Human Ecology
https://doi.org/10.1007/s10745-022-00336-2

Constraints on Rice Cultivation in Eastern Madagascar: Which Factors Matter to Smallholders, and Which Influence Food Security?

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Accepted: 6 May 2022

Abstract

In the eastern rainforests of Madagascar, rainfed swidden rice cultivation remains prevalent despite efforts to encourage uptake of irrigated systems to reduce deforestation. We used agricultural surveys with a stratified sample of 171 households to investigate constraints on and productivity of irrigated and rainfed rice perceived by farmers, and actual rice yields. Irrigated rice plots had higher median yields (1.72 t/ha compared to 0.62 t/ha), but farmers perceived the type of rice cultivation they practised themselves as more productive, possibly reflecting differences in the land suitability, farmers experience, and other constraints. While some factors, such as pests and water, were mentioned to limit yields, access to fertiliser was not frequently mentioned by smallholders. Higher food security was related to irrigated rice farming, higher rice yields, and owning more livestock. Conservation initiatives need to target households with and without access to irrigable land to improve food security and reduce deforestation, as exclusively promoting a cessation of swidden agriculture is neglecting its cultural value and the scarcity of irrigable land in the region.

Keywords Corridor Ankeniheny-Zahamena · Deforestation · Eastern Madagascar · Irrigated rice · Sustainable development · Swidden agriculture

Introduction

The majority of the world's farms (84%) are typically classified as smallholder farms, occupying less than 2 ha (Lowder et al., 2016; Thapa, 2009). Despite being important contributors to global food production, smallholders are estimated to make up half of the hungry worldwide and three quarters of the hungry in Africa (Ricciardi et al., 2018; Sanchez & Swaminathan, 2005). Climate change will likely exacerbate food insecurity among smallholders due to their reliance on rainfed agriculture and limited financial resources for adaptation measures (Morton, 2007; Stocker et al., 2019).

Madagascar is among the countries with the lowest food security worldwide and was ranked 108 of 113 countries in the 2019 Global Food Security Index (The Economist Intelligence Unit, 2019). Poverty is often considered a major cause of food insecurity (Mathys & Maalouf-Manasseh, 2013) and about 78.8% of the Malagasy population lived below the poverty line of $1.90 per day in 2012 (World Bank, 2021). Coincidentally, the island is a global biodiversity hotspot with a high rate of endemism among several species groups with, for example, the iconic lemurs being one of the main tourist attractions to the island and tourism accounting for 6% of the country's GDP (Myers et al., 2000; World Travel & Tourism Council, 2018; Wright et al., 2014). However, Madagascar is also one of the hotspots with highest deforestation rates:

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Published online: 27 June 2022

the island has lost around 44% of its forest cover in the last 60 years and many endemic species are forest dependent (Goodman & Benstead, 2003; Myers et al., 2000; Vieilledent et al., 2018). The International Union for Conservation of Nature's (IUCN) Red List considers about 98% of all lemur species as threatened, and about 30% as critically endangered, due to habitat loss and hunting (IUCN, 2021; Schwitzer et al., 2014). Delineating protected areas has been one of the government's main strategies to halt deforestation and to protect flora and fauna (Rakotomanana et al., 2013; Virah-Sawmy et al., 2014). However, it also forecloses access to land and natural resources for local people and has the potential to aggravate poverty and food insecurity (Adams et al., 2004; Fisher & Christopher, 2007; Golden et al., 2011). Even though initiatives such as Reducing Emissions from Deforestation and Forest Degradation (REDD+) have been implemented in the country to generate revenue and to compensate people affected by conservation restrictions, these schemes have not succeeded in eastern Madagascar (Poudyal et al., 2018).

Agriculture, mainly subsistence farming, is the main occupation for around 80% of the Malagasy population (Sharma et al., 2018) and swidden agriculture, locally known as *tavy,* is the traditional and dominant land use in eastern Madagascar for producing rainfed rice. To this end, forests or fallows are cut and the vegetation is dried and then burned prior to land cultivation (Styger et al., 2009). The clearance of old-growth forest through *tavy* is specifically known as *teviala.* For farmers, fires are an efficient and inexpensive tool for land management and *teviala*, and being the first person clearing and working the land or forest has been the traditional way to gain its ownership (Kull, 2004; Laney, 2002; Widman, 2014). A land tenure reform in 2005 and 2006 facilitated registering land ownership and recognising traditional land rights (Burnod et al., 2014). However, access to formal land titling remains financially or logistically inaccessible for many smallholders due to low coverage of offices issuing certificates and because forest land is excluded from the law changes and remains state land (Burnod et al., 2014; Crowl, 2014; McConnell, 2002; Rajaonarivelo et al., 2021). Generally, land tenure insecurity may hold back smallholders to invest in more labour intensive crops and production on untitled land (Bilsborrow, 2002; Crowl, 2014; Kramer et al., 2009; McConnell, 2002).

At low population densities and low land use pressure, *tavy* can be sustainable (Scales, 2014), but fallow periods in eastern Madagascar have shortened significantly over the last three decades, leading to a cycle of accelerating land degradation and the need for new, fertile *tavy* plots (Styger et al., 2007). Besides *tavy*, deforestation in eastern Madagascar is also driven by illegal logging and artisanal mining, with the latter a growing threat to forests (Brown, 1998; Cabeza et al., 2019; Jones et al., 2018; Portela et al., 2012; Randriamalala & Liu, 2010; Styger et al., 2007). The use of *tavy* is banned by law, and the issuance of authorizations for clearing forest land for cultivation was stopped by the Forest Service around 1990 (Kull, 2002; Kull & Laris, 2009). However, because of weak law enforcement and the reliance of smallholders on this land management tool, *tavy* persists in the study region and throughout Madagascar (Kull & Laris, 2009; Styger et al., 2007).

It is important to note that historically, deforestation in Madagascar cannot only be attributed to swidden agriculture and population growth (Jarosz, 1993; Kull, 2000; Scales, 2014). Other factors, such as the introduction of cash crops like coffee, cloves and vanilla during the French colonial period (1896–1960), and the exploitation of forests for timber and precious woods to increase the colony's revenue, have driven deforestation before but are overlooked in today's discussion of forest conservation in Madagascar (Jarosz, 1993; McConnell, 2002; Raik, 2009; Randrup, 2010). Supporting this, Sussmann and Green estimated that in 1950, at a time with lower population densities (about 1/5 of today's population) and sufficiently long fallow periods, about 1/3 of the original forest cover in eastern Madagascar was already lost (Green & Sussman, 1990; Jarosz, 1993; Styger et al., 2007).

The cessation of swidden agriculture has been repeatedly presented as the solution to deforestation in Madagascar while overlooking the actual needs and farming conditions of many smallholders (Hume, 2006; Jarosz, 1993; Laney & Turner, 2015; Scales, 2014). In our research we put smallholders' needs at the centre and contribute to a deeper understanding on how smallholders understand, perceive and manage currently low-yielding rice cultivation systems, including swidden agriculture. We highlight what currently limits rice farming based on smallholders' perceptions and discuss how food security can be improved. This knowledge is crucial for developing more targeted conservation schemes, enhancing food security and other socioeconomic benefits among smallholders while effectively reducing deforestation.

In this paper, we specifically focus on constraints on rice cultivation systems and their relation to smallholder food security around the Corridor Ankeniheny-Zahamena (CAZ) in eastern Madagascar. Our aims are: (1) to identify constraints on smallholders farming and expanding rainfed and irrigated rice, (2) to assess agricultural productivity of both rice cultivation systems, (3) to evaluate which factors limit rice yields according to the perception of smallholders and how productivity is perceived by smallholders. Furthermore, we are interested in (4) the factors associated with smallholder food security and discuss implications of our results for conservation schemes.

We expect land and labour availability to determine how much land the smallholder family cultivates, as new agricultural land is becoming more scarce is eastern

Madagascar and smallholders rely primarily on their family workforce (Okoye et al., 2016). We assume irrigated rice farming to be more productive as reported yields have consistently been higher for irrigated rice than for rainfed rice. As nutrient depletion of soils significantly reduces rice yields in Madagascar (Andriamananjara et al., 2016, 2018; Rabeharisoa et al., 2012), we expect farmers to name soil fertility and fertiliser among the most influential factors regarding their rice production. Based on reviewing previous literature on smallholder food security and as smallholders rely on their own production for subsistence, we assume that in our study, the rice yield, the livestock owned, the number of crops farmed, farming cash-crops such as coffee and the available labour within a household may affect the household's food security (Mathys & Maalouf-Manasseh, 2013; Minten & Barrett, 2005; Noromiarilanto et al., 2016; Poudyal et al., 2016). Furthermore, we also anticipate that having off-farm income, the household head's gender and education, as well as being member in an association and having received (agricultural) training might improve food security (Mathys & Maalouf-Manasseh, 2013; Minten & Barrett, 2005; Noromiarilanto et al., 2016). Finally, we also hypothesize that a larger proportion of working age people within a household may increase the household workforce for subsistence farming and thus agricultural output, while women's control over income may be beneficial (Mathys & Maalouf-Manasseh, 2013).

Background: Rice Cultivation Systems and Technical Innovation in Madagascar

Rice is the most important staple in Madagascar and can make up 60% of the daily diet (Golden et al., 2019). Rice is cultivated either on rainfed or on irrigated plots. On steep land, farmers use swidden agriculture for cultivating rainfed rice (Malagasy: *tavy*): one cultivation period (one rainy season) is followed by a fallow period of several years to restore soil fertility prior to the next cultivation period (Brown, 1998; Styger et al., 2009). The vegetation on the plot (initially forest and in later cycles the regrowing fallow vegetation) is cut, dried and burned with the ash functioning as fertiliser, and the fire facilitating land preparation and clearing weeds before planting at the onset of the rainy season (Kull, 2004; Scales, 2014; Styger et al., 2009). After land preparation, farmers dig holes at regular spacing across the plot and sow a few rice grains directly in the hole covering them with soil afterwards (Andriamananjara et al., 2018; Jarosz, 1993). Overall, this cultivation system does not require levelling of plots but depends on steady rainfalls during the rainy season as these fields do not have a system regulating water supply (Brown, 1998; Desbureaux & Damania, 2018; Harvey et al., 2014). Smallholders in eastern Madagascar witnessed more variable rainfall patterns and seasons as well as stronger cyclones in the last 10 years (Harvey et al., 2014). Less predictable rainfall may more severely affect farmers only practising rainfed agriculture as there is no irrigation system to buffer droughts. Weed infestation is a regular problem for farmers in rainfed rice, as in the latter system there is no constant water level suppressing the emergence of weeds (Ranaivoson et al., 2018).

Along rivers, in river valleys or on levelled terraces on slopes, farmers plant irrigated rice (paddy rice). It is typically farmed without long fallow periods and with one to two cultivation cycles per year, using a system of, inter alia, channels, dams and bunds to achieve a constant water level avoiding flooding or drying up fields (FAO, 1977; Zaehringer et al., 2016). As technical progress among smallholders is low, terraces and channels are created and maintained by hand (Minten & Barrett, 2005). Irrigation is gravity fed and the channel walls (levee) made of soil are vulnerable to flooding (Portela et al., 2012). Furthermore, due to the hilly topography and erosion occurring on bare slopes, irrigation systems are prone to siltation and often require maintenance at the beginning of each planting season (Portela et al., 2012). The investment and maintenance costs for irrigation infrastructure as well as the scarcity of irrigable land limit irrigated rice cultivation in the studied region in Madagascar (Whitman et al., 2020).

For farming irrigated rice, seeds are not sown directly in the field but in small, separated areas (nursery) and are transplanted after 20–30 days into the prepared field with equal spacing (10×10 to 20×20 cm) and with 3 to 4 seedlings per bunch (Stoop et al., 2002). Land preparation includes ploughing done with a spade (Malagasy: *angady*) or with the use of zebu (Brimont et al., 2015; Rakotondralambo & Ravelombonji, 2010; Zaehringer et al., 2017). Despite a constant water level suppressing emergence of weeds to some extent, farmers need to control weed infestation to avoid harvest losses also in irrigated rice: as chemical weed control is nearly absent among smallholders in Madagascar, weeding is typically done by hand with help of a spade or, more rarely, by using a mechanical rotating weeding tool (Ranaivoson et al., 2018; Rodenburg et al., 2019; Whitman et al., 2020).

Productivity and technical innovation in Madagascar are low (Sharma et al., 2018) and rainfed rice plots in the east of the country are left fallow for about five years, which is too short to sustain soil fertility (Styger et al., 2007; Zaehringer et al., 2017). Depending on cultivation cycle and plot age, rainfed rice yields vary considerably between 0.8–2.5 t/ha (Stoop et al., 2002; Styger et al., 2007) and irrigated rice yields about 2.1–2.9 t/ha (Barison & Uphoff, 2011; Uphoff & Randriamiharisoa, 2002). Irrigated rice yields in Asia and Africa were similar in the 1960s but increased in Asia to today's average of 4.8 t/ha (irrigated rice) (FAOSTAT, 2020) after a multiplication of fertiliser input and with the introduction of modern high-yielding varieties (*"The Green Revolution"*, Fig. S1, Supplementary Information) (Estudillo & Otsuka, 2013). However, in Madagascar, most smallholders cannot afford inorganic fertiliser (Ramilison, 2004). During the last decade, Madagascar was not self-sufficient in rice production (domestic production about 90% of rice consumption) and imported between 110 and 620 Gt rice per year (USDA, 2020). Low productivity, lack of economic alternatives and population growth fosters agricultural expansion at the expense of forests (Styger et al., 2007). As Madagascar's population of around 26 million people is expected to double by 2050 (UN DESA, 2019) and swidden agriculture is expected to persist (Heinimann et al., 2017), the safeguarding of remaining forests will largely depend on increasing rice yields per area and improving food security of smallholders (Brooks et al., 2009; Hewson et al., 2019).

Methods

Study Area and Villages

We conducted our study around the Corridor Ankeniheny-Zahamena (CAZ) in eastern Madagascar (Fig. 1). The

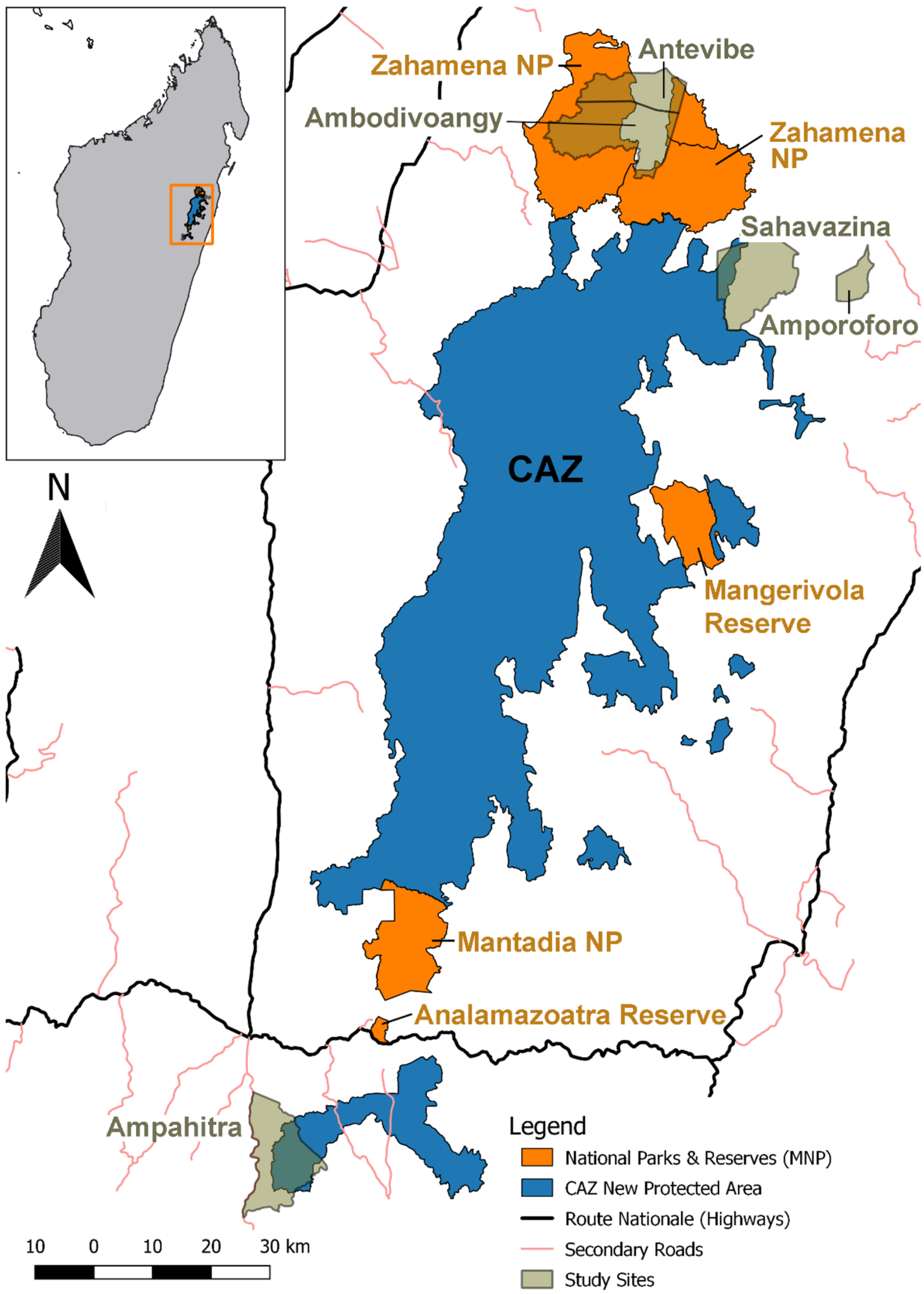


Fig. 1 Study area and location of the five fokontany (smallest administrative unit in Madagascar, comprising one or several villages) around the Corridor Ankeniheny-Zahamena (CAZ) in eastern Madagascar

CAZ protected area was established in 2006 and formally gazetted in 2015 with the support of the World Bank as a REDD + (Reduction of Carbon Emissions from Deforestation and Forest Degradation) pilot project. Conservation International oversees the protected area on behalf of the Malagasy government (Jones et al., 2018). It is part of the Durban Vision put forward in 2003 by the former Malagasy president Marc Ravalomanana to triple the country's protected area coverage (Virah-Sawmy et al., 2014).

The study area is characterised by a diverse land use mosaic of agriculture, fallows, forest fragments, settlements as well as community-managed zones and government-managed protected areas (Portela et al., 2012) (Fig. 2). The corridor itself covers 381,000 ha of humid rainforest, littoral forest, wetlands and rivers and connects existing protected areas, such as the Zahamena and Mantadia National Parks and the Mangerivola and Analamazoatra Special Reserves (Portela et al., 2012). The climate is subtropical and moist with annual rainfall ranging from 2,500–4,000 mm/yr (USAID, 2007) and the topography is hilly including steep slopes and narrow valleys (Portela et al., 2012; Whitman et al., 2020). Elevation above sea level decreases from 1,300 m in the west to about 200 m at the eastern boundary of the CAZ, and land at lower elevation is more easily accessible facilitating cultivation (Tabor et al., 2017). The CAZ contains one of the largest rainforest remnants in eastern Madagascar and is home to great biodiversity: many endemic species found in the area, such as the Indri *(Indri indri),* Black-and-white Ruffed Lemur *(Varecia variegata)* and the Diademed Sifaka *(Propithecus diadema),* are listed as critically endangered by the IUCN (IUCN, 2021; King et al., 2013).

Forests in CAZ are under pressure from swidden agriculture (*tavy*), charcoal production, mining, and illegal logging (Portela et al., 2012; Ratsimbazafy et al., 2011). Fallow periods of tavy fields in eastern Madagascar shortened significantly over the last 3 decades from 8–15 years to 3–5 years leading to accelerating land degradation and the clearance of forests for new, fertile plots (Styger et al., 2007). Mining became an increasing pressure on protected areas in Madagascar in the last decade (Cabeza et al., 2019; Gerety, 2019; Ratsimbazafy et al., 2011). Artisanal mining includes gold and sapphires: miners cut forests, particularly along rivers, to then dig up the soil to access layers where they expect gold and sapphires and wash the soil in close by rivers (Cabeza et al., 2019; Gerety, 2019; Perkins, 2016). Rubies and sapphires were found repeatedly in eastern Madagascar and the discovery of blue sapphires close to the fokontany Didy and Ambodivoangy in the CAZ drew ten thousands of miners into the protected area in 2012 and in 2015 (Ohanesian & Tullis, 2019; Pardieu et al., 2017; Perkins, 2016). Mining continued in the CAZ after the last sapphire rush attracting particularly people who are otherwise jobless (Conservation International Africa Field Division, 2020; Pardieu et al., 2017).

Besides the extraction of precious metal and stones, the CAZ suffers from illegal logging of precious wood, such as ebony (Genus *Diospyros*), rosewood and palisander (Genus *Dalbergia*), which are popular in Asian countries and used, for example, for luxury furniture and music instruments (Innes, 2010; Ratsimbazafy et al., 2016). As logs are heavy, additional trees are cut to build rafts for transporting the precious logs leading to further forest destruction (Randriamalala & Liu, 2010). After a spike in logging of precious wood in 2009, Madagascar banned cutting and export of rosewood and ebony. Since 2013, all *Dalbergia* and *Diospyros* species are listed in Appendix II of CITES allowing export only with a permit and

Fig. 2 Shifting cultivation practised by smallholders around the Corridor Ankeniheny-Zahamena (CAZ) in eastern Madagascar to cultivate slopes. Fallow vegetation is burned prior to the next cultivation cycle and the ash serves as fertiliser. The photograph also shows that plots in valleys are used for irrigated rice farming: farmers level plots and install terraces, irrigation and drainage channels and bunds to keep a constant water level in the plots

a scientific authority verifying extraction not being detrimental to the species population (Randriamalala & Liu, 2010; Ratsimbazafy et al., 2016). However, extraction of precious wood in the CAZ continues with most logs being transported to Antananarivo and Toamasina and shipments including illegal ebony and rosewood from Madagascar have been confiscated around the world including after the CITES Appendix II listing (Ratsimbazafy et al., 2016; Wilmé et al., 2020).

About 350,000 people live in and around the CAZ relying on subsistence farming (rice, manioc, banana), cash crop production (coffee, lychee), small livestock (poultry) as well as on forest resources for their livelihoods (Harvey et al., 2014; Portela et al., 2012; Poudyal et al., 2016). Most households live below the national poverty line, experience seasonal food insecurity, and lack access to, for example, electricity, clean water, and basic healthcare (Dostie et al., 2002; Poudyal et al., 2018). Furthermore, within the last 10 years, extreme weather events in eastern Madagascar including droughts, floods and cyclones increased and one out of two farmers witnessed harvest losses aggravating food insecurity (Harvey et al., 2014). Several local community associations, known as Communauté de Base (COBA) or Vondron'Olona Ifotony (VOI), were created to sustainably manage buffer zones of the CAZ through a contract with the Malagasy Ministry for the Environment and Sustainable Development (Brimont & Karsenty, 2015; King et al., 2013). However, the delineation of the CAZ still comes at a cost for the local communities (comparable to 27–84% of annual income) and, despite the intention of REDD+to compensate affected households, funding did not reach all and did not compensate costs fully (Poudyal et al., 2018; Poudyal et al., 2016).

We selected five *fokontany* (smallest administrative unit comprising one or several villages) in the region around the CAZ following reconnaissance visits and pilot surveys. The fokontany were selected to be similar in terms of access and differ in their relation to conservation and the forest (Jones et al., 2018; Poudyal et al., 2018): Ambodivoangy and Antevibe border the long-established Zahamena National Park (founded in 1997, with conservation history dating to 1927) and thus have long conservation experience (LC) and forest use restrictions. MNP (Madagascar National Parks; governmental organisation) manages all National Parks in Madagascar and a share of the entrance fees are used to support park bordering communities through development interventions. Ampahitra and Sahavazina border the recently established CAZ protected area and thus have only short conservation experience (SC) so far. Several households in Ampahitra received compensation through REDD+after delineation of the CAZ, while in Sahavazina no household received compensation (Poudyal et al., 2018). Amporoforo is situated around 20 km from the forest frontier with no conservation experience (NC) as the forests around the fokontany were lost before the 1950s (Harper et al., 2007).

Data Collection

Data collection for this study took place in two steps: First, a household survey on socio-economic characteristics of 499 households across the five fokontany was conducted between July 2014 and March 2015. Second, a stratified random sub-sample of 171 households were interviewed for a detailed agricultural survey between August 2014 and June 2015. Only the households who had agreed to be part of the second round of surveys (over 90% in all sites) were included in drawing the sub-sample. The stratification was based on household size, and size and age of the plots used by the households. Interviews were carried out by native Malagasy speakers familiar with the dialect of the region, primarily RM, NSA, and AR within the research team. We held interviews with household heads and targeted other adult household members in case the household head was not available. For this paper, we used data from both surveys for the selected 171 households.

Household Socio-economic Survey

The household socio-economic survey included all variables listed in Table 1 and assessed the building material of houses as an estimate of the households' living conditions. We established if the household head was born in the fokontany of residency ("non-migrant") or not ("migrant") following the definition of Jones et al. (2018). Households reported their food security defined as the number of months the household had sufficient food for two meals per day within the last farming year. Numbers of each type of livestock owned were used to calculate the tropical livestock units per household (Chilonda & Otte, 2006). To obtain an estimate of the workforce available in each household, we divided the number of resident individuals aged between 15 and 64 years (working age) by the total number of residents.

Agricultural Survey

The agricultural survey comprised all variables listed in Table 2, such as the landholdings and harvest for 2013/2014 agricultural year. We distinguished landholdings and their reported use into rainfed rice (Malagasy: *tavy*), irrigated rice (Malagasy: *tanimbary*), home gardens (Malagasy: *tanimboly*), fallow (Malagasy: *savoka*) and other. A detailed description of the rainfed and irrigated rice cultivation systems and their differences are given in the introduction. Based on reported rice yields, measured plot size and reported labour input, we calculated the agricultural productivity per area and unit labour for all rice farming plots

Table 1 Socio-economic variables of household survey

Variables	Description	Summary statistics
Gender	Gender of household head	Female = 13% Male = 87%
Household age [years]	The years household has been established as an independent unit	Min = 1 Median = 10 Max = 60
Ethnic	Ethnic group of household head	Betsimisaraka = 91.2% Bezanozano = 5.3% Other = 3.5%
Marital status	Marital status of household head	Married = 86.0% Widow/widower = 4.7% Divorced = 8.2% Never married = 0.6% Other = 0.6%
Household members total	Number of individuals resident in household	Min = 1 Median = 5 Max = 12
Household workforce	Ratio of household members of working age (15–64 years) / household members total	Min = 0 Median = 0.4 Max = 1
Migrant	If household head was born in fokontany of residency	Migrant = 32.8% No migrant = 67.3%
Education [years]	Years of school attendance of household head	Min = 0 Median = 2 Max = 13
Occupation	Main occupation of the household head	Agriculture = 93.6% Governmental job = 0.6% Private job = 0.6% Daily wage = 4.1% Business/trade = 0.6% Other = 0.6%
Food security [months]	The number of months a household has sufficient food for two good meals per day during the 2013/2014 agricultural year	Min = 1 Median = 7 Max = 12
Staple foods bought [%]	The share of the staple foods bought on the market for household consumption	Median August-November = 25% Median December-March = 60% Median April-July = 0%
Tropical livestock unit	Total livestock ownership of household measured as "Tropical Livestock Unit"	Min = 0 Median = 0.05 Max = 14.2
Off-farm income [Ariary]	Total off-farm income of household (farming year 2013/2014)	Min = 0 Median = 120,000 Max = 309,600
Training	If household has participated in any training in the last three years	Yes = 17.5% No = 82.5%
Membership	If household is member in an association (COBA, farmer's association, women's association, youth association, religious association)	Yes = 30.4% No = 69.6%
Roof	Construction material for the roof of the household's main dwelling	Thatch = 87.1% Tin = 12.9%
Walls	Construction material for the walls of the household's main dwelling	Ravinala = 5.3% *(Commonly occurring palm-like plant species used for construction and water provision)* Pandanus = 8.2% Bamboo = 58.5% Other = 27.7% *(i.e. mud, wood, mud-wood)*
Rooms	Number of rooms in the household's main dwelling	1 room = 66.9% 2 rooms = 29.0% > 3 rooms = 4.1%

owned by the households within the agricultural survey (Table 2). We asked respondents for factors limiting their area of rainfed and irrigated rice cultivation as well as factors limiting productivity of the two systems. Respondents could give more than one answer per question and were requested to name the most important limiting factor for each question. To facilitate analysis, we categorised answers given during the interview. Furthermore, we asked respondents which type of rice farming they consider to be more productive per unit of area and effort needed in an agricultural season. Households also reported the proportion of staple foods purchased in different seasons during the year (winter season from August to November, rainy season from December to March, spring season from April to July).

Data Analysis

We conducted all data analysis in R version 3.5.0 (R Core Team, 2018). For continuous variables of the household socio-economic and the agricultural survey, we report the median as it is less influenced by extreme values and provide frequency distribution plots in Figs. S2 and S3 in the Supplementary Information. For factors limiting area and productivity of rainfed and irrigated rice, we considered them as important if more than 1/3 of respondents named them as most important in the agricultural survey.

We used a generalised linear model (GLM) with Poisson distribution to determine variables associated with food security of households, adapting the approach of Noromiarilanto et al., 2016 analysing food security and associated factors among smallholders in south-western Madagascar. We used the Poisson distribution because the food security (dependent variable) was defined as the number of months the household had sufficient food during the last agricultural year and thus consisted only of positive integers (count data). For the comparison of research results, we used a GLM including a similar set of explanatory variables which have been reported to influence food security in Noromiarilanto et al., 2016 and other studies, such as total rice yield, tropical livestock unit, number of crops farmed, off-farm income and education of the household head (Mathys & Maalouf-Manasseh, 2013; Minten & Barrett, 2005; Noromiarilanto et al., 2016). Furthermore, we included the household workforce (household members of working age/household members total), the gender of the household head, the rice farming practice (rainfed and/or irrigated), farming cash crops (coffee, cocoa, vanilla), having received training and being member in any association as explanatory variables. We selected these variables based on reviewing previous literature on food security: we hypothesised that a lower household workforce (more young and elderly household members) may decrease the food security while, for example, women's control over income may be beneficial (Mathys & Maalouf-Manasseh, 2013). We further hypothesise that access to irrigated rice and cash cropping may positively affect food security (Minten & Barrett, 2005; Poudyal et al., 2016). Data of several explanatory variables was missing for 11 households; hence, these observations were discarded, and we fitted the GLM using data of 160 households.

To assess model fit, we used the deviance of the fitted model with respect to a null model (intercept only; considered as worst model) to ensure the fitted model is significantly different and thus better than a null model. We used the deviance of the fitted model with respect to a saturated model (perfect fit; including as many explanatory variables as observations but thus of no statistical use) to ensure that the fitted model fits the data equally as well as a saturated model but with fewer explanatory variables. We used the DHARMa package (Hartig, 2020) for residual diagnostics of the fitted model to ensure that no underlying statistical assumptions are violated and that model results are trustworthy: we checked that the data are not over- or under-dispersed, for linearity and for homogeneity of variance (Fig. S5). Furthermore, we used the Cook's distance to identify influential observations (outliers) within our dataset (Fig. S6). We created effect plots (Fig. S7) for all explanatory variables in the fitted model using the effects package (Fox, 2003). The plots facilitate interpretation showing how strong and in which direction the explanatory variable influences the food security (dependent variable).

Results

Household Characteristics

An overview of socio-economic characteristics of households is given in Table 1. Around 87% of households were male headed and 13% were female headed. About 91% of respondents were of Betsimisaraka ethnicity. The main occupation of respondents was agriculture (94%). Education of household heads was low (median = 2 years). The median household size was five people and the majority of households were typically comprising the nuclear family of the household head, the spouse and their children. However, 28% of households also included more family members (often grandchildren, son or daughter in law, step or foster children) and only in rare cases the parents of the household head, parents in law, siblings or siblings in law were living in the same household (< 6%). Median household's livestock ownership was 0.05 tropical livestock units (equivalent to 5 chickens), 87.1% of households owned at least one chicken while only 21.1% of households owned any cattle. One third of household heads were not born in the fokontany they live in and we did not see a difference in male and female household heads to be a migrant (32% of male household heads; 36% of

Table 2 Variables included in the agricultural survey

	Variable	Description	Summary statistics
Household-level	Total area owned [ha]	Total area owned by household	Min = 0.07 Median = 2.02 Max = 23.87
	Total area farmed [ha]	Area farmed by household in 2013/2014	Min = 0.07 Median = 1.28 Max = 6.61
	Total rice yield [kg]	Total rice yield household received from their agricultural land in 2013/2014	Min = 0 Median = 688 Max = 4,400
	Rice farming practice	Rice farming systems used by household in 2013/2014	Only rainfed = 44.4% Rainfed and irrigated = 48.5% Only irrigated = 5.9% No rice farmed = 1.2%
	Total labour [days]	Total labour input on agricultural land of household in 2013/2014	Min = 8 Median = 178.2 Max = 745.5
	External labour	If household hired external labour on their agricultural land in 2013/2014	Yes = 93.0% No = 7.0%
	Share of rice yield sold [%]	The amount of the 2013/2014 rice yield sold by household	Min = 0 Median = 11.2 Max = 89.7
	Crop diversity	Number of different crops and vegetables farmed by household in 2013/2014	Min = 1 Median = 5 Max = 10
	Cash crops	If household farmed cash crops (coffee, cocoa, vanilla)	Yes = 35.7% No = 64.3%
Plot-level (all plots)	Plot type	Type of the farm plot	Rainfed rice = 23.3% Irrigated rice = 17.5% Tanimboly *(home garden)* = 40.8% Savoka *(fallow)* = 18.2% Other = 0.3%
	Plot area [ha]	Plot area measured or estimated	Min = 0.0015 Median = 0.19 Max = 11.14
	Plot age [years]	Age of the plot in years since the first forest clearance	Min = 1 Median = 40 Max = 100
	Plot ownership	How the household gained ownership of the agricultural plot	Inherited = 50.6% Rented = 3.3% Bought = 10.0% Borrowed = 9.6% Cleared by household = 24.6% Other = 1.9%
	Plot farmed	If the plot has been cultivated in the 2013/2014 agricultural year	Yes = 78.8% No = 21.2%

Table 2 (continued)

	Variable	Description	Summary statistics	
Plot-level (only rice plots)	Last fallow length of rainfed rice plots [years]	Length of the last fallow period of the plot *(Only rainfed rice plots)*	Min = 0 Median = 5 Max = 22	
	Rice yield per unit area [t /ha]	Calculated by dividing the reported rice yield by the measured field size	**Rainfed rice:** Min = 0 Median = 0.62 Max = 23.1	**Irrigated rice**: Min = 0 Median = 1.72 Max = 29.4
	Rice yield per unit labour [t / day]	Calculated by dividing the reported rice yield by the reported labour input	**Rainfed rice:** Min = 0 Median = 0.003 Max = 0.03	**Irrigated rice:** Min = 0 Median = 0.005 Max = 0.03
	Plot area [ha]	Plot area measured or estimated for rainfed and irrigated rice	**Rainfed rice:** Min = 0.02 Median = 0.57 Max = 4.94	**Irrigated rice:** Min = 0.01 Median = 0.11 Max = 1.54
	Plot age [years]	Age of the rainfed or irrigated rice plot in years since the first forest clearance	**Rainfed rice:** Min = 1 Median = 40 Max = 100	**Irrigated rice:** Min = 1 Median = 41 Max = 100
	Plot ownership	How the household gained ownership of the rainfed or irrigated rice plot	**Rainfed rice:** Inherited = 38.8% Rented = 8.1% Bought = 10.0% Borrowed = 17.7% Cleared by household = 23.4% Other = 1.9%	**Irrigated rice:** Inherited = 65.9% Rented = 2.9% Bought = 9.6% Borrowed = 7.7% Cleared by household = 13.5% Other = 0.5%

female household heads). Migration more frequently occurred in Ampahitra (60% migrants, SC) and in Sahavazina (38% migrants, SC), both villages adjacent to the recently established CAZ protected area and with short conservation experience. The two villages adjacent to the Zahamena National Park with long conservation experience had the least migrants (< 8% of household heads). In Amporoforo (NC), the village with no conservation experience and with forests lost decades ago, about 20% of household heads were migrants. Main reasons for migration around the CAZ were access to land and marriage (Jones et al., 2018). About 1/3 of households were members of an association: about 16% were member of a COBA (community association granted the management of natural resources around the protected area through a contract signed with the Ministry of the Environment and the Commune), 9% were members of a women, youth, or religious association and 6% were part of a farmer association. Houses of farmers typically have a thatch roof, walls consisting of bamboo, wood, or mud, and most houses have only one or two rooms.

Farming Systems

An overview of results from the agricultural survey is given in Table 2. The median landholding of households was 2.02 ha and median area farmed was 1.28 ha. Median age of agricultural plots was 40 years and plot ownership was typically gained through inheritance (50.6%) or clearance by the household itself (24.6%). Generally, land can also be inherited by women and land is divided among both female and male in the following generation when elders die (Laney & Turner, 2015). Rainfed and irrigated rice plots showed no difference in span of age (1 to 100 years, median age 40 and 41 years, respectively). However, rainfed rice plots were significantly bigger (median = 0.57 ha) than irrigated rice plots (median = 0.11 ha). Furthermore, plot ownership differs between rainfed and irrigated plots: irrigated plots are significantly more inherited (65.9%) than rainfed plots (38.8%) while forms of temporally limited land use like borrowing or renting occur less frequently among irrigated plots (Table 2).

Rainfed rice plots were left fallow for around 5 years during the last fallow period. One fokontany (Ampahitra, SC) was characterised by lower median plot age of 10 years and plots most frequently obtained by land clearing (> 60% of plots). Many respondents (49%) used both rainfed and irrigated rice cultivation. In Ampahitra (SC), Antevibe and Ambodivoangy (LC), most respondents relied on rainfed rice farming alone (> 54%) while in Amporoforo (NC) and

Sahavazina (SC) the combination of rainfed and irrigated rice farming was more frequent among respondents (> 83%). While a shorter conservation experience and less restricted access to land may explain plots to be younger in Ampahitra, we did not observe a longer conservation experience of a fokontany to lead to a structural change in land use and to more irrigated rice farming.

Rice yields in rainfed plots were usually lower than in irrigated plots, regardless of plot age (Fig. S4, Supplementary Information). Overall, median rainfed rice yields were about 0.62 t/ha while irrigated rice yielded about 1.72 t/ha (Table 2; Fig. 4b). Around 63% of households sold rice from their harvest, mainly between June and August directly after harvest. Households only farming rainfed rice sold a higher median percentage of their rice yield than households farming irrigated rice (Fig. 5c). A median household farmed five different crops and 36% of households farmed at least one kind of cash crop (coffee, cocoa, vanilla). Around 93% of households used external labour to farm their fields (labour of people not part of household), primarily for cutting, burning, harvesting, planting, and weeding. External labour is paid with cash, in-kind-payment (e.g., share of harvest for harvesting) or labour exchange (Laney & Turner, 2015).

Constraints on Agricultural Area and Productivity

Respondents reported labour availability (28%), pests (20%) and soil fertility (18%) to determine the area of rainfed rice cultivated each year (subset of all rainfed plots owned) with labour availability ranked as most important factor (Fig. 3a). Labour availability is primarily based on the household workforce, as 94% of household heads and 92% of spouses main occupation is agriculture (following the definition for smallholder farmers relying on the involvement of family in labour). Furthermore, external labour plays an important role for some farming practises (see section on farming systems above).

Around 12% of respondents had increased their area of rainfed rice in the last 5 years and 38% of respondents considered increasing their area but did not (Fig. 3b). The most important factor for respondents who considered increasing their rainfed rice area but did not were enough capital to buy or to rent land (38%) and not being able to increase area due to restrictions on *teviala* (32%).

Solely rainfed rice cultivation was used by 44% of respondents. The main factors for respondents not having irrigated rice cultivation were land availability (28%) and lacking the capital to buy or rent land (22%) or invest in irrigation infrastructure (21%) (Fig. 3c). More than 88% of respondents not having irrigated rice considered farming irrigated rice in the future.

The factors limiting productivity of rainfed and irrigated rice differed (Fig. 3d): Respondents reported pests (31%), weeds (27%) and soil fertility (19%) as limiting productivity of rainfed rice with pests considered the most important factor. Production of irrigated rice was limited by drought (24%), weeds (21%) and irrigation infrastructure (19%) with drought named as most important. A detailed description of the cultivation systems and their differences are given in the introduction.

Respondents not farming irrigated rice themselves most often considered rainfed rice as more productive per area and per effort needed in an agricultural season (Fig. 4a). Respondents having irrigated rice plots considered irrigated rice as more productive per area and per effort. Measuring actual rice yields, our results showed higher yields per unit area and per unit labour for irrigated rice (Fig. 4b).

Food Security of Smallholders

About 88% of households faced food insecurity at least one month during a year. Median households had sufficient food for 7 months per year (Fig. 5a). Food security of households was higher in Amporoforo (9 months, NC) and lower in Ampahitra (5 months, SC). The amount of staple foods bought by households varied across seasons (Fig. 5b), with a higher proportion of staple foods bought during lean season between December and March, and fewer staple foods bought during harvest period between April and July.

The fitted GLM to explain smallholder food security differed significantly from a null model (worst model; $p < 0.01$ but did not differ significantly from a saturated model (perfect-fit model; $p = 0.51$) and thus was an appropriate model to describe the observed data (Table 3). Furthermore, visual inspection of DHMARMa diagnostic plots did not reveal over- or underdispersion of the data or the violation of other underlying statistical assumptions like linearity and homogeneity of variance (Fig. S5, Supplementary Information). The Cook's distance did not reveal influential observations within the dataset (Fig. S6, Supplementary Information) and thus the full dataset was used to fit the GLM.

The GLM showed a significant association between three variables and the food security of households (Table 3; Fig. S7, Supplementary Information), supporting our hypothesis regarding factors influencing food security to some extent: as we anticipated, households with higher food security had a higher rice yield, access to irrigated rice farming and a higher tropical livestock unit. Not farming rice was negatively associated with food security in our GLM. However, only two households did not farm rice themselves and both households were in Ampahitra (SC) with the household heads being divorced, female and owning very little land (< 0.11 ha). The workforce within households and the diversity of cultivated crops were associated with food security of households ($p < 0.1$), following our prior

Table 3 Output of the GLM to assess factors influencing the food security of smallholders around the CAZ in eastern Madagascar

Coefficient		Estimate	Std. Error	Z-statistic	
Rice farming practice:	*Rainfed + irrigated*	0.2406	0.0698	0.0006	***
	Only irrigated	0.3969	0.1374	0.0039	**
	Not farming rice	-1.5129	0.7175	0.0350	*
Total rice yield		0.6457	0.1647	0.0000	***
Tropical livestock unit		0.6344	0.2494	0.0110	*
Workforce		0.2352	0.1416	0.0966	
Crop diversity		0.2816	0.1703	0.0982	
Household head gender: *female*		0.0271	0.1024	0.7909	
Household head education		0.1604	0.1523	0.2921	
Training: *Yes*		0.0801	0.0835	0.3377	
Membership: *Yes*		0.0082	0.0676	0.9031	
Cash crops: *Yes*		-0.0718	0.0721	0.3197	
Off-farm income		-0.0750	0.2588	0.7719	
Deviance Residuals:	Min: -2.63 1. Q.: -0.80 Median: -0.03 3. Q.: 0.68 Max: 1.79				
Null Deviance:	217.61 on 159 degrees of freedom				
Residual Deviance	144.74 on 146 degrees of freedom				
AIC:	767.19				

Asterix show the significance level: *** < 0.001; ** < 0.01; * < 0.05; . < 0.1

expectation. However, we did not find a significant effect of variables, such as education, training, cash crop farming and off-farm income on food security (Table 3) as we initially expected. The effect plots in Figure S7 in the Supplementary Information facilitate visual interpretation of the results and confirm the positive relationship of, for example, the tropical livestock unit (Fig. S7c) and the rice yield (Fig. S7b) with smallholder food security while the other effect plots, like for gender (Fig. S7f) and education (Fig. S7g), do not show any relationship with smallholder food security.

Discussion

The Prevalence of Low-yielding Swidden Agriculture

Rainfed rice cultivation was the prevalent farming method among households around the Corridor Ankeniheny-Zahamena (CAZ) in eastern Madagascar, despite yield returns per unit area and unit labour being lower in rainfed than in irrigated systems. The median rice yield we found for rainfed rice (0.62 t/ha) and for irrigated rice (1.72 t/ha) were rather low compared to the range of 0.8–2.5 t/ha given in the literature for rainfed rice (Stoop et al., 2002; Styger et al., 2007) and the range of 2.1–2.9 t/ha for irrigated rice in Madagascar (Barison & Uphoff, 2011; Uphoff & Randriamiharisoa, 2002). Interestingly, farmers tended to rate the type of rice farming they practised themselves as the more productive one. This is particularly striking for farmers solely relying on rainfed rice, and in contrast to measured yield returns (Fig. 4b). This result might be related to not having any experience or knowledge of irrigated rice cultivation in this group of farmers, which was stated as one of the reasons for not practising irrigated rice (Fig. 3c). It may also be that farmers are biased through the age of their rainfed plots: recently cleared plots are more fertile than older plots, leading to the impression of higher fertility if farmers only compare recently cleared rainfed plots and already older irrigated plots (Fig. S4, Supplementary Information). Given the investment required to develop irrigated rice, farmers will likely select the best land for it. Thus, the fact that current irrigated fields have higher yields does not mean that converting all rainfed plots to irrigated rice would necessarily increase yields on those plots.

The prevalence of low yielding rainfed rice might be explained by its low input requirements, its adaptability to steep slopes and high one-off costs for acquiring irrigable land and the irrigation infrastructure. Given the low mechanisation and technology adoption in agriculture in Madagascar (Minten & Barrett, 2005), smallholders may choose rainfed rice farming over irrigated rice due to less labour being required to prepare land (Kull, 2004; Scales, 2014). The topography of the CAZ area is hilly and slopes make up most of the farmland limiting land suitable for irrigation (Whitman et al., 2020). Acquiring such land and installing irrigation infrastructure is costly and thus a matter of household wealth, which is generally low among smallholders in eastern Madagascar (Harvey et al., 2014).

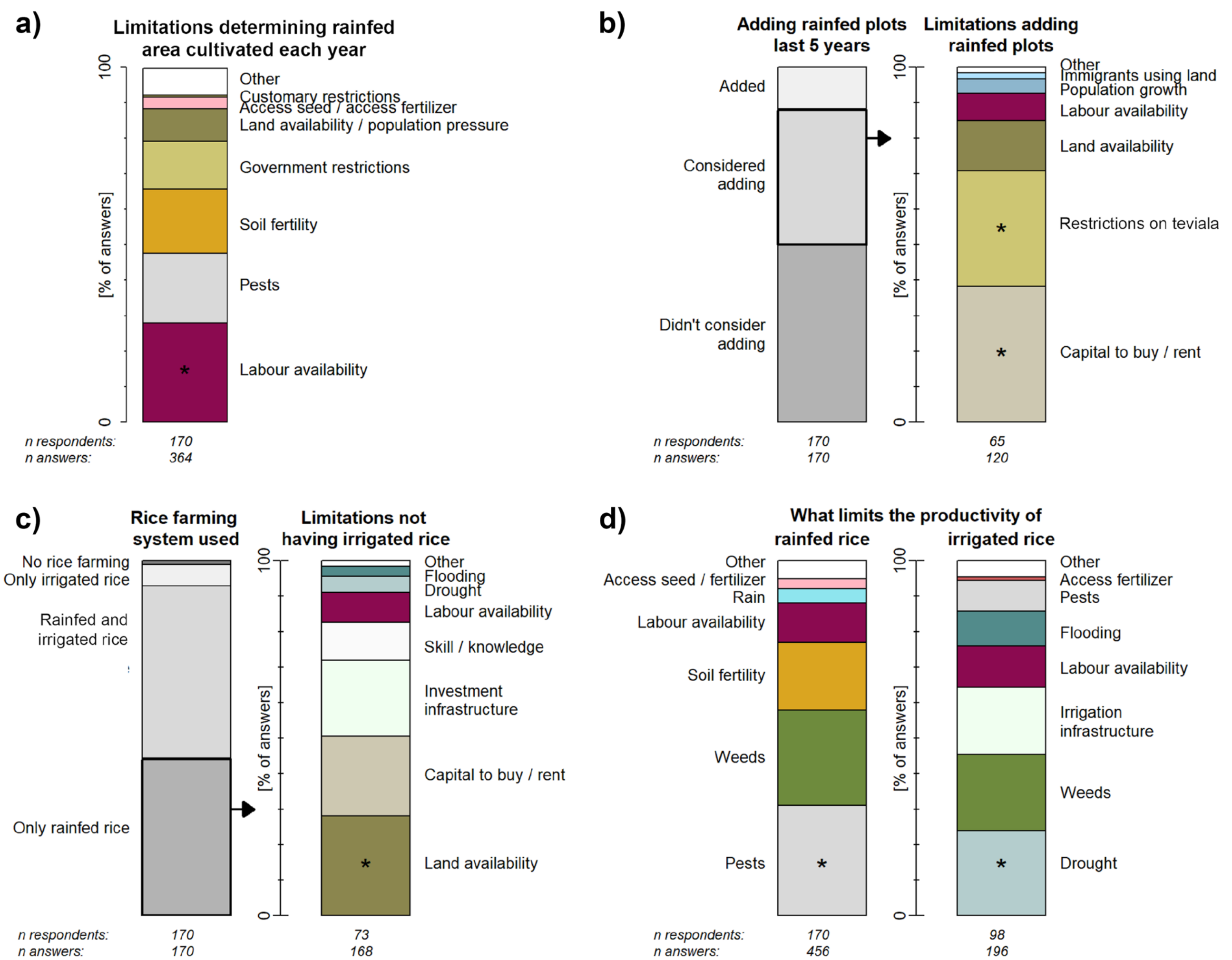
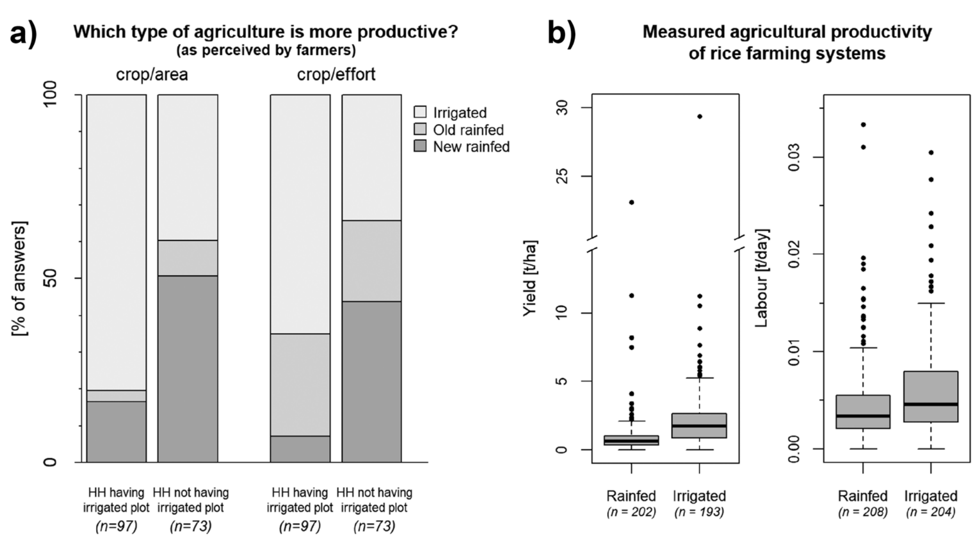


Fig. 3 Factors limiting the area and productivity of rainfed and irrigated rice cultivation reported by households around the CAZ in eastern Madagascar: **a** limitations determining rainfed rice area cultivated each year, **b** limitations if households consider adding rainfed rice plots but could not, **c** limitations for not farming irrigated rice, **d** limitations to the productivity of rainfed and irrigated rice. Respondents could give more than one answer per question. * Indicates the answer category considered as most important by more than 1/3 of respondent

Fig. 4 Perceived and measured productivity of rainfed and irrigated rice production: **a** perceived productivity by farmer for crop value per area and per effort needed in an agricultural season, **b** measured productivity of agricultural plots of respondents as yield per unit area and yield per unit labour



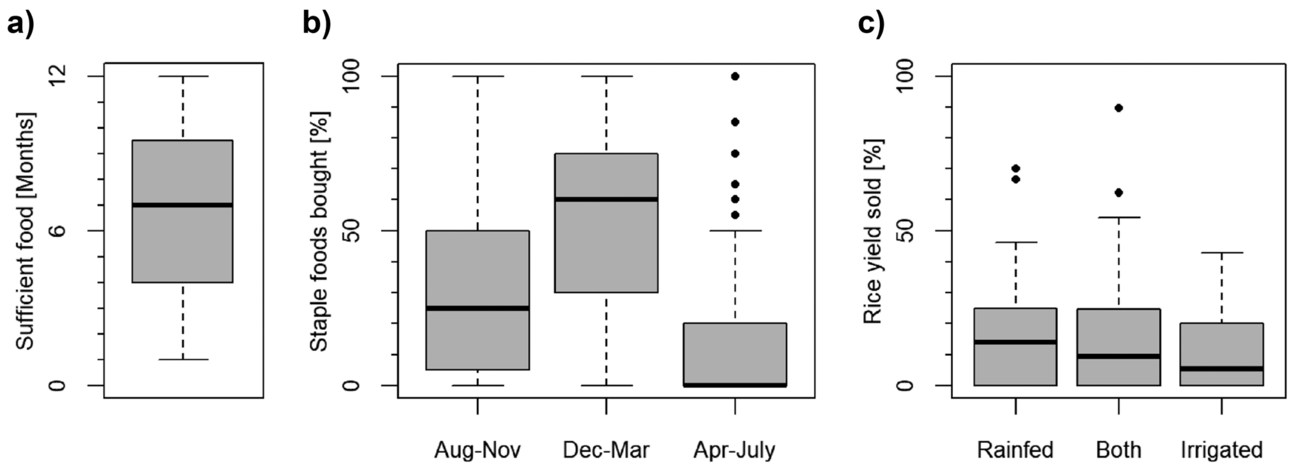


Fig. 5 Food security of smallholders around the CAZ in eastern Madagascar: **a** number of months household had sufficient food for two meals a day, **b** the share of staple food bought on the market by households, **c** the share of rice yield sold depending on rice farming practises (rainfed; rainfed and irrigated; irrigated)

Furthermore, irrigated rice fields in our study region were significantly more inherited than rainfed rice fields, determining farming strategy and resources of a household. This fact may also disadvantage migrants, particularly if only steep farmland suitable for lower yielding swidden agriculture remains available. Access to land has been a frequent reason for migration and drew migrants particularly to fokontany with short conservation experience, where forests were still available and access has only been restricted recently (Ampahitra; Sahavazina) (Jones et al., 2018). Absence of forest land available for clearance may lead to an intensification of land use: Amporoforo, which lost its remaining forests decades ago, was the fokontany with the highest share of farmers practising irrigated rice farming. A more intensified land use may also be facilitated by other local characteristics, such as the mentioned topography and elevation. A lower elevation makes land more accessible and may explain more households in Amporoforo having irrigated rice compared to, for example, Ampahitra bordering the CAZ to the west at a higher elevation.

Productivity Constraints in Rainfed and Irrigated Rice Cultivation

Smallholders around the CAZ in eastern Madagascar considered different factors to limit productivity in rainfed and in irrigated rice: pests, weed infestation, and soil fertility were the major factors limiting productivity in rainfed rice while productivity in irrigated rice was constrained by water management and weed infestation (Fig. 3d). Soil fertility is frequently cited as a major limitation in upland rice in Madagascar (Andriamananjara et al., 2018; Rabeharisoa et al., 2012) but pests and weeds might be equally important (Husson et al., 2004). For example, weed competition is a frequent reason for farmers in Laos to move to a new swidden agricultural field (Roder et al., 1995). In Madagascar, herbicide and pesticide use is low as smallholders typically cannot afford them and instead rely on, for example, labour intensive hand weeding (Achandi et al., 2018; Minten et al., 2006; Rodenburg et al., 2019). Weeding of rice fields is done by all family members including children. However, for women the work may interfere with other household tasks and thus might fall short during times of labour shortage (Brown, 1998; Gezon, 2002). High weed infestation might also be a sign of low soil fertility interlinking both aspects particularly in rainfed systems (N'cho et al., 2014).

Against our expectation, access to fertiliser was not considered to be a relevant factor by smallholders for rice productivity in both cultivation systems. In Madagascar, most smallholders cannot afford inorganic fertiliser (Ramilison, 2004) and the country is one of the lowest fertiliser users in Africa with 4 kg/ha on average (NEPAD, 2011). Phosphorus is the main limiting nutrient in rice cultivation in Madagascar (Rabeharisoa et al., 2012) and combinations of farmyard manure and mineral fertiliser improve rainfed and irrigated rice yields significantly (Andriamananjara et al., 2016, 2018). The use of organic fertiliser requires livestock and hence its use might be low among poor households (Randrianarisoa & Minten, 2005). Still, about 87.1% of households in our study owned chickens and 21.1% of households owned cattle but none of the households used manure in their rice fields nor was access to fertiliser considered relevant for rice productivity (Fig. 3d). As zebu and poultry often roam free, manure can be difficult to collect and farmers might lack training and skills for compost production from manure, rice straw and household greens (Alvarez et al., 2014; Bloesch, 1999; Kull, 1998; Rakotovao et al., 2021). Thus, many smallholders in eastern Madagascar might not be aware of the yield gap caused by no or low nutrient compensation after harvests in rainfed and irrigated rice simply because they do not have access to or experience with fertiliser. High weed infestation can be an indicator for low soil fertility (N'cho et al., 2014) and was, in contrast, recognised by smallholders as a major constraint in both rice cultivation systems in our study. This supports that nutrient depletion of soils is a problem in rice cultivation systems in Madagascar, despite smallholders not recognising access to fertiliser as a primary constraint.

Rice Yields, Livestock, and Smallholder Food Security

Our results confirm a close link between rice harvests, livestock and food security of smallholders in eastern Madagascar, as it has been reported in previous studies and following our expectations (Minten & Barrett, 2005; Noromiarilanto et al., 2016; Poudyal et al., 2016). Rice is the most important staple crop in Madagascar (Golden et al., 2019) and it is thus not surprising that the type of rice farming (through differences in productivity) and the amount of rice harvested are the most relevant factors to food security of households. Against our expectations, we could not confirm other factors, such as education, training, and off-farm income, to be relevant to smallholder food security around the CAZ. This might be explained by, for example, the off-farm income being too low or too seasonal to have a significant impact on overall, year-round food security. Median off-farm income was about 120,000 Ariary per year per household, resulting in theoretically 10,000 Ariary additionally available per month. Assuming a rice price of 1,500 Ariary per kg, this may translate into 6.6 kg of rice covering the need for about five days for a median size household of five per month (average rice consumption of about 300 g per person per day) (Golden et al., 2019; Smith et al., 2016).

In our study, about 88% of households faced food insecurity and, despite being food insecure, more than half of the households sold rice from their harvests. Rice selling after harvesting is an indicator of financial constraints for households as rice prices are low during this period (Dostie et al., 2002; Minten & Barrett, 2005). Thus, households become more reliant on buying rice during the lean season (Fig. 5b) when rice prices are high (Minten et al., 2006). Livestock acts as a kind of insurance to households and selling livestock is one strategy to cope with food shortage (Harvey et al., 2014; Noromiarilanto et al., 2016). Also, households with access to irrigated rice farming showed the tendency of selling a lower share of their rice harvest (Fig. 5c). These households might be wealthier and less dependent on selling rice as the access to irrigated rice farming is a matter of capital. Thus, our results underpin the entanglement of poverty and food insecurity in Madagascar described by (Mathys & Maalouf-Manasseh, 2013).

Implications for Agricultural Development Schemes Enhancing Food Security of Smallholders

During the last years, Madagascar has been reliant on rice imports to meet domestic consumption (USDA, 2020). With Madagascar's population estimated to double by 2050 and with low yields particularly of rainfed rice, self-sufficiency in rice production will be difficult to achieve, although the Malagasy government is committed to increasing domestic production with an emphasis on irrigated rice (Hewson et al., 2019; JICA, 2013).

Irrigated rice farming needs high initial investment of capital and labour, both low among rural households in eastern Madagascar (Harvey et al., 2014). Development schemes and conservation initiatives can support smallholders to start irrigated rice farming, allowing them to grow more food in the same area and reducing the need for further farmland and deforestation (Maertens et al., 2006; Zeller et al., 1999). For example, the Wildlife Conservation Society (WCS) installed a dam close to Maroantsetra in north-eastern Madagascar to increase irrigated rice farming (Brimont et al., 2015). Likewise, development schemes can improve the access to credit (e.g., implementing microfinance services) by reducing liquidity constraints and allowing riskier but efficient investments like in irrigation infrastructure (Mwangi & Kariuki, 2015). Only 13.7% of the rural population in Madagascar had an account at a formal financial institution in 2017 (World Bank, 2018) and access to credit is particularly low for subsistence farmers in Madagascar (Cadot et al., 2006; Harvey et al., 2014). However, as faced by WCS installing the dam in Maroantsetra, securing funding for such projects can be difficult and, despite being effective to combat food insecurity, the projects have the potential to exacerbate inequalities (Bhattarai & Hammig, 2001; Brimont et al., 2015). A study on REDD + around the CAZ in eastern Madagascar revealed socio-political power (e.g., a high position in a local association) to facilitate access to financial benefits and thus microfinance schemes might fail to reach most disadvantaged households if not governed rigorously (Poudyal et al., 2016). Furthermore, microfinance schemes need to be designed carefully, ensuring they are directed to farmers also committing to improving farming practises as, for example, receiving a loan per se did not lead smallholder rice farmers in northern Ghana to improve their technical efficiency (Anang et al., 2016). Cummings (1978) describes a case of Vietnamese smallholders abandoning their traditional cultivation method switching to high yielding irrigated rice. However, poor farmers were lacking the additional labour and financial resources needed (e.g., for fertiliser) and were consequently stuck at previous yield levels. Contrastingly, wealthier farmers were able to invest in additional inputs increasing the wealth gap between farmers (Cummings, 1978). Hence, interventions to increase irrigated rice farming, either through supporting infrastructure or facilitating investment, have the potential to increase food security but need to be designed carefully and need to account for socio-economic characteristics of farmers to not only benefit households which are already better off (Kafle et al., 2021; Magistro et al., 2007; Manero & Wheeler, 2021).

Despite the potential of irrigated rice farming for improving food security, it is not sensible to promote the cessation of swidden agriculture, sometimes done in development projects with a strong focus on forest conservation (Laney & Turner, 2015; Moser & Barrett, 2006; Scales, 2014). The area around the CAZ is hilly, limiting irrigated rice farming typically to valleys, and swidden agriculture is a tradition deeply rooted in Malagasy culture. The conversion of lands at higher elevation and steeper slopes requires disproportionate capital and labour inputs (Whitman et al., 2020). Scarcity of irrigable land is also illustrated by such plots being more frequently inherited than rainfed plots in our study. Furthermore, promoting a complete suppression is not sensible because swidden agriculture can have cultural value including rituals to appease ancestors inhabiting agricultural land and a cessation of these rituals can entail the loss of the identity as a farmer (Erdmann, 2003; Hume, 2006). Instead, the maintenance of already existing swidden agricultural fields including soil conservation farming practises, a basic recirculation of nutrients through fertiliser and adequate fallow periods (Erni, 2015; Styger et al., 2007) might act as a safety net function for smallholders complementing irrigated rice farming. Like crop diversification, a diversification of agricultural practises using rainfed and irrigated rice farming may help buffer the effects of climate change such as unpredictable rainfall. Agroforestry and animal husbandry are options to target smallholders who do not have access to irrigable land (Laney & Turner, 2015; Messerli, 2006). Cultivating cash crops on slopes, like cloves, vanilla, and fruits, can increase purchasing power for staple foods and animal husbandry can increase food security as a protein source or through selling animals (Borgerson et al., 2019; Harvey et al., 2014). However, cash cropping requires access to markets and neglects the importance of staple foods in remote villages (Harvey et al., 2014; Laney & Turner, 2015; Scales, 2014). Small-scale livelihood projects on agriculture and livestock implemented around the CAZ by Conservation International and financed by the REDD + scheme already proved to benefit smallholders regarding food security, overall household wellbeing and income generation (Harvey et al., 2018). Among the support provided were improved seed varieties, fertiliser, agricultural tools (e.g., mechanical weeder) and material for hen houses and pig pens (Harvey et al., 2018). It furthermore included training on, for example, land preparation, soil conservation, composting, biological pest control as well as livestock breeding, management, and health (Harvey et al., 2018). Chickens were the prevalent livestock around the CAZ but are vulnerable to diseases (e.g., Newcastle disease) and community-centred interventions can support smallholders to afford vaccinations, particularly to target households without access to irrigable land (Annapragada et al., 2019; Borgerson et al., 2019; Maminiaina et al., 2007). Most of the small-scale livelihood projects implemented around the CAZ lasted less than a year but continuation and increasing efforts based on the gained experience will be key to improve food security and reduce deforestation (Harvey et al., 2018; Tabor et al., 2017). A study by Tabor et al. (2017) found some evidence that the small-scale livelihood projects and the conservation activities in the CAZ led to less deforestation and fire incidence, particularly with higher and longer sustained funding.

Conclusions

We analysed constraints on rainfed and irrigated rice cultivation and their relation to smallholder food security around the Corridor Ankeniheny-Zahamena (CAZ) in eastern Madagascar, a region characterised by smallholder agriculture, high seasonal food insecurity and high biodiversity. Around the protected area, rainfed systems were predominant, inter alia, due to its adaptability to cultivate slopes. Access to irrigated rice farming basically indicated greater wealth among households, being able to acquire irrigable land and infrastructure, and yield returns per unit area and unit labour were higher in irrigated systems. Productivity constraints differed between the two rice cultivation systems: smallholders considered rainfed rice to be mainly limited by pests, weeds, and soil fertility while irrigated systems are constrained by factors related to water management and its infrastructure. Access to fertiliser was low and thus many smallholders might not be aware of the actual yield gap caused by no or low nutrient compensation after harvesting.

Food insecurity was prevalent in the study region with almost 9 out of 10 households facing food insecurity at least one month per year. Households with higher food security had access to irrigated rice farming, higher actual rice yields and more livestock. Agricultural development schemes assisting with irrigation infrastructure may increase food security, but only benefit households with access to irrigable land, which might already be better off and more food secure. To target households without access to such land, other interventions on, for example, animal husbandry and disease prevention are needed. Promoting a cessation of swidden agriculture including rainfed rice cultivation is not sensible due to the geographic context (steep slopes and scarce irrigable land). Instead, improved agricultural practises on already existing swidden agricultural fields might act as a safety net for smallholders, diversifying agricultural practice and buffering unpredictable rainfall due to climatic changes.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10745-022-00336-2.

Acknowledgements We thank local leaders and all the people interviewed for participating in this research. Research permission was granted by the Ministry of Environment, Ecology and Forests (45/14/MEF/SG/DGP/DCB. SAP/SCB).

Funding Open access funding provided by University of Bern. This work was part of the p4ges project (www.p4ges.org) funded by the ESPA programme (NE/K010220/1). JCL was funded by the Swiss National Science Foundation under grant P2BEP2_191790. NH was funded by the Climate Adaptation and Resilience (CLARE) Program of the UK Foreign, Commonwealth and Development Office through the Forests4Climate&People project.

Data Availability The full data set is archived with ReShare, the UK data services online repository (Poudyal et al., 2017; Poudyal et al., 2016). The data aggregated at the household level and used for the GLM, the R script to run the GLM, the results on limitations on the rice cultivation systems and the yield results are archived with Mendeley Data (Dröge et al., 2020).

Declarations

Informed Consent Informed consent was obtained for all respondents and research was approved and conducted under Bangor University research ethics framework.

Conflict of Interest We declare no financial or other conflict of interest among the authors.

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