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RESEARCH ARTICLE

Climate Change Perceptions and Adaptive Behavior Among Smallholder Farmers in Northeast Madagascar

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Abstract

Climate change is impacting the food security and health of people worldwide, and the risk for smallholder farmers is particularly high. While many studies have forecast changes to food production at regional scales, fewer studies have directly assessed the effects of climate change on agricultural communities and the factors that influence climate adaptation at local scales. We surveyed 479 smallholder farmers in two villages in rural northeast Madagascar to characterize their perceived changes in rainfall and temperature, the impact of these changes on their livelihoods, health, and food security, and ways that they are altering their farming practices to adapt to climate change. We hypothesized that farmers with greater market-based wealth and more farming experience would have higher odds of adaptation. We also hypothesized that farming practices among an individual's peers (friends, family, and neighbors) would influence their climate change adaptation strategies. Nearly all participants reported perceiving increases in temperature (94%) and decreases in rainfall (91%) in the previous five years, and most reported that they expect to have much less (57%) or somewhat less (35%) food to feed their families in the future due to changes in temperature and rainfall. Despite these concerns, few participants (21%) reported changing their farming practices to adapt to climate change. Farmers who had greater market-based wealth had higher odds of adopting new farming methods (model averaged OR [95% CI]: 1.37 [1.09-1.73]), and men had higher odds of adopting new farming methods than women (model averaged OR [95% CI]: 2.08 [1.27-3.41]). Farming experience and peers' farming practices were not associated with adaptation. These results suggest that climate change is a significant challenge for farmers in northeast Madagascar, yet adaptation is limited by existing socioeconomic inequalities involving access to market activities and gender.

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Introduction

Climate change is a major threat to the global food system, particularly for small-scale subsistence farmers in low-income countries [1]. In 2020, nearly 12% of the global population was identified as severely food insecure, with 347 million severely food-insecure people living in Africa [2]. Evidence suggests that smallholder farmers in the tropics are particularly vulnerable to the effects of climate change on food security because they are directly dependent on crop yields for subsistence and cash needs and even temporary shortfalls can have long term consequences for health and wellbeing [3,4]. Smallholder farmers are also commonly dependent on rainfed agriculture, which makes them particularly aware of and vulnerable to changes in rainfall patterns [5]. Although smallholder farmers have managed climate instability in the past – through strategies such as crop diversification [6] – the degree of instability caused by anthropogenic climate change is unprecedented [1]. Understanding the complex links among climate change, food systems, and health in rural low-income settings is thus critical to building resilience among those most threatened by future climate shocks.

Climate change is already impacting farmers in Madagascar. From 1961 to 2017, annual precipitation declined at 14 out of 15 long-term weather stations across the country, minimum average temperatures increased at all locations, and maximum average temperatures increased at all but one location [7,8]. In northeast Madagascar, annual rainfall is projected to drop by 5-10%, while maximum and minimum temperatures are both expected to rise by 3.0° to 5.0°C by 2100 under moderate and high greenhouse gas emissions scenarios (RCP 4.5 and RCP 8.5) [7–9]. These climate shifts are projected to alter the distribution of forested areas and will have important implications for crops such as rice, a core component of the Malagasy diet [10,11].

To address this complex problem, greater integration is needed between climate data and observations of human behavior. However, climate models are often operationalized at regional and global scales; as such, these models may be less predictive of farmers' adaptive behaviors than farmers' own perceptions of climate variability [12,13]. Local observations of climate change are important drivers of individual, household, and community-level decision making and have been linked to decisions about migration [14], family planning [15], and crop diversification [16–18]. In contrast, regional-scale climate models can miss important shifts in ecological systems that affect vital resources for subsistence communities, such as changes in animal migration patterns and the distribution of animal and plant pathogens [19]. These regional-scale climate models are built by downscaling from an ensemble of global models, which depend on data from weather stations that are unevenly distributed across geographic contexts and may miss important changes at smaller scales [20–22]. Data on local observations of climate change provided through surveys, focus groups, and ethnographic interviews can help address these gaps and offer distinctive insights into the finer scale climate variability that affects the everyday lives of individuals for whom climate adaptation is most important.

In addition to understanding how climate is perceived locally, identifying factors that lead to climate adaptation – or changes made to manage risk in response to or in expectation of changes in climate [1] – is a critical task for the social sciences. Climate adaptation is a form of cultural adaptation and must be grounded in local knowledge systems to be effective and sustainable [23]. The political-economic context of climate adaptation can also affect the long-term success of adaptations as well as who is best able to adapt [24]. Many smallholder farmers live in settings with a shifting economic landscape, where ongoing market integration results in mixed economies with people relying on both subsistence and commercial agriculture. The joint effects of climate change and economic globalization have been conceptualized as a “double exposure” that can have particularly negative consequences for smallholder farmers [24,25]. In Madagascar, for example, climate change can have substantial impacts on food production, but the high volatility of markets and limited market access due to poor road infrastructure can be just as consequential for farmers’ livelihoods [26]. It is therefore essential to understand how local cultural and political-economic factors influence farmers’ ability to adapt to climate change.

Previous research on farmers’ adaptation to climate change has documented a wide range of factors that affect their adoption of new farming practices. Several studies have found that more experienced farmers are more likely to pursue adaptation strategies [27–30]; however, more experienced farmers may be reluctant to adopt some strategies (e.g., changing their crop varieties) while readily adopting others (e.g., planting shade trees, rotating crops) [28]. Notably, age and farming experience are not always equivalent, with younger farmers being more likely to adapt their farming practices in response to climate change in some settings [27,29,31] but not others [32]. Economic resources are major factors influencing farmers’ ability to adapt, including income, access to credit and microfinance, and availability of affordable materials [27,33–35]. Although only a few studies have investigated the effect of peer influence on whether farmers adapt to climate change, evidence suggests that the adaptive behavior of family, friends, and neighbors – as well as cultural norms related to adaptive behaviors – affect individual-level farming practices [36,37]. Overall, however, meaningful predictors of adaptive behavior tend to be context specific, requiring local studies to inform intervention strategies.

In this study, we asked smallholder farmers in the SAVA region of northeast Madagascar about their perceptions of climate change, its impacts on health and food security, and how they have changed their farming practices to adapt to climate change. With these and other sociodemographic data, we investigated the factors that predict perceived changes in climate and the uptake of adaptation strategies. We hypothesized that greater market-based wealth and farming experience would be associated with a higher probability of adaptation because wealth and experience provide farmers with the options and crucial knowledge needed to adjust their farming practices [26–28]. In addition, because behavior change often requires multiple, reinforcing exposures to a new behavior through observation and knowledge sharing, peer influence is expected to play a role in the diffusion of complex behaviors like changes in farming practices [38]. Therefore, we also hypothesized that the adoption of adaptation strategies would be affected by whether farmers’ peers (friends, family, and neighbors) had adopted new farming practices to adapt to climate change. Investigating these hypotheses in northeast Madagascar provides valuable insight into the challenges facing farmers who practice small-scale rainfed agriculture while navigating the “double exposure” of climate change and economic globalization.

Materials and methods

Study setting

Study participants were recruited from two villages (Mandena and Sarahandrano) in the SAVA region of northeast Madagascar (Fig 1). The two villages are located on the southeastern border of Marojejy National Park, where most people’s livelihoods are based on small-scale farming. The SAVA region is one of the world’s largest producers of vanilla, and market production has rapidly increased in recent decades [39–41]. Although vanilla is the predominant cash crop in the region, farmers also produce cloves, coffee, and cocoa for export, and they grow a wide variety of subsistence crops, including rice, tubers, beans, and tropical fruits [39,42]. The growing year is divided into a rainy season when harvests are most productive and a lean season when farmers need to purchase more food from markets [42]. One village in our study (Mandena, estimated population size = 3200) is also the main gateway to Marojejy

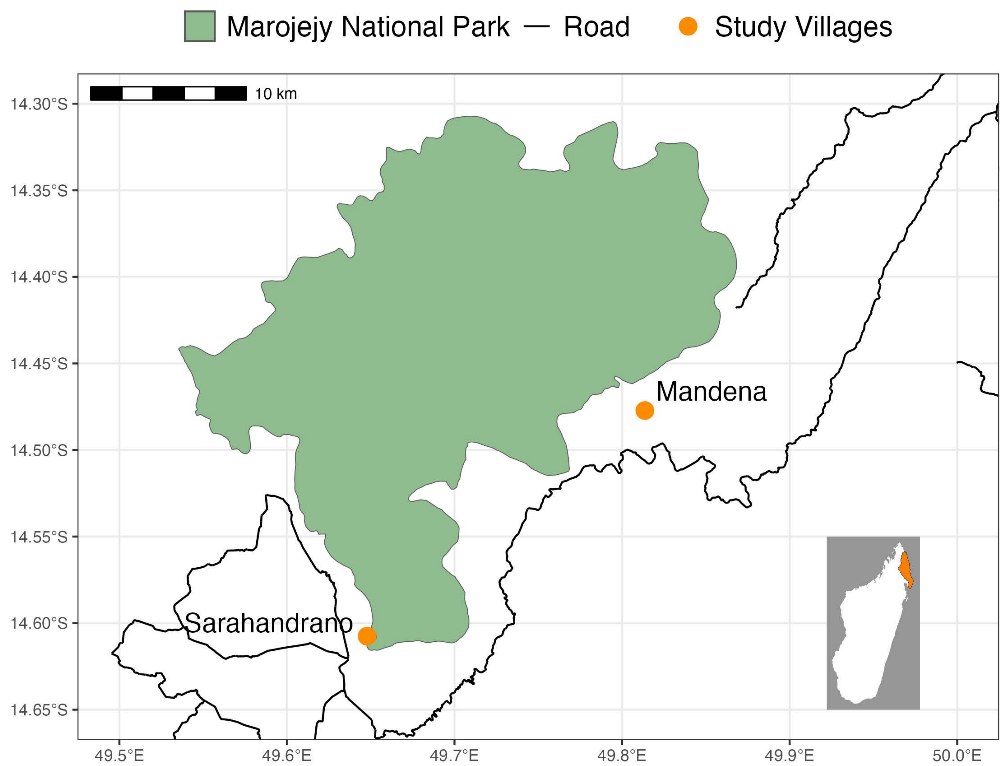

Fig 1. Map of study villages in the SAVA region of northeast Madagascar. The two study villages (Mandena and Sarahandrano) are shown as orange circles. The green area in the center of the map is Marojejy National Park. The shapefile for the study area base map was obtained from OpenStreetMap (openstreetmap.org), and the shapefile for the Madagascar inset map was obtained from the Humanitarian Data Exchange (https://data.humdata.org/dataset/cod-ab-mdg).

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National Park, which received an average of 1399 visitors per year between 2012 and 2016. This proximity and tourist interest allowed some individuals in Mandena to earn supplemental income from ecotourism and income-generating conservation projects [43]. The second study village (Sarahandrano, estimated population size = 900) does not have direct access to the ecotourism industry, and residents of this village sometimes quarry gravel for supplemental income. Marojejy National Park serves as the main source of water for farmers in both villages, and village residents are known to use the natural resources' of this Park and surrounding forests to gather wood for fuel and construction and to forage for wild foods [40,43]. Findings from this setting are likely relevant for understanding climate change perceptions and adaptation in other contexts where smallholder farmers practice rainfed agriculture, face distinctive challenges of island climates like regular cyclones, and are experiencing rapid social and economic change related to expanding markets for agricultural products and ecotourism.

Data collection

Surveys were administered to 479 participants in the local Malagasy dialect by a trained research team between February 15 and April 12, 2023. Farmers were enrolled in the study if they had previously participated in a social network survey conducted by the authors between October 3, 2019 and August 4, 2022 [44,45]. The original social network survey data were collected using snowball sampling, where we enrolled individuals who were named by a participant as someone with whom they spent free time, exchanged farmwork, and/or exchanged food [44,46]. Questions for the climate change survey were fine-tuned through focus groups and were pretested with a small sample of farmers. The climate change survey questions captured information about farmers' perceptions of climate change and their adaptive behavior, and data from these surveys were linked with the social network survey data collected between October 3, 2019 and August 4, 2022 to obtain demographic, economic, and social network information not included in the climate change survey. Data from the 2019-2022 surveys were accessed for this analysis on May 4, 2023. We also recorded the GPS coordinates of participants' house location. All study participants were 18 years or older at the time of data collection and provided informed verbal consent, which was documented by the interviewer in the survey form. Study protocols were approved by the Duke University Institutional Review Board (Duke IRB Numbers 2019-0560 and 2023-0255) and the Malagasy Ethics Committee for Biomedical Research within the Ministry of Public Health (Permit Number 114 MSANP/SG/AGMED/CERBM on 4 November 2019).

We used the surveys to obtain demographic, economic, and agricultural data. Participants reported their age, gender, marital status, and education level. We asked participants whether they owned or rented their land, whether they inherited the land from family, the number of years they had worked their land, and whether they participated in a vanilla certification program. Vanilla certification programs are often sponsored by NGOs and certify farmers' production of sustainable vanilla (e.g., Fairtrade and Organic certifications) and aim to support price stabilization [40,42]. We used two measures to assess participants' level of engagement with the market economy (market integration). First, we created a durable goods index that captured the number of durable goods owned by a household, focusing on cell phones, televisions, bicycles, motorcycles, generators, refrigerators, and computers [47,48]. The index ranged from 0 (no durable goods owned) to 7 (all listed durable goods were owned). Second, we used a household lifestyle index to characterize the degree to which houses were constructed with purchased materials [49]. House components (floors, walls, and roofs) were ranked by the material used for their construction, ranging from locally gathered materials (e.g., dirt, bamboo, and raffia palm) to purchased materials not available locally (e.g., bricks and metal roofing sheets). Values for each house component were standardized, and we summed the standardized values to create the household lifestyle index. Higher values indicated houses constructed with more purchased materials, and lower values indicated houses constructed with more locally gathered materials.

To determine whether participants' adaptive behavior was influenced by their peers' adaptive behavior, we constructed two weighted social networks using survey data and GPS data. First, we used five name generating questions to identify social network ties [50]. We asked participants to name up to five individuals with whom they: (1) spend their free time, (2) provide assistance with food, (3) receive assistance with food, (4) provide assistance with farming, and (5) receive assistance with farming [44]. We then summed the number of relations shared by two individuals to create a weighted network edge (i.e., a valued connection between two individuals ranging from zero to five). Second, we used the GPS coordinates of participants' homes to construct a network where edges between all households were weighted by their inverse distance, i.e., houses that were farther apart had a lower edge weight.

Several questions on the survey assessed participants' perceptions of climate change. First, we asked: "Over the past five years, have you noticed that the temperature has" (1) "become much cooler than usual," (2) "become somewhat cooler than usual," (3) "stayed the same," (4) "become somewhat warmer than usual," or (5) "become much warmer than usual?" Second, we asked: "Over the past five years, have you noticed that the amount of rainfall has" (1) "become much less than usual," (2) "become somewhat less than usual," (3) "stayed the same," (4) "become somewhat more than usual," or (5) "become much more than usual?" We also asked participants whether they noticed that some natural water points have dried up over the past five years ("yes" or "no") and whether they had to reduce the amount of time they worked outside due to extreme heat and rain, with response options including "yes, for more than seven consecutive days," "yes, for more than two consecutive days," "yes, for one or two days at a time," and "no." To better understand participants' background knowledge of climate change, we asked "how much do you know about climate change?", with response options including "I don't know anything," "I know a little," and "I know a lot."

To assess perceived impacts of climate change on the local ecology and population health, we asked whether participants noticed a decrease, no change, or increase over the previous five years in the types of wild plants they see, the types of wild animals they see, the number of rodents and mosquitoes they see, and the number of people getting sick with malaria, diarrheal disease, and respiratory illness. We also asked two questions to assess the perceived influence of climate change on food security: (1) "Have there been any times in the last three years when you have not had enough food for your household needs?" ("yes" or "no"), and (2) "Do you expect changes in the amount of food your family will have to eat due to changes in rainfall and temperature?" (response options included: "I expect my family will have much less food to eat," "I expect my family will have somewhat less food to eat," "I do not expect any changes," "I expect my family will have somewhat more food to eat," or "I expect my family will have much more food to eat"). Participants also reported cyclone-related crop and land damage.

To capture adaptive behavior, we asked: "What farming practices have you adopted to improve or maintain your crop yields over the last five years?" Participants were then read a list of options to select, including bucket irrigation from rivers, cover crops, agroforestry, mulching, manure/organic fertilizer, inorganic fertilizer, herbicides/insecticides, crop rotation, changing cropping calendar, fallowing, terracing, land expansion, irrigation from well, runoff harvesting, deep tillage, hedges, ridge cultivation (making ridges or raised beds to plant crops on and reduce erosion and runoff), trash line (building ridges/mounds using old crops for a barrier to decrease runoff), mixed cropping, crop diversification, planting drought resistant crops, growing crops in the off season, and switching to short maturing varieties. Additional description of each practice was provided as requested by participants. We also asked whether participants needed to leave their village either temporarily or permanently in the past five years because of food/cash shortages due to reduced crops and what other solutions they use to deal with food/cash shortages. Response options for coping strategies included sale of livestock, fuelwood collection and sale, barter trade, reduced number of meals, loans, small-scale businesses, harvesting immature crops, consuming seed stock held for next season, relying less on preferred foods, harvesting food from forests, borrowing food from family or friends, fishing, and taking children out of school.

Data analysis

We computed descriptive statistics to characterize demographics, market integration, agricultural practices, and perceptions of climate change in the two study villages. The social network and house proximity network were constructed and characterized using the *igraph* package in R [51]. We used a model averaging approach to assess which variables best predicted uptake of climate adaptation strategies. The global network autocorrelation model used a logistic regression structure to predict adaptation as a binary response variable and incorporated two terms that accounted for social and spatial network-based dependencies to test whether adaptation was associated with peers' adaptive behavior [52,53]. The model also included relevant demographic, economic, and agricultural variables. Years of farming experience was natural log transformed to account for a skewed distribution and all continuous variables were standardized prior to analysis. We then used sample-size adjusted Akaike Information Criteria (AICc) to compare the predictive performance of models with different variable sets [54,55]. We computed weighted coefficients based on a set of component models that had a delta AICc less than two. We used the *MuMIn* package to perform model comparisons and averaging [56]. All analyses were conducted in R version 4.3.1 [57].

Results

Demographic and socioeconomic characteristics

Across the 479 adults in two villages, participants' median (interquartile range [IQR]) age was 37 (27-50) years, and 43% (n = 207) were women (Table 1). Men had marginally more social network connections than women in both Mandena (mean [SD] weighted degree centrality: 12.48 [7.2] versus 11.11 [6.54]) and Sarahandrano (mean [SD] weighted degree centrality: 9.9 [6.44] versus 8.12 [5.66]). The median (IQR) household size was 4 (3-5) people, and most participants (82%, n = 391) were married or living with a partner. Half of the participants (50%,

Table 1. Participant characteristics by village.

Characteristic	Mandena (N = 236)	Sarahandrano (N = 243)	Both Villages (N = 479)
Age, Median (IQR)	43 (33-56)	31 (25-43)	37 (27-50)
Gender, n (%)			
Women	108 (46%)	99 (41%)	207 (43%)
Men	128 (54%)	144 (59%)	272 (57%)
Marital Status, n (%)			
Living Together	157 (66%)	200 (82%)	357 (75%)
Married	28 (12%)	6 (2%)	34 (7%)
Never Married or Living Together	47 (20%)	31 (13%)	78 (16%)
Separated or Divorced	2 (1%)	0 (0%)	2 (0.4%)
Widowed	2 (1%)	4 (2%)	6 (1%)
Unknown	0 (0%)	2 (1%)	2 (0.4%)
Education			
None	12 (5%)	10 (4%)	22 (4%)
Primary	143 (61%)	93 (38%)	236 (49%)
Secondary	61 (26%)	106 (44%)	167 (35%)
Higher	20 (8%)	31 (13%)	51 (11%)
Unknown	0 (0%)	3 (1%)	3 (1%)
Household Size, Median (IQR)	4 (3-5)	4 (3-5)	4 (3-5)
Durable Goods Index, Median (IQR)	1 (1-2)	1 (0-2)	1 (0-2)
House Lifestyle Index, Median (IQR)	-1.57 (-1.57-1.77)	0.59 (-0.59-1.77)	-0.39 (-1.57-1.77)
Years of Farming Experience on Land, Median (IQR)	12 (6-25)	4 (2-8)	7 (3-20)
Land Ownership, n (%)			
Owned, Inherited from Family	191 (81%)	169 (70%)	360 (75%)
Owned, Purchased	29 (12%)	14 (5%)	43 (9%)
Rented, Inherited from Family	7 (3%)	24 (10%)	31 (7%)
Rented, Not Inherited	9 (4%)	36 (15%)	45 (9%)
Grows Vanilla (Yes), n (%)	187 (79%)	211 (87%)	398 (83%)
Vanilla Certification Member (Yes), n (%)	88 (37%)	59 (24%)	147 (31%)

https://doi.org/10.1371/journal.pclm.0000501.t001 n = 236) completed primary school, while 35% (n = 167) completed secondary school, 11% (n = 51) completed higher education, and 5% (n = 22) did not attend school. Most participants (84%, n = 403) owned their farmland, and most of these participants (89%, n = 360) inherited the land from family, with the others (n = 43) purchasing their land. Of the 76 individuals who rented their land, 40% (n = 31) inherited the rental from their family. Overall, participants reported working their land for a median (IQR) of 7 (3-20) years. Participants from Sarahandrano had worked their land for a shorter amount of time than participants from Mandena (median [IQR] of 4 [2–8] years versus 12 [6-26] years). Most participants grew vanilla (83%, n = 398), and approximately one third of participants (31%, n = 147) were a member of a vanilla certification program. Participants owned few durable goods (median [IQR]: 1 [0–2]), and had homes constructed of relatively few purchased materials (median [IQR] household lifestyle index: -0.39 (-1.57-1.77).

Perceptions of climate change and its effects on health and food security

Most participants (92%, n = 442) reported knowing at least a little about climate change, and nearly all perceived an increase in temperature (94%, n = 450) and a decrease in rainfall (91%, n = 437) over the previous five years (Fig 2). Three quarters of participants (75%, n = 357) noticed that natural water points had dried up over the previous five years, and 41% (n = 197) reported that their crops and land were damaged in the most recent cyclone. These changes in weather have impacted participants' ability to work their land, with 75% (n = 361) having to reduce the amount of time they worked outside in the previous five years due to extreme heat and 85% (n = 409) having to reduce the amount of time they worked outside in the previous five years due to extreme rain. They also reported changes in animal and plant life. Most participants noted decreases in the species of wild animals (90%, n = 349) and plants (73%, n = 349) they observed over the previous five years, and most reported an increase in the number of rodents (73%, n = 451) and mosquitoes (66%, n = 317) observed in villages and fields.

Participants reported high rates of food insecurity and increasing rates of diseases linked to climate change. The majority of participants (87%, n = 419) reported that there have been times in the previous three years that they did not have enough food for their household needs

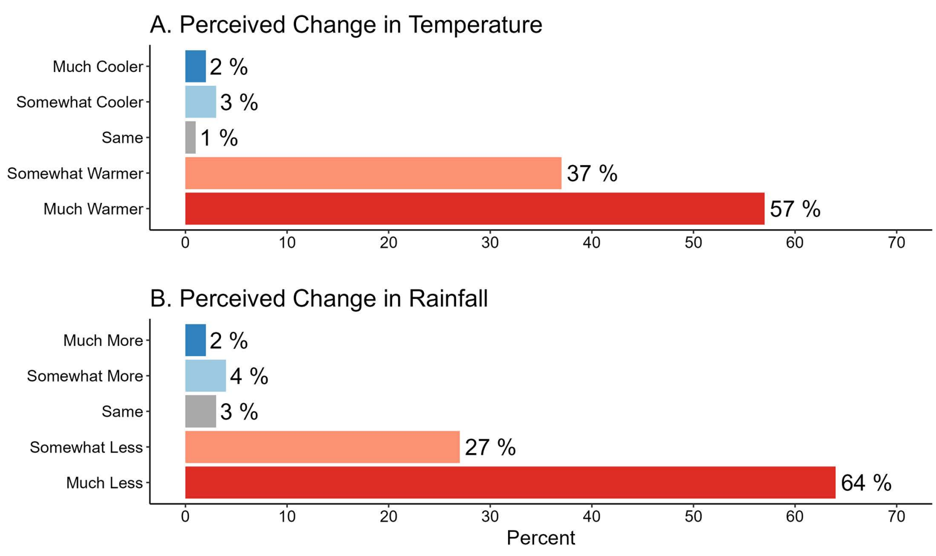

Fig 2. Perceived changes in temperature (Panel A) and rainfall (Panel B) over the previous five years (n = 479).

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(Fig 3). Most also expect to have much less (57%, n = 272) or somewhat less (35%, n = 169) food to feed their family in the future due to changes in temperature and rainfall. Although few people (17%, n = 80) reported noticing an increase in the number of people getting sick due to respiratory illnesses over the previous five years, approximately half (48%, n = 230) reported increases in the number of people getting sick due to diarrheal diseases and most (71%, n = 338) noticed increases in the number of people getting sick due to malaria.

Adaptations to climate change

Although more than 90% of participants were aware of climate change and perceived climate-related changes over the previous five years, remarkably, only 21% (n = 100) reported adjusting their farming practices to cope with these changes. The most frequently reported changes were using organic (40%, n = 40) or inorganic (13%, n = 13) fertilizer, mulching (38%, n = 38), and/or changing their cropping calendar (24%, n = 24). Some participants also reported that they practiced fallowing (12%, n = 12), used herbicides (8%, n = 8), rotated their crops (6%, n = 6), used cover crops (3%, n = 3), grew crops in the off season (2%, n = 2), used agroforestry techniques (2%, n = 2), and practiced mixed cropping (1%, n = 1).

A small number of all farmers reported that they were forced to leave their homes either temporarily or permanently due to an extreme weather event (12%, n = 57) or experienced a food/cash shortage related to crop failure (5%, n = 22). To cope with food shortages, participants tended to borrow from others in their community (17%, n = 83), sell their livestock (15%, n = 71), forage (15%, n = 71), and/or reduce their number of meals (13%, n = 60).

We assessed which factors best predicted adaptation by modeling a binary response variable indicating whether farmers engaged in any of the adaptation practices or none of the adaptation practices (Fig 4). Overall, we found that men had 108% higher odds than women of reporting engagement in any adaptation practice (model averaged OR [95% CI]: 2.08 [1.27-3.41]), and that a one standard deviation increase in the number of durable goods owned was associated with 37% higher odds of adaptation (model averaged OR [95% CI]: 1.37 [1.09-1.73]). Village was also an important predictor of whether farmers adapted. Participants from Sarahandrano had 79% lower odds of adaptation than participants from Mandena (model averaged OR [95% CI]: 0.21 [0.12-0.36]). Each of these three variables were included

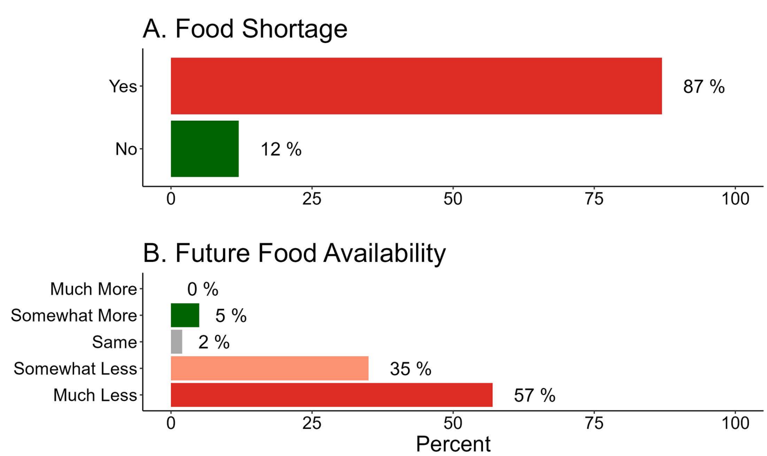

Fig 3. Climate change and food security. Panel A shows the percentage of farmers who reported that there was a time in the previous three years when they did not have enough food to meet their household needs. Panel B shows farmers' expectations about changes in the availability of food to feed their family in the future due to changes in temperature and rainfall.

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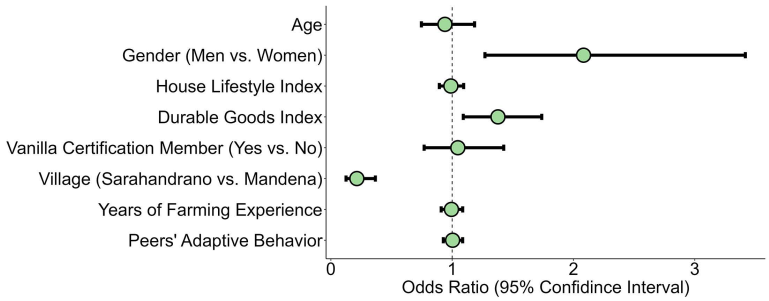

Fig 4. Predictors of adaptation strategy uptake. Men and individuals who owned more durable goods had higher odds of adopting adaptation strategies. Individuals from Sarahandrano had lower odds of adopting adaptation strategies than individuals from Mandena. Points and error bars represent odds ratios and 95% confidence intervals computed from model averaging of candidate logistic regression models with a delta AICc less than two (S1 Table).

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in all seven component models that were used in model averaging (summed AICc weight = 1). Years of farming experience and peer influence based on social connections were not associated with adaptation (model averaged OR [95% CI]: 0.99 [0.91-1.08] and 1.00 [0.92-1.08], respectively) and were only included in one of the seven component models (summed AICc weight = 0.10). Model details and the other variables included in component models (all at less than 0.4 summed AICc weight) are given in S1 Table. Notably, education level and peer influence based on house proximity were not included in any of the component models (summed AICc weight = 0), and thus not meaningful predictors of adaptation in this setting.

Discussion

Climate change is expected to alter Madagascar ecosystems and negatively affect the cultivation of key subsistence crops like rice [10,11]. We found that farmers in the SAVA region of Madagascar are already experiencing the effects of climate change on their livelihoods, with a majority reporting that they perceived less rainfall and higher temperatures in the previous five years and that changes in the frequency of extreme rainfall and heat events have reduced the time they can spend outside doing farm work. Despite these observations, few farmers in our study have changed their agricultural practices to adapt to climate change. Men and individuals with greater market-based wealth (indexed by ownership of durable goods) had higher odds of adopting at least one adaptation strategy, suggesting the presence of socioeconomic barriers that may need to be overcome to implement effective climate change adaptation in this region of Madagascar.

Our finding that most farmers observed climate-related changes in weather is congruent with studies of local and Indigenous perceptions of climate change in Africa [28,35,58,59] and other regions [19]. In contrast to other studies of small-scale agriculturalists, we found that markedly fewer farmers in our study reported adopting climate change adaptation strategies. For example, prior studies in Africa found that 54% of farmers surveyed in Nigeria, 65% of farmers surveyed in Ethiopia, and 80% of farmers surveyed in Burundi had changed their agricultural practices to adapt to the effects of climate change on growing conditions [28,33,35]. The highest rate of adaptation we found documented in the literature was 88% in China [30], and the lowest rate we found was 29% in Pakistan [27], which is 8 percentage points above the 21% adaptation rate that we documented.

We found support for our hypothesis that greater market-based wealth is associated with higher odds of adaptation. Prior research on smallholder farmers' vulnerability to climate change in Madagascar found that high volatility in the price of both agricultural inputs like fertilizers and products like vanilla present major risks to agricultural livelihoods [26]. Furthermore, studies in other African countries showed that proximity to market centers facilitates the adoption of adaptation strategies and that improved transportation infrastructure may be vital to helping rural farmers adapt to climate change [60,61]. These findings suggest that farmers with greater market access and market-based wealth may be better able to weather the double exposure of market integration and climate change by having better access to the resources needed to implement successful adaptation strategies [24,25].

Like other studies of climate change adaptation among smallholder farmers, we found a gender gap in adaptation, with men having higher odds of adaptation than women [60,62,63]. Climate change adaptation can have a bidirectional relationship with gender relations, making it difficult to parse the causal pathways influencing gender differences in agricultural decision making [64]. Prior studies found that women farmers often face more resource constraints on adaptation, such as less access to information and agricultural extension services and fewer social connections [63,65]. Women farmers also face additional challenges where gender norms related to domestic labor require them to maintain household and farm responsibilities simultaneously [62]. Although we focused on on-farm adaptation strategies in this study, other studies have found that women are more likely to adapt to climate change through off-farm strategies like selling produce and other goods at a market, whereas men are more likely to adapt through on-farm strategies like the use of fertilizer and changing the types of crops they grow [66]. Future studies in Madagascar should aim to capture potential gendered differences in adaptation strategies to ensure equitable interventions.

We also found village-level differences in adaptation, with individuals in Sarahandrano – which is not involved in the ecotourism industry and is not as heavily engaged in income-generating conservation projects – having lower odds of adaptation than residents of Mandena. Farmers in Mandena have an opportunity for more diversified livelihood strategies that are less available to residents of Sarahandrano, as Mandena is the only Madagascar National Parks approved entry point to Marojejy National Park for tourists. Livelihood diversification is a primary mechanism through which rural households increase their quality of life [67], and it has been linked to successful climate change adaptation among smallholder farmers [68]. In other settings, ecotourism has been identified as an effective pathway to livelihood diversification, and it may be a promising route to securing the wellbeing of farmers and surrounding ecosystems in the context of climate change [69].

We did not find support for our hypotheses that more years of farming experience and peer adaptation are associated with higher odds of climate adaptation. Prior studies have documented the importance of education programs like agricultural extension services in helping farmers implement climate change adaptation strategies [61]. In contexts like northeast Madagascar where access to extension services is severely limited, more experienced farmers may not have the information needed to implement new farming strategies even if they are willing to do so. Programs that emphasize information sharing and demonstrate the effectiveness of different adaptation strategies can help improve farmers' willingness to change their farming practices. In Nepal, for example, farmers who participated in labor exchange programs were more likely to participate in climate change adaptation programs [70]. In Uganda, an NGO-established network of model women farmers helped farmers who were already implementing more progressive farming practices to establish demonstration plots and share their strategies with neighboring farmers [71].

Social influence has been highlighted as an important driver of adopting adaptation strategies among smallholder farmers [36,37]. However, we did not find an association between peers' adaptive behavior and participants' odds of engaging in adaptive farming practices. Ethnographic work in the highlands of Madagascar suggests that successful farmers may be hesitant to share their knowledge with other farmers due to concerns that community members will be suspicious of their success and that they will be boycotted or sabotaged as a leveling mechanism [72]. In contrast, successful farmers may address these concerns by sharing their agricultural knowledge to maintain *fihavanana* (horizontal solidarity), and this approach should be considered when implementing climate change adaptation programs in the region [65,72]. The lack of social influence on farmers' adoption of adaptation strategies may also be due to minimal agricultural extension services in northeast Madagascar because complex behaviors like farming practices require multiple, reinforcing touch points to produce behavior changes [36]. Notably, we found few other studies that directly investigated the role of social networks in climate change adaptation, despite their vital role in the spread of adaptive behavior and community resilience [73].

If adaptation strategies are not implemented in the SAVA region of Madagascar, there may be particularly dire health consequences. Most farmers surveyed expect to experience decreases in their future food availability due to changes in temperature and rainfall. Prior studies have already documented high levels of food insecurity in this region of Madagascar [74], and we found further evidence that an extraordinarily high number of farmers experienced a time in the previous three years when they did not have enough food to meet their household needs.

Climate change will also likely have health impacts beyond food insecurity for farmers in Madagascar. Along with less rainfall and hotter temperatures, farmers in our study reported decreases in wild animal and plant species and increases in rodents and mosquitoes. These changes in local ecology may affect food security due to changes in the abundance of foraged foods, but they also have important implications for infectious disease ecology. For example, decreases in wildlife diversity may increase infectious disease transmission from wild and domesticated animals to humans [75], and rodents and mosquitoes are vectors for pathogens that pose a significant threat to human health in Madagascar, including hantaviruses, *Leptospira*, plague, malaria, and dengue [76–80]. Although participants reported increases in diarrheal diseases and malaria over the previous five years, more detailed studies using serological methods are needed to more directly investigate the link between climate change and infectious disease ecology in Madagascar.

This study had several limitations worth noting. First, we did not directly observe longitudinal changes in temperature and rainfall to compare with participants' perceptions of climate change, and existing climate data for this region of Madagascar are limited. In an ongoing research effort, we are using weather stations to collect detailed microclimate data in Mandena and inside Marojejy National Park. These data will provide insights into climate patterns that are important for smallholder farmers practicing rainfed agriculture, like changes in rainfall onset. Second, given that our sampling was driven by a social network survey, it is possible that some participants were in the same household; however, participants tended to name individuals outside of their household, limiting the number of intrahousehold responses. Nonetheless, this limitation means that we are unable to make inferences about whether household members were aligned in their decision-making process for climate change adaptations, despite the importance of joint decision making in many Malagasy farming households. Third, we used only a single question to capture food security over a three-year period. Given other ongoing research in the region, we expect that a culturally specific food security questionnaire will be available for future research. Finally, cyclone Cheneso made landfall in the SAVA region of Madagascar in January 2023 prior to data collection for this study. This event may have impacted how participants responded to the survey.

Conclusion

In this study of climate change perceptions and adaptive behavior among smallholder farmers in two villages in rural Madagascar, we found significant concern among study participants about the effects of climate change on their livelihoods. Despite this concern, few participants reported implementing farming strategies that would help them adapt to the effects of climate change. Although we were not able to directly observe longitudinal changes in precipitation and temperature, local observations from the farmers in our study provided insights into the everyday impacts of climate change that may be missed by large-scale climate models and weather data. These insights are vital to understanding the link between the experience of climate change and adaptive behavior. Our findings suggest that improved education programs and agricultural extension services are needed in this region of Madagascar to help farmers address their concerns about the consequences of climate change for their livelihoods.

Supporting information

S1 Table. Component models predicting odds of adaptation that met the inclusion criteria for model averaging (delta AICc < 2).
(DOCX)

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