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ORIGINAL PAPER

How are higher rice yields associated with dietary outcomes of smallholder farm households in Madagascar?

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Abstract

It is widely expected that agriculture would contribute to farmers' food security and nutrition in developing countries. However, studies that directly explore the link between agricultural productivity and micronutrients intake by farmers are scarce. In this paper, we contribute to filling this gap by exploring two key channels by which agricultural production can influence dietary outcomes: a food consumption pathway and a cash revenue pathway. To achieve this, we used three-years panel data of rice farmers collected in the Vakinankaratra region of Madagascar. The results suggest that rice yield is positively and significantly associated with farmers' calorie and micronutrients intake, though the observed elasticities are low. Secondly, raising rice yield has a positive significant impact not only on rice consumption but also on the share of the output sold and the cash revenue from rice sales. Lastly, the results suggest that households with higher cash revenue from rice sales purchase more nutritious foods. Therefore, we conclude that the market represents the channel through which increased rice yield translates into improved micronutrient intake. The findings of this study imply that in order to improve farm households' nutrition through agricultural production, interventions that target yield enhancement should be accompanied by market access measures.

Keywords Rice · Agricultural productivity · Nutrition · Cash revenue · Madagascar

1 Introduction

It has been established that the growth of agricultural productivity and food production has helped to reduce hunger (Gödecke et al., 2018; Khoury et al., 2014; Pingali, 2012). Nevertheless, nutritional deficiencies, which are less related to general food shortages than to low dietary quality and diversity deficiencies remain a major concern, especially in sub-Saharan Africa (SSA) and South Asia (FAO et al., 2021; Headey & Ecker, 2013; IFPRI, 2017). Furthermore, malnutrition is still among the major causes of premature deaths, infectious diseases, physical and mental growth retardation in children, and many other types of health problems in developing countries (IFPRI, 2017).

Agriculture and malnutrition are closely linked because the majority of undernourished people live in rural areas, and many of them are smallholder farmers (Pinstrup-Andersen, 2007; Sibhatu et al., 2015). Recent studies have highlighted the role of agriculture in improving nutritional outcomes. More specifically, they support the hypothesis that increase in agricultural production, either from higher productivity (Darko et al., 2018; Kim et al., 2019; Slavchevska, 2015) or from increased commercialization (Carletto et al., 2017; Ogutu et al., 2019; Ruel et al., 2018; von Braun, 1995), is associated with improved nutrition.

At the macro and meso levels, several studies have shed light on the potential of increased agricultural productivity to improve farming households' nutrition (Devkota & Upadhyay, 2013; Ogubdari & Awokuse, 2016). For example, Ogubdari and Awokuse (2016) examined 41 countries in sub-Saharan Africa (SSA) and found that an increase in agricultural value-added per hectare and cereal production

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per hectare contributed positively and significantly to food availability per capita in terms of weight, calorie, and protein supply. In the specific case of rice, Minten and Barrett (2008) found that communes with higher rice yields had higher real wages and prices, and were less likely to be food insecure. A study by Headey and Hoddinott (2016) suggests that there is a significant association between growth in rice productivity and child nutritional outcomes at the district level in Bangladesh.

At the household level, Morioka and Kondo (2017) suggested that growth in agricultural productivity in real terms has a positive impact on household food security in Nepal. Moreover, they found that the impact was stronger at the lowest levels of income. Similarly, a systematic literature review of studies in South Asia by Shankar et al. (2019) found evidence that higher agricultural production per unit of land is significantly associated with improved household dietary outcomes.

Studies that empirically examine the link between agricultural productivity and nutrition at the household level are scarce in SSA, particularly with regard to micronutrient intake. Most studies have focused on food consumption or broader food security measures. For instance, a study by Sarris et al. (2006) in Tanzania showed that productivity directly affected household consumption per capita. Dzanku (2015) examined the farm productivity-poverty relationship in Ghana and found that labor productivity significantly increased food expenditure, while there was no significant association between land productivity and food expenditure. However, Darko et al. (2018) found that an increase in maize yield per hectare positively impacted household caloric intake in Malawi. Although, in terms of economic magnitude, both the direct effect and the economy-wide spillover effect of a percentage increase in agricultural productivity on poverty and food security measures were small. Similarly, a recent study by Villacis et al. (2022) in Nigeria found that an increase in agricultural productivity increased food security, as measured by experience-based indicators.

In general, although the potential of agricultural productivity to improve food and nutrition security has been widely recognized, there is little empirical evidence that it improves the key measures of dietary outcomes, such as micronutrient intake. More specifically, even though much effort has been made to induce a green revolution in rice production in SSA (Balasubramanian et al., 2007; deGraft-Johnson et al., 2014; Otsuka & Larson, 2016; Otsuka & Muraoka, 2017), empirical studies that focus on the direct impact of household rice productivity on micronutrient intake at the household level are scarce. This study seeks to fill this knowledge gap by exploring the nutritional impact of lowland rice yields in the Vakinankaratra region of Madagascar.

The contribution of this paper is threefold: First, this study adds to the knowledge of agricultural-nutrition literature by providing micro-level empirical evidence of the impact of agricultural land productivity on farm households' dietary outcomes. Most of the empirical evidence compiled on the subject in SSA is at the macro or meso-level (Lee et al., 2017; Minten & Barrett, 2008; Ogubdari & Awokuse, 2016; Schneider & Gugerty, 2011). Moreover, and most importantly, we extended the measures of household dietary outcomes to include micronutrient intake. Additionally, the few existing studies in SSA barely examine the channel through which an increase in agricultural productivity improves farm households' nutrition. In this study, we consider both the consumption and cash revenue pathways through which higher crop productivity can be linked to improved dietary outcomes at the household level.

Second, rice is the most important staple food in most regions in Madagascar, including our study site. Madagascar differs in this regard from other SSA countries where several staple foods coexist. As a result, many projects aim to enhance rice productivity in Madagascar, and rice yield is relatively high there compared with other SSA countries. However, its consequences on rice producers' nutrition have been poorly examined. Moreover, it is widely known that the nutritional status of farm household members is low in Madagascar (FAO et al., 2021). For example, according to the World Bank, Madagascar is one of the ten worst countries in the world in terms of the prevalence of stunting among children under five years old (World Bank, 2019). However, to the best of our knowledge, no study has examined the relationship between rice productivity and nutrition in the Malagasy context. The dearth of nutritional and agricultural data in Madagascar has undoubtedly been a constraint to exploring such a relationship. Furthermore, important policy implications could be drawn from this study regarding interventions that target nutrition security, through the promotion of yield enhancement of the main staple food crops such as maize, sorghum, and millet in other SSA countries.

Third, one of the major limitations of most studies that use a seven-day recall questionnaire to capture rural households' consumption data is that they are not free from seasonality effects. Seasonality in the reported data may lead to an overestimation or underestimation of the effects of the variables of interest. The data used in this study were collected during both the lean season and immediately after the harvest. Therefore, we used the weighted average of both seasons. This allowed us to reduce the effect of seasonal consumption patterns on our estimates.

The remainder of this paper is organized as follows. Section 2 provides an overview of agriculture and nutrition in Madagascar. Section 3 lays out the conceptual link between agriculture and nutrition at the farm level, and develops the research hypotheses. Section 4 describes the data used in this paper and the econometric approach used to test the hypotheses. Section 5 presents and discusses the results, and Section 6 concludes the paper.

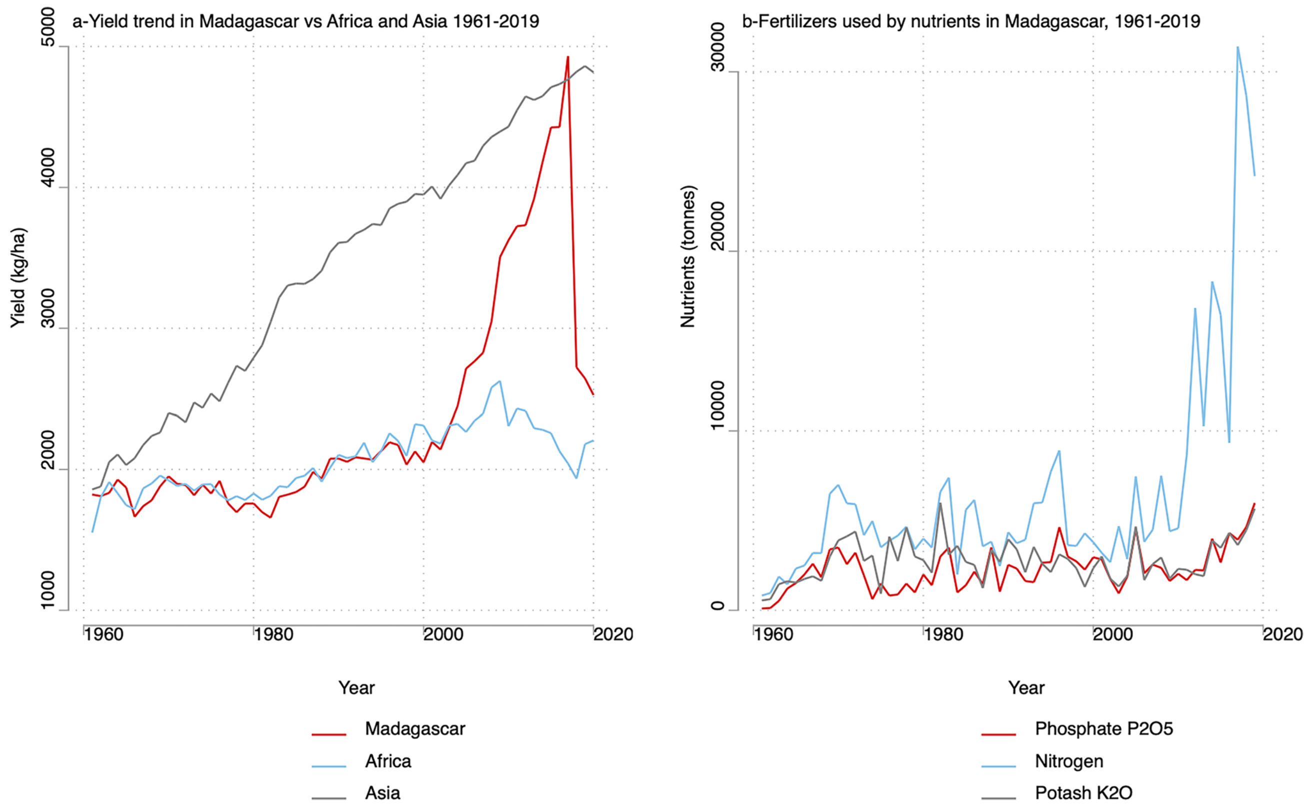

Fig. 1 Trends in rice yields and chemical fertilizers used in agriculture in Madagascar, 1961–2020. Source: Constructed by authors based on the FAO data, 2021

2 Background on agriculture and nutrition in Madagascar

2.1 Agricultural production in Madagascar

Agriculture employed 74% of Madagascar's population and accounted for almost 23% of GDP in 2019 (FAO, 2019). It is characterized by extensive agricultural production and is highly susceptible to climate hazards (Harvey et al., 2014). The production is carried out by small family farms, with approximately 85% of farmers cultivating rice (Global Rice Science Partnership, 2013). In Madagascar, rice is mainly produced in rain-fed lowland plots, where water can be retained during the rainy season. Consequently, rice production is highly seasonal, with most production occurring during the rainy season, and dry season production heavily constrained by a lack of water. Rice production has been extended to upland plots since the early 2000s, following the introduction of new cold and drought-tolerant varieties (Raboin et al., 2014). For example, most lowland rice producers grow upland rice at the study site (Ozaki & Sakurai, 2020).

Figure 1 uses FAO production data to show the trends in rice yields and chemical fertilizers used in agriculture in Madagascar between 1961 and 2020. Before 2000, rice yield in Madagascar was stagnant, as in other African countries, but since 2000, Madagascar has experienced rapid growth in rice yield (Fig. 1a). As shown in Fig. 1b, the quantity of nitrogen used in agriculture began to increase exponentially after 2000, which interestingly corresponds to the high growth in rice yield shown in Fig. 1a,[1] although we do not have any evidence of a causal relationship. Indeed, the use of chemical fertilizers in rice production is still limited. For example, according to World Bank data, fertilizer consumption in agriculture was approximately only 12.6 kg/ha of arable land in Madagascar for the year 2018. This application rate is much lower than those recorded in Asian countries over the same period, such as 149 kg/ha in Thailand, 318 kg/ha in Indonesia, 236 kg/ha in Bangladesh, and approximately 415 kg/ha in Vietnam (World Bank, 2019). In the case of rice production, a previous study at our study site showed that almost 75% of lowland rice plots received no chemical fertilizer at all, while the application rate was less than 40 kg/ha for any that did (Ozaki & Sakurai, 2021).

[1] The reader should be cautious since high yield in Fig. 1a may hide the huge disparity across rural areas of Madagascar. For example, in our study site rice yield is always below 3,500 kg/ha.

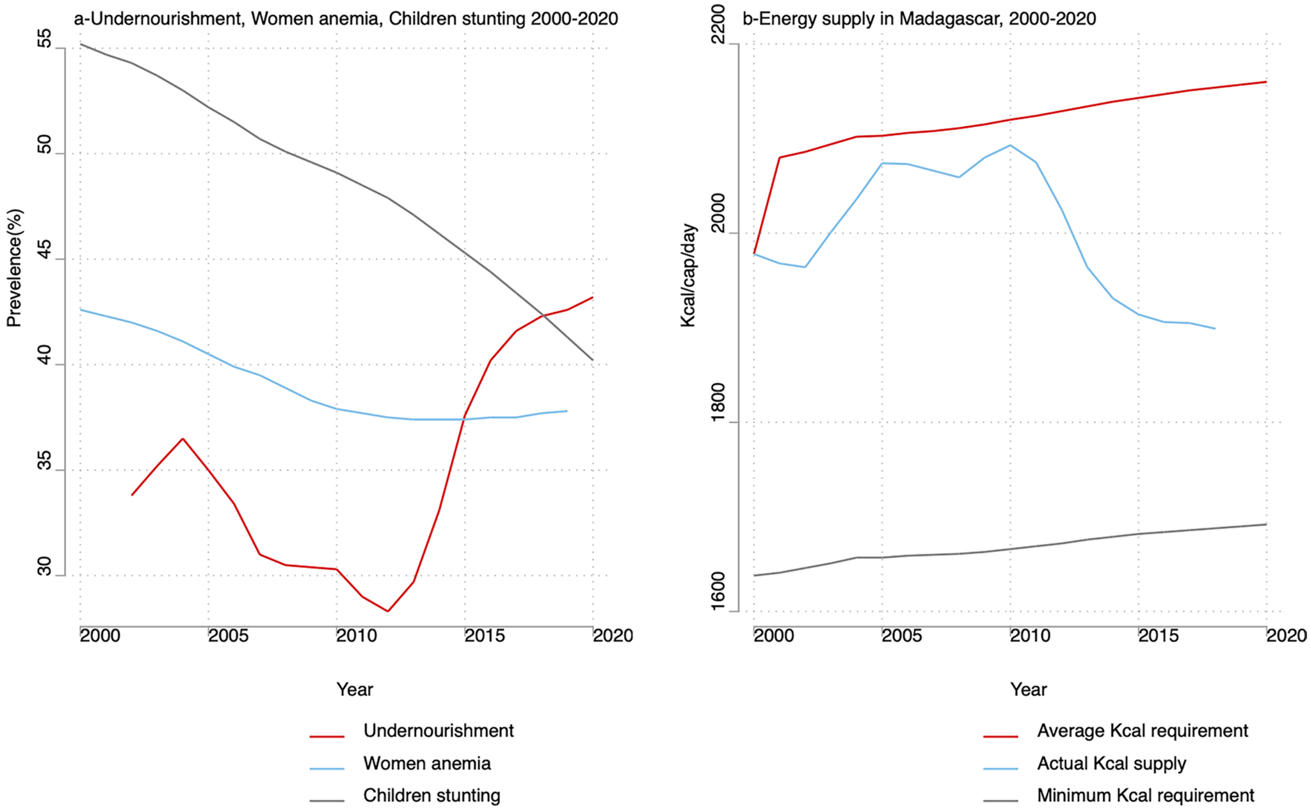

Fig. 2 Trends in the Average dietary energy requirement and nutritional status in Madagascar, 2000–2020. Source: Constructed by authors based on the FAO food balance sheets, 2021

2.2 Dietary and nutrition trends in Madagascar

Similar to other sub-Saharan African countries, Madagascar is permanently threatened by food insecurity. Figure 2 uses FAO Food Balance Sheets to plot trends in the food supply and nutritional status of households in Madagascar.[2] Although the prevalence of undernourished people is declining over time it remains high, accounting for more than 40% of the total population in 2020 (Fig. 2a). The daily energy supply, although higher than the minimum requirement, remains lower than the dietary energy requirement defined by the FAO (Fig. 2b). In addition, there are malnutrition problems in Madagascar. For example, Fig. 2a shows that since 2015, the prevalence of anemia among women of reproductive age is higher than 37%, while the proportion of children under 5 years old who are stunted is approximately 42%.

Rice is the main staple food in Madagascar, with the per-capita annual rice consumption estimated at 157 kg in 2018, making it one of the highest-ranking countries in the world in terms of rice consumption per capita (FAO, 2018). This implies that rice is an extremely important source of caloric intake. For example, in 2018, rice's contribution to the daily calorie supply was 1,075 kcal/per capita, which represents 56% of the nation's total calorie consumption (FAO, 2018). Furthermore, rice is also one of the most important income sources for most farm households in Madagascar (World Bank, 2016). Therefore, we expect that the increase in household cash revenue that would follow an increase in rice yield would result in more purchasing of food unproduced by the household, specifically highly nutritious food.

3 Conceptualizing the linkage between rice productivity and household nutritional outcomes

The linkage between agricultural production and nutrition is complex and highly context-specific. Moreover, there are many interactions among the different pathways that connect agricultural production to nutritional outcomes. A review by Kadiyala et al. (2014) identified six routes of this linkage that can be summarized into three main channels: (a) food

[2] This figure needs to be treated with caution because there may be systematic errors in FAO Food Balance Sheets, particularly misreporting of production for foods that are not traded in large volume (Headey & Hoddinott, 2016).

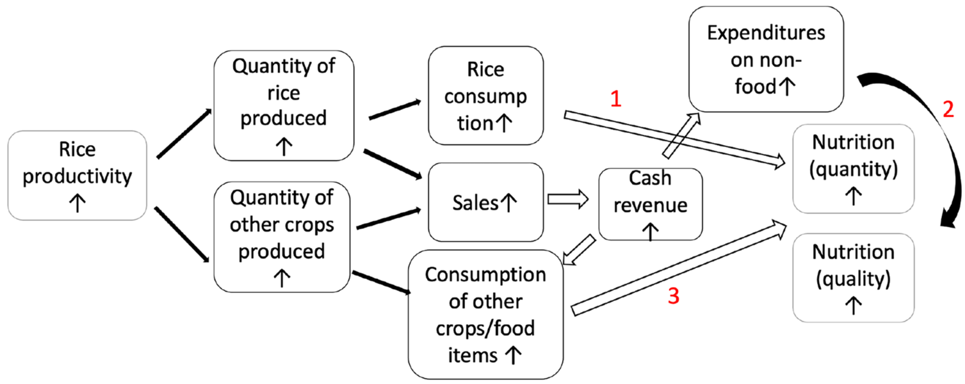

Fig. 3 Linkage between rice yield and farm household nutrition outcomes. Source: Constructed by authors

production, which can affect the food available for household consumption as well as the prices of diverse foods; (b) agricultural income for expenditure on food and non-food items; and (c) women's empowerment, which affects income, caring capacity, practices, and female energy expenditure.

Figure 3 provides a simplified picture of how an increase in rice production per unit of land improves farmers' nutritional outcomes in Madagascar. Rice production may have a direct effect on farm households' nutrition. That is, like channel (a), pathway (1) in Fig. 3 suggests that higher rice productivity would increase the quantity of rice available for each household member, and thus their calorie intake also. However, while an increase in rice productivity directly increases energy intake by enabling greater rice consumption, it does not guarantee that the quality, variety, or nutritional value of the food will increase. To achieve this, an increase in rice productivity must produce an increase in the household's cash revenue (3), as suggested by Kadiyala et al. (2014) in channel (b). More specifically, this implies that higher rice productivity may improve the nutritional status of nutritionally vulnerable households by increasing their cash revenue, which enables better access to more diverse and/or nutritious foods that are not produced by households, and thus must be purchased on the market. Furthermore, the additional cash revenue could be used to acquire non-food items such as sanitary and cooking utensils, and consumables, which could further improve nutrition quality (2).

There is another pathway through which higher rice yields can improve households' quality of nutrition. The increase in rice productivity may free up additional land to produce other crops, which could improve households' nutrition in two ways. First, the increase in the production of other crops could directly increase the quantity and/or diversity of home-produced food crops (Khonje et al., 2022). Second, the cash revenue generated from the sales of other crops could indirectly improve nutrition by enabling further purchasing of food items that are not produced by households (3).

In this study, we postulate and test the following hypotheses:

1. Increased rice yield is associated with higher calorie and micronutrient intake by households.

   With respect to the mechanism through which increased household rice productivity improves the household's micronutrient intake, we postulate three additional hypotheses:
2. Increased household rice yield is associated with higher rice consumption.
3. Increased household rice yield is associated with higher household cash revenue.
4. Increased household cash revenue from rice sales is associated with larger purchases of highly nutritious foods.

4 Method and data

4.1 Method

To test the first hypothesis (1), we model the relationship between dietary outcomes and rice yield as:

$$N_{ivt} = \delta_0 + \delta_1 yield_{ivt} + \delta_2 yield_{ivt} * D_i + \delta_3' X_{ivt} + \delta_4' T_t + \delta_5' T_t * V_v + \mu_i + \varepsilon_{ivt} \quad (1)$$

where N_{ivt} refers to the dietary outcome for household i in village v of year t and $yield_{ivt}$ refers to household i's rice yield in natural logarithm. The parameter of interest is δ_1, which represents the effect of the rice yield on the household's dietary outcomes. D_i is the distance of household i from the main road. The "main road" is the RN34 ("Route Nationale 34" in French) of Madagascar. It is the only paved, national road that runs through the east and west of our study site (three districts of the Vakinankartra region). All villagers in our study site used this road to travel to the region's capital city, Antsirabe. The distance is measured using the GPS coordinates of the household; X is a vector of time-variant household and farm characteristics, including household socio-demographics and asset variables. T_t is a vector of time dummies for the years 2018, 2019, and 2020, which captures all structural changes such as economic growth, improvements in communication and transportation infrastructure, and climate shocks. Interaction terms between year dummies (T_t) and village dummies (V_v) were also added. μ_i denotes the household fixed effect.

To test hypotheses (2), (3), and (4), we estimated the following equations:

$$Y_{ivt} = \alpha_0 + \alpha_1 yield_{ivt} + \alpha_2 yield_{ivt} * Di + \alpha_3' X_{ivt} + \alpha_4' T_t + \alpha_5' T_t * V_v + \mu_i + \varepsilon_{ivt} \tag{2}$$

$$Exp_{ikvt} = \beta_0 + \beta_1 CR_{ivt} + \beta_2 CR_{ivt} * Di + \beta_3' X_{ivt} + \beta_4' T_t + \beta_5' T_t * V_v + \mu_i + \varepsilon_{ivt} \tag{3}$$

where Y_{ivt} is the natural logarithm of the monthly rice consumption per adult equivalent (or cash revenue per adult equivalent), and Exp_{ikvt} is the natural logarithm of the monthly expenditure on food group k of household i in village v of year t. $yield_{ivt}$, D_i, X, and T_t are as above.

4.2 Endogeneity issues

From Eqs. (1)–(3), we have three potential sources of endogeneity. The first source is omitted variables that could be correlated with our variables of interest (yield and cash income) and the outcome variables. We used a household fixed effects model to deal with the endogeneity caused by the time-variant omitted variables (e.g., access to water sources for irrigation, soil quality, household preferences, and cultural practices). For time-variant omitted variables, it would be ideal to use time-variant instruments for both the yield and cash revenue. However, the data did not contain such potential instruments. Instead, we included year-village dummies that would pick up time-varying location shocks, including weather, food availability, wage and price shocks. For example, the year-village dummy explains approximately 25% of rice yield and cash revenue variability in our sample.[3] Additionally, we controlled for household asset value (both farm and non-farm assets), which is a proxy for long-term economic wealth status. Moreover, we used the approach developed by Oster (2019) to check the stability of the estimates. This approach assumes that the observables and unobservables have the same explanatory power in explaining the dependent variable and calculating the bias-adjusted estimate.[4]

The second source of endogeneity may be the measurement error in the rice yield. However, the plot size of lowland rice was measured using GPS, which minimized the extent of this potential measurement error.

The third source of endogeneity is that the relationship between agricultural productivity and dietary outcomes may not be unidirectional. On the contrary, individuals with better nutrition, consequently better health, are likely to be able to perform more strenuous activities with fewer breaks, and hence have higher productivity (Egbetokun et al., 2012; Gkiza & Nastis, 2017). Fortunately, the survey recorded detailed information about each household member's daily routines, including both farming and non-farming activities. Therefore, we took advantage of this by including the physical conditions of individual household members in the calculation of the adult male equivalent. More specifically, as suggested by Weisell and Dop (2012), the level of each member's physical activity is included in the calculation of the adult male equivalent (AE). We then converted all dietary outcome variables into an AE, which served to minimize the effect of nutrition on rice productivity. While we performed different robustness checks for the estimates, we must treat the results below as suggestive, rather than definitive evidence of causal linkages between rice productivity and dietary outcomes at the household level.

4.3 Data

This study used data collected by the FertilitY sensing and Variety Amelioration for Rice Yield (FyVary)[5] project led jointly by the Japan International Research Center for Agricultural Sciences and the Malagasy Ministry for Agriculture, Livestock, and Fishing (MINAE). One of the major goals of this project is to increase the rice yield under low-fertility conditions through rapid diagnosis of soil fertility, and the development of nutrient-use-efficient breeding lines. The project site was the Vakinankaratra region in central Madagascar, one of the most important rice-producing regions of this island country in terms of volume. The sample households were chosen through two steps. First, a census survey was conducted in 60 villages across three out of the six districts of the Vakinankaratra region from December 2017 to January 2018. Villages were selected according to the size of each district. Second, from the households listed in the census, ten lowland rice-growing households were randomly selected from each of the 60 villages. This yielded an initial sample size of 600 households.

The data collected included demographic information, agricultural input and output, monthly rice purchases and sales, monthly expenditure on food and non-food items, 7 day

[3] We regression rice yield and cash revenue on year-village dummy. The associated R-squared were 0.28 and 0.26 for rice yield and cash revenue respectively. The results are available upon request from the authors.

[4] A brief description of the calculation of the bias-adjusted estimate can be found in the supplementary material.

[5] https://www.jircas.go.jp/en/satreps

and 24 h recall questionnaires about food consumption, and non-agricultural/off-farm activities. To capture the dry season activities as well as the seasonality in food consumption, farmers were interviewed at least twice every year: the first round of interviews took place after the harvest, and the second round during the lean season. The data covers three rice productions for the years 2018, 2019, and 2020. We retained households that appeared at least twice during the three years. Additional exclusion of households with missing values yielded an unbalanced panel of 1,587 observations including 487 households that appear in each of the three years. As the total number of observations should have been 1,800 over three years, the attrition rate was 11.8% or less than 4% per year on average. Therefore, we followed the approach developed by Wooldridge (2010) to test for attrition bias.

5 Results and discussion

5.1 Variables and summary statistics

Table 1 presents the summary statistics of the key independent variables. Lowland rice yield (kg/ha) was the variable of interest in this study. As some farmers have several plots, we computed the average yield weighted by plot size. On average, the yield of lowland rice for our sample was 3,363.4 kg/ha, which is in the regional average yield range of 3,000–3,500 kg per ha during the period of study (WFP, 2019). Moreover, Table 1 shows that more than 54% of households in our sample sold rice, which suggests that many farmers in the study site obtained cash revenue from lowland rice production. Also, Table 1 shows

Table 1 Summary statistics on rice production and households' characteristics

Variables	2018 Mean (1)	2019 Mean (2)	2020 Mean (3)	Pooled Mean (4)	SD (5)
Lowland rice yield (kg/ha)	3432	3203.6	3455.7	3363.4	1294.17
Lowland production (kg/AE)	227.8	227.8	244.8	233.2	502.2
Total land size for lowland rice (ha)	0.32	0.29	0.28	0.3	0.57
Commercialization of lowland rice (1/0)	0.62	0.67	0.54	0.61	0.49
Share of the lowland rice production sold (%)	22.32	23.68	21.90	22.60	30.87
Cash revenue from lowland rice sales (1000 MGA/AE)	44.25	38.14	51.02	44.57	94.60
Household buys rice (1/0)	0.88	0.84	0.79	0.84	0.36
Household buys and sells rice in a year (1/0)	0.48	0.46	0.34	0.43	0.49
Crop diversification[a]	1.52	1.74	2.13	1.79	1.58
Income from other farm activities (1000 MGA/AE)	232.0	143.22	178.47	185.51	382.91
Off-farm income (1000 MGA/AE)[b]	218.81	306.20	352.48	290.73	38.565
Age of the household's head	53.16	46.66	47.45	49.19	69.79
Ratio of dependence (0–1)	0.375	0.355	0.341	0.357	0.223
Consumption questionnaire respondent[c] (1/0)	0.35	0.52	0.39	0.42	0.49
Yesterday was a special day (1/0)	0.04	0.05	0.00	0.03	0.18
Total size of land cultivated (ha)	0.87	0.9	0.88	0.88	3.57
Livestock holdings (Tropical Livestock Unit, TLU)	2.77	2.74	2.74	2.75	3.21
Distance to the main road (km)	5.37	5.44	5.40	5.40	5.09
Value of total asset (1000 MGA/AE)	140.87	136.95	156.90	144.70	279.30
Number of Observations	550	529	508	1587	

AE is Adult Equivalent, *MGA* Malagasy Ariary is Malagasy currency (1000 MGA = US$ 0.026 as of July 27th, 2021)

[a]Crop diversification is the number of other crops cultivated

[b]The income from other farming activities includes income from dry season farming, non-rice crops, and upland rice cultivation

[c]Consumption questionnaire respondent takes 1 if the respondent is different from the person who knows better about household consumption and 0 otherwise

that only 20% of the total output was sold. However, it is worth noting that selling rice does not necessarily mean that those farmers produced a sufficient amount of rice for self-consumption. Indeed, many farmers purchase rice during the lean season in Madagascar (Minten et al., 2006). In this study, we found that more than 43% of the sample were simultaneously rice sellers and buyers (Table 1).

Furthermore, Table 1 shows that the average size of total land cultivated is 0.88 hectares and the average livestock holding is 2.75 Tropical Livestock Unit (TLU), which suggests that our sample is composed of smallholder farmers. The household sociodemographic variables recorded included the age of the household head, and the ratio of dependency. In addition, when we analyzed household food consumption and expenditure, we included two further control variables: one is the identity of the respondent, to reduce the effect of a possible measurement error. This variable takes 1 if the respondent is different from the person who knows better about household food consumption (usually the wife). The second variable is a binary variable to control for unordinary food consumption in the 24 h before the interview (e.g., a day of ceremony or feast).

Table 2 presents the summary statistics of the outcome variables. In total, we conducted seven survey rounds to amass the consumption data collected during the three years. We calculated the average value of the outcome variables weighted by household size in the AE (adult equivalent). First, Panel A of Table 2 presents monthly food consumption and rice purchases. This shows that food consumption was 36,520 Malagasy Ariary (MGA) per AE, which is equivalent to USD 0.305 per/AE per day. The non-purchased food consumption was converted into MGA. The market plays an important role in food consumption, with an average food purchase of 19,550 MGA per AE, which is equivalent to

Table 2 Summary statistics of consumption and micronutrients supply

Variables	2018 mean (1)	2019 mean (2)	2020 mean (3)	All mean (4)	SD (5)
A. Food consumption					
Total food consumption (1000 MGA/month/AE)	35.10	35.08	39.52	36.52	260.8
Consumption of purchased food (1000 MGA/month/AE)	21.61	16.91	20.05	19.55	21.34
Consumption of non-purchased food (1000 MGA/month/AE)	13.5	18.16	19.46	16.97	13.84
Total rice consumption (1000 MGA/month/AE)	25.45	23.03	28.11	25.51	12.17
B. Purchase of different food groups					
Staple foods (1000 MGA/month/AE)	13.00	5.76	14.03	10.91	11.85
Rice purchased rice (kg/month/AE)	5.28	5.00	3.49	4.61	7.38
Rice purchased rice during lean season (kg/month/AE)	6.73	6.30	3.43	5.53	7.16
Pulses (1000 MGA/month /AE)	1.22	1.35	1.05	1.21	1.48
Tubers and Roots (1000 MGA/month/AE)	0.40	0.92	1.24	0.87	1.61
Vegetables (1000 MGA/month/AE)	1.76	2.14	2.00	1.96	8.8
Fruits (1000 MGA/month/AE)	0.42	0.64	0.41	0.50	1.17
Meat and Fish (1000 MGA/month/AE)	5.36	3.50	4.30	4.40	6.51
C. Expenditure on non-food items					
Expenditure on sanitary, cooking, and cleaning consumables (1000 MGA/month/AE)	1.70	1.17	1.42	1.43	2.00
D. Diet quality, Energy, and micronutrients intake					
Household Dietary Diversity Score (HDDS)[a]	5.03	5.21	5.64	5.29	1.11
Calorie intake (kcal/day/AE)	2639.1	2446.3	2696.4	2593.9	1070.7
Prevalence of undernourishment (%)[b]	52.2	60.60	46.20	53.00	49.9
Iron intake (mg/day/AE)	13.94	12.78	14.63	13.78	8.96
Zinc intake (mg/day/AE)	9.27	7.20	9.23	8.57	4.67
Vitamin A intake (μg RAE/day/AE)	220.1	148.6	242.0	203.5	185.9
Number of Observations	550	529	508	1587	

AE is Adult Equivalent. *MGA* Malagasy Ariary is Malagasy currency (1,000MGA = US$ 0.026 as of July 27th, 2021), *RAE* retinol activity equivalents

[a]HDDS is number of different food groups consumed (both home-made and purchased) during the 24 h preceding the survey [0–12]

[b]The percentage of the household with calorie consumption lower that 2,500 kcal/day/AE

53% of the total food consumption. On average, households in this sample purchased 4.61 kg/AE of rice per month, which increased by approximately 20% during the lean season. Additionally, panel B of Table 2 shows that a large share of the household budget was allocated to staple food groups (e.g., rice and maize), followed by meat and fish.

Panel C of Table 2 presents the calorie and micronutrient intake of households calculated based on 24 h dietary recall. On average, the sample calorie intake was 2,594 kcal/day/AE, which is slightly higher than the standard requirement for an adult leading an appropriately active life of 2,500 kcal/day/AE (WHO, 2005). However, the prevalence of calorie deficiency was 53%, which suggests that a high number of undernourished people (calorie intake < 2,500 kcal/day/AE) were included in this sample. In terms of micronutrients, we focused on iron, zinc, and vitamin A, for which deficiencies are particularly widespread in sub-Saharan Africa (Mason et al., 2015). For this sample, the average iron intake was 13.78 mg/day/AE, which is close to the recommended[6] amount, whereas zinc intake was lower than the recommended level of 11 mg/day/AE WHO (2005). A striking observation from Table 2 is that vitamin A intake was 203.5 μg RAE/day/AE on average, which is far below the standard requirement of 800 μg RAE/day/AE advised by the WHO (2005).

5.2 Results of the econometric estimation

The results of the econometric estimation are presented in Tables 3, 4, and 5. Since we included the interaction between yield and distance to the main road, we focused on the interpretation of the marginal effects (elasticities) at the mean values of the sample. The full regression output can be found in Tables S1, S2, S3, and S4 in the supplementary material. Columns (2), (3), (4), and (5) show the range of the estimates based on the robustness check that follows the approach developed by Oster (2019). The range of estimates does not contain zero and the upper bounds are within the 95% confidence interval of the controlled estimates. Moreover, the delta was greater than 1 for the significant coefficients (Tables S1, S2, S3, and S4 of the supplementary material). This suggests that the estimates are robust to omitted variable bias (González & Miguel, 2015; Nghiem et al., 2015; Oster, 2019).

Next, since our data is a three-year panel, we followed Wooldridge (2010) by including a lead of the attrition indicator to test for attrition bias.[7] We found that the attrition indicator is not statistically significant. Additionally, we estimated the fixed effects model with the subsample of households that appear only in all three years, yet the coefficients remain stable (Tables S6, S7, and S8).

Table 3 Impact of rice productivity on the calories and micronutrients intake (Household fixed effects)

Nutritional outcomes	Coefficients (Standard errors)	Range of Estimates based on Oster (2019)	Elasticities at the sample mean (Standard errors)	Effect size (30% increase in the rice yield)
Independent variable: ln of lowland rice yield	(1)	(2)	(3)	(4)
Energy	0.30***(0.03)	[0.30 0.33]	0.33*** (0.02)	212.41
Zinc	0.28***(0.04)	[0.28 0.31]	0.23***(0.04)	0.67
Iron	0.77***(0.04)	[0.77 0.80]	0.70***(0.04)	3.08
Vitamin A	0.37***(0.04)	[0.35 0.37]	0.30***(0.04)	21.33
HDDS	0.64***(0.09)	[0.64 0.65]	0.66***(0.08)	0.17

All outcome variables are in natural logarithm. The independent variable is the natural logarithm of the lowland rice yield. Elasticities at the sample mean in the column (3) are computed as follow: $e_{yield/y} = \hat{\delta}_1 + \hat{\delta}_2 * \ln(\overline{distance})$

Full regression output can be found in the Table S1

The controls include interaction between yield and distance in Ln, age of the household's head, the ration of dependency, questionnaire respondent is different from the main person in charge of cooking, the day of the survey is special, Ln of the household asset value, livestock holding (TLU), total land size, crop diversification, and Year-village dummy

Robust standard errors in column (1) are clustered at the village level in parentheses. Robust standard errors in column (3) are computed using Delta-Method. Number of households in the panel is 550

*** p < 0.01, ** p < 0.05, * p < 0.1

[6] WHO (2005) recommends a daily amount of iron of 8.7 mg/day for men over 18 years old and 14.8 mg/day for women aged 19 to 50 years.

[7] Available upon request from the authors.

Table 4 Impact of rice productivity on rice consumption and cash revenue (household fixed effect)

Variables Independent variable: ln of lowland rice yield [a]	Coefficients (Standard error) (1)	Range of Estimates based on Oster (2019) (2)	Elasticities/Marginal effects at the sample mean (Standard errors) (3)
A. Rice consumption			
Rice production per AE	0.31***(0.07)	[0.31 0.35]	0.30***(0.07)
Value of rice consumption	0.22***(0.03)	[0.21 0.22]	0.20***(0.03)
Amount of rice purchased (monthly)	-0.16*(0.09)	[-0.17 -0.16]	-0.13***(0.04)
Monthly rice purchased (lean season)	-0.81***(0.07)	[-0.82 -0.81]	-0.80***(0.08)
B. Cash revenue from rice production			
Commercialization (1/0): linear probability model	0.16***(0.03)	[0.16 0.18]	0.08**(0.03)
Share of the production sold (0–100)	9.17***(1.81)	[9.17 8.95]	5.44**(2.00)
Cash revenue from rice sales	0.39***(0.08)	[0.35 0.39]	0.41***(0.11)

All outcome variables are in natural logarithm except commercialization (1/0) and the share of the production sold. The independent variable is the natural logarithm of the lowland rice yield. Full regression output can be found in the Tables S2 and S3

The controls include interaction between yield and distance in Ln, age of the household's head, the ration of dependency, Ln of the household asset value, livestock holding (TLU), total land size, crop diversification, and Year-village dummy

Robust standard errors in column (1) clustered at the village level in parentheses. Robust standard errors in column (3) are computed using Delta-Method. Number of households in the panel is 550

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Lastly, the polynomial regression suggests that there is a linear relationship between the dietary outcome variables and rice yield, except for iron intake (Fig. S1). However, after controlling for other variables in the iron-intake model, the quadratic term was not statistically significant. Therefore, we maintained linear specifications for each of the models.

Table 5 Elasticity of cash revenue from lowland rice production on food and non-food items

Variables Independent variable: ln of cash revenue [a]	Coefficients (Standard error) (1)	Range of Estimates based on Oster (2019) (2)	Elasticities the sample mean (Standard errors) (3)
A. Food consumption			
Total food consumption	0.09***(0.02)	[0.09 0.11]	0.08***(0.02)
Purchased food consumption	0.14***(0.02)	[0.14 0.18]	0.14***(0.02)
Non-purchased food consumption	0.03(0.02)	[0.03 0.04]	0.03(0.02)
B. Expenditure on different food groups (purchased food items)			
Staples	0.001 (0.04)	[0.001 0.003]	0.01(0.03)
Pulses	-0.004 (0.04)	[-0.005 -0.004]	-0.007(0.04)
Tubers and roots	0.01 (0.05)	[0.010 0.012]	-0.003(0.05)
Vegetables	0.15***(0.04)	[0.15 0.17]	0.14***(0.04)
Fruits	0.13**(0.05)	[0.13 0.16]	0.11**(0.05)
Meat and Fish	0.09***(0.03)	[0.09 0.12]	0.09***(0.03)
C. Expenditure on non-food items			
Expenditure on sanitary, cooking, and cleaning consumables	0.25***(0.04)	[0.25 0.30]	0.24****(0.04)

All outcome variables are in natural logarithm. The independent variable is the natural logarithm of cash revenue from the lowland rice production. Full regression output can be found in the Table S4.The controls include interaction between cash revenue and distance in Ln, age of the household's head, the ration of dependency, Ln of the household asset value, livestock holding (TLU), total land size, crop diversification, a selection indicator, and Year-village dummy, and a selection indicator

Robust standard errors clustered at the village level in parentheses

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

5.2.1 Rice productivity, calorie, and micronutrients intake

The effects of rice productivity on calorie and micronutrient intake are shown in Table 3. First, the estimates show that increasing rice yield has a positive and significant impact on households' calorie and micronutrient intake (column 1 of Table 3). For instance, column (3) of Table 3 shows that an increase in lowland rice yield of 1% was associated with an increase in the calorie intake per AE by 0.33%; zinc intake by 0.23%; iron intake by 0.70%, and vitamin A intake by 0.30% at the mean values in the sample. This result supports Hypothesis (1) that higher household rice yields are associated with higher calorie and micronutrient intake. However, the magnitude of the observed effects remained low for important micronutrients, such as zinc and vitamin A (column 3). For instance, Ozaki and Sakurai (2021) found in the same study site that farmers who adopted chemical fertilizers had a 30% higher rice yield than those who did not, which is interestingly close to one standard deviation of rice yield in this study. Column (3) of Table 3 shows that the increase in rice yield that follows the adoption of chemical fertilizers would be associated with an increase in zinc and Vitamin A intake of only 1.4 mg/day/AE and 48.8 µg RAE/day/AE respectively, which would still not be enough to satisfy the daily standard requirements. The magnitude of these observed effects is consistent with those reported by Dzanku (2015), suggesting that a large increase in rice productivity would be required to achieve a meaningful increase in micronutrient intake.

The results also suggest that an increased household rice yield is associated with a higher household dietary diversity score. For example, 0.66 in column (3) of Table 3 suggests that an increase in the rice yield of 10% will increase the Household Dietary Diversity Score (HDDS) by 0.06 ($0.66 \times \ln[1.1]$) food groups. A hypothetical increase in rice yield of 30% relative to the sample mean would increase the HDDS by 0.17 food groups only, which represents 3.2% increase relative to the sample mean. This low effect size is consistent with the low level of rice yield elasticities of micronutrient intake.

Our results are consistent with the findings of Darko et al. (2018), who found that an increase in maize yield of 1% was associated with an increase in calorie intake of 0.06% in Malawi. However, in our study, the yield elasticity of caloric intake was higher. One explanation is that while rice is the main source of calorie intake and cash revenue for farmers in Madagascar, this is not the case for maize in Malawi.

5.2.2 Rice productivity, rice consumption, and cash revenue

To understand the transmission channel of the observed effects, we first estimate the impact of rice yield on rice consumption. Panel A in Table 4 presents the results. An increase in lowland rice yields has a significant impact on households' rice consumption. For example, an increase in rice yield of 1% is associated with an increase in rice consumption by 0.20% at the mean values in the sample. This result supports Hypothesis (2), that increased household rice yield is associated with higher rice consumption (food consumption pathway). The results also suggest that higher rice yield is positively associated with the amount of rice produced per AE, which suggests that rice production has a direct effect on nutrition by increasing the amount of food (rice) available for the household. Moreover, raising the rice yield significantly reduces rice purchases during the lean season, a fact that is consistent with the results outlined above. For example, an increase in rice yield of 1% is associated with a decrease in rice purchase during the lean season by 0.8% at the mean values in the sample. These results support the findings of previous studies that agricultural production can influence farmers' dietary outcomes directly through an increase in home-produced food consumption (Headey et al., 2012; Kadiyala et al., 2014).

Next, we examined the relationship between rice yield, rice commercialization, and the cash revenue from rice production (Panel B of Table 4). As expected, higher lowland rice yield was significantly associated with higher cash revenue per AE. An increase in the lowland rice yield of 1% was associated with an increase in the household cash revenue per AE by 0.41% at the mean values in the sample. For instance, a hypothetical increase in the rice yield by 30% relative to the sample mean–would be translated into additional cash revenue of 5,062 MGA per AE (US$ 1.32), which represents a 11.36% increase relative to the sample mean. This finding supports hypothesis (3) that higher yields are associated with higher cash revenue. Moreover, in line with the above finding, Panel B of Table 4 shows that a higher lowland rice yield was significantly associated with farmers' decision to sell rice and the share of the production that was sold, although the magnitude of the observed impact was low. For example, a hypothetical increase in the rice yield of 30% relative to the sample mean would be associated with an increase in the share of the rice sold by two ($7.64 \times \ln[1.3]$) points. These findings are in line with those of Minten and Barrett (2008), who found that growth in agricultural productivity could increase the earnings of low-income farmers.

Furthermore, we investigate the effect of market access on rice sales. To do so, we used the household location relative to the main road, and specifically, the distance. As location is time-invariant, we used the interaction term between road distance and household rice yield. The results suggest that distance from the main road negatively affects rice commercialization at the highest level of rice yield (Table S4). This result suggests that the low commercialization that follows the yield enhancement may be explained by the higher number of transactions associated with long transportation distances.

5.2.3 Cash revenue from rice production and food expenditure

For a higher yield to translate into more purchases of highly nutritious foods, it is necessary that the increase in yield produces higher cash revenue. However, the cash revenue gain can increase economic access to food, which, in turn, may increase the consumption of calories, but not necessarily micronutrients (Remans et al., 2015). Therefore, to deepen our analysis, we estimated the effect of additional cash revenue on the expenditure of different food groups and non-food items. Table 5 presents the results.

First, as expected, higher rice yield was associated with higher food consumption. Moreover, this association was stronger when only purchased food was considered. For example, an increase in the household cash revenue from lowland production of 1% was associated with an increase in the expenditure on purchased food by 0.14% (Panel A of Table 5). This result is in line with the findings of previous studies in Tanzania, Ghana, and Malawi (Darko et al., 2018; Dzanku, 2015; Sarris et al., 2006).

Next, we examine the effect of cash revenue on the expenditure on different food groups (Panel B of Table 5). The estimates show that rice yield does not significantly affect expenditures on staple foods (e.g., rice and maize), tubers, and pulses. Interestingly, however, we observed a positive and significant effect on the purchase of micronutrient-rich foods such as vegetables, fruits, and meat/fish. For example, an increase in rice yield of 1% was associated with an increase in the households' expenditure on vegetables by 0.15%, fruits by 0.10%, and meat and fish by 0.09% at the sample mean. These findings are consistent with the results shown in Panel A of Table 5, and support Hypothesis (4), that an increase in households' rice yield is associated with more purchases of highly nutritious foods. However, as is consistent with the results in Table 3, the cash revenue elasticities of micronutrient-rich food groups were low. Moreover, our results are in line with those of previous studies which show differences in income elasticities according to food group. (Bhagowalia et al., 2012; Colen et al., 2018; Van den Broeck et al., 2021). More specifically, the demand for basic foods such as cereals, tubers, starchy root crops, and legumes and nuts are less responsive to agricultural income change, while the income elasticities for fruits, vegetables, dairy, meat, and fish seem to increase with agricultural income growth.

Furthermore, in line with the agriculture-nutrition literature, the results in Panel C of Table 5 show that the cash revenue from rice production significantly affects expenditure on non-food items that could help to improve the quality of the households' nutrition (Gillespie et al., 2019; Kadiyala et al., 2014).

Lastly, as discussed in Sect. 3, a higher rice yield could free additional land[8] to grow other crops and thus affect household dietary outcomes through pathway (3).To verify this, we estimated the effect of rice yield on other sources of income. We also estimated the impact of rice productivity on the number of crops grown by households. The results are presented in Table S5 in the supplementary material. This suggests that raising lowland rice yield is not significantly associated with income generated from the production of other crops (column (1) of Table S5). The Malagasy context is likely to be subject to various market failures (Barrett, 1997). Therefore, one would expect that additional free land resulting from the increase in rice yield may be used by farmers to diversify their diets (Kadiyala et al., 2014). However, the results show that the lowland rice yield did not affect the number of crops grown by farmers (column (2) of Table S5). Furthermore, the rice yield did not significantly affect off-farm income (Column (3) of Table S2). These findings indicate that rice yield does not affect households' nutrition through the reallocation of land to other crops. One possible explanation is that lowland plots are generally small, and rice production is far below the self-sufficient quantity at the study site.

Overall, the results of this study are consistent with those of previous studies that state that agriculture production contributes to farm household dietary outcomes directly through the increase of rice produced for consumption at home (i), and indirectly through the cash revenue generated from rice production (ii). However, this study goes further by demonstrating that cash revenue from staple crop sales can be enhanced by boosting crop yield. More specifically, the positive effects on calorie and micronutrient intake suggest that the additional cash revenue that follows the increase in rice yield improves households' economic access to food, and overall dietary quality. Households with higher rice productivity not only gain greater access to energy-dense foods (including rice itself), but also purchase foods that contribute to improved micronutrient intake, such as vegetables, fruits, meat, and fish. Furthermore, the results suggest that poor market access is associated with low crop sales and low food purchases (see Tables S3 and S4), which may explain the small size of the observed effects. These results are consistent with the conclusion of Minten and Barrett (2008) that the effect of productivity change on household welfare outcomes depends on the degree of integration of the local market into larger regional, national, and/or international markets.

[8] Alternatively, higher yield could free up labor and allow farmers to engage in non-farm and or off-farm activities, which in turn could affect households' nutrition through pathway (3).

6 Conclusion and policy implications

Nutritional deficiencies remain the main cause of many major health problems in sub-Saharan Africa. Improving agricultural productivity has a vital role to play in alleviating malnutrition among the poorest people in this part of the world. This has motivated academics, practitioners, and policy communities to attempt to improve the productivity of major staple food crops, such as rice, in this region. Although previous studies have shown that staple crops' yield response to the adoption of modern inputs, such as fertilizers and improved seed variety, has been significantly positive, how such an increase translates into greater and more diverse micronutrient intake at the household level has not been well investigated in SSA. In this study, we aimed to fill this gap by exploring the association between lowland rice yield, and energy and micronutrient intake. To achieve this, we compiled three-year panel data on smallholder farmers in the Vakinankaratra region of Madagascar. Moreover, we used a household fixed-effects model to control for unobservable time-invariant factors that may correlate with both dietary outcomes and rice yield. Additionally, we controlled for several time-variant variables, including other sources of income, household assets, and socio-demographic and year–village dummy variables.

First, the results suggest that an increase in rice yield is significantly associated with an increase in calorie and micronutrient intake. Second, as expected, the results suggest that rice production directly contributes to increasing households' rice consumption. Third, and more importantly, our regression supports a linkage between rice productivity and households' dietary outcomes through the market in the following way: (i) higher rice yield induces higher cash revenue per AE through higher commercialization of rice, and (ii) higher cash revenue from rice production is significantly associated with higher purchase of nutritious food.

This study's findings have important policy implications. First, although the effect size of rice yield on micronutrient intake is low, significantly raising the productivity of rice, which is the most important crop for farm households, would benefit nutrition policies in rural Madagascar in the short run. More generally, this study suggests that not only might better dietary outcomes be achieved through rice yield improvement in African countries, where rice is the main staple, but that this principle could also be applied in other countries, through a significant increase in the yield of their main staple food crops. However, it is important to support productivity improvement efforts through local strategies that aim to increase farm households' market access. Developing market-related infrastructure would be important to this process, as it would help facilitate farmers' commercialization of the additional product that would be generated by the increase in yield, and would further aid the purchase of nutritious foods from the market.

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Declarations

Conflict of interest No potential conflict of interest was reported by the author(s).

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References

Balasubramanian, V., Sie, M., Hijmans, R. J., & Otsuka, K. (2007). Increasing Rice Production in Sub-Saharan Africa: Challenges and Opportunities. *Advances in Agronomy, 94*(6), 55–133. https://doi.org/10.1016/S0065-2113(06)94002-4

Barrett, C. B. (1997). Liberalization and food price distributions: ARCH-M evidence from Madagascar. *Food Policy, 22*(2), 155–173. https://doi.org/10.1016/S0306-9192(96)00033-4

Bhagowalia, P., Headey, D., & Kadiyala, S. (2012). *Agriculture, Income, and Nutrition Linkages in India*. IFPRI Report. Retrieved August 11, 2021, from http://www.ifpri.org/sites/default/files/publications/ifpridp01195.pdf.

Carletto, C., Corral, P., & Guelfi, A. (2017). Agricultural commercialization and nutrition revisited: Empirical evidence from three African countries. *Food Policy, 67*, 106–118. https://doi.org/10.1016/j.foodpol.2016.09.020

Colen, L., Melo, P. C., Abdul-Salam, Y., Roberts, D., Mary, S., Gomez, Y., & Paloma, S. (2018). Income elasticities for food, calories and nutrients across Africa: A meta-analysis. *Food Policy, 77*, 116–132. https://doi.org/10.1016/j.foodpol.2018.04.002

Darko, F. A., Palacios-Lopez, A., Kilic, T., & Ricker-Gilbert, J. (2018). Micro-Level Welfare Impacts of Agricultural Productivity: Evidence from Rural Malawi. *Journal of Development Studies, 54*(5), 915–932. https://doi.org/10.1080/00220388.2018.1430771

deGraft-Johnson, M., Suzuki, A., Sakurai, T., & Otsuka, K. (2014). On the transferability of the Asian rice green revolution to rainfed areas in sub-Saharan Africa: An assessment of technology intervention in Northern Ghana. *Agricultural Economics (united Kingdom), 45*(5), 555–570. https://doi.org/10.1111/agec.12106

Devkota, S., & Upadhyay, M. (2013). Agricultural Productivity and Poverty Reduction in Nepal. *Review of Development Economics, 17*(4), 732–746. https://doi.org/10.1111/rode.12062

Dzanku, F. M. (2015). Household Welfare Effects of Agricultural Productivity: A Multidimensional Perspective from Ghana. *Journal of Development Studies, 51*(9), 1139–1154. https://doi.org/10.1080/00220388.2015.1010153

Egbetokun, O. A., Ajijola, S., Omonona, B. T., Omidele, M. A., & State, O. (2012). Farmers' Health And Technical Efficiency In Osun State, Nigeria. *International Journal of Current Research, 4*(1), 011–017.

FAO. (2018). *Food Balance Sheet*. Retrieved July 25, 2021, from http://www.fao.org/faostat/en/#data/FBS/report

FAO. (2019). *FAOSTAT: Employment Indicators*. Retrieved August 5, 2021, from http://www.fao.org/faostat/en/#data/OE

FAO, IFAD, UNICEF, WFP, & WHO. (2021). The State of Food Security and Nutrition in the World 2020. *The State of the World.* FAO, IFAD, UNICEF, WFP and WHO. https://doi.org/10.4060/ca9692en

Gillespie, S., Poole, N., van den Bold, M., Bhavani, R. V., Dangour, A. D., & Shetty, P. (2019). Leveraging agriculture for nutrition in South Asia: What do we know, and what have we learned? *Food Policy, 82*, 3–12. https://doi.org/10.1016/j.foodpol.2018.10.012

Gkiza, I. G., & Nastis, S. A. (2017). Health and women's role in agricultural production efficiency. *Applied Economic Perspectives and Policy, 39*(3), 428–440. https://doi.org/10.1093/aepp/ppw025

Gödecke, T., Stein, A. J., & Qaim, M. (2018). The global burden of chronic and hidden hunger: Trends and determinants. *Global Food Security, 17*, 21–29. https://doi.org/10.1016/j.gfs.2018.03.004

González, F., & Miguel, E. (2015). War and local collective action in sierra leone: A comment on the use of coefficient stability approaches. *Journal of Public Economics, 128*, 30–33. https://doi.org/10.1016/j.jpubeco.2015.05.004

Harvey, C. A., Rakotobe, Z. L., Rao, N. S., Dave, R., Razafimahatratra, H., Rabarijohn, R. H., Rajaofara, H., & MacKinnon, J. L. (2014). Extreme vulnerability of smallholder farmers to agricultural risks and climate change in Madagascar. *Philosophical Transactions of the Royal Society B: Biological Sciences, 369*(1639), 20130089. https://doi.org/10.1098/rstb.2013.0089

Headey, D., Chiu, A., & Kadiyala, S. (2012). Agriculture's role in the Indian enigma: Help or hindrance to the crisis of undernutrition? *Food Security, 4*(1), 87–102. https://doi.org/10.1007/s12571-011-0161-0

Headey, D., & Ecker, O. (2013). Rethinking the measurement of food security: From first principles to best practice. *Food Security, 5*(3), 327–343. https://doi.org/10.1007/s12571-013-0253-0

Headey, D., & Hoddinott, J. (2016). Agriculture, nutrition and the green revolution in Bangladesh. *Agricultural Systems, 149*, 122–131. https://doi.org/10.1016/j.agsy.2016.09.001

IFPRI (2017). 2017 Global Food Policy Report. Washington, DC: International Food Policy Research Institute. https://doi.org/10.2499/9780896292529

Kadiyala, S., Harris, J., Headey, D., Yosef, S., & Gillespie, S. (2014). Agriculture and nutrition in India: Mapping evidence to pathways. *Annals of the New York Academy of Sciences, 1331*(1), 43–56. https://doi.org/10.1111/nyas.12477

Khonje, M. G., Ricker-Gilbert, J., Muyanga, M., & Qaim, M. (2022). Farm-level production diversity and child and adolescent nutrition in rural sub-Saharan Africa: A multicountry, longitudinal study. *The Lancet Planetary Health, 6*(5), e391–e399. https://doi.org/10.1016/S2542-5196(22)00071-7

Khoury, C. K., Bjorkman, A. D., Dempewolf, H., Ramirez-Villegas, J., Guarino, L., Jarvis, A., Rieseberg, L. H., & Struik, P. C. (2014). Increasing homogeneity in global food supplies and the implications for food security. *Proceedings of the National Academy of Sciences of the United States of America, 111*(11), 4001–4006. https://doi.org/10.1073/pnas.1313490111

Kim, J., Mason, N. M., Snapp, S., & Wu, F. (2019). Does sustainable intensification of maize production enhance child nutrition? Evidence from Rural Tanzania. *Agricultural Economics (united Kingdom), 50*(6), 723–734. https://doi.org/10.1111/agec.12520

Lee, J., Koh, M., & Jeong, G. (2017). Analysis of the impact of agricultural R&D investment on food security. *Applied Economics Letters, 24*(1), 49–53. https://doi.org/10.1080/13504851.2016.1161708

Mason, N. M., Jayne, T. S., & Myers, R. J. (2015). Smallholder Supply Response to Marketing Board Activities in a Dual Channel Marketing System: The Case of Zambia. *Journal of Agricultural Economics, 66*(1), 36–65. https://doi.org/10.1111/1477-9552.12066

Minten, B., & Barrett, C. B. (2008). Agricultural Technology, Productivity, and Poverty in Madagascar. *World Development, 36*(5), 797–822. https://doi.org/10.1016/j.worlddev.2007.05.004

Minten, B., Dorosh, P., Jenn-treyer, O., Magnay, J., & Razafintsalama, Z. (2006). Rice Markets in Madagascar in Disarray : Policy Options for Increased Efficiency and Price Stabilization. *World Bank Africa Region Working Paper Series*, *101*, 73. Retrieved from July 5, 2021, from http://www-wds.worldbank.org/external/default/WDSContentServer/WDSP/IB/2007/02/21/000020953_20070221140454/Rendered/PDF/387060PAPER0MG1rkets0wp10101PUBLIC1.pdf.

Morioka, M., & Kondo, T. (2017). Agricultural Productivity Growth and Household Food Security Improvement in Nepal. *Review of Development Economics, 21*(4), e220–e240. https://doi.org/10.1111/rode.12325

Nghiem, H. S., Nguyen, H. T., Khanam, R., & Connelly, L. B. (2015). Does school type affect cognitive and non-cognitive development in children? Evidence from Australian primary schools. *Labour Economics, 33*, 55–65. https://doi.org/10.1016/j.labeco.2015.02.009

Ogubdari, K., & Awokuse, T. (2016). *Assessing the Contribution of Agricultural Productivity to Food Security levels in Sub-Saharan African countries* (p. 26). Agricultural and Applied Economics Association (AAEA) Conferences. https://doi.org/10.22004/ag.econ.235730 2016 Annual Meeting.

Ogutu, S. O., Gödecke, T., & Qaim, M. (2019). Agricultural Commercialisation and Nutrition in Smallholder Farm Households. *Journal of Agricultural Economics, 71*(2), 534–555. https://doi.org/10.1111/1477-9552.12359

Oster, E. (2019). Unobservable Selection and Coefficient Stability: Theory and Evidence. *Journal of Business and Economic Statistics, 37*(2), 187–204. https://doi.org/10.1080/07350015.2016.1227711

Otsuka, K., & Larson, D. F. (2016). In Pursuit of an African Green Revolution. In K. Otsuka & D. F. Larson (Eds.), *Springer* (2nd ed.). Springer Japan. https://doi.org/10.1007/978-4-431-55693-0

Otsuka, K., & Muraoka, R. (2017). A Green Revolution for Sub-Saharan Africa: Past Failures and Future Prospects. *Journal of African Economies, 26*(suppl_1), i73–i98. https://doi.org/10.1093/jae/ejx010

Ozaki, R., & Sakurai, T. (2020). The Adoption of Upland Rice by Lowland Rice Farmers and Its Impacts on Their Food Security and Welfare in Madagascar. *Japanese Journal of Agricultural Economics, 22*, 106–111. https://doi.org/10.18480/jjae.22.0_106

Ozaki, R., & Sakurai, T. (2021). Profitability of Chemical Fertilizer Application: Comparison of Lowland and Upland Rice Cultivation in Madagascar. *Japanese Journal of Agricultural Economics, 23*, 119–124. https://doi.org/10.18480/jjae.23.0_119

Partnership, G. R. S. (2013). *Rice Almanac* (4th ed.). Los Baños (Philippines): International Rice Research Institute.

Pingali, P. L. (2012). Green revolution: Impacts, limits, andthe path ahead. *Proceedings of the National Academy of Sciences of the United States of America, 109*(31), 12302–12308. https://doi.org/10.1073/pnas.0912953109

Pinstrup-Andersen, P. (2007). Agricultural research and policy for better health and nutrition in developing countries: A food systems approach. *Agricultural Economics, 37*(S1), 187–198. https://doi.org/10.1111/j.1574-0862.2007.00244.x

Raboin, L.-M., Randriambololona, T., Radanielina, T., Ramanantsoanirina, A., Ahmadi, N., & Dusserre, J. (2014). Upland rice varieties for smallholder farming in the cold conditions in Madagascar's tropical highlands. *Field Crops Research, 169*, 11–20. https://doi.org/10.1016/j.fcr.2014.09.006

Remans, R., DeClerck, F. A. J., Kennedy, G., & Fanzo, J. (2015). Expanding the view on the production and dietary diversity link: Scale, function, and change over time. *Proceedings of the National Academy of Sciences of the United States of America, 112*(45), E6082. https://doi.org/10.1073/pnas.1518531112

Ruel, M. T., Quisumbing, A. R., & Balagamwala, M. (2018). Nutrition-sensitive agriculture: What have we learned so far? *Global Food Security, 17*(January), 128–153. https://doi.org/10.1016/j.gfs.2018.01.002

Sarris, A., Savastano, S., & Christiaensen, L. (2006). *Agriculture and poverty in commodity dependent African countries* (pp. 1–85). FAO. Working Paper. Retrieved July 11, 2021, from https://art.torvergata.it/bitstream/2108/48867/1/Sarris_Savastano_Christiaensen_FAO%20Technical%20Paper%209.pdf.

Schneider, K., & Gugerty, P. M. K. (2011). Agricultural Productivity and Poverty Reduction: Linkages and Pathways. *Evans School Review, 1*(1), 1–27. https://doi.org/10.7152/esr.v1i1.12249

Shankar, B., Poole, N., & Bird, F. A. (2019). Agricultural inputs and nutrition in South Asia. *Food Policy, 82*, 28–38. https://doi.org/10.1016/j.foodpol.2018.10.011

Sibhatu, K. T., Krishna, V. V., & Qaim, M. (2015). Production diversity and dietary diversity in smallholder farm households. *Proceedings of the National Academy of Sciences of the United States of America, 112*(34), 10657–10662. https://doi.org/10.1073/pnas.1510982112

Slavchevska, V. (2015). Agricultural Production and the Nutritional Status of Family Members in Tanzania. *Journal of Development Studies, 51*(8), 1016–1033. https://doi.org/10.1080/00220388.2015.1018906

Van den Broeck, G., Mardulier, M., & Maertens, M. (2021). All that is gold does not glitter: Income and nutrition in Tanzania. *Food Policy, 99*, 101975. https://doi.org/10.1016/j.foodpol.2020.101975

Villacis, A. H., Mayorga, J., & Mishra, A. K. (2022). Experience-based food insecurity and agricultural productivity in Nigeria. *Food Policy*. https://doi.org/10.1016/j.foodpol.2022.102286 in Press.

von Braun, J. (1995). Agricultural commercialization: Impacts on income and nutrition and implications for policy. *Food Policy, 20*(3), 187–202. https://doi.org/10.1016/0306-9192(95)00013-5

Weisell, R., & Dop, M. C. (2012). The adult male equivalent concept and its application to Household Consumption and Expenditures Surveys (HCES). *Food and Nutrition Bulletin, 33*(3 Suppl), 157–162. https://doi.org/10.1177/15648265120333s203

WFP. (2019). La filière riz à Madagascar face à la fortification. Rome, Italy: World Food Program.

WHO. (2005). *Human Vitamin and Mineral Requirements*. 2nd ed. World Health Organization. Retrieved August 5, 2021, from http://apps.who.int/iris/handle/10665/42716.

Wooldridge, J. M. (2010). *Econometric Analysis of Cross Section and Panel Data*. The MIT Press Cambridge, Massachusetts. https://doi.org/10.2307/j.ctv5rdzwc.1

World Bank. (2016). Madagascar Economic Update. The world Bank. https://doi.org/10.1596/27824

World Bank. (2019). *World Bank. World Development Indicators*. Retrieved August 11, 2021, from https://data.worldbank.org/indicator/AG.CON.FERT.ZS?view=chart&locations=MG.

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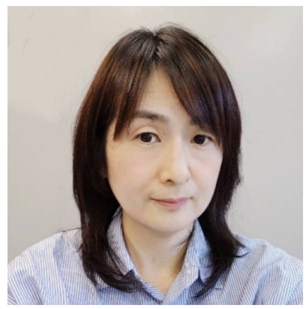

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