status of children aged 6 - 60 months (fixed-effects model)

Variables	HAZ	Stunted	Severely stunted
	(1)	(2)	(3)
Rainfall variability in rainy season	388.4***	-95.0**	-130.2***
	(77.7)	(43.4)	(35.7)
Average annual temperature	-6.10***	1.35**	1.86***
	(1.05)	(0.59)	(0.47)
Interaction village-survey	Yes	Yes	Yes
Survey dummies	Yes	Yes	Yes
Household characteristics	Yes	Yes	Yes
Child characteristics	Yes	Yes	Yes
Observations	229	229	229

Notes: In each regression, we control for child and household characteristics as described in Table 6.3. We also control for survey dummies, and the interaction terms between village and survey dummies. *** p<0.01 ** p<0.05 * p<0.10. All standard errors are clustered at child level.

Table A 6.4 Marginal effect of yearly rainfall on consumption share and micronutrient supply from each food group

***Panel A*: Consumption shares**	Rice	Cereal	Tuber	Pulse	Vegetable	Fruit	Meat	Fish	Egg	Milk
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Rainfall variability	-0.24	-0.15***	-0.15	0.18***	-0.029	0.034	0.025	0.10	0.0017	0.018
	(0.17)	(0.033)	(0.11)	(0.055)	(0.057)	(0.030)	(0.084)	(0.085)	(0.0031)	(0.019)
Average annual temperature	0.013	0.00022	-0.011*	-0.0059	-0.0027	0.00085	-0.0043	-0.0082*	0.00035	0.0019
	(0.012)	(0.0032)	(0.0063)	(0.0037)	(0.0033)	(0.00098)	(0.0056)	(0.0044)	(0.00040)	(0.0018)
***Panel B*: Energy**	Rice	Cereal	Tuber	Pulse	Vegetable	Fruit	Meat	Fish	Egg	Milk
(kCal/AE/day)	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Rainfall variability	-13.8	1300.4***	1247.9***	291.8	201.4***	62.1	223.1*	-18.9	33.6	-1.91
	(515.8)	(500.9)	(428.3)	(326.3)	(57.1)	(106.2)	(119.1)	(34.8)	(26.9)	(3.43)
Average annual temperature	101.1**	23.9	-31.2	-58.1***	-3.04	4.86	5.71	2.83	-1.76	-0.14
	(40.1)	(40.1)	(21.6)	(21.4)	(3.46)	(5.65)	(5.90)	(3.48)	(1.44)	(0.19)
***Panel C*: Protein**	Rice	Cereal	Tuber	Pulse	Vegetable	Fruit	Meat	Fish	Egg	Milk
(mg/AE/day)	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Rainfall variability	-0.25	57.1***	10.5***	14.6	6.67***	0.65	20.3*	-1.77	3.27	-0.17
	(9.30)	(15.6)	(3.43)	(19.6)	(2.37)	(1.52)	(10.5)	(5.39)	(2.32)	(0.30)
Average annual temperature	1.82**	0.62	-0.30	-3.64***	-0.26*	0.18	0.21	0.29	-0.15	-0.012
	(0.72)	(1.07)	(0.19)	(1.35)	(0.15)	(0.14)	(0.46)	(0.25)	(0.12)	(0.016)
***Panel D*: Vitamin C**	Rice	Cereal	Tuber	Pulse	Vegetable	Fruit	Meat	Fish	Egg	Milk
(μg/AE/day)	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Rainfall variability	0	-19.7**	159.8***	3.15***	107.4***	27.2	0.45	1.59	0.54	0
	(.)	(8.07)	(53.3)	(1.11)	(27.7)	(113.5)	(0.46)	(3.97)	(0.39)	(.)
Average annual temperature	0	-0.55	-4.03	-0.20	-1.91	15.3	0.0082	0.093	-0.025	0
	(.)	(0.40)	(2.83)	(0.13)	(1.45)	(11.4)	(0.020)	(0.17)	(0.020)	(.)

Notes: For each regression in each panel, we control for household variables as described in Table 6.3. We also control for the year dummies, interaction term between year dummies and village dummies, and household fixed-effects. Standard errors in parentheses are clustered at household level; * p<0.10 ** p<0.05 *** p<0.01

Table A 6.5 Marginal effect of annual rainfall on consumption share of specific food within the tuber category

Consumption shares	Cassava	Taro	Sweet	Potatoes	Yam
	(1)	(2)	(3)	(4)	(5)
Annual rainfall	0.0092**	0.00017	-0.000059	0.00035	0.0000026
	(0.0042)	(0.00016)	(0.00040)	(0.00046)	(0.0000031)
Annual rainfall in squared term	-0.0000029**	-0.000000049	-7.0e-09	-0.000000091	-7.8e-10
	(0.0000013)	(0.000000050)	(0.00000012)	(0.00000015)	(1.0e-09)
Household characteristics	Yes	Yes	Yes	Yes	Yes
Interaction village-survey	Yes	Yes	Yes	Yes	Yes
Survey dummies	Yes	Yes	Yes	Yes	Yes
Observations	1624	1624	1624	1624	1624

Notes: For each regression in each panel, we control for household variables as described in Table 6.3. We also control for the year dummies, interaction term between year dummies and village dummies, and household fixed-effects. Standard errors in parentheses are clustered at household level; * p<0.10 ** p<0.05 *** p<0.01

Table A 6.6 Marginal effect of annual rainfall and its squared term on each food group production

Food group production	Cereal	Tuber	Pulse	Vegetable
	(1)	(2)	(3)	(4)
Annual rainfall	-0.0028	0.028*	-0.058***	0.028*
	(0.0051)	(0.016)	(0.017)	(0.015)
Annual rainfall in squared term	0.00000068	-0.0000073	0.000017***	-0.0000085**
	(0.0000015)	(0.0000050)	(0.0000052)	(0.0000042)
Household characteristics	Yes	Yes	Yes	Yes
Interaction village-survey	Yes	Yes	Yes	Yes
Survey dummies	Yes	Yes	Yes	Yes
Observations	1624	1624	1624	1624

Notes: For each regression in each panel, we control for household variables as described in Table 6.3. We also control for the year dummies, interaction term between year dummies and village dummies, and household fixed-effects. Standard errors in parentheses are clustered at household level; * p<0.10 ** p<0.05 *** p<0.01

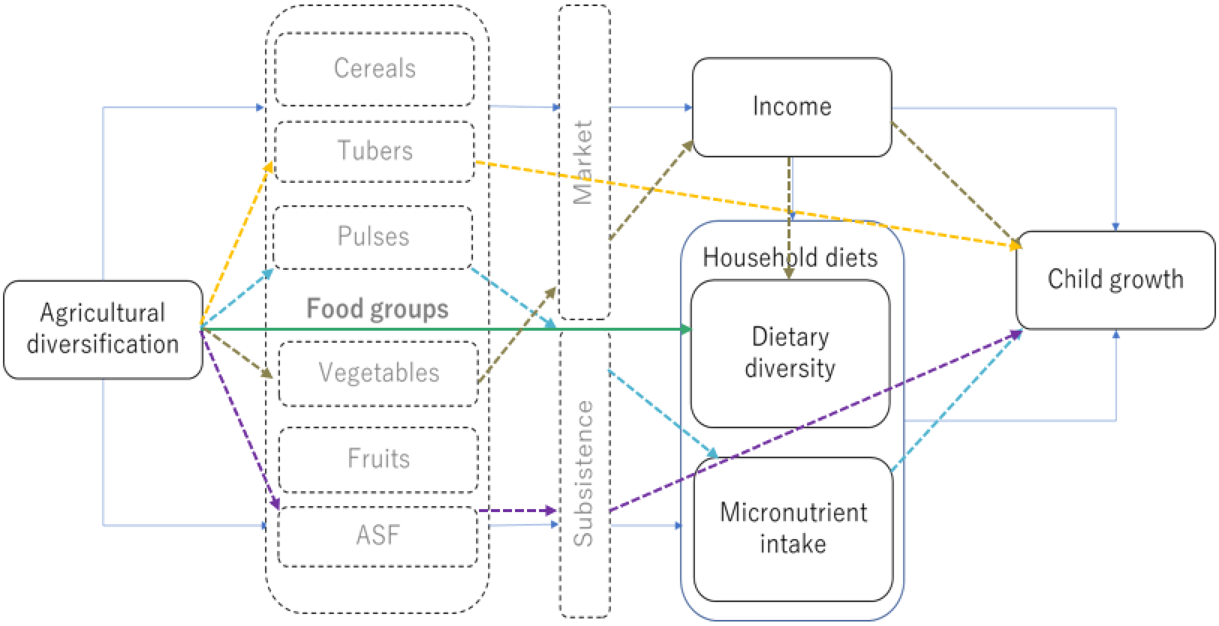

Fig. A 6.1 Linkage between agricultural diversification and child nutritional status, with a focus on Micronutrient pathways, Vegetable Commercialization, Animal-Sourced Food Production, and the Impact of Climate Change

General Conclusions

7 Conclusion

In this dissertation, the following hypotheses were posited:

i. The association of household agricultural production and micronutrient intake is positive and significant through self-consumption in the case of foods whose market is missing (i.e. not always available in the market);

ii. The association of household agricultural production and household dietary diversity is positive and significant in the case of marketable foods through income generated by crop sales;

iii. Micronutrient intake, either by self-production or through market-based dietary diversification is potentially associated with better nutritional status of children and a stronger likelihood of reducing stunting;

iv. Insufficient and excessive rainfall in tropical developing countries negatively impact child health outcomes and the availability of calories and nutrients sourced from specific food groups within households.

Hypothesis 1: *The association of household agricultural production and micronutrient intake is positive and significant through self-consumption in the case of foods whose market is missing (i.e. not always available in the market);*
Hypothesis 3: *Micronutrient intake, either by self-production or through market-based dietary diversification is potentially associated with better nutritional status of children and a stronger likelihood of reducing stunting.*

Chapter 3 of this study delved into the pathways connecting agricultural production diversity and dietary diversity, specifically focusing on the micronutrient pathway. Differentiating between the subsistence pathway and the market pathway, we obtained distinct results for each pathway. Firstly, we found that there is a partial association between production diversity and dietary diversity, with a positive relationship observed between production diversity and a child's weight. However, production diversity did not show a significant association with reduced child stunting. It became evident that dietary quality masks the underlying mechanisms which we sought to investigate through the micronutrient pathway. Secondly, our findings revealed that a specific food group, pulses, indicated a significant association with increased calorie and micronutrient intake. Moreover, micronutrient intake, particularly zinc from the subsistence pathway (and partially from the market pathway), showed a significant correlation with child linear growth and a reduction in stunting among preschool children. These important associations would have been overlooked if crude proxies of nutritional status had been used. Therefore, this chapter provides a valuable insight, emphasizing the need to move beyond widely used diversity scores and instead explore the micronutrient pathway to comprehend the actual mechanisms connecting agricultural production diversity and chronic malnutrition in children.

Hypothesis 2: *The association of household agricultural production and household dietary diversity is positive and significant in the case of marketable foods through income generated by crop sales.*

Chapter 4 focused on the role of vegetable production, particularly the commercialization of vegetables. Firstly, despite the well-known benefits associated with vegetable production, our study aimed to identify the primary dynamic factors that hinder farmers from engaging in commercializing vegetable production. The findings revealed that both younger and older household heads showed reluctance in entering the commercial vegetable sector. Additionally, factors such as the availability of family labor and land played significant roles. Moreover, climate change-induced alterations in precipitation patterns were found to decrease the likelihood of farmers engaging in commercial vegetable farming.

Secondly, the study found a significant association between increasing total value per-AE from commercial vegetable production and several factors, including the HDDS, income, and expenditures. This suggests that such commercial vegetable production is income generating while allowing farmers to diversify their nutritional intake. However, dietary diversity through the market pathway was found to be insignificantly associated with child stunting. Interestingly, the chapter highlighted another pathway through which commercial vegetable production influences child stunting, namely, increased expenditures on non-food items. Improved access to energy and daily commodities sourced from commercial vegetable production was found to have a significant association on reducing child stunting. In particular, this expenditure pathway has not been previously explored in existing studies, making it a valuable outcome of this Chapter.

Hypothesis 1: *The association of household agricultural production and micronutrient intake is positive and significant through self-consumption in the case of foods whose market is missing (i.e. not always available in the market).*

Chapter 5 of this study focused on investigating the relationship between nutrient-rich food groups, specifically ASF, and child growth in central Madagascar - a region characterized by limited milk intake and high stunting rates. This chapter introduces novelty through the use of high-frequency panel data and the incorporation of lagged analysis. At the child level, the findings consistently demonstrate a significant correlation between lagged milk production and improved child HAZ, as well as a reduction in stunting among preschool children in central Madagascar. However, no significant associations were observed for other types of ASF. At the household level, the results suggest that increased milk consumption occurs primarily through the subsistence route. This chapter highlights the critical role of ASF, particularly the significance of regular and adequate milk consumption, in promoting child growth. The inclusion of lagged analysis also underscores the importance of consistent and appropriate levels of milk production among preschool children as a crucial factor in combating chronic malnutrition in this population. These findings provide valuable insights into the potential strategies and interventions necessary to address child malnutrition in regions where milk intake is limited.

Hypothesis 4: *Insufficient and excessive rainfall in tropical developing countries negatively impact child health outcomes and the availability of calories and nutrients sourced from specific food groups within households.*

Chapter 6 of this study explored the relationship between climate change, specifically altered precipitation patterns, and child growth in tropical regions of Madagascar. At the child level, the findings revealed that both insufficient and excessive rainfall had detrimental effects on child HAZ and significantly increased the prevalence of severe stunting among preschool children. At the household level, the results consistently indicated that the same patterns of rainfall were associated with reduced tuber consumption, particularly cassava. Moreover, further investigation highlighted that the decreased intake of cassava, especially its protein content, had a significant influence on child HAZ and contributed to the reduction in stunting growth. Overall, these findings emphasize the necessity of increasing protein intake from alternative sources to mitigate the adverse effects of climate change on child growth. Efforts should be directed towards diversifying dietary options and promoting the consumption of protein-rich foods to enhance child nutritional status in the face of changing climatic conditions.

In conclusion, this dissertation underscores the significance of adopting a diversification strategy to combat child malnutrition, emphasizing the pivotal role played by each food group and its implications. The unique nutritional patterns observed in central Madagascar allowed for a comprehensive understanding of the distinct contributions of individual food groups within agricultural diversity production. The findings highlight the urgent need for transformative measures within the agricultural sector in central Madagascar to tackle existing challenges and enhance nutrition outcomes. Shifting towards the production of nutrient-dense foods and commercially viable crops with supportive markets is crucial. In addition, efforts should be directed towards improving the diversity and quality of diets, while also prioritizing the availability and accessibility of micronutrient-rich food groups for targeted population segments. While ASF hold importance in terms of nutrition and health improvements, it is essential to acknowledge that global environmental concerns are not primarily associated with rural smallholder farmers in SSA. Rather, these challenges require broader systemic approaches. Additionally, the study underscores the vulnerability of agricultural production systems in Madagascar to shocks such as climate change, which further aggravate the already precarious nutrition situation.

In light of these findings, a comprehensive overhaul of the agricultural sector is imperative to effectively address the identified issues and improve nutrition outcomes in central Madagascar. These transformative measures should encompass various dimensions, including production practices, market development, dietary diversification, and resilience-building strategies, to ultimately promote sustainable and nutritious food systems.

"*Madagascar does not just need green revolution, He needs 'greener' revolution*." (Zo)