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Impact of price shocks and payments on crop diversification and forest use among Malagasy vanilla farmers

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ABSTRACT

Crop diversification can help buffer farmers from market volatility and provide alternatives to unsustainable export-driven cash crop monocultures that are also driving forest clearing. We developed a discrete choice experiment (DCE) and an innovative tablet-based experimental game to predict the effects of price shocks and payment incentives on vanilla farmers' willingness to diversify their crops and support forest conservation in northeast Madagascar. The games incorporated spatial and ecological dynamics, and were conducted in groups of six participants using a within-subject design. The results of the DCE showed that farmers highly valued vanilla monocrops and were indifferent to diversified vanilla agroforestry. Women valued the relative earnings from diversified vanilla agroforestry more than men. In the games, the presence of shocks (a drop in vanilla price), led farmers to significantly diversify their crops. Shocks also incentivized more diversified land uses at the landscape level. Payments resulted in improved environmental outcomes through increased vegetation, but decreased crop diversity at the farm level. Payments also discouraged crop diversity among younger respondents. Focus groups followed the games and gave critical insights into game behavior. These findings shed light on the importance of market dynamics and payment schemes in encouraging pro-conservation behavior and crop diversification among farmers reliant on cash crops such as vanilla. We demonstrate how games can provide a low-risk, low-cost tool to predict the impacts of policy interventions.

1. Introduction

Cash crops are a significant source of revenue in many low-and-middle income economies, especially in the tropics. They significantly contribute to income opportunities in rural economies (Achterbosch et al., 2014; Giller, 2020) and can strongly influence cultural and political identity (Pengl et al., 2022), but cash crops can also lock communities into highly vulnerable export market dependencies (Roessler et al., 2022). Agrarian communities at forest frontiers can also face complex land management challenges, navigating difficult trade-offs between export cash crop production, soil health, and forest conservation.

In tropical regions, commercial and subsistence agriculture are considered the main drivers of land degradation, deforestation, and biodiversity loss (Geist and Lambin, 2002; Phalan et al., 2013; Jayathilake et al., 2021). Specifically, in the Global South, agricultural exports have been positively correlated with deforestation (DeFries et al., 2010). When farmers adopt monocultural cash cropping systems without adequate inputs, soil fertility depletion can rapidly occur, driving farmers to seek better quality lands, often resulting in forest clearance (Jellason et al., 2021; Piquer-Rodríguez et al., 2018). When monocultural systems sustain high yields or before soil quality is depleted, the relatively high price of cash crops can incentivize farmers to expand agricultural production to capitalize on market opportunities,

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particularly at the forest frontier (Miranda et al., 2024). Therefore, market-driven agricultural intensification often leads to land expansion and degradation, driving land transitions during periods of high commodity prices (Byerlee et al., 2014).

In many regions across the African continent, cash crop expansion is primarily led by small and medium-scale farmers, but growing evidence highlights the profound influence of distant global markets and human consumption on local land-use change (Ordway et al., 2017, Hoang and Kanemoto, 2021, Wilting et al., 2017). Smallholder farmers often cultivate fewer than five hectares, while medium-scale farmers, often associated with urban elite investments, typically cultivate tens to hundreds of hectares (Jayne et al., 2014, 2019). The effects of global market orientations on farmer land-use decisions are particularly pronounced in cash crop-based export economies.

Simplified or monocultural cash cropping systems can lead to the loss of natural vegetation, landscape diversity, and critical ecosystem services, thereby increasing the vulnerability of these systems to issues such as insect outbreaks and the impacts of climate change (Altieri et al., 2015, Wright et al., 2021, Mangan et al., 2023). Although agricultural intensification has been endorsed as an efficient land sparing approach, reducing the need for agriculture to encroach on natural habitats (Green et al., 2005; Phalan et al., 2011; Fischer et al., 2008), critics argue it fails to account for the beneficial functions of biodiversity (Perfecto and Vandermeer, 2010; Tscharntke et al., 2012). In addition, intensified models—such as large-scale monocultures—have historically led to the significant expansion of agroforests into natural forests (e.g., Andriatsitohaina et al., 2024).

Monocultural systems can also make farmers highly vulnerable and reactive to price volatility and uncertainty, and short-term spikes and drops in the price of crops (Achterbosch et al., 2014). These conditions can drive food crises (Tadesse et al., 2014), and can directly affect farmer risk-taking and decision-making processes (Goers et al., 2012). For instance, price volatility can signal a threat to producers, leading them to expand cultivated areas and diversify income sources as a means of income buffering or hedge-betting (Assouto et al., 2020). Agricultural price shocks and volatility threaten the poorest people's access to food and economic welfare (Akter and Basher, 2014, Amolegbe et al., 2021).

In contrast, diversified farming systems are suggested to reduce the negative environmental and social externalities and vulnerabilities associated with monocultural systems and enhance agricultural sustainability (Rasmussen et al., 2024; Yang et al., 2024). Agroecological practices, which include landscape and farm diversification, have been proposed as transformative and adaptive approaches to tackle challenges of global food systems, including the loss of biodiversity, land degradation, food insecurity, and to mitigate the impacts of climate change (Dale, 2020, Kerr et al., 2023). Relative to intensified monocultural farming systems, diversified systems support significantly greater biodiversity, carbon sequestration, and soil quality (Kremen and Miles, 2012), and can improve overall ecosystem service benefits (Leakey, 2018). Additionally, crop diversification is identified as one of the most dominant climate adaptation strategies by African farmers (Magesa et al., 2023), supporting the relevance of diversification strategies.

In northeast Madagascar, the agroecosystems are a mosaic of diverse agricultural land-uses including shifting agriculture, paddy rice, primary and secondary forests, and vanilla cultivation (Zaehringer et al., 2016; Martin et al., 2024). Agroecosystems also include small forest patches, or are adjacent to protected forests with some of the world's highest levels of biodiversity and endemism (Goodman and Benstead, 2005, Ganzhorn et al., 2001, Goodman, 2023). Vanilla production by smallholder farmers includes a spectrum of more diversified to simplified agroforests with variation in the conservation-value of systems, largely contingent upon land-use history (i.e., whether vanilla cropland is forest or fallow-derived) (Martin et al., 2024). As the largest vanilla producing region in the world (Iftikhar et al., 2023), the vanilla value chain in northeast Madagascar has a major influence on farmer income, creating a cash crop lock-in-effect that is characterized as lucrative but risky due to price volatility, climate change, and crop theft (Celio et al., 2023).

Following decades of price volatility, the vanilla market "bubble" burst in 2018, leaving farmers struggling with persistently low farm gate prices (Khan et al., 2022). Historically, price crashes have pushed many farmers to shift to alternative crops (Khan et al., 2022). Cash crop booms on the other hand, have intensified agricultural pressure on forests as production expands (Llopis et al., 2019). This expansion has produced mixed outcomes for protected areas and local well-being in Madagascar, where expanded cultivation often clashes with conservation efforts, impacting both ecosystem health and livelihoods (Llopis et al., 2022).

Deforestation driven by subsistence rice farming is also persisting, with small forest patches the most vulnerable to conversion (Zaehringer et al., 2016). Soil fertility quickly declines in upland rice cultivation, especially with shorter fallow cycles (Styger et al., 2007, 2009). In northeastern Madagascar, most households depend primarily on rice and vanilla farming for income (Hänke et al., 2018; Herrera et al., 2021). Recent studies indicate a positive association between food security and factors such as rice yields, vanilla yields, and land size (Herrera et al., 2021).

Little is known about how to effectively incentivize both agricultural diversification and forest conservation in such landscapes. Payments schemes can help incentivize agricultural diversification and positive environmental outcomes (Ferraro and Kiss, 2002; Bell et al., 2023), however, some studies also find that payments might reduce land-use diversification and increase land homogenization (Ochoa et al., 2019). Exposure to shocks such as extreme climate events, political crises, and price drops may also influence farmers' decisions to diversify their crops (Birthal and Hazrana, 2019; Rakoto Harison et al., 2024), change land use practices, and can lead to accelerated deforestation (Girard et al., 2021; Neugarten et al., 2024).

While forest-extraction for subsistence or income—such as foraging, harvesting timber, non-timber forest products, and agricultural land expansion—is often cited as a leading response to buffer against shocks, forest-based shock responses are nuanced and differ in relation to shock type (Wunder et al., 2014). An understanding of how farmers react to payments and shocks can provide important policy implications for how best to achieve positive environmental and social outcomes. This can involve gaining a careful understanding of the factors driving land use change, particularly in relation to coping and livelihood strategies, while aligning with the heterogeneous circumstances faced by specific demographics.

This study examines the impact of price shocks and payments on farmer land-use behavior using a mixed-methods approach, including a discrete choice experiment (DCE) survey, a novel experimental game, and focus group discussions. We investigate farmers' preferences for land-uses and gain qualitative insights into their motivations. We first administered a DCE survey to 204 households to test farmer preferences for diversified vanilla-based agroforestry and mono-crop vanilla. Next, we developed a spatially and temporally explicit experimental game called 'FallowMe' to predict how farmers respond to socio-economic shocks—in this case, the devaluation of vanilla crops—and to payments for forest conservation. The 204 participants of the DCE survey were grouped into sets of six to play the game and took part in post-game focus group discussions (34 games and discussions in total).

Games are an immersive method to engage stakeholders by simulating real-world conditions and stakeholder strategies allowing for the testing of hypothetical scenarios and observing participant responses (Redpath et al., 2018; Rakotonarivo et al., 2021a), and have been used to investigate the role of financial incentives for resolving conservation conflicts (e.g., Rakotonarivo et al., 2021a, 2021b; Bell et al., 2023). We demonstrate how games can offer a low-cost and low-risk approach to studying behavior and predicting the impacts of policy interventions, particularly where real world trials are not possible (Redpath et al., 2018, Rakotonarivo et al., 2021a). Our game was framed around farmers' land management strategies and was explicitly designed to represent the agroecosystem landscape of northeast Madagascar. Gameplay involves six participants (each representing one household) who make decisions on a digital farming landscape broken down into discrete cells. Finally, we use focus group debriefing discussions to contextualize the DCE and game results and to understand farmers' attitudes surrounding land-use decisions.

2. Methods

2.1.1. Case study and sampling

The study was conducted in Madagascar's northeast SAVA Region, in the communities of Andrapengy and Mandena. These communities were purposely selected for their agroecosystem features and their accessibility and proximity to forests with distinct tenure arrangements. Andrapengy borders a formerly classified forest (Forêt Classée), used as a community forest with little government oversight. The forest continues to be accessed and used traditionally with plural land claiming and tenure systems surrounding the forest. In contrast, Mandena borders Marojejy National Park, a well-known protected area with restricted access to local communities. Run by Madagascar National Parks and collaborating organizations, this park has a long history of tourism and active management.

In each of the communities, we first compiled a full list of households residing in the village provided by key-informants, primarily the village head and local community leaders ensuring isolated households and hamlets were also included. We then randomly sampled 25 % from each list allowing for substitution if the selected household was not present in the villages at the time of the study or was not willing to participate. In total, we administered the DCE and the games to 204 participants. Only one representative per household, the one who makes most agricultural decisions, was invited to participate in the games. Participants were compensated ~1 day of local labor wage (2 USD) for their time, plus a performance bonus based on their scores in one randomly drawn game at the end of the session; this bonus ranged from 0.2 to 1 USD.

We carefully piloted the DCE and the games, followed by focus group discussions in a nearby village in January 2023, and conducted the rest of the field work between April and June 2023. Local enumerators were trained in ethics, and in facilitating the game and conducting the DCE. All the questionnaires and game instructions were in Malagasy.

We obtained an ethical clearance from Boston University (#FWA00002457; IRB Protocol 6934×). Respondents gave their verbal consent after they were informed about the aim of the study, the potential use of the datasets, and the assurance that their data would remain anonymous, accessible only by the research team. They were told that they could decide not to answer any questions or stop the interview at any time.

2.1.2. Discrete choice experiment and survey

We developed a survey embedded with a discrete choice experiment (DCE). The first section of the DCE survey included questions on socioeconomic characteristics and land holding size, the proportion of land in vanilla, rice, other crops, and in fallow, the proportion of land for selling crops and for household consumption, and the price of vanilla in good and bad years (Appendix A). The survey also included questions about the farmers' earnings from vanilla and several questions about coping strategies in times of stress related to the use of natural resources. These were followed by belief statement questions about the sustainability of vanilla cultivation and the management of forests and farmlands (Fig. S1 in Appendix B). The DCE concluded the survey.

The DCE design was informed by initial semi-structured interviews and refined to key attributes through piloting. Our final design was simplified to three attributes: i) proportion of lands in monocultural vanilla - [0.6, 0.7, 0.8], ii) proportion of land in mixed agroforestry vanilla (including the proportion of other crops used for sale or household consumption) - [0, 0.1, 0.2], and iii) value of mixed agroforestry vanilla relative to the value of monocultural vanilla - [0.3, 0.4, 0.5]. This design aimed to estimate how much mixed vanilla must be valued to match participants' utility (preference) for monocrop vanilla. That is, the DCE addresses the question: How valuable would mixed vanilla agroforestry need to be in order for vanilla farmers to prefer it over monocrop vanilla? We used a d-efficient design with 15 unique choice tasks, of which participants received a randomly selected, randomly ordered subset of 5 choice tasks. In each choice set, participants chose between two options and their 'status quo' defined by their own agricultural land uses and relative earnings (Fig. 1).

2.1.3. Game design

The game "FallowMe" was framed around farmer decision-making in a mosaic agroecosystem, incorporating vanilla monocrop cultivation, diversified non-vanilla crops, and forested lands. The game was designed to simulate real-world social and ecological conditions; i.e., social coordination in shared and private lands, and environmental conditions like fluctuating soil quality with successive cropping years and ecosystem services spill-over effects from forested lands (Appendix C and D). FallowMe is part of the Elm-lab.org family of Netlogo-based games, played on tablet computers connected via a mobile hotspot, that explore land use decisions and human-environment dilemmas. This family includes NonCropShare, games focusing on insect-based ecosystem services (Bell et al., 2016; Bell and Zhang, 2016), GooseBump, which examines conservation and human-wildlife conflicts (Rakotonarivo et al., 2020; Rakotonarivo et al., 2021a, Sargent et al., 2022), and Sharedspace (Rakotonarivo et al., 2021b).

In the game, six farmers make decisions on a 15 × 15 grid-cell digital landscape (225 cells in total). Each farmer manages an equal share of private land on 5 × 5 grid-cells (25 cells) and shared management on common lands 5 × 15 grid-cells (75 cells) (Fig. 2). Common (or public) lands were located in the center of the game screen boarding all private cells. Participants could farm up to 30 grid-cells in each round, using cells from their private land (25 cells), the shared land (75 cells), or a combination of both, without exceeding a total of 30 grid cells.

Each game session included one practice session prior to the start of game play and a 5–10-minute group review session to make sure participants understood game rules and could ask clarifying questions. Each game had 8–12 rounds, where each round is analogous to one year of agricultural cultivation. The number of rounds per game was randomized to prevent participants from anticipating the end of the game.

Participants sat around a table with individual tablets and were allowed to communicate with each other, enabling discussion and coordination on land use decisions, mirroring real-life interactions. Game decisions were made in parallel by each participant every round. In each grid-cell, participants could choose to i) conserve forest or fallow land, ii) farm vanilla only (as in a monocrop system), and iii) farm diversified crops (non-vanilla crops) (Fig. 3). Non-vanilla crops were defined as including either annual or perennial crops (e.g., market vegetables, subsistence foods, and cash crops) cultivated within a farming system including three or more crop types.

The game was temporally and spatially dynamic, where the condition of the land depends on previous decisions, affecting ecosystem services and soil quality based on neighboring cells' conditions. On grid-cells where farming occurs, the yield and soil fertility vary (Fig. 3). Soil fertility was indicated with two white dots per cell that vanish as soil fertility declines. The yield of vanilla on more fertile land was 18, and 10 once fertility had dropped. The yield for 'other crops' was 12 and 10 after fertility had dropped (Fig. 3). At the start of each round, the cells were framed as "forest" and then players decide to farm, keep land forested, or restore land via fallowing after farming in the previous round. The cultivation-fallow-forest cycle is necessarily simplified and stylized to enhance the game's tractability, while still capturing key ecological processes. Games as experimental and learning tools strike a

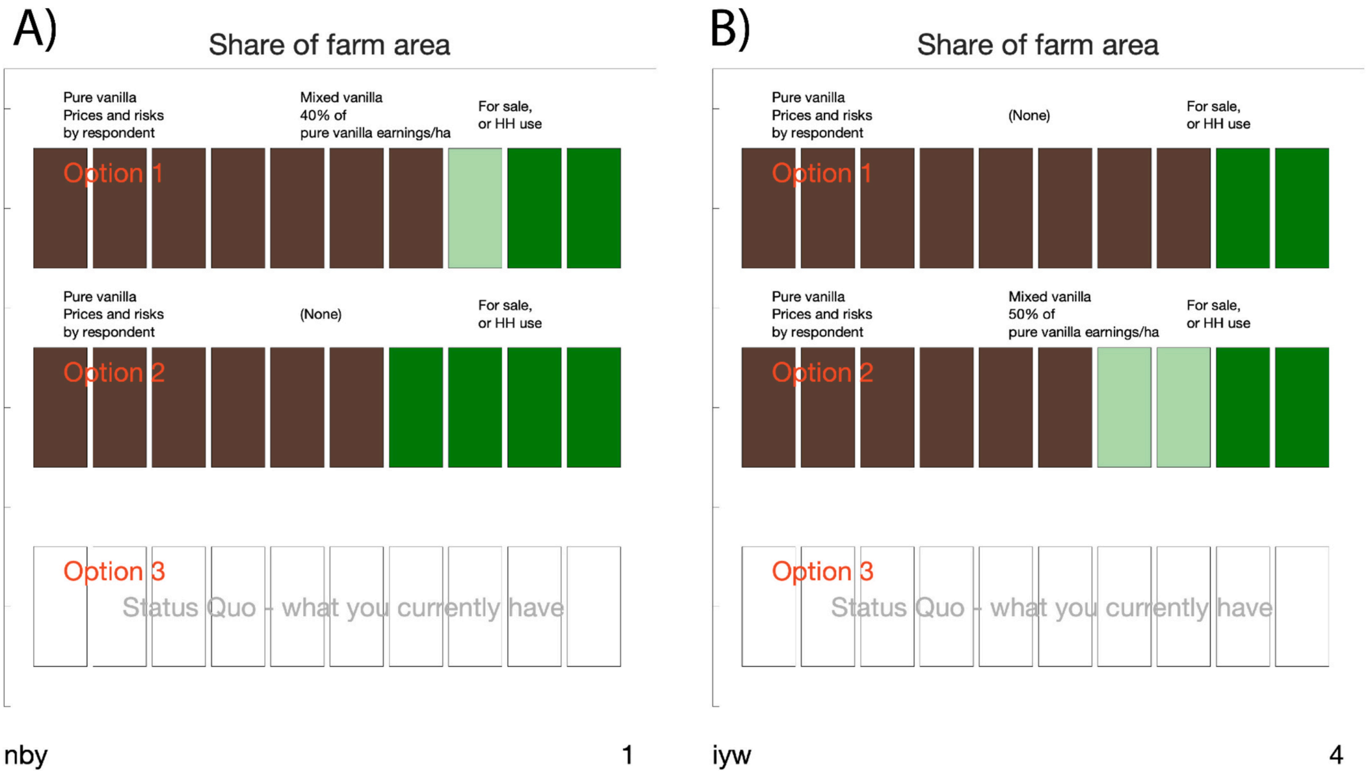


Fig. 1. Sample choice cards.

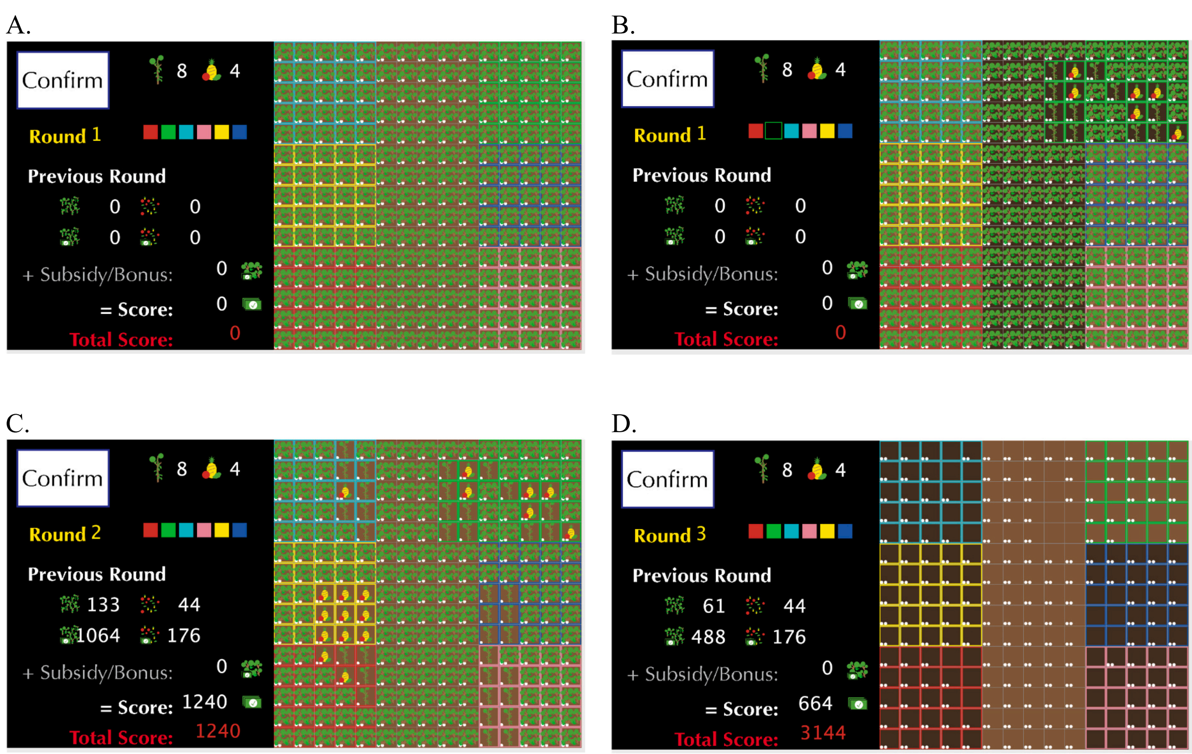


Fig. 2. Sample game screenshots describing game proceedings. A) Game screen at the start of the game: participants are color-coded, each participant has a 5 × 5 square cell. The shared land is the 5 × 15 area located in the center. The player can farm up to 30 cells in total at any given time, on their private plots or the shared land. The left side of the screen displays the game settings, including the crop prices (vanilla and non-vanilla), the round number, and the yields. B) Game interface of the active player (green) once they have confirmed their choices. C) Game screen at the start of round 2. The player scores (yields from the previous round) and their price are displayed on the left-hand side of the screen. Players can only view their own scores but can see the decisions made by others in real time. D) Game screen at the end of a game session (practice round) showing the player's total score. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

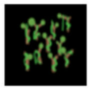
		1.Farm Vanilla 		2.Farm non-vanilla crops 		3.Fallow 
		High Yield*	**Low Yield****	**High Yield***	**Low Yield****	
Yield		18	10			0
				12	10	0
Neighborhood effect		+1 for all neighbouring forest/fallow cells (in a radius of two cells around the cell)		+1 for all neighbouring forest/fallow cells (in a radius of two cells around the cell)		0
Subsidy		0		0		**20*****
Crop price		**With no shock** 8	**With Shock ****** 4	Unchanged 4		0

Fig. 3. Game parameters.
*At the start of each session, the yield on all cells is at the high level when the land is farmed.
**Yield drops to the lower level in any given round if the cell is farmed with vanilla in the two previous rounds. It recovers the higher level after two consecutive rounds of fallowing.
***In the payment treatment, a subsidy of 20 points is awarded to each forest or fallow cell.
**** In the shock treatment, the vanilla price decreases to half of its initial price from round 5.

balance between realism and tractability that helps focus attention around the core dilemma(s) of the game – in this case, the choice of high vs. low risk crops and restoration in a competitive, shared landscape.

Once a cell was farmed by a participant in the shared land, no other participant can use that cell until it has returned to forest whereby it is considered unclaimed common land. Cells are allocated on a first-come, first-serve basis during the round. These features of the game were designed to reflect real-life tenure and land claiming strategies in Madagascar. The round ends after all participants have made their decision and select 'confirm' on the screen. At the conclusion of each round, a color-coded participant identity box is displayed with associated player scores and the overall game score with final participant actions displayed.

We used a within-subject design; each game session consists of one practice session (three rounds) followed by three different game treatments: i) baseline, ii) payments, and ii) vanilla price shocks, played in random order in each game session. In the payment treatment, participants got a subsidy for each forestland. The 'subsidy/bonus' row displays the value of the payment and calculates the number of grid-cells dedicated to forest/fallows by each player. In the vanilla price shock treatment, the price value attributed to vanilla cropping is reduced from 8 (without a shock) to 4 (with the shock), while the price of 'other crops' remains unchanged.

The game parameters were specified to reflect a plausible range of potential costs and benefit scenarios under simplified conditions (for instance, for a single game round). We have provided a detailed explanation of the theory underlying our game design in Appendix D. While such theoretical predictions were useful for calibrating the game parameters, our analyses do not aim to test specific game theoretic predictions, but instead focus on how farmers respond to policy interventions and how these responses vary across different sub-groups.

2.1.4. Focus group debrief discussions

We conducted focus group discussions after participants had played the game to understand how the game related to farmers' real-life experiences and to explore the farmers' motivations regarding land-use decisions. We conducted a total of 34 focus groups (17 in each community) with six participants per group, totaling 204 participants. The discussions took place immediately after the game session, with the six players remaining seated in a circle for a 40–45-minute focus group led by a facilitator (Appendix E). These discussions helped elucidate participants' experiences with the game and contextualize the results of the quantitative analysis. We primarily employed an inductive approach to thematic analysis to gain insights on participants' lived experience, perspectives, feelings, and behaviors (Braun and Clarke, 2006). However, a hybrid approach to thematic analysis for mixed methods was also employed, incorporating both deductive and inductive elements, (i.e., with pre-ordinate themes developed and the generation of novel themes from the data) allowing for the re-interpretation of data (Proudfoot, 2022). In this way, we integrated elements of the abductive approach post theme development, to employ more creative and interactive processes for generating and double-checking inferences with all study data (Timmermans and Tavory, 2012). The analysis was conducted using Nvivo 14 (Version 14.23.2) after transcriptions were translated from Malagasy (Betsimisaraka and Tsimihety North) into English from audio recordings by a native language speaker.

2.1.5. Data analysis

We used a mixed logit model to estimate participant-level estimates of utility coefficients in the DCE, according to:

$$U_{ijt} = \beta_i X_{ijt} + \varepsilon_{ijt}$$

The specific vector of attributes for the model we fit includes i) all main effects (each of the three attributes in the DCE design specified earlier); ii) squared terms for the attributes of fraction of vanilla land and fraction of mixed vanilla agroforestry land (to identify any curvature in the utility of these attributes); and iii) the interaction of the fraction of mixed land with the relative value of mixed land (to identify any effect of prices on the perceived utility of mixed land).

The game design aimed to explore the dynamics of decision-making and the potential trade-offs between personal and group benefits in land use strategies. We explored six game outcomes at the individual household level ('farm level'): 1) vanilla lands, 2) other crop lands, 3) alpha diversity, 4) use of the common land (public land use), 5) vanilla in common land, 6) other crops in common land. At the landscape level, we explored five group-based outcomes: 1) total fallow, 2) total vanilla land, 3) beta diversity, 4) gamma diversity, 5) total fallow in common land. We analyzed the game results at the level of the round, including all rounds from 1 to 8 and dropping rounds 9–12 to avoid end game effects in each of our completed games. Outcomes expressed (such as vanilla lands, other croplands, alpha, beta and gamma diversity, and common land use) are all summed or averaged across the farm level (individual game outcome) or the landscape (group game outcomes).

To evaluate farm-level and landscape-level land use diversification strategies in the games, we assessed three types of diversity based on the distribution of land use categories (vanilla cultivation, other crop cultivation, and forest/fallow land) following Jost (2006): alpha diversity, representing the diversity of land use choices within individual farms; beta diversity, reflecting the differences in land use between different farms; and gamma diversity, indicating the overall diversity of land use across the entire landscape.

To relate behavior in the game to attitudinal variables, we included belief statements from the questionnaire survey in the model. We also controlled for other socio-economic variables such as age, gender, education, area of vanilla, and other crops. In addition, we considered two-level interactions between the treatments and other participant-related variables (such as gender, age, village ID, and land holdings). Table S1 provides a summary of the explanatory variables included in our models.

All analyses explaining outcomes (utility coefficients or game outcomes) were robust ordinary least squares regression. Standard errors clustered at the village level (for DCE results) or at the game session level (for game results). These analyses were performed using Stata 16.

3. Results

3.1. Participant socio-demographics and attitudes

On average, study participants were 43 years old (SD = 13) and had 6.8 years of formal education (SD = 3). Of the 204 participants, 44 % identified as female and 56 % male. The mean amount of rice used to plant their fields—measured in *daba*, a local unit representing both rice volume and land size (analogous to a bushel)—was 5.6 *daba*. This proxy for land size relies on participants' subjective estimates, which may introduce variability; however, our unpublished calibration data suggest that 1 ha corresponds to approximately 4 *daba*. The average land for vanilla cultivation was 1.74 *daba*, with 75 % of participants indicating they grew crops other than vanilla. Participants had 1.78 *daba* dedicated to food, but reported that only 50 % of their overall food needs were met from what they grew on this land. Participants from the community of Mandena had, on average, twice as much farmland as those from Andrapengy, 2.5 times more land in paddy rice cultivation, and double the land in fallow and vanilla cultivation (see Table S1 in Supplementary materials). The attitudinal data (belief statements) suggest that only a third of respondents valued mixed vanilla agroforestry and most farmers disapproved of collective forest management (Fig. S1).

3.2. Discrete choice experiment results

The DCE revealed key insights into farmers' preferences and attitudes towards land use and cropping strategies. It showed that farmers positively valued vanilla monocrops but were indifferent to diversified vanilla agroforestry (Table 1). The DCE results further suggested that the importance respondents placed on the fraction of vanilla was positive but decreasing with higher vanilla land (concave); and the importance they placed on the value of mixed vanilla production was positive and increasing with the amount of land they have committed to it (Table 1).

Analysis of the DCE and survey belief statements showed farmers with a positive perception of diversity are more likely to value the relative earnings from diversified vanilla agroforestry (Table 2). This indicated good content validity of the DCE. The DCE also showed that women tend to value the relative earnings from diversified vanilla agroforestry more than men (Table 2).

Survey results revealed several motivations for adopting mixed vanilla agroforestry (vanilla mixed with other crops such as cloves, mango, coffee, orange, and so forth, see Table S2). The most prevalent reason was crop diversification, cited by 12.75 % of farmers. Some farmers (10.78 %) practiced mixed vanilla agroforestry for shading vanilla plants and supplementary income. Land scarcity is another critical factor for 9.31 % of farmers, who engaged in mixed vanilla agroforestry.

3.3. General gameplay across treatments

Farm-level game results (gameplay at the individual level) show that older participants were more likely to diversify and less likely to use the common forestlands. Larger landholdings were positively associated with crop diversification. Women tended to plant less monocrop vanilla on their privately held land. Participants in Mandena (neighboring Marojejy National Park) were less likely to plant other crops or use the common forestlands compared to those in Andrapengy. People who had positive perceptions of diversified vanilla agroforestry were less likely to use the common land. Farmers with more years of education were more likely to plant vanilla monocrop in the common land (Table 3).

At the landscape level, we found that groups of farmers were more likely to maintain forested lands in the commons if they had more young farmers, more educated households, a positive perception of diversified agroforestry, and larger landholdings (Table 4). Landscape diversity (gamma diversity) was higher in Mandena than in Andapengy. During the game, players were allowed to discuss, collaborate, and create an agreement on land use if they wished. In Mandena, participants in 11 games formed land use agreements, of which only two were not followed through by all players. One group agreed for each player to farm only 5 grid cells and leave the rest as a forest reserve. Two groups agreed to not use any of the common land to preserve the forestlands. In Andrapengy, two groups discussed the use of the common land and collectively decided that the use of the common land was permitted.

3.4. Game results: the impacts of shocks and payments on agricultural diversification, use of common lands, and forest conservation

We found that shocks significantly incentivized crop diversification in the games (less vanilla monocrops and more other crops, Table 4). Shocks also led to more diverse land uses defined as a heterogeneous landscape with a mix of vanilla crops, forests and other crops (gamma diversity at the landscape levels, Table 4). One participant explains the benefits of diversification strategies in the presence of shocks:

> "In general, there are two kinds of crises that are common here; food shortage and money shortage… a good way to maintain a yield for sustainable farming in the face of those crises is planting other crops apart from vanilla and rice. If you focus on just vanilla farming and rice, you will still suffer from those shortages. So, you need to calculate when the crisis seasons are and plant crops accordingly… Cassava, sweet potatoes, peanuts are some examples of crops we can plant. That's how we fight against crises here."

Table 1
Mixed logit model showing DCE individual-specific preferences.

Variables	Coef.	SE
Fraction of vanilla land	8.205***	1.961
Fraction of mixed vanilla land	1.024	3.716
Relative value of mixed land	0.251***	0.007
(Fraction of vanilla land)^2	-8.995***	1.884
(Fraction of mixed vanilla land)^2	-14.207*	7.878
Fraction of mixed land x Relative value of mixed land	0.154*	0.711

*** p<0.01, ** p<0.05, * p<0.1
Significant effects are colored blue (positive coefficients) or orange (negative coefficients), with darkest shading for p-values less than 0.01.

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.
Significant effects are colored blue (positive coefficients) or orange (negative coefficients), with darkest shading for p-values <0.01.

Table 2
Utility coefficients explained by socio-economic variables and belief statements.

Variables	Fraction vanilla (1)	Fraction mixed vanilla (2)	Relative value of mixed vanilla (3)	(Fraction vanilla)^2 (4)	(Fraction mixed vanilla)^2 (5)	Fraction of mixed vanilla x Relative value of mixed (6)
Male	-0.134	0.111	-0.00878**	-0.305	0.604	0.0294
Mandena	0.158	-0.0823	0.00664	-0.175	-0.147	-0.0256
Age	-0.00145	0.00269*	-4.99e-05	-0.00520	0.00481	0.000396
Education	-0.00988	-0.00809	0.000152	-0.0386	0.0271	0.00435
Total land holdings	0.0224	0.000940	0.000467	0.0380	-0.00453	-0.00158
Vanilla lands	-0.0387	-0.0323	0.00181	-0.0421	-0.117	0.0328
Sustainability	0.0578	-0.0166	0.00249	0.0714	-0.210	0.0119
No rules	0.0120	-0.0320	0.000945	0.0390	0.425	-0.00391
Diversity	0.00892	0.00192	0.000637**	0.0100	-0.0307	0.00547*
Community management	0.0496	-0.191*	-0.00748	-0.156	-0.560	-0.0414
Constant	8.572***	2.260***	0.0216*	-8.421***	-10.32***	0.0640
Observations	193	193	193	193	193	193
R-squared	0.060	0.057	0.105	0.033	0.040	0.037

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.
Significant effects are colored blue (positive coefficients) or orange (negative coefficients), with darkest shading for p-values <0.01.

(Male, age 28, Mandena)

We also examined how participants engaged with the public common forestlands, representing a third of grid cells located in the middle of the game landscape. In the presence of price shocks, we found participants were more likely to plant other crops and significantly decreased vanilla monocropping in the shared lands (Table 4). As participants explain:

> "When the vanilla price went down, I increased the land for other crops. I reduced the plantation of vanilla and I left some parts of my land forested because I do not want my land to lose its fertility so that I can use it again later. With good fertility, you do not have to plant a lot of vanilla to have good products."
>
> (Male, age 23, Mandena)

> "When the vanilla price went down to as much as the pineapple price [other crops]— I didn't ruin my land, I just planted other crops on a small part of the public lands."
>
> (Male, age 40, Mandena)

Next, we examined the effects of payments on farmers' diversification strategies in the game. Payment was more likely to increase forests and decrease monocrop vanilla at the farm-level. We also found that when participants were awarded payments, there was less land cover diversity within individually held lands (Table 3). In Mandena, the community neighboring the national park, we found that the payments had a greater effect in disincentivizing vanilla monocropping compared to Andrapengy. At the landscape-level (Table 4), payments were more likely to increase forest cover and decrease monocrop vanilla.

In focus groups, some participants expressed why they were not in favor of payments for maintaining forests on the entirety of their privately held lands. Rather, they preferred to keep at least some portion of their land cultivated (n = 23) or expressed the continued imperative of farming (n = 16). These reasons included farming as the basis of life and food security, distrust and uncertainty in receiving payments, personal and cultural values associated with cultivation as a means to provide for one's family through one's own hard work. As a participant suggests:

> "In the Holy Bible, it is said: 'You will win your bread by the sweat of your forehead.' So, gifts and bonuses won't be sufficient to feed the whole family. Then, I tried hard to plant. If we endlessly depend on bonuses from others it won't work. We never know! The boat might sink or be broken apart. The gift won't get here."
>
> (Male, age 64, Andrapengy)

Others express uncertainty with food insecurity in the future as reasons for continuing to farm despite payments:

> "As long as we are here, we must farm, because we do not know what the future holds."
>
> (Female, age 62, Andrapengy)

> "We don't know what else we could do for a living. We never feel assured with what we have. We don't feel we have enough food security. For that reason, we keep on farming."
>
> (Female, age 48, Andrapengy)

Table 3
Game results at the individual farm level.

Variables	Total vanilla (1)	Total other (2)	Alpha (3)	Public land use (4)	Vanilla in public land (5)	Other crops in public land (6)
Game round	-0.181***	0.115***	-0.00310	0.0107	-0.0759	0.0866***
Payment	-2.878***	-0.758***	-0.0416***	-0.0118	-0.0940	0.0822
Shock	0.395	-0.692*	-0.00970	0.769	0.526	0.243
Shock x Game round	-0.382***	0.556***	0.00471	-0.0295	-0.142**	0.113**
Male	1.440*	-0.438	-0.0212	0.668	0.756	-0.0885
Mandena	-0.937	-1.418**	-0.00794	-1.793*	-1.229*	-0.564
Fraction of vanilla land	1.000***	-0.0603	0.00788	0.372	0.464**	-0.0920
Fraction of mixed vanilla land	-0.0641	-0.0561	-0.00276**	0.0421	0.00762	0.0345
Relative value of mixed land	-24.15	-10.51	-0.476	-23.99	-15.68	-8.309
Age	0.000661	-0.00216	0.000305***	-0.0227*	-0.0141	-0.00857*
Education	0.285**	-0.00321	0.00352	0.279**	0.202**	0.0775
Total land holdings	0.108	-0.0193	0.00513***	-0.0824	-0.0545	-0.0279
Vanilla lands	-0.0554	-0.0625	-0.00926	-0.0923	0.0438	-0.136
Sustainability	0.00640	0.0138	-0.00489	0.464	0.327	0.137
No rules	-0.291	-0.356	-0.00469	-0.681*	-0.322	-0.359*
Diversity	-0.0351	0.0186	7.12e-05	-0.0416*	-0.0277	-0.0139*
Community management	-0.462	-0.617	-0.00541	-0.508	-0.149	-0.358
Constant	15.79***	9.645***	0.932***	10.38***	6.237***	4.142***
Observations	5,031	5,031	2,551	5,031	5,031	5,031
R-squared	0.081	0.083	0.053	0.088	0.062	0.064

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.
Significant effects are colored blue (positive coefficients) or orange (negative coefficients), with darkest shading for p-values <0.01.

Table 4
Game results at the landscape level.

Variables	Total fallow (1)	Total vanilla (2)	Beta diversity (3)	Gamma diversity (4)	Total fallow in public land (5)
Game round	0.494	-1.146***	0.00137	0.00143	-0.109
Fraction of vanilla land	-2.458	3.027	-0.0117	0.00612	-1.159
Fraction of mixed vanilla land	4.910***	-0.492	-9.94e-05	-0.0207***	1.173
Relative value of mixed land	-80.20	-207.0	0.967*	1.755*	156.1
Age	-0.201***	0.184**	0.000240	0.000109	-0.0989*
Education	-31.87	1.306	0.00258	-0.00489	2.294*
Andrapengy	2.491	3.133	-0.00661	-0.0515*	7.054
Total land holdings	-3.797*	4.451**	0.0119*	-0.00245	2.242*
Vanilla lands	21.99***	-13.84**	-0.0252*	-0.0599*	7.047
Sustainability	5.514	-3.257	-0.00571	-0.00813	-3.043
No rules	10.26	7.401	-0.00816	-0.103***	7.987
Diversity	1.563***	-0.567	0.00166	-0.00613**	1.113***
Community management	30.01***	-3.520	-0.0286	-0.0755***	6.273
Payment	22.12***	-18.27***	0.0148	-0.0317	-0.133
Shock	2.211	1.808	-0.00242	-0.0141	-4.406
Shock x Game round	-1.106	-2.196***	-0.00145	0.0110***	0.121
Constant	-3.575	77.40	0.117	1.562***	-48.00
Observations	889	889	888	889	
R-squared	0.305	0.196	0.052	0.282	0.253

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.
Significant effects are colored blue (positive coefficients) or orange (negative coefficients), with darkest shading for p-values <0.01.

Those in favor of payments for maintaining forest cover (no explicit proportion) reported reasons such as monetary benefits (n = 7), soil fertility benefits from maintaining forests (n = 6), and pro-environmental attitudes (n = 3).

In focus groups, of the 23 participants who discussed using the common lands, 39 % stated they used the commons to preserve the soil quality of their privately held farm plots or to seek land with higher soil quality. Further, 34 % said they saw a vacancy and wanted to expand their farmland, and another 30 % said they used the common lands because a group use agreement was established with other participants. The 10 participants that commented they preferred not to use the commons stated their reasons were to protect ecosystem services and to maintain the forest as a safety net of resources.

3.5. Interaction effects of game treatments and socio-demographic variables

We also explored interaction effects with the shock treatment and socio-demographic variables. Younger participants were much more responsive to shocks; shocks significantly decreased vanilla farming on private and common lands among younger participants compared to older participants (Table 5). Additionally, we found that farmers with lower education levels were less likely to farm other crops in the presence of shocks. In 70 % (24/34) of focus groups, 64 participants expressed their preference to continue cultivating vanilla despite price drops. One participant explained:

> "The reason why someone continues planting [vanilla] even when the price declines is that they hope that the price of vanilla will rise. They're always steady if we compare it to a race. When the commander says 'go!' They go with no hesitation. In real life, when the vanilla price rises they're ready and always have enough to sell. Plus, they don't want to regret having not farmed vanilla when the price is good."
>
> (Female, age 30, Andrapengy)

Focus group discussions also shed light on a tendency for farmers to prefer a balanced approach to crop and livelihood diversification that explicitly includes vanilla farming, other crops, and other sources of income. When asked how to promote the protection of livelihoods, 36 % of participants suggested crop and land use diversification, and 30 % suggested protecting the environment, while the rest provided unique responses. As one participant described:

> "If we see that the land starts to lose its fertility, we should leave it forested. And it is also necessary to plant other crops because vanilla season is only once a year. So, other crops will help you protect livelihoods. And together with vanilla plantations, we should have another plantation that helps make money. And we should never forget to leave some lands forested because without forests all that you plant won't grow well."

Table 5
Game results showing the interaction effects between treatments and socio-economic variables.

Variables	Total vanilla (1)	Total other (2)	Alpha (3)	Public land use (4)	Vanilla in public land (5)	Other in public land (6)
Game round	-0.204***	0.139***	-0.00251	-0.0232	-0.0949**	0.0717**
Game with subsidy treatment	-0.659	-1.962**	-0.174***	0.385	0.348	0.0365
Male	0.915	-0.406	-0.0466***	0.359	0.332	0.0275
Mandena	-0.838	-1.780***	-0.00691	-2.351***	-1.571**	-0.780**
Age	-0.00547	-0.00318	4.95e-05	-0.0244*	-0.0177**	-0.00667
Education	0.270*	-0.0937	0.00130	0.210	0.171	0.0389
Total land holdings	0.127	-0.0166	0.00257	-0.0845	-0.0425	-0.0420
Vanilla lands	0.297	-0.0511	-0.0137	0.225	0.312	-0.0870
Interaction between Payment x Gender	0.396	0.829	0.0510*	0.565	0.519	0.0468
Payment x Mandena	-1.655*	0.711	-0.0157	0.127	-0.213	0.340
Payment x Age	-0.00790*	0.00667*	0.000523***	-0.00720*	-0.00514	-0.00206
Payment x Education	-0.0196	0.0625	0.00481	0.0460	0.0438	0.00219
Payment x Total land holdings	-0.143	0.108	0.0107***	-0.0144	-0.0762	0.0618
Payment x Vanilla land	-0.243	-0.453*	0.000781	-0.446	-0.213	-0.233
Shock x Game round	-0.561***	0.466**	-0.00204	-0.0861	-0.199	0.113
Shock x Game round x Gender	0.227*	-0.190	0.00501	0.0791	0.113	-0.0338
Shock x Game round x Mandena	0.0376	-0.00986	-0.00221	0.0299	0.0808	-0.0508
Shock x Game round x Age	0.00433***	-0.00167	3.75e-06	0.00276***	0.00326***	-0.000497
Shock x Game round x Education	-0.0107	0.0382**	0.000148	0.0152	-0.00517	0.0204*
Shock x Game round x Total Landholdings	0.0190	-0.0231	-0.000412	0.0192	0.0132	0.00605
Shock x Game round x Vanilla lands	-0.0832	0.0325	0.00293	-0.127***	-0.0929**	-0.0336
Constant	13.91***	7.467***	0.928***	8.353***	5.749***	2.604***
Observations	5,220	5,220	2,644	5,220	5,220	5,220
R-squared	0.059	0.082	0.057	0.065	0.045	0.051

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.
Significant effects are colored blue (positive coefficients) or orange (negative coefficients), with darkest shading for p-values <0.01.

(Male, age 28, Mandena)

The interaction effects between payments and individual socio-demographic variables suggested some key patterns. First, we found that payments were more effective at increasing farm-level diversity among men and for participants with larger land holding size. One participant comments on the role of land holding size relative to forest conservation which demonstrates the tension between land availability, farming, and food security:

> "People are not used to leaving lands forested. Actually, space to farm has become smaller compared with the size of the population. And here, life is farming. If you do not farm, you won't eat. And as long as there are buyers of vanilla, even with very low prices, people will keep on farming it."
>
> (Male, age 66, Mandena)

Payments encouraged more use of the public lands and discouraged land use diversity among younger participants. In the focus groups, only three participants shared that they used the public lands when there was payment in the game. They all stated they used public lands to preserve, care for, and maintain soil quality of their own private land by leaving it fallow/forested and expanding their farmlands to the commons.

4. Discussion

4.1. Navigating shocks and maintaining balance

We investigated the impacts of price shocks and payment schemes on farmers' land use decision-making within a complex agroecosystem landscape. In this system, the production of cash crops and the imperative for forest conservation create challenging trade-offs for farmers. We found that farmers generally valued vanilla monocrops more highly than diversified vanilla agroforestry systems, but that crop and land use diversity are widely used strategies in the face of price shocks across study sites. We found that shocks (at the individual farm-level) led people to plant less vanilla monocrop and more other crops in private and public common lands. Additionally, shocks enhanced land use diversity at the landscape level (gamma diversity) through farmers' diversified cropping and land use, which would likely provide greater conservation value compared to vanilla monoculture. Similarly to women, younger farmers were highly reactive to shocks; they decreased monocrop vanilla, including in common lands in the face of shocks.

We also found that a balanced agroecosystem approach and crop diversification are salient farmer strategies in the presence of shocks. Several studies demonstrate that crop and on-farm diversity are adaptive strategies harnessed by farmers in the face of climate shocks (Asfaw et al., 2019) to improve household food security (Mulwa and Visser, 2020) and agricultural resilience (Birthal and Hazrana, 2019). This may also demonstrate how farmers in mosaic agroecosystems actively manage ecosystem processes using a balanced approach, accounting for ecosystem services and disservices in relation to tree cover (Ango et al., 2014). Our study adds to this literature and shows that economic shocks alone (in the real world context of recurring shocks) can also encourage diversification.

Despite farmers' strategies favoring a more balanced agroecosystem approach in the face of shocks, on-going extreme boom and bust cycles of vanilla prices have led farmers to assert that even if the price drops, "it will rise sooner or later" (Male, age 32, Andrapengy). This sentiment might help clarify the results of the DCE, which showed that farmers placed significantly higher value on vanilla monocrops compared to diversified vanilla farming. Thus, vanilla will likely continue to be a fixture in the northeast agroecosystem, in the absence of severe prolonged climatic disturbances. Coping with these cycles is not a new phenomenon for farmers in northeast Madagascar. These communities have a long history of harnessing complex ways to navigate the volatility of vanilla markets, suggesting that vanilla may continue to shape the region's "export cultures" (Zhu, 2018).

Vanilla farming spans a spectrum from diversified and complex systems with high conservation value to simplified monocultural systems with less biodiversity (Martin et al., 2024, Hending et al., 2020, 2023). Identifying strategies to support sustainable complex agroforestry practices with higher biodiversity is essential. As our study found, 75 % of participants already cultivate vanilla agroforestry systems that have other crops grown alongside vanilla and its tutor tree. These more complex vanilla agroforestry systems could benefit from initiatives focused on sustainable intensified diversification, for example through syntropic agriculture (Andrade et al., 2020) and ecological intensification (Garibaldi et al., 2019; Kremen, 2020).

Determining the target demographics for policy and program interventions is also important. Our study showed that farmers with larger land holding size and older farmers (presumably more experienced farmers) were more likely to adopt diversification strategies. We also found that women are key drivers of diversification, particularly on their own private land. However, the motivations for diversification likely differ between women and relatively land-wealthy older men. For women, diversification may be driven by household food security needs and serve as a coping strategy. The role of women in enhancing household food security in Africa has long been acknowledged (Lado, 1992; Kotze, 2003). Thus, recent research underscores the importance of gender-sensitive approaches and women's empowerment as a specific pathway for crop diversification (De Pinto et al., 2020).

Crop diversification is a longstanding coping strategy for Malagasy farmers, offering sustainability and resilience benefits. We found that participants were more likely to diversify their crops and decrease vanilla monocropping in the common forestlands (and hence vanilla-driven forest loss) in the presence of price shocks. This highlights the role of crop diversification in supporting biodiversity conservation (Rasmussen et al., 2024). However, the relationship between crop diversification and deforestation remains context-dependent. In focus groups, participants highlighted the issue of land scarcity (in relation to soil degradation) as a key driver of agricultural expansion, echoing findings from previous studies (Gomiero, 2016). Therefore, crop diversification alone may not be enough to stop forest clearing where land availability is a constraint. Evidence also suggests that multiple ecosystem services in land-use decisions—which can represent increased diversification—can reduce tropical deforestation, though the effect depends on the share of forest in the landscape (Knoke et al., 2022). Addressing land scarcity may require additional strategies such as collective landholdings (Williams and Holt-Giménez, 2017) to explore how aggregating smallholder farming landscapes while diversifying cropping systems can simultaneously decrease forest pressure and food insecurity. Payments and supporting financial instruments for crop diversification, for instance, might also encourage a shift from diversification as a necessary coping mechanism to a robust and thriving diversified agricultural system that boosts farm productivity and enhances biodiversity conservation.

4.2. Key considerations for payment schemes

This study provided valuable insights to test and qualitatively analyze the impacts of payments on farming decisions and pro-forest conservation behavior. Payment schemes were effective in generating pro-forest conservation outcomes, particularly at increasing forest cover at the landscape level, but they also produced negative externalities and had varying impacts across the two study sites. These externalities resulted from payments encouraging i) youth cropland expansion into public lands and ii) a less heterogeneous landscape.

First, we found that for younger participants, payments discouraged land use diversity at the farm level and led to cropland expansion in the commons. This indicates that payment schemes for leaving land forested may not always have the desired effect if they lead to unintended environmental consequences elsewhere; i.e., leakage. These results reflect similar findings (Ochoa et al., 2019), where payments increased land homogenization and reduced land-use diversification. Yet, payments were more effective at increasing farm-level diversity among men and for participants with larger land holdings. Conditions of land scarcity and high unemployment rates have driven increased deforestation by youth in Ghana, particularly through agricultural land expansion (Kyere-Boateng and Marek, 2021). The constraints placed on youth due to limited access to land and productive resources highlight the need for resilience-enhancing, youth-specific agricultural policies (Mabiso and Benfica, 2019) and the development of youth-friendly land policies to address these barriers (Kumeh and Omulo, 2019).

Second, contrary to promoting a balanced approach and crop diversification, we found that payment schemes reduced farm and landscape diversity, resulting in landscapes with increased forest cover and more monocultural vanilla cultivation. The effect of payments resulted in greater land homogenization. Despite payments increasing the proportion of land contributing to positive conservation outcomes, this may underscore a critical conservation trade-off. In a community like Mandena, where large areas of forestlands are protected, with more positive attitudes towards communal management (*this study*), conditions may favor a land sparing approach. In this context, sustainable vanilla intensification and payment schemes for forest preservation may together encourage better conservation outcomes. This can be accomplished through measures such as certification programs, niche market opportunities, and financial incentives to promote diverse and nutrient-rich crops (Waha et al., 2018). However, land sparing approaches through land-use intensification have complex conservation outcomes, as seen in northeast Madagascar, where native and exotic species richness increased with land-use intensity, but the presence of endemic species decreased (Raveloaritiana et al., 2021). Conversely, in Andrapengy, there is a tendency for diversification, and fewer lands are dedicated to vanilla cultivation. These conditions may favor a land sharing oriented approach that emphasizes promoting and strengthening existing diversified agricultural practices.

An examination of collective management and land-use coordination across study sites offers insights into conditions that may enhance their effectiveness. We observed that landscape diversity (gamma diversity) was consistently higher in Mandena than in Andrapengy. In Mandena, participants also held discussions on land-use coordination in over half of the games, and relied less on vanilla monoculture in the presence of payments. In contrast, only two groups in Andrapengy discussed land uses and agreed to allow farming on common lands. Beyond the propensity for coordination, Mandena's dynamics may also be influenced by factors such as a clearly defined top-down forest management regime including forest restrictions imposed by the national park. There is also a history of consistent participation in vanilla cooperatives with secure market access. Additionally, Mandena had twice the landholdings (in rice, vanilla, and total holdings), a reasonable proxy for wealth. In contrast, Andapengy is adjacent to an unmanaged former government forest reserve (Forét Classé) with a complex history of forest exploitation and land tenure insecurity, while the community lacks consistent market networks, likely contributing to greater financial instability and uncertainty. These conditions—along with other factors we did not explore, such as community history, migration patterns, and demographic disparities— may position a community like Mandena for more successful collective action. It is particularly important to examine how payment schemes and collective action interact within the context of telecoupling, as such schemes may benefit some people while negatively impacting those more reliant on forest resources (Llopis et al., 2020), with the potential to exacerbate existing inequalities.

4.3. Methodological contributions and instrument validity

In this study, we address the construct validity of the games by examining how covariates of actual farm behavior relate to participants' gameplay. Focus group discussions after gameplay further helped participants explain how their game choices corresponded to real-life farming practices. During these debriefs, we assessed validity by asking participants to interpret the game's goal. Many participants (n = 63), representing all focus groups, noted that the game reflected their practices and had real-life applications. Games in rural contexts often exhibit high incentive compatibility, with participants making choices that mirror their real-life decisions (Rakotonarivo et al., 2021a; Bell et al., 2023). Although the game is designed to simulate reality, participants bring various behavioral layers into gameplay—reflecting not only farm-related decisions, but also aspects of play, exploration, and interpersonal dynamics (Cárdenas and Ostrom, 2004).

This study demonstrates the effectiveness of mixed-methods game-based research approaches to investigating complex agroecosystem and conservation trade-offs, as well as testing potential land management policy interventions. The approach can serve as a useful tool for aligning policies with specific community needs and localities based on their land use configurations. Our study highlights that games represent an effective, immersive, and cost-efficient method for studying behavioral responses and predicting the impacts of policy interventions. Low-cost, rapid tools like immersive experimental games, integrated with mixed-methods approaches, can help inform policy interventions to address complex social-ecological and conservation challenges in the most vulnerable agroecosystems.

5. Conclusion

We investigated farmers' preferences for crop diversification as well as the impacts of shocks and payments on farmers' willingness to diversify and support forest conservation in northeast Madagascar. Our findings revealed a strong preference for vanilla monocrops over diversified systems among farmers. We found vanilla price shocks prompted increased crop diversification. Gender (women), land size, and age were also positively associated with crop diversification. Young people were the most reactive to shocks, opting to plant other non-vanilla crops on privately held and common land when vanilla prices collapsed. Taking a mixed method approach allowed us to elucidate farmer behavior and learn more about the important role of crop and land use diversification as an adaptive strategy for navigating the impacts of economic shocks.

We also tested the role of payments on farmers' land use and found that payments could achieve positive conservation outcomes, but resulted in negative externalities. Specifically, payments discouraged land use diversity among young people on privately held lands, but increased their use of public lands, suggesting cropland expansion encroaching on unclaimed forest as an unintended consequence of payment schemes. The distinct characteristics of the communities in this case study underscore the unique preferences for land use within the same region, particularly in the context of payments, highlighting the complex interplay of necessity-driven and market-driven land use motivations within rural communities.

CRediT authorship contribution statement

Marie Fleming: Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Andrew Bell:** Writing – review & editing, Visualization, Validation, Methodology, Formal analysis, Data curation, Conceptualization, Design of the experimental games in Netlogo: https://www.elm-lab.org/. **Henintsoa Rakoto Harison:** Writing – review & editing, Validation, Project administration, Methodology, Investigation, Data curation. **James Herrera:** Writing – review & editing, Validation, Project administration, Methodology, Investigation. **A. Bradley Duthie:** Writing – review & editing, Validation, Methodology, Conceptualization. **Randall Kramer:** Writing – review & editing, Validation, Project administration, Methodology. **O. Sarobidy Rakotonarivo:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization.

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Declaration of competing interest

We have nothing to declare.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biocon.2024.110915.

Data availability

Data will be made available on request.

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