Environmental Science and Policy 159 (2024) 103819

Contents lists available at ScienceDirect

Environmental Science and Policy

journal homepage: www.elsevier.com/locate/envsci

Uncertainty and perceived cause-effect help explain differences in adaptation responses between Swidden agriculture and agroforestry smallholders

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ARTICLE INFO

Keywords:
Cognitive maps
Decision-making under uncertainty
Mental models
Natural hazards
Perceived causal effects
Risk perception

ABSTRACT

Swidden smallholders are among the most vulnerable groups to climate change. Many efforts have focused on incentivizing their transition to agroforestry, often with limited results. Such transitions, embedded in complex socio-environmental changes, generate uncertainties, often ignored in the science-policy interface. In this paper, we examine dispersed disciplinary developments in decision-making under uncertainty, apply the insights to a case study, and discuss results in the context of prevalent knowledge production assumptions and incentivized livelihood transitions policies. We use interview data from three communities in the Mexican Maya region to create aggregated mental models of smallholders who adopted agroforestry, and those who continue to practice traditional swidden agriculture. The mental models depict perceived causal connections—including uncertain or delayed—between hazards, causes, consequences and responses. Our results show substantial differences in mental models driven by length of explanatory pathways, attribution of hazards and portfolios of responses, suggesting that agroforesters were more prone to proactive behavior and/or more responsive to outside discourses. Agroforestry is effective in reducing some uncertainties in its bundled approach, but new uncertainties for which smallholders have no prior experience arise. Contrastingly, recurrent themes point to lower self-efficacy in swidden smallholders, which may help explain non-adoption. We caution that not recognizing differences in mental models among potential beneficiaries of incentivized interventions may inadvertently exacerbate inequalities, while unaddressed uncertainties may lead to future disadoption. As a scientific tool, mental model mapping can inform the design of adaptation measures by identifying new knowledge and conflicting rationales, and segmenting strategies for potential (non)adopters.

1. Introduction

Although agroforestry is an adaptation tool with associated environmental co-benefits for rain-dependent swidden farmers (Quandt et al., 2019; Wilson and Lovell, 2016), many interventions to promote smallholder adoption have low uptake (Rahman et al., 2017) or have high rates of disadoption after initial commitment (Frey et al., 2013). The disparity between agroforestry research-touted promises and its uptake in practice have attracted attention to the role of the subjective experience and the formation of beliefs that guide smallholders' choices (Mase et al., 2017; Salite, 2019; Schattman et al., 2021), as well as questioning the scientific assumptions about people's motivations guiding such policies. Decisions such as adopting agroforestry may be driven by and leave an in-print in a person's mental model—i.e. working

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https://doi.org/10.1016/j.envsci.2024.103819
Received 4 March 2024; Received in revised form 19 June 2024; Accepted 21 June 2024
Available online 26 June 2024
1462-9011/

representation of the world—, so the comparison of mental models can help explain non-adoption and provide information on future behavior.

Yet mental models are composed of shifting and incomplete information bits connected in non-deterministic configurations (Carlton and Jacobson, 2016) giving rise to uncertainties. Uncertainty is a critical but rarely disentangled factor in adoption studies. The uncertainties of decision-makers are "messier", harder to quantify, and thus, to act upon, so they are often left out from the science-policy interface (Lemos and Klenk, 2020), especially when the knowledge framework does not conform to scientific paradigms, as often the case with indigenous knowledge (Latulippe and Klenk, 2020). Changing livelihood practices may result in re-shaped mental models as people's attention shifts targets and some knowledge becomes redundant. Swidden agriculture and agroforestry share common features, but specialized knowledge needs do not fully overlap (Meijer et al., 2014; Valdivia et al., 2012). For the individual, the usefulness of their knowledge is compromised when the contextual meaningfulness changes (Dewulf et al., 2020). For example, the environmental cues that guide swidden farmers' decision-making may be irrelevant or even confounding when applied to the new practice (Pontara, 2019), and this may be perceived as an identity loss (Tschakert et al., 2019).

Leveraging the recent rollout of a large agroforestry program in Mexico, this study compares the mental models of smallholders who did and did not enter the program, and explores the role of uncertainty sources in both agricultural models (agroforestry, swidden farming) in explaining the differences. In the next section we review key concepts and developments in the study of decision-making under uncertainty, and persistent gaps. We then review key literature on mental models and cognitive model mapping, and specify the expected contribution of our paper.

1.1. Sources of uncertainty and uncertainty preferences in interdisciplinary research

The many published typologies of uncertainty are testament to the difficulty in finding its conceptual boundaries. A useful start is to understand it as a multidimensional concept, which hinges on the purpose of analysis. A commonly used macro-framework distinguishes between the nature of uncertainty (e.g. epistemic, aleatory or ambiguity), its degree (i.e. from total ignorance to determinism), and its source, which are helpful to define, measure, or map uncertainties, while not mutually exclusive (Fig. 1). Our study is concerned with the source of uncertainty: we map the entry points of uncertainty in the decision-making process from the perspective of the individual making a decision (Moure et al., 2023). The framework below is pinned on the individual's experience of uncertainty, yet decision-making uncertainty, for instance, in knowledge co-production or deliberative settings fluctuates in relation to others (Lemos and Klenk, 2020; Moallemi et al., 2023). Sometimes called ambiguity or relational uncertainty (Brugnach et al., 2008; Brugnach and Ingram, 2012), we understand it at its core as belonging to the situation or a person's role therein.

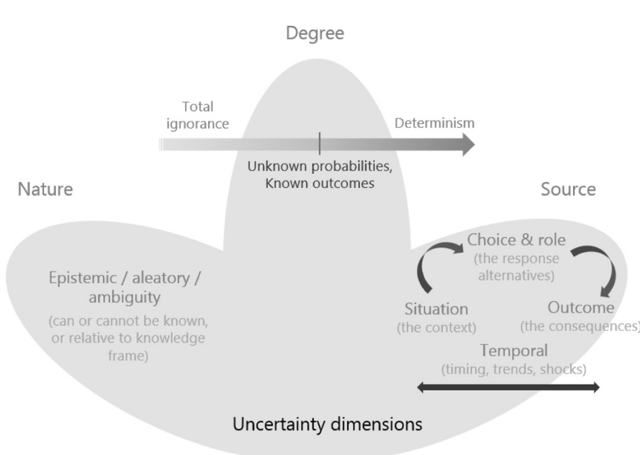

Fig. 1. Framework of the dimensions of decision-making uncertainty. Adapted from Lipshitz and Strauss, 1997; Moure et al., (2023); Skinner et al., 2014; Dewulf and Biesbroek, 2018; Walker et al., 2003.

The concept of uncertainty preferences, also called uncertainty (in) tolerance in healthcare and psychological fields, refers to individual differences in people's responses to, or acceptance of, uncertain conditions (Cavatorta and Schröeder, 2019). Similar to the concept of risk preferences, it comprises the spectrum from uncertainty-averse to uncertainty-seeking. In economics, a prevalent concept to measure uncertainty in choices is ambiguity aversion. It refers however to the aversion toward uncertain outcomes in contrast to outcomes with known probabilities, even when the known probability is low (i.e. risky) and the unknown probability could entail the best outcome (e.g. a lottery win) (De Groot and Thurik, 2018; Ellsberg, 1961). Much uncertainty research in economics is confined to one aspect (unknown probabilities) and one source (the outcome of decision/action). However, when smallholders adopt new practices, not only the probabilities but also outcomes may not be known (or believed), in addition to the other sources of uncertainty.

Research in adaptation planning has made vast contributions on how to prepare and flexibly manage uncertainty (Coates and Tapsell, 2019; Lawrence and Haasnoot, 2017). This is often done from the perspective of the analyst or manager, and thus not easily translatable to the experience of an individual, especially in a high vulnerability context where access to information and resources differ, as do the stakes (Castro and Sen, 2022). In complex decisions, such as those related to livelihood choices under increasing environmental change, there are many parameters and thus sources of uncertainty (Moure et al., 2023; Sword-Daniels et al., 2018). For example, considerations of market incentives, regulation and social norms (Müller-Mahn et al., 2020), all of which may be uncertain to varying degrees. Literature about climate adaptation in agriculture usually focuses on the effect of climate information on the intention to change (Roudier et al., 2014; Ziervogel et al., 2010), often ignoring other sources of uncertainty, for example, whether one knows what to do with the information. Few studies have compared uncertainty in the mental models of people who have adapted to those who have not (e.g. (Findlater et al., 2019), and so there is little knowledge about how sources of uncertainty connect to beliefs and expectations of how the world works, their relative saliency, and variation across individuals making different adaptation choices.

1.2. Mental model mapping

At the core of the concept of mental model mapping—also called cognitive modeling or schema mapping—is the assumption that people make sense of the world through "working models" in their minds (Spicer, 1998). These working models weave into cause-effect narratives scattered pieces of knowledge, sensorial experiences, and beliefs. As expressed in the "bounded rationality" theory, due to our cognitive limitations, these constructs are a simplified model of the world that emphasizes the aspects more salient to individuals (Slovic, 2000). The expectations of causality emerging from these constructs reduce uncertainty in decision-making and allow people to predict the behavior of others and natural systems (Otto-Banaszak et al., 2011). Additionally, mental models enable generalizations from experiences and their application to novel contexts (Jones et al., 2011). Although mental models are individual, it is increasingly recognized that everyone's cognition has a social component (Moon et al., 2019). Aggregated mental group models, therefore, explore similarities in causal knowledge about how a system works that arise from shared experiences and norms, and can be used to compare groups with similar characteristics (van Esch and Snellens, 2022).

Mental models can reveal enduring structural beliefs and not just situational knowledge (Doyle et al., 1998). They have been used in a variety of fields, such as conservation (Moon et al., 2019), hazard risk (van Winsen et al., 2013), sustainability (Kok, 2009), and resource management (Hamilton and Salerno, 2020). To study climate change adaptation barriers, this method adds explanatory value to commonly used qualitative research approaches as perceptions of cause-effect are made explicit, particularly useful for complex problems that require public involvement and benefit from local knowledge (Özesmi and Özesmi, 2004) – see Section 2.3 for details.

Despite its relevance, this method is relatively novel in our subject context, presenting an opportunity to advance the methodological tools to analyze decision-making uncertainty in adaptation choices. To the best of our knowledge, no published paper has compared group mental models using a control and treatment group as a basis to identify barriers to adaptation. Instead, previous research analyzed individual mental models (Findlater et al., 2019), a single aggregated cognitive map (Kulsum et al., 2020), or a comparison of farmers' and experts' mental models (Eitzinger et al., 2018). Furthermore, while not fully dynamic, our mental models incorporate delayed effects and uncertain connections, thus providing nuance to the strength of the beliefs and allowing to capture learning from cumulative evidence (Doyle and Radzicki, 2008).

This study aims to address two gaps in the literature about barriers to climate change adaptation through agroforestry adoption. First, we provide empirical evidence about patterns of beliefs and perceived causal pathways linked to agroforestry adoption outcomes. Our assumption is that patterns in group mental models provide a basis for formulating hypotheses regarding the mechanisms of (non)adoption. Second, we explore the proposition that preferences in uncertainty sources and trade-offs therein play a role in explaining people's choices to reduce risks from an interdisciplinary approach. These two goals are operationalized in the following two research questions:

RQ1. Do traditional smallholders and smallholders transitioning to agroforestry systems have distinct mental models?

RQ2. Do the two groups perceive and respond differently to (different sources of) uncertainty?

We answer these questions by eliciting and constructing mental models that map the explanatory architecture guiding smallholders' behavior, hinged on farmers' perception of risks. We then aggregate and compare the two models across groups: one that joined an agroforestry program and one that did not. Finally we discuss these findings in relation to policy impact.

2. Methods

2.1. Study area

Our study leverages the implementation of a recent flagship governmental program in Mexico, *Sembrando Vida* (SV), which incentivizes smallholder farmers to transit to agroforestry. The program requires smallholders to establish an agroforestry production system on an area of 2.5 ha, combining traditional annual crops (e.g. maize) with fruit and timber trees, such as avocado (*Persea americana*), mango (*Mangifera indica*), ciricote (*Cordia dodecandra*), Spanish cedar (*Cedrela odorata*), and mahogany (*Swietenia macrophylla*). Beneficiaries received a monthly pay of 5000 MXN (ca. 260 USD), raised to 6000 MXN (ca. 315 USD) in 2023 (DOF, 2022), a competitive income twice the rural poverty income line per capita (CONEVAL, 2020). Besides material incentives, beneficiaries have access to extension services covering both agricultural and social development aspects. Peer-to-peer exchange is also incentivized by the creation of "communities of learning". Climate change was not an objective of SV in its inception, but the government has since reframed the contributions of the program to encompass biodiversity, mitigation and adaptation goals (INECC, 2023).

We focus on the Yucatan Peninsula in Mexico (Fig. 2), an area increasingly at risk of climate hazards (Mardero et al., 2015). The three study communities—Dzulá, Señor, and Xcabil— have a high prevalence of extreme poverty, defined as being below the national poverty line and unable to cover food expenses even if all income is allocated to this (Secretaría de Bienestar, 2022a, 2022b). The communities are classified as highly vulnerable to climate hazards (INECC, 2022, 2021). Traditional swidden agriculture in the region—the *milpa*, a slash-and-burn, rainfed system—depends on stable/predictable rainfall patterns. The predominant soil types in the study region are leptosols and calcisols, characterized by a very shallow profile depth which makes them unattractive for rainfed agriculture and more suitable for forests (INEGI, 2021; Zech et al., 2022). The three communities are *ejidos*, a type of communal land tenure characterized by assembly-based governance and communal forest resource management with profits, if any, shared among right-holders (Green et al., 2020).

Fig. 2. The three study sites in the State of Quintana Roo in the Yucatan Peninsula. The state location in Mexico is shown in the insert map.

2.2. Data collection

We conducted 20 individual interviews and four smallholder focus group discussions in the three study communities in late 2021. Individual interviews lasted ca. 45 min and were recorded with prior written consent. Local research assistants translated from/to Maya when necessary. We used a purposeful sampling strategy to identify knowledgeable informants (Palinkas et al., 2015). The number of interviews was determined by the theoretical saturation of information, that is, no new variables arising with a new interview (Nyantakyi-Frimpong and Bezner-Kerr, 2015). The swidden and agroforestry groups were similar in terms of age, years cultivating, area cultivated, household size and schooling (Table 1; all $p \geq 0.139$).

We followed a semi-structured approach of broad-to-narrow elicitation of risks (Bostrom et al., 1994; Findlater et al., 2019). First, we asked general questions about agricultural practices, information sources, and decision-making. Second, we elicited a broad range of risks operationalized as worries (van Winsen et al., 2013): "What do you worry that can affect your work? Think broadly about any kind of risks and concerns that you face as a smallholder". Framing uncertainty in terms of affective responses (and particularly concern) is consistent with neurobiological evidence (De Groot and Thurik, 2018) and natural hazard risk research (Anderson et al., 2023; Slovic, 2000). For each

Table 1
Overview of the characteristics of the interviewed respondents. Group means with standard deviation in parenthesis are given for the first four variables, modal answer for schooling, and percentages for the rest.

	Traditional milpa (n=10)	Agroforestry (n=10)
Age	64.4 (8.3)	60.2 (15)
Years of experience in agriculture	52.5 (9.4)	42.2 (20.6)
Cultivated land (ha)	2.5 (1.2)	3.25 (0.8)
Household size	3.7 (2.1)	3.6 (1.5)
Schooling (mode)	Primary school (up to 6 years)	Primary school (up to 6 years)
Beneficiary of other agricultural programs	90 %	20 %
Other economic activities	Farm/forest related= 50 % Non-farm/forest related = 20 % Both= 0 % None= 30 %	Farm/forest related = 20 % Non-farm/forest = 20 % Both= 30 % None= 30 %

worry, we prompted elaboration on cause-effect linkages, the values at stake, uncertainties, responses, and timeframes. Although we hinge the structure of the mental models on the hazards and derived perceived causality from there, we capture opportunity-seeking rationales through additional questions about people's outlook for the future (optimistic vs pessimistic views of the future for themselves and farmers in general). The full interview guide is available in Supplementary Materials (SM 1).

2.3. Data analysis

The interviews and focus group recordings were transcribed and coded using content analysis in MAXQDA (VERBI Software, 2021). The codes were partly pre-defined based on the literature and partly emerged from the iterative coding process (coding scheme in SM 2). Starting with researcher-generated codes is particularly suitable for comparing across individual mental models (Moon et al., 2019).

Mental model mapping techniques range from quantitative approaches, such as fuzzy cognitive mapping (Özesmi and Özesmi, 2004) or Bayesian belief networks (Smith et al., 2018), to qualitative approaches based on mapping conceptual relationships. We used qualitative influence diagrams since it fits our case best, both from a practical and theoretical perspective. Consultations during the pre-testing phase of the instruments made us aware that respondents could find the task of giving weights to every connection burdensome and arbitrary; and qualifying rather than quantifying relationships is thought to be a more natural process in the psychology literature (e.g. Zadeh, 2005). In agreement with evidence suggesting that people rarely think of uncertainty in probabilistic terms (Kahneman, 2003), we approached uncertainty relationships in *possibilistic* terms (Borodin et al., 2016), e.g., "rather likely to happen" or not.

The transcript codes were used as building blocks (Fig. 3) to create the mental models using yEd graph editor (yyWorks GmbH, 2022). The variables (nodes) in the influence diagram were connected by lines with arrowheads (edges) indicating the directionality of the perceived causal effect (Moon et al., 2019). The lines are respectively wide, dotted, or plain depending on whether the connection had a delayed effect (e.g. the response occurred in the next growing season), the connection was uncertain, or it was neither.

After graphing the individual mental models, we aggregated them into each group's (traditional swidden agriculture and agroforestry) mental model. In this process, variables were refined, and categories abstracted to the closest conceptual common denominator. For example, the node 'pests & diseases' encapsulates farmers' identification of 'locusts', 'worms', and 'fungal diseases' as hazards. While this approach has the disadvantage of relying on the analyst judgement for aggregation (Fairweather, 2010), it is preferable in an exploratory study as it allows new variables to emerge. Variables from the individual mental models were transferred to the parent group mental model irrespective of frequency. As this approach can overestimate marginal opinions, we provide frequencies and context in the results as appropriate.

We analyzed a measure of centrality for each group mental model. In social network theory, centrality measures serve to identify the most important nodes in a network (Obiedat et al., 2011), determined by the number of connections (edges) with other concepts (nodes) (van Esch and Snellens, 2022). However, measures used in social networks where

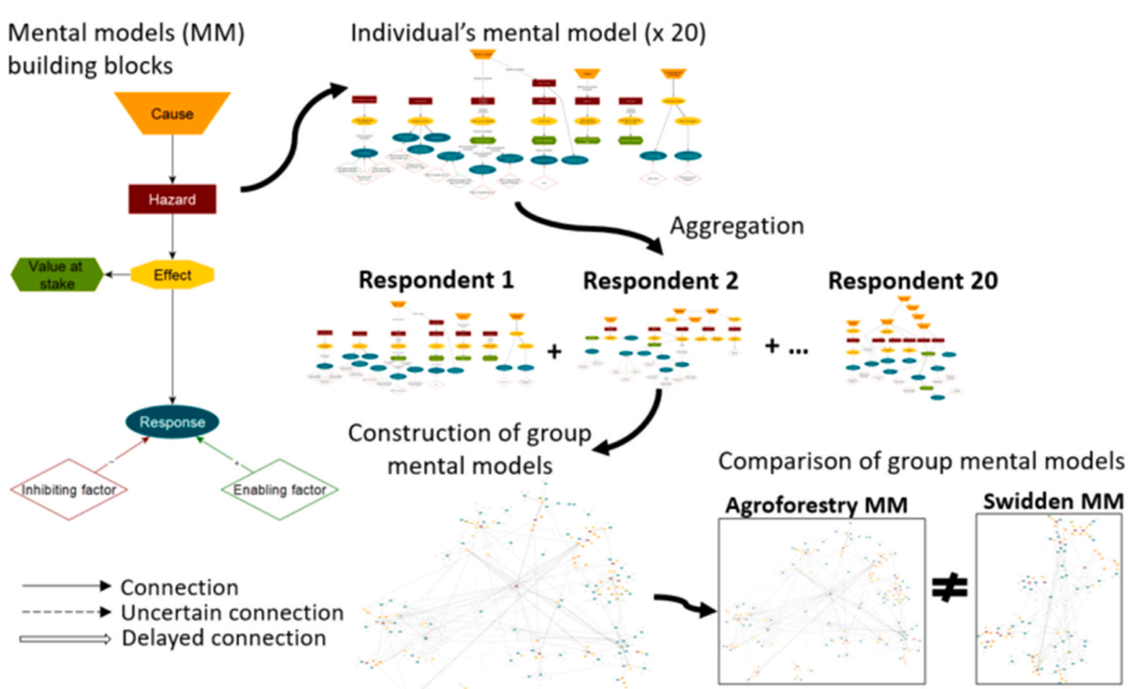

Fig. 3. Schematic of the mental model mapping process from coding and diagramming to comparison of group mental models.

connectedness refers to information flows between people are not always appropriate to understand directed graphs (Moon and Adams, 2016). Therefore, instead of measuring centrality based on the position and distance of nodes with respect to others (e.g. betweenness measures), we opted for the simpler measure of number of out- and in-going edges (degree centrality), which are then normalized (0, 1) with 1 being the node with the most connections. This measure has the advantage of ease of interpretation (Landherr et al., 2010).

Lastly, for every response identified in the transcripts, we applied the framework introduced in Fig. 1 to classify them according to the source of uncertainty the response is meant to reduce, and if the mental model included consequences of response, the effect it might have on other sources of uncertainty. This was used to identify potential trade-offs (see section 3.2). Whenever possible, we also code the strategies for dealing with uncertainty (Table 2). When providing direct transcript quotes, respondents are given an identifier composed of the initials of the mode of data collection (interview or focus group) and the village name (Dzulá, Señor, and Xcabil), as well as a unique number (e.g. I-S-17).

3. Results

3.1. Comparing mental models

We see substantial differences between the two groups' mental models (SM 3–4). The agroforestry mental model is more sophisticated than the swidden mental model, with 30 % more nodes and edges. Clusters tend to be more elaborate, that is, they more frequently contain long paths connecting causes, consequences, responses, and indicate the positive/negative attributes of responses. In contrast, paths in the traditional agriculture model often appear truncated, e.g. connecting hazards to consequences without identifying a cause or a response. These differences are substantial given that the two groups are otherwise very similar (see Table 1). Likewise, years of formal education do not play a significant role in explaining differences in the mental models: in neither group did respondents study past secondary school (nine years), and most had not finished primary school (six years).

Table 2
Overview of sources of uncertainty and strategies to deal with uncertainty used to categorize responses in mental models, and identify potential trade-offs. Adapted from Moure et al. (2023).

Variable	Definition
Source of uncertainty	
Situation uncertainty	Related to external factors outside household control. Questions about what is going on, e.g. with climate, prices, rules, and regulations.
Choice uncertainty	Related to the measures or actions contemplated in a given situation, e.g. if choices are equally attractive. Questions about what (best) to do, how to do it, and whether one feels capable of doing it.
Outcome uncertainty	Related to the consequence of a decision or enacted measure. Questions about what will happen if I do or do not act a certain way.
Temporal uncertainty	Transversal to the other three sources of uncertainty. Incorporates aspects of expected trends, timing of hazard/responses, time lags, surprises, frequency, etc. Questions such as what if, when, for how long, how often a hazard occurs.
Dealing with uncertainty	
Reducing epistemic uncertainty	Reducing uncertainty through increasing knowledge. Collecting additional information, knowledge acquisition; seeking backing or advice; relying on formal and informal rules of conduct; assumption-based reasoning.
Acting upon uncertainty	Recognizing uncertainty of future risks and hedging against them through actions. E.g., improving readiness; preempting; diversifying assets; avoiding irreversible action; weighing pros and cons.
Suppressing	Ignoring uncertainty; acting based on "intuition"; taking a gamble, assuming certainty of future events.
Forestalling	Delaying action/decision (hesitancy, indecisiveness, procrastination).

The comparison of topmost connected nodes, a measure of the influence of a node in a network, provides some insight into the structural differences between the models (Fig. 4). Notably, responses (circles) were more salient in the agroforestry mental model and hazards (squares) in the swidden one. Only 40 % of the top nodes overlap in both models, but these also differ in their saliency and connection to other top nodes. For instance, in both models, droughts are attributed to climate change, but in the swidden model the causality was reported with skepticism and therefore represented as uncertain. Also, not all hazards are equally relevant for the two groups e.g. young trees are mostly unaffected by animal pests.

Agroforestry as implemented by the SV program is the most central node in the agroforestry model and seen as a response to the risk of yield loss or crop failure from multiple hazards. It is also a way to access fertilizer (produced in the program), which is one identified response to reduce the impacts of droughts, albeit one with uncertain efficacy. The saliency of 'agroforestry' as a top node is remarkable since smallholders were not asked any direct questions about their experience with agroforestry, yet it was mentioned unprompted in connection to ways to mitigate hazards.

Another difference is the more recurrent appearance of delayed effects (broad arrow) connecting hazards or their consequences to responses in the swidden model. This suggests a preference for cumulative evidence (e.g. of impacts) as a basis to take action. This preference is associated with passive responses to hazards (or the uncertainty of one happening) by forestalling action until more information has been gathered (Jacobsen and Thorsen, 2003), which can lead to fewer response options.

Beyond the topmost connected nodes, the main differences between the mental models lie in the perceptions of the causes to hazards and the type of responses available to avoid or reduce impact, which we expand on in the next sections.

3.1.1. Perceived causes of hazards

In the agroforestry model, a higher proportion of hazards was attributed to anthropogenic causes (Table 2), such as environmental destruction, swidden agriculture, and pesticide overuse. A few respondents—both new agroforesters and swidden smallholders—identified the SV program itself as a driver of increased animal pests in milpas as a result of the ban on slash-and-burn. In contrast, the swidden model tended to attribute hazards to natural phenomena such as seasonal weather fluctuations. In this model, deforestation and swidden agriculture were not explicitly described as causing hazards. Both groups also provided metaphysical interpretations of hazard origins, such as disturbances caused by spirits, with the swidden model containing more instances of hazards attributed to Christian faith, such as God's punishment for various offenses.

Some beliefs about hazard causality were common to both groups and seem to be part of a larger culturally-embedded worldview. The frequent observation of droughts and dry spells was related in both groups to alternating cycles of four to seven years of below and above-average rainfall. Most respondents emphasized that after about five years of drought, they finally got "good" rain in the last couple of years. Also, an often-mentioned belief is that there is a fixed amount of precipitation available each year. Therefore, if the rainy season starts with heavier than usual rainfall, smallholders will expect dry spells later as the precipitation "quota" has been reached. In several cases, hazards are perceived as causing other hazards. For example, *chocó há* (hot rain, in Maya), described as "rainfall with abnormal chemical properties" that turns crops red and halts their development (González M. and Rodríguez C., 2017, p. 108) is widely believed to be caused by dry spells or the steamy rainfall brought about by tropical storms.

3.1.2. Responses to hazards

Group mental models differed greatly in their responses to dealing

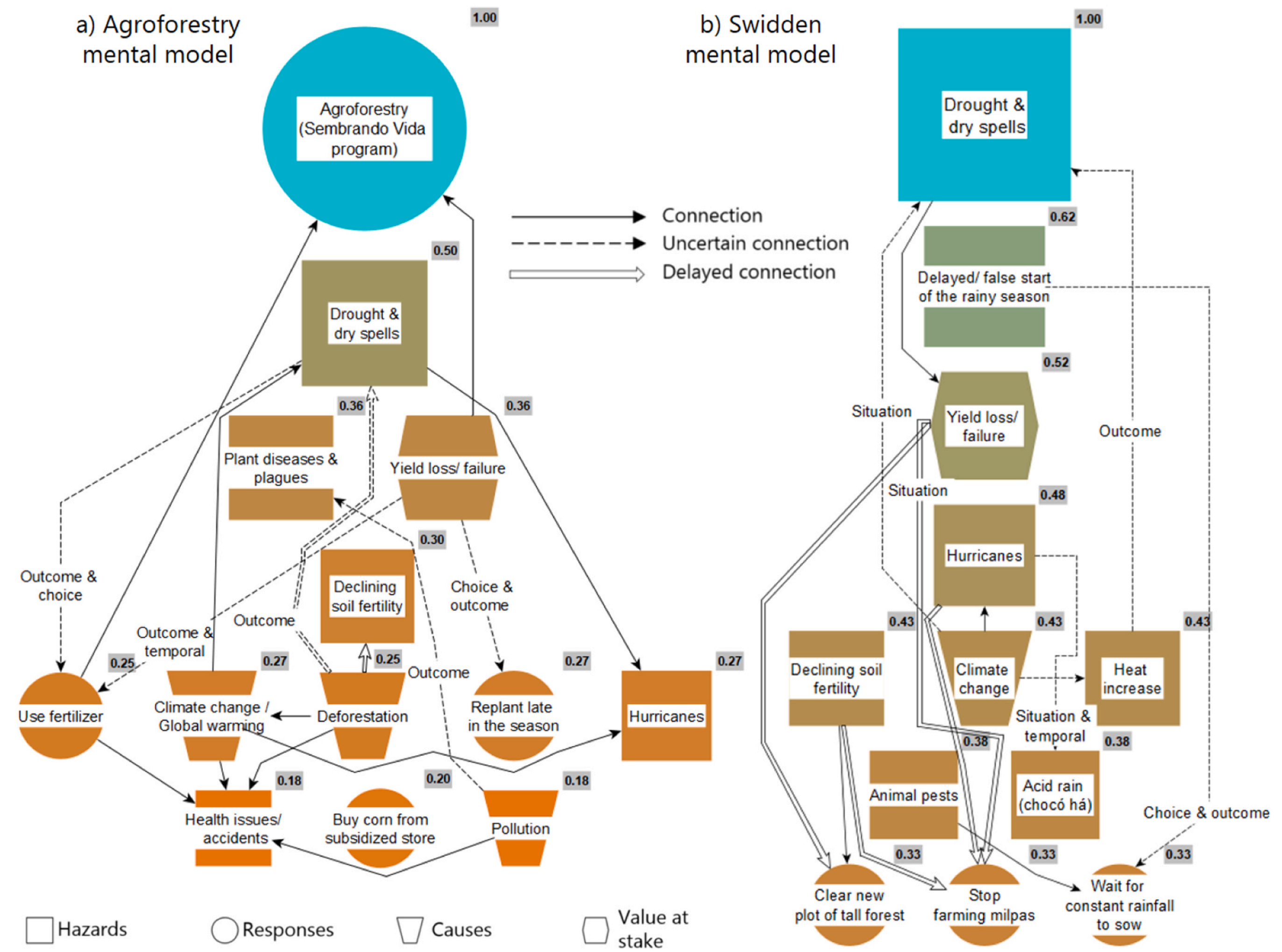

Fig. 4. Comparison of measures of centrality of top most central nodes based on number of ingoing and outgoing edges in the mental models for a) Agroforestry, and b) Traditional agriculture. The color gradient goes from blue to orange, where blue are the nodes with more connections and orange with the least. Grey labels at top right of nodes contain normalized centrality measure weights (0, 1).

with hazard risk. From the 67 identified responses to hazards, only 26 (39 %) were common to both models, while 16 (24 %) were unique to the swidden, and 25 (37 %) to the agroforestry model. Both groups had a large portfolio of responses for dealing with rainfall related hazards (Fig. 5). However, the types of responses varied widely, from basic agronomic responses, like applying fertilizer directly to the roots to maximize absorption, to metaphysical responses, such as performing rituals to protect fields from hurricanes.

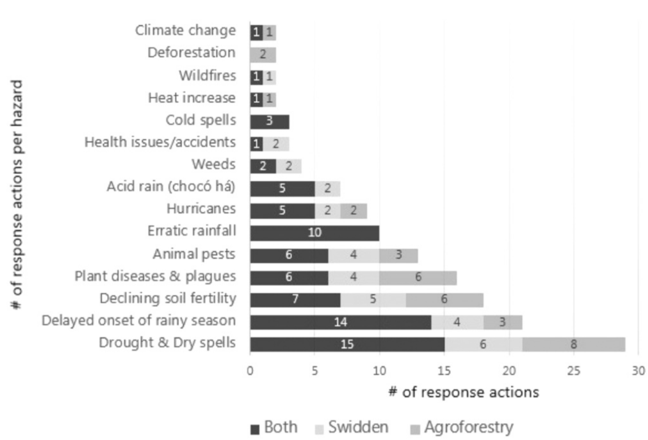

Fig. 5. Distribution of responses to specific hazards. The most worrisome hazards to livelihoods identified in the mental models for both groups (in black), the swidden agriculture group (in light grey), and the agroforestry group (in medium grey). N= 67 responses, but some responses are used against more than one hazard.

Only the agroforestry model identified responses to deforestation, believed to be a meta-cause for several hazards. For instance, half of the agroforesters suggested that timber extraction by the *ejido* should follow more strict guidelines to protect mature forest, regulated by permits and quotas. One agroforester also stated that swidden agriculture should stop. Agroforestry was mentioned as a more sustainable alternative, and so was tourism. The swidden model identified responses to hazards that the milpa is more sensitive to (e.g. acid rain, weeds, delayed onset of rainy season), but also to some hazards common to both production systems (e.g. personal health issues, wildfires, drought).

The group mental models also differed in the temporality of responses with agroforesters being slightly more proactive and swidden farmers more reactive. Responses were categorized as taking place before the hazard occurs, while it is unfolding, after it has occurred, or when it is a latent risk rather than an unfolding hazard (Fig. 6). Some responses are only tenuously connected to a specific hazard; instead, they are the result of cumulative losses where one event was perceived as a tipping point; for example, the decision to skip a growing season to pursue odd jobs outside the village. For swidden smallholders, some of

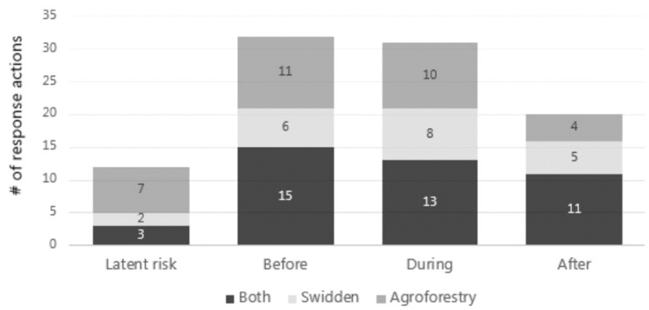

Fig. 6. Timing of response actions relative to hazard occurrence (N= 67 responses). Some responses can belong to more than one category (e.g. mulching to retain humidity before or during a dry spell).

the crucial decisions taken *before* the hazards materialize are the choice of seed varieties and planting time, which have implications for the risks they will face later in the season and their ability to respond to them. For instance, farmers have to "gamble" on whether to sow short or long-cycle varieties: the stalks of short-cycle maize are thinner and more susceptible to wilting during dry spells, and the long-cycle maize, while more tolerant to water stress, is not ready for harvest at the height of the hurricane season and so may be endangered.

In terms of the nature of the responses, agroforesters resorted less to damage control measures, such as eating seeds saved for sowing—a measure that carries a social stigma—, instead seeking to reduce vulnerability rather than just dealing with the hazard consequences, suggesting greater adaptive capacity. Swidden smallholders also reduced vulnerabilities, for instance, by growing more tubers, which are generally less affected by droughts, pests, or hurricanes, but they did so less consistently.

3.2. Key uncertainties linked to each agricultural system

We found overall similarities between the two groups in the frequencies of sources of uncertainty (Fig. 7a), with agroforesters slightly more motivated by the outcome and temporal uncertainties and swidden smallholders by situation and choice uncertainties. Both groups dealt with uncertainty using similar strategies (Fig. 7b), mostly by incorporating uncertainties into their decisions/acting upon them, even when this resulted in increasing another source of uncertainty (Table 3).

Yet, the broad category frequencies in Fig. 7 can be qualitatively disaggregated into a few recurrent themes characteristic of each group. One of the agroforesters' chief concerns was the temporal uncertainty

Table 3
Top five hazards and their proximal (direct connection) and distant (two degrees of separation) causes as perceived by respondents; n is the number of respondents identifying a hazard as a major concern; N=20.

Hazards	Mental model	Proximal	Distant
Drought and dry spells n=19	Agroforestry	Deforestation	Swidden agriculture Environmental destruction
	Swidden	Natural fluctuation	
	Both	Climate change Heat increase Rain quotas/cycles	
Plant diseases and plagues n=17	Agroforestry	Pollution Planting during midsummer drought Natural/seasonal Excess rain Bugs come with the rain/fog Weed infestation	Pesticide overuse (pest/disease resistance) Environmental destruction
	Swidden	Climate change Bad (poor) seeds	
	Both	Acid rain	
Climate change n=16	Agroforestry	Deforestation Environmental destruction	Swidden agriculture
	Swidden	The sun is getting closer to the Earth	God's will/ punishment
	Both	Emissions from "steam and gases"	
Hurricanes n=15	Agroforestry	Droughts and dry spells	Deforestation Environmental destruction
	Swidden		
	Both	Climate change	
Animal pests n=13	Agroforestry	Spirits/sacred land disturbed Fewer people practicing traditional agriculture	
	Swidden	God's will/punishment	
	Both	Restrictions by SV policies (no burning)	

regarding the continuation of the SV program. A history of shifting political priorities and programmatic discontinuity in Mexico (Moure et al., 2021) makes it unclear whether the program will continue beyond the current administration. For beneficiaries, the currently reliable income could stop. Relying only on the potential—but still

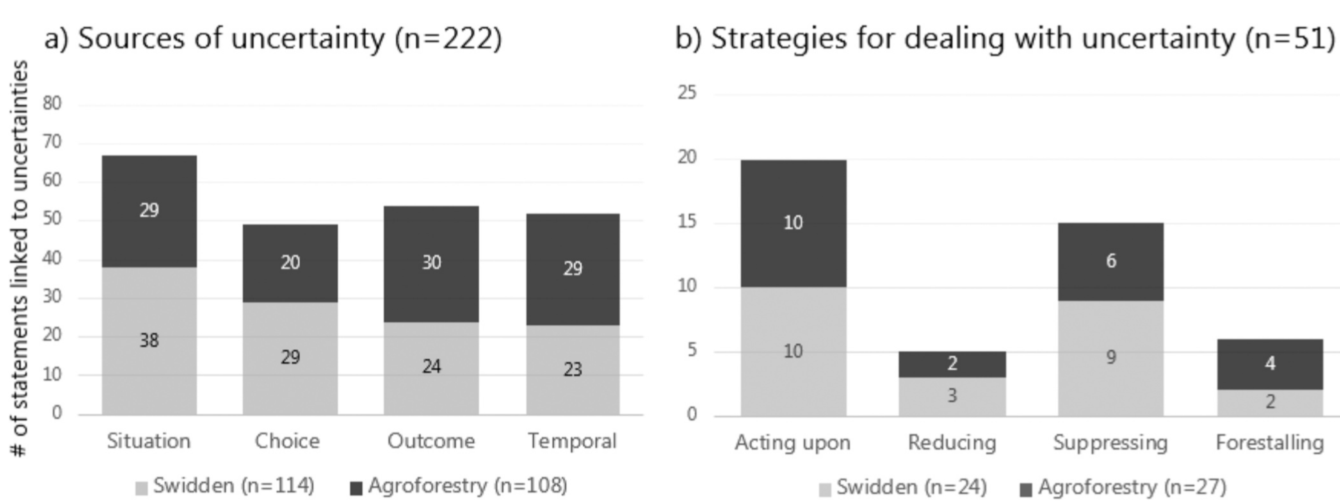

Fig. 7. Count of transcript statements explicitly linked to a) sources of uncertainty, and b) strategies to deal with uncertainty. The same transcript extract could be coded as related to more than one source of uncertainty, and not all extracts were linked to a strategy to deal with uncertainty.

Table 4
Examples of uncertainty responses from interviews, their categorization, and identified trade-offs across uncertainty sources. In the column of dealing with uncertainty the letters in parentheses (S, C, O, T) correspond to the source of uncertainty (situation, choice, outcome and temporal) being affected. Arrows indicate the directionality of the trade-off (increased ↑, reduced ↓, unchanged ↔); dashes (–) indicate no information.

Group	Example of response	Dealing with uncertainty	Trade-offs in uncertainty source			
			Situation	Choice	Outcome	Temporal
Swidden	Smallholders wait until late June to start sowing. People who plant earlier sometimes succeed, but they are more likely to lose crops (I-S-13)	Forestalling	↓	↑	↓	↑
Swidden	Rain is erratic, so smallholders look at signs from nature to predict—months ahead—the best time to clear land and prepare the plot for sowing (I-X-16)	Reducing (S, C, T) Suppressing (O)	↓	↓	↔	↓
Agroforestry	If smallholders expect a bad season (e.g. insufficient rain), many families eat seeds instead of sowing them (I-D-01)	Acting upon (S) Reducing (O) Suppressing (T)	↑	–	↓	↔
Agroforestry	An 80-year old smallholder wanted to plant trees, but thought his time was running out. Now he works the SV plot of his daughter. He does not think he will be able to harvest anything, but he participates because of the money (I-X-17)	Acting upon (S, C) Suppressing (O, T)	↓	↓	↔	↔

hypothetical—harvests from agroforestry plots was a source of concern. Uncertainty about agroforestry outcomes was exacerbated by respondents' age:

> "Oh God! It will take like six years until they [the trees] grow a bit and start to produce. It is still a long way! We do it for the pennies, for the money. Yes, because it's difficult to profit from the harvesting. If you are young, you can harvest. But at my age, it's very difficult. I am 80 now; imagine that I reach 90, I still won't be able to harvest!" (**I-17-X**).

If subsidies end, agroforesters believed *others* would cut down the trees and reconvert the land to *milpas*. Additionally, there was concern about the communal land system, because the *ejido* assembly can decide to distribute profits from wood harvesting among *ejidatarios*, a big disincentive for new agroforesters, especially those without *ejido* rights. Agroforesters were also unsure of how to grow and commercialize non-traditional crops (e.g. cinnamon or coffee). Possible gluts in production was another point of concern, as one smallholder expressed it: "If everyone grows the same crops, for example limes, where will one sell the produce? They [SV personnel] will need to find markets outside the village, and there is no plan for that" (**I-X-15**).

In contrast, swidden smallholders uncertainties related more often to the occurrence, timing, and distribution of hazards (situation uncertainty), and how to minimize losses (choice uncertainty) given the absence of stable income e.g. "Well, I don't think it's going to rain anymore. So, what are we going to do? How are we going to eat? I tell my wife: if it doesn't rain, what am I going to do to provide for my kids? I can't do anything." (**I-09-D**).

We found qualitative evidence that participants made trade-offs in the sources of uncertainty they face: responses to hazards sometimes reduced a specific source of uncertainty while increasing another. For example, waiting for several days of consecutive rain before sowing reduces the uncertainty about the weather (situation uncertainty) and the risk of compromising the harvest early in the season (outcome uncertainty), while it increases lock-in (fewer options for reacting to other hazards, e.g. re-planting; choice uncertainty) and the risk of late-season hazards (Table 3, first example).

The desire to have agency over one's fate, also called self-efficacy (Bandura, 1999), was a distinctive trait of some people in both groups. The following quote illustrates this trade-off between outcome uncertainty (harvest success) and choice uncertainty (ability to do a different job):

> "Once I got upset and I told my dad that I'm tired of this [yield failure] and I'm thinking of going to Cancun [...] And he told me "what are you going to do, if you never went to school. Those who go to Cancun have a little bit of studies," he says. "Well, I'm going to build bungalows, whatever there is to do, but I'm going", I tell him. I'm worried about the weather! We haven't had a maize harvest for two years. Where are we going to find something to eat? You have to go out to work, somewhere else, to find money to buy maize." (**I-01-D**).

Making trade-offs was common in both groups, but we found no distinct group-specific patterns of source of uncertainty being traded-off for another.

4. Discussion

Given substantial challenges in getting swidden smallholders to adopt and maintain agroforestry systems despite adaptation gains, we use a novel approach to mental model mapping to investigate the differences in the cognitive models of swidden and new agroforestry smallholders. Here, structured under the headings of the research questions, we discuss the main findings that 1) both groups share awareness of risks but differ in the attribution of hazards and the portfolios of responses; 2) agroforesters have substantially more intricate aggregated mental models; 3) decisions are subject to multiple sources of uncertainty, 4) groups exhibit subtle differences in predominant uncertainties with unique themes, 5) people's responses to hazards involve trade-offs in the sources of uncertainties they face.

4.1. *Do traditional smallholders and smallholders transitioning to agroforestry systems have distinct mental models?*

We found substantial differences in the structural beliefs between traditional smallholders and those transitioning to agroforestry, but also culturally-embedded similarities. The latter included shared awareness of risks in a complex system. The environment, humans, and the climate are tightly interconnected in Mayan cosmogony (Barrera-Bassols and Toledo, 2005; Camacho-Villa et al., 2021). For instance, when asked about their concerns, respondents listed not only climate hazards but other environmental and health hazards perceived to be causally interconnected. Hence, new agricultural programs targeting narrow rather than holistic objectives could seem inadequate to Maya smallholders. Likewise, both groups believed in the existence of alternating rainfall cycles of four to seven years of below and above-average, fitting well with the effect on precipitation caused by the El Niño and La Niña phenomena (Andrade-Velázquez et al., 2021; De la Barreda et al., 2020). While both groups in our study held this belief, reactive responses were more common in the swidden mental model pointing at a lag between belief update and behavioral change.

We found differences in terms of knowledge points, explanations of cause-effect, and behavioral patterns. Agroforesters' substantially larger and more intricate mental model suggests that they hold—or at least expressed—more explanatory causal pathways about the risks they face. This included more manmade causes, including the role of slash-and-burn in deforestation. Further, agroforesters' responses were more adaptive than coping, and active rather than passive, which points toward higher perceived behavioral control. This is theorized to influence behavioral change (Ajzen and Albarracin, 2007) and has also been empirically linked to farmers' intention to adopt and stay in agroforestry (McGinty et al., 2008).

Why do we see differences in the group mental models? Given our data, we can compare the groups but cannot test whether differences stem from the experience of agroforestry within this program or prior beliefs—that is, whether agroforesters' mental model changed after entering the program or was different from the onset. However, a combination of the two mechanisms is likely at play: the updating of mental models (i.e. learning) and self-selection, the first one linked to the manmade narrative of hazard causes, the second to an intrinsic proclivity for proactive behavior.

A hypothesis is that agroforesters might have adopted *a posteriori* beliefs, for example, the negative beliefs about the impact of the swidden system on the environment, as a way to justify joining the program despite it going against social norms and tradition (Rodríguez-Robayo et al., 2020). Mental models play a role in filtering new information (Otto-Banaszak et al., 2011) as people tend to seek information that supports current understandings and ignore information that contradicts it (confirmation bias) to align beliefs and actions (Heimlich and Ardoin, 2008). In the process, new agroforesters likely become more receptive to exogenous and instrumental discourses that conflate climate change drivers with easier-to-adjust practices (Eguavoen, 2013). Evidence of an update of mental models is that other recent — yet pre-SV— smallholder perception studies in the region (Metcalfe et al., 2020) did not find similar instances of "cultural attributions of blame" (Eguavoen, 2013) linking swidden agriculture to climate change. This suggests a shifting narrative, perhaps spurred by SV programmatic rhetoric that explicitly proclaims that agroforestry is better for the environment than swidden agriculture, although the evidence behind this claim is mixed. While the milpa system has been empirically linked to local increases in wildfires, soil erosion, and increased annual average local temperature (Rodríguez-Robayo et al., 2020), it is unlikely to significantly contribute to climate change related hazards (Salinas Melgoza et al., 2015; Tschakert et al., 2007). In this case, the more sophisticated causal pathways in the agroforestry mental model could be due to a combination of learning through practicing agroforestry (e.g. recalibration of risks) and exposure to SV programmatic discourse.

It is also possible that people who are intrinsically more open to change, or whose views already reflected those of the SV program (or the government) were more likely to join it. This is also known as self-selection or participation bias (Elston, 2021): groups do not represent independent random samples separated only by agricultural practice. We rely on a natural experiment of sorts to sample people that did and did not join the program, but it is unlikely that participation was randomized. Degree of affinity with the political party of the current administration may have predispose to (mis)trust the program. Likewise, relationships with local leaders and land tenure rights may have influenced the decision. Furthermore, more intrinsically optimistic people may be more open to venturing into a new agricultural system. Recent research found a significant relation between hope and the adoption of new agricultural technologies in Senegal (Peles and Kerret, 2021). As mentioned above, higher self-efficacy has also been linked to adoption of agroforestry (McGinty et al., 2008). Thus it might not only be the motivation to reduce risk, but to seize opportunities that influence the decision to adapt. Such factors should be investigated in future research.

4.2. *Do traditional smallholders and smallholders transitioning to agroforestry systems perceive and respond differently to (different sources of) uncertainty?*

We see overall commonalities in the exposure to multiple sources of uncertainty regardless of whether smallholders continue practicing swidden agriculture or whether they have adopted new agricultural practices. One could have expected more uncertainties to arise in the transition to a considerably different livelihood practice, but we cannot discount the effect that having access to agricultural extension, peer communities of learning and regular cash transfers might have had in tampering some types of uncertainties. Indeed, the bundled design of the SV program (Amarnath et al., 2023) rather than the experience of agroforestry itself may have effectively reduced some of the most salient uncertainties of swidden farmers—as seen in the comparison of top mental models nodes—even if new uncertainties emerge.

In terms of central concern themes, agroforesters appear slightly more motivated by outcome and temporal uncertainties, and swidden smallholders by situation and choice uncertainties. This makes sense given the differences in temporalities: agroforestry with longer time leads vs milpa as an annual crop system. The latter is, to a large degree, dependent on crucial choices (e.g. time of planting) and smallholders' ability to respond to hazards (e.g. managing pests). For choice uncertainty, providing evidence of the efficacy of available adoption options might be better at increasing buy-in than stressing the certainty of damages from climate change (Bernedo and Ferraro, 2016). Additionally, unlike agroforesters in the SV program who have a regular income, swidden smallholders' decisions may be more influenced by exogenous uncertainties with implications for the short term, like labor price (Do et al., 2020).

Agroforestry introduces uncertainties stemming from inexperience, multi-temporal scales and delayed rewards. In the context of switching from subsistence to market-oriented farming, agroforesters have not yet developed strategies to deal with the emerging uncertainties, like finding markets for the produce. A study by Do et al. (2020) in Vietnam showed that farmers prefer annual crops due to the relatively short time-lag for returns, despite an expected decrease in returns over time due to soil degradation. Agroforestry adoption is often deterred by the initial cost of establishment and the perspective of no harvest for several years (Iiyama et al., 2018). Given that the SV program subsidizes agroforestry establishment and guarantees income during the first 5–6 years, it would be reasonable to expect (situational) economic uncertainty to decline and beneficiaries to be more patient—have lower discount rates—assuming smallholders trust the program, a key uncertainty found in similar studies (Gómez-Rodríguez et al., 2023).

Are uncertainties a barrier for adoption of new practices? It is clear that both agricultural practices are linked to a host of uncertainties, but we argue that some sources are more critical in hindering behavioral change, namely, choice uncertainty, linked to the alternative response measure and one's ability to carry it out. The fact that swidden farmers in our sample expressed lower self-efficacy and identified more reactive responses to deal with hazards helps explain non-adoption of agroforestry, which entails a number of obligations. A review of decision-making uncertainty in climate change adaptation studies (Moure et al., 2023) found that studies focusing on individuals/households had a relatively higher proportion of uncertainties regarding response choice (e.g. self-efficacy or the opportunity cost of response alternatives) than studies focusing on other actors (e.g. scientists, governmental agents). For smallholders, fewer resources and higher stakes may make changes associated with private costs more of a barrier if there is no certainty of favorable outcomes (Do et al., 2020). Furthermore, increasing climate adaptive capacity may be less important, even when smallholders recognize the risks they are exposed to, as there are other more pressing concerns. For instance, we found the respondents' health to be a severe concern, since the ability to work and provide for the family depends on it, and they have no formal support in case of incapacity.

We hypothesized that comparing mental models of new agroforestry smallholders and traditional swidden smallholders would reveal differences in the sources of uncertainty perceived as more salient. In our exploratory approach we found subtle but telling differences in the prevalence and nature of sources of uncertainty between the groups, and evidence that people's actions reflect trade-offs in the sources of uncertainty they prefer to avoid. While our unit of analysis was too coarse to distinguish systematic patterns, these results are a starting point for re-assessing assumptions about people's decision-making in incentivized livelihood transition contexts. The economic literature has focused on risk and time preferences to explain technology adoption among farmers (Sarwosri and Mußhoff, 2020), with conflicting results regarding investments for adaptation (Bernedo and Ferraro, 2016). Ambiguity aversion has increasingly been used to explain what might appear as empirical inconsistencies (Alpizar et al., 2011; Duersch et al., 2017), although measures are mostly confined to outcome uncertainty.

Interdisciplinary research in uncertainty source preferences is incipient but of relevance for a large swath of societal issues. Validated and easy to operationalize instruments to elicit uncertainty preferences are needed so that comparisons across case studies are possible. Given growing evidence that uncertainty and risk preferences are not equivalent, one promising avenue of research is to explore whether uncertainty preferences might supersede risk preferences in adaptation decisions (Alpizar et al., 2011; Moure and Jacobsen, 2024), and whether it may also affect decision-making strategies. For example, affecting strategies by favoring minimizing regret (outcome uncertainty) rather than maximizing utility (Nielsen and Jacobsen, 2020), as mainly assumed in economic theory. In practice, this means that interventions such as the SV program requiring productivity quotas are misaligned with beneficiary expectations, and could cause unnecessary distress.

5. Scientific and policy implications

Agroforestry has been posited as a tool for climate change adaptation, but despite its promise, many efforts worldwide have struggled to engage the intended beneficiaries. The introduction in Mexico of a conditional cash transfer program, *Sembrando Vida*, allowed comparisons of the perceptions of traditional swidden smallholders who switched to agroforestry against those who did not. We find that despite similar opportunity, the motivation (perceived cause-effect) and perceived ability (contrasting uncertainty about self-efficacy) differed between the groups (Conallin et al., 2022). Our article thus offers timely contributions to the literature on agroforestry adoption in particular, and to the environmental decision-making science-policy interface in general.

The bundled-benefits approach of the SV program is perceived to mitigate hazard risk and effectively reduce some uncertainties, supporting the role of agroforestry as an adaptation tool. Yet, we identified four important considerations for design and implementation. First, the observed differences in mental models elevates the importance of having segmented strategies to reach the intended population, else risk inadvertently favoring the already more risk-taking, proactive and like-minded, while leaving out the segment with the lower adaptive capacity. Second, the manner in which a program's objectives and theory of change are communicated may alienate potential beneficiaries with a different understanding of cause-effect and aversions to specific sources of uncertainty, making the program's rationale seem inappropriate. Having ongoing project enrolment over a period of time instead of a one-time sign up may assuage the more hesitant as they learn more from observing peers' experiences. Third, switching livelihoods, especially if going from a subsistence to a market-oriented system, entails a reconfiguration of (usable) knowledge. On the one hand, disadoption risk is high if outcomes uncertainties are not addressed, for example, establishing concrete systems to market produce. On the other hand, beneficiaries may experience reduced usefulness—or recognition—of prior specific knowledge, which can result in cultural or identity loss. Designing interventions that relate to and make use of personal experience and traditional knowledge may thus reduce role uncertainty and increase engagement. Finally, the programmatic discourse likely has an impact in reshaping beneficiaries' mental models, and thus policies have a responsibility to limit the risk of knowledge imposition, especially if it can be locally divisive.

There is a long tradition of studying decision-making under uncertainty in psychology and economics, which have set the framework for understanding decision-making uncertainty in adaptation contexts (Constantino and Weber, 2021) and have set the standard for policy-relevant knowledge to the detriment of more encompassing approaches (Warner and Dewulf, 2023). However, contrary to the assumptions in mainstream economics, we found a first indication that multiple sources of uncertainty are not given the same weight, and that people's actions reflect trade-offs. Given the forward-looking nature of livelihood adaptation, understanding uncertainty preferences is likely a key factor for increased agroforestry adoption. Much progress has been made in communicating scientific uncertainties (e.g. in climate projections) but there is much work needed in addressing other sources of decision-making uncertainties. Research and adaptation interventions ought to consider all dimensions of uncertainty (nature, degree and sources) as illustrated in our framework (Fig. 1), including interactions among them, to obtain a more complete representation of people's reasoning. In policy design, identifying and addressing all dimensions of uncertainty may attenuate ambiguities, foster critical rethinking of goals at different time scales, and integrate adaptive planning to deal with different scenarios. Yet, while the potential benefits are obvious, there is no blueprint for "embracing uncertainty" in institutional settings (Tschakert et al., 2014) and uncritical attempts to co-produce knowledge may be counterproductive (Lemos et al., 2018).

We make the case that mental model mapping as a tool can bolster the diagnosis of barriers and design of adaptation plans (Moser and Ekstrom, 2010). It can do so by allowing new knowledge creation (Olazabal et al., 2018), recognizing narratives of causality that either go against or support the rationale for change. It allows concerns, conflicting views, and uncertainties to emerge and be addressed timely; it can help identify potential early adopters and segment the interventions to leverage intrinsic proclivity to change practices. Additionally, the process of elicitation, which validates people's understanding of the world and gives them voice, is known to help build rapport, a crucial element in successful community adaptation (Owen, 2020; Plate et al., 2020).

Funding

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 801199.

Author statement

Mar Moure's research focuses on decision-making under uncertainty, climate change adaptation and risk perception.

CRediT authorship contribution statement

Mar Moure: Writing – original draft, Visualization, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Carsten Smith-Hall:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Birgit Schmook:** Writing – review & editing, Supervision, Investigation. **Sophie Calmé:** Writing – review & editing, Supervision, Investigation. **Jette Bredahl Jacobsen:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data and supplementary materials were deposited at the Open Science Framework: https://osf.io/pge3h/?view_only=19136093b7d643d5bcb950e214ccb68a (DOI 10.17605/OSF.IO/PGE3H)

Acknowledgements

We are extremely grateful to our field assistants and Maya interpreters, Rosalía Caamal, Guadalupe Cimá, Marcos Canté and Miguel Puc. We also appreciate the support of local authorities in Dzulá, Señor and Xcabil for facilitating meeting arrangements and venues. Finally, we are very grateful to all the smallholders that shared their time and wisdom with us.

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