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## Unraveling the complexity of land use change and path dependency in agri-environmental schemes for small farmers: A serious game approach

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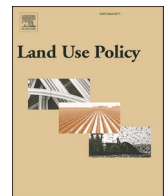
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# Unraveling the complexity of land use change and path dependency in agri-environmental schemes for small farmers: A serious game approach

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## ABSTRACT

This study investigates how Maya farmers in Mexico respond to agri-environmental subsidies aimed at promoting sustainable land use decisions. We do so through a serious games approach, using a tailor-designed board game to identify the land use behaviors of Maya farmers. The game simulated three different subsidy programs promoting mechanized agriculture, forest conservation, and agroforestry. We find that farmers tend to clear forested areas in response to agroforestry subsidies. Also, we observe that land use decisions are path-dependent, with farmers adhering to traditional and mechanized agriculture and hesitant to engage in conservation and agroforestry. These findings highlight the potential of serious games as a tool to improve understandings of how farmers make land use decisions and the resulting land use change patterns. Specifically, our findings show that serious games are well suited to understand how path dependency in decision-making can influence the effect of subsidies – and whether subsidies thereby achieve the intended goals, such as reduced deforestation.

## 1. Introduction

Over the last decade, about 4.7 million ha of forests have been lost globally, with agricultural activities as a primary driver (FAO, 2020; Radwan et al., 2021; Ramankutty et al., 2018). This phenomenon has been partially exacerbated by agricultural subsidies, with governments worldwide investing USD 700 billion annually (Ding et al., 2021; OCDE, 2020). While these subsidies are well-intentioned, they inadvertently encourage land-use decisions that contribute to deforestation (Ding et al., 2021; Meza-Hernandez, 2022). A comprehensive understanding of how subsidies influence farmers' land use decisions and resulting land use outcomes becomes imperative in addressing the challenges of integrating sustainable food production and forest conservation objectives into policy instruments (Malek et al., 2019; Villamor et al., 2014; Schreinemachers and Berger, 2007).

The impact of agricultural expansion on forests is evident in the Mexican context as well: 939,221 ha of forest have been converted to agriculture over the past two decades (Bonilla-Moheno and Aide, 2020; CONAFOR, 2022; Mendoza-Ponce et al., 2018). In 2020, The National Forestry Commission of Mexico reported a forest loss totaling 174,190 ha, of which 168,727 ha underwent conversion to cropland and grasslands (CONAFOR, 2022). This pattern continued in 2021 with a reported forest loss of 167,811 ha, wherein 162,620 ha were converted into agriculture and livestock-related land uses (CONAFOR, 2022).

In addressing deforestation trends in Mexico, there is a growing consensus on the need to promote sustainable agricultural practices (González-Abraham et al., 2022). The Mexican government has also implemented environmental policies, including protected natural areas and payments for environmental services (Perevochtchikova, 2014; Perevochtchikova et al., 2012). However, it remains unclear how local

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communities have adjusted their land use decisions in response to these initiatives (Dessart et al., 2019; Ibarra et al., 2011). Gaining insight into how farmers' decisions are shaped by agri-environmental policies is crucial for assessing the efficacy and broader effects of these policies.

The study of farmers' responses to agri-environmental policies can benefit from using serious games as a method (Duke and Geurts, 2004; Rissanen et al., 2020). Serious games, a form of participatory research and experimental methods, provide a unique opportunity to understand decision-making in land use (Barreteau et al., 2021; Gissi and Garramone, 2018). Bakhanova et al. (2020) emphasize that game-based experiments create an artificial environment where players interact and receive feedback based on their strategies, without real-world consequences (Wesselow and Stoll-Kleemann, 2018). Games hold the potential to foster dialogue between researchers and diverse populations, effectively facilitating the communication of intricate processes between public policies and natural resources (Barreteau et al., 2021; Gissi and Garramone, 2018).

One of the strengths of games lies in their ability to simulate and track decisions over time, offering an advantage over static methods like discrete choice experiments or questionnaires (Gordon and Yianakoulias, 2020). Games can reveal complex behaviors, changing preferences, reactions to shocks, competition, cooperation, individualism, and cognitive biases (Van Dijk and De Dreu, 2021). They can also capture and elucidate mechanisms behind time-related processes such as path dependency and lock-ins (Coomes et al., 2011; Egidi and Narduzzo, 1997). Understanding these processes is crucial for unraveling the social, technological, or economic factors that may lead to lock-ins in land resource management, subsequently triggering path dependency (Chavez and Perz, 2013; Conti et al., 2021; Goldstein et al., 2023).

The use of serious games by practitioners (e.g., land use planners) may not yield specific solutions for harmonizing agri-environmental policies, but it does provide insights for policy-making through interaction with the target population (Bakhanova et al., 2020; Maaß, 2021). Numerous experiences have demonstrated the success of games in engaging stakeholders in integrated natural resource management

planning, including scenarios involving human impacts on marine food webs, identifying drivers for the integrated management of food-water-energy resources, and land allocation among small-holder farmers (Ghodvali et al., 2022; Michalscheck et al., 2020; Steenbeek et al., 2020; Wu, 2012).

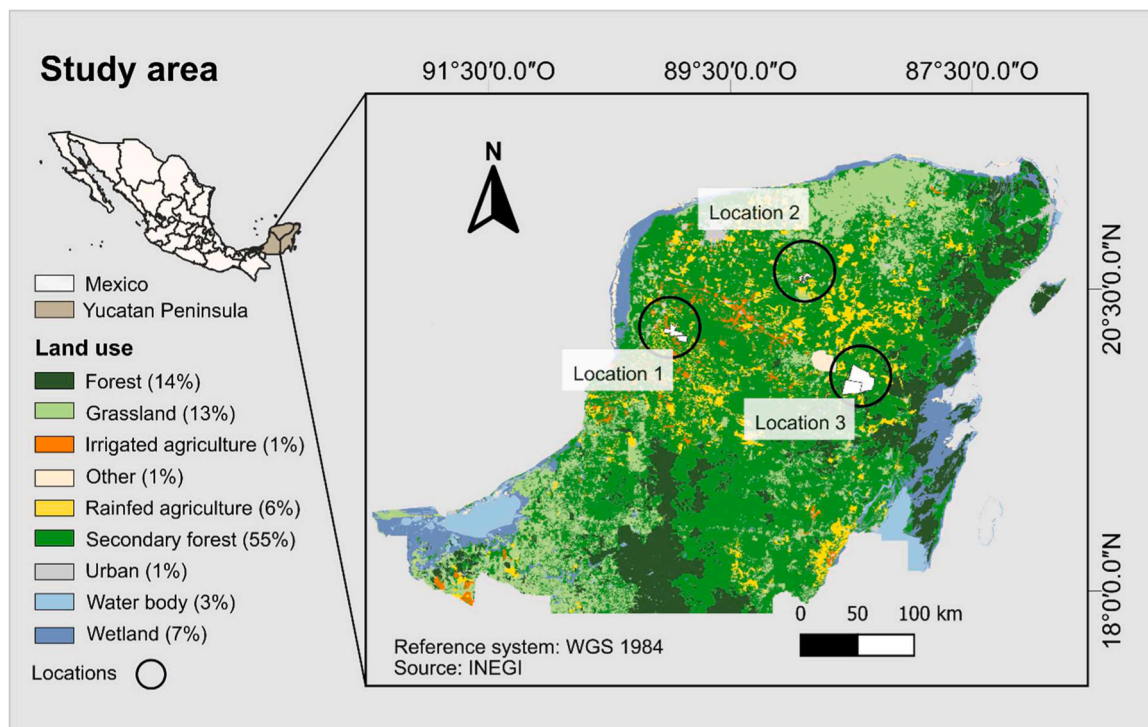
This paper presents the outcomes of utilizing games as a tool to unravel how farmers change their land use decisions in response to three agri-environmental subsidies implemented by the Mexican government. Our spatially explicit game takes into account spatial interactions, land competition, and natural site characteristics, focusing on the decision-making process among the Maya farmers of the Yucatan Peninsula. Aiming at capturing the overall land use behavior of Maya farmers, we address the following three questions with our game: How do the land use preferences and decisions of farmers change after the implementation of agri-environmental subsidies? What are the effects of agri-environmental subsidies on the overall composition of land use? And to what extent does path dependency play a role in land use change?

## 2. Materials and methods

### 2.1. Study area

The study was conducted in the Yucatan Peninsula, where secondary forest dominates (Fig. 1). Across 145,000 square kilometers, rainfed agriculture occupies 6%, and irrigated agriculture 1% (INEGI, 2018a; Mardero et al., 2018). The region has a relatively uniform biophysical context, a warm climate with an average annual temperature of 25–28 °C, and widespread presence of poor soils unsuitable for agriculture (Alfaro-Reyna et al., 2023; Alonso Velasco and Velasquez Torres, 2019). The karst geomorphology of the region, devoid of surface waterbodies, further limits agricultural potential (Gondwe et al., 2010).

More than 700,000 Maya people reside on the peninsula, primarily as farmers who combine traditional and modern land practices resulting from national agricultural subsidies that emerged in the 1990 s. These subsidies, historically known as PROCAMPO, PROAGRO, or, more



**Fig. 1.** Distribution of land uses and covers in the Yucatan Peninsula and the three locations composing the study area. Edited based on the national map of land use and vegetation for Mexico (INEGI, 2018a).

recently, *producción para el bienestar*, have encouraged traditional and mechanized agriculture, with farmers receiving money for each ha of cultivated land (Klepeis and Vance, 2003; Mendoza-Leon, 2015). In addition, payments for environmental services have been in place since 2003 to collectively compensate rural communities for forest conservation efforts via five-year compensation schemes based on the conserved area (Ezzine-De-Blas et al., 2016; McDermott and Ituarte-Lima, 2016). Under the current presidential administration (2018–2024), the *Sembrando Vida* program promotes implementation of agroforestry systems (2.5 ha per household) as a strategy for afforestation and sustainable land management (Hernández-Paulin and Esteva-Rosales, 2021).

Policy-driven rural modernization in Mexico during the 1970s favored agricultural expansion, contributing to the deforestation in the Yucatán Peninsula (Aguilar et al., 2003; Rivera de la Rosa and Ortiz Pech, 2019). Between 1993 and 2002, Campeche and Yucatan states experienced annual losses of over 20,000 ha (Alonso Velasco and Velasquez Torres, 2019; Ellis et al., 2017a). During this period, Quintana Roo also experienced deforestation at a rate of 11,300 ha per year (Alonso Velasco and Velasquez Torres, 2019). Currently the expansion of livestock activities has emerged as the primary driver of forest loss at the regional scale (Ellis et al., 2017a). Nonetheless, in various zones of the peninsula, traditional milpa agriculture and mechanized agriculture have been the main drivers of forest loss (Ellis et al., 2017b; Maritnez-Romero and Esparza-Olguín, 2010).

2.2. Game development

A stylized and standardized game, including representative elements of the Maya land management, was used to maintain consistency across all players (Le Page and Perrotton, 2018). A single board setting (Fig. 2) was used to eliminate potential variation in the strategies that may have arisen if different boards, e.g., with a real map of each location, were used. We divided the square board into nine rows and nine columns to create 81 cells, each of which represented one ha of land (Fig. 2A). Sixty-four cells were designated for making land use decisions and the remaining 17 represented roads and the village.

We designed the game rules and elements to model the influence of biophysical and economic factors on Maya farmers’ land-use decisions, with a particular focus on soil types. Maya farmers possess traditional knowledge about local soils and their suitability (Bautista et al., 2005;

Bautista and Zinck, 2012). We represented four common soil types in the study area using local names: red (Kakab), black (Ká’an kab), flood-prone (Akalche), and stony (Tselkel). These soil types were evenly distributed among the 64 cells (16 cells each, Fig. 2). The game depicted soil suitability, where specific soil types could enhance yields for certain land uses, while others resulted in zero yields (Table S1). For example, traditional agriculture was suited for black soils, flood-prone soils were unsuitable for cultivation, mechanized agriculture favored red soils, and stony soils had limited outputs.

Eight land uses were identified, representing the prevailing land use types among the Maya farmers (Fig. 3A). Each land use had associated implementation costs (both monetary and labor-related) and output products (e.g., maize, firewood, cattle) with monetary value (Table S1). Costs and output products were also visually represented on the physical game board.

Among the eight land uses, three land uses were used to mirror the traditional milpa system of the Maya:

- 1) Traditional agriculture (milpa or kool): This practice encapsulates the enduring agricultural farming system of the Maya, characterized by intercropping of maize, beans, and squash (García-Frapolli et al., 2007; Terán Contreras, 2010). Traditional agriculture predominantly hinges on manual labor, minimizing the need for financial investment. As such, traditional agriculture only required labor for its management. To mimic declining land productivity as a function of years under cultivation, yields of cells cultivated for more than three continuous years were set to zero.
- 2) Fallow (jubché): Fallows are an integral part of the management of traditional agriculture, with benefits from firewood and other non-timber forest products, accumulation of nutrients in the biomass which are released to the soil when burned, and out-shading of weeds which makes subsequent cultivation less labor intensive (Ayala Sanchez et al., 2002; González Cruz et al., 2014; van Meerveld et al., 2021). Within the game setting, fallows emerge firstly as herbaceous vegetation for three years followed by a phase of shrubbery/woody vegetation ending in a secondary forest. Fallows are a common pool resource accessible to all players but marked by the player who using them. This marking helps players in remembering their previous moves and assessing whether other players using the same cell for fallow influenced choices.

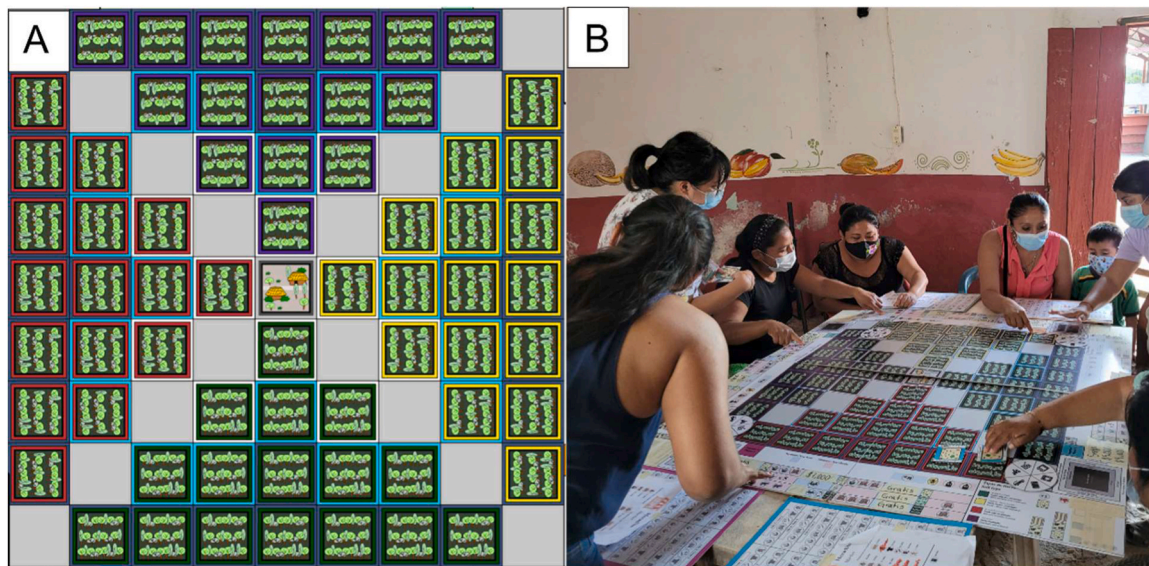
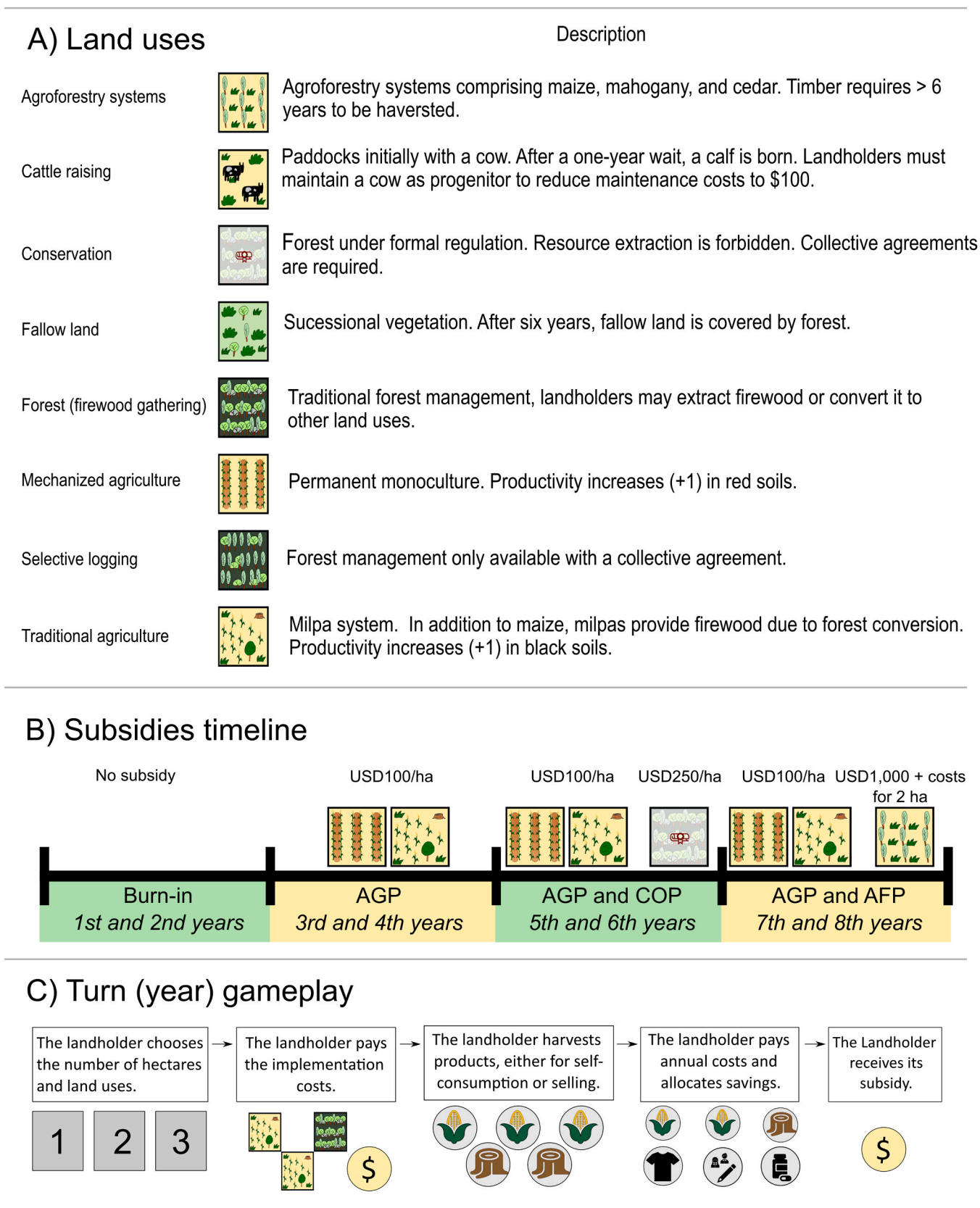


Fig. 2. A): Board game layout. Cells with black soils are delineated by a dark green border, stony soil cells by a yellow border, flood-prone soil cells by a purple border, and red soil cells by a red border. B): Image of a game session.



**Fig. 3.** Game structure. A) land use types used in the 11 game sessions, B) the sequence of subsidies across the four periods, C) actions taken in each turn (year). AGP: agricultural subsidy period; COP: conservation subsidy period; AFP: agroforestry subsidy period.

3) Forest (ka'ax): Forests provide valuable resources to the Maya, including medicinal herbs and game food (Ford and Nigh, 2015). Forests in most Maya territories are managed collectively as a common pool resource, allowing farmers to freely gather forest resources as needed (Hartel et al., 2014; Quiroz-Carranza and Orellana, 2010). Firewood extraction is particularly important as an energy source in many Maya communities (Quiroz-Carranza and Orellana, 2010). In the game, the forest has two states: unmanaged forest, encompassing all intact cells accessible to any player (common pool resource), and forest (gathering), representing forest cells used for firewood extraction and exclusive to the player who claimed them during one turn. The secondary forest after fallow has the same attributes as the initial forest in the base board configuration.

Furthermore, the game also included representations of five non-traditional land uses.

- 4) Cattle raising: Among Maya farmers, small-scale extensive cattle raising occurs as a prevalent practice (Porter-Bolland et al., 2008). The players received the explanation that the cost of cattle raising simulates the acquisition of a cow and the establishment of a basic fenced enclosure. Establishing cattle raising in the game took a turn without pay-off, followed by an additional turn to produce a calf that players could sell as a source of income. If a player opted to persist with cattle raising in the same cell and conserved the "parent" cow, this decision led to a reduction in management costs since it eliminated the need to purchase a new cow and fence.
- 5) Mechanized Agriculture: This category covered the mechanized monoculture of maize, which constitutes a means to increase crop yields and income for households with access to land suitable for mechanical tillage (Ellis et al., 2017c; Gómez de Silva, 2001; Pat-Fernández, 1999). It was elucidated to all players that the investments in mechanized agriculture mirrored expenses related to machinery rental (a common practice among small-scale farmers), and procurement of fertilizers and improved seeds. As a monoculture, maize yields are higher and, owing to fertilizers, maintain consistent output.
- 6) Conservation: Conservation in the game involves designating areas where players cannot cut firewood or convert forests into farmland. Unlike in the real world, players can choose these areas freely, allowing for both individual and group decision-making. For instance, players can collectively agree to conserve only areas with poor soils or make individual choices, even if it affects others' land use options.
- 7) Agroforestry: Agroforestry refers to systems combining fruit-bearing and timber trees with maize cultivation, aligning with the objectives of the current *Sembrando Vida* (DOF, 2022). To account for the temporal aspect of tree growth, participants had to wait for 7 turns to fully realize the benefits of managing each ha - except for one ton of maize per ha that players received during all the turns they opted to manage agroforestry.
- 8) Selective logging: Selective logging refers to designating forested areas for the sequential extraction of valuable timber, (e.g., cedar and mahogany) through zone-based cutting. In the game, players must collectively decide on the area for timber extraction, and the determined quantity of cells were distributed across the remaining game turns after implementation, with a minimum of one cell allocated per turn. Across the turns, players could gather the timber and sell it.

We identified maize, firewood, cattle, wood, and fruit trees as essential output products (Barrera-Bassols and Toledo, 2005; Porter-Bolland et al., 2008). Representing their annual needs, during each turn players were required to produce two tons of maize, one tricycle-load of firewood, as well as allocate USD 100 for education, USD 100 for clothing, and USD 100 for health care. These prices mimicked actual prices obtained from the National Institute of Statistics and Geography and the National Council for the Evaluation of Social

Development Policy (CONEVAL, 2022; INEGI, 2018b).

All players could use up to three cells on the board to establish desired land uses without incurring additional costs beyond those described in Table S1. These three cells represented the manual labor a farmer can manage without requiring paid assistance. Using additional cells incurred an extra charge of USD 50, representing hiring costs for land management.

The game included three agri-environmental policies: an agricultural subsidy (AGP), a conservation subsidy (COP), and an agroforestry subsidy (AFP). Each game ran for eight turns divided into four periods, each comprising two turns (Fig. 3B). Players became familiar with the dynamics of the game in the first period (burn-in period), which involved the initial settlement of a new village in an area covered by forest. No subsidies were introduced during this period, designed to mimic the Mexican agrarian reform of the mid-twentieth century that established new ejidos (Arias, 2019). The AGP, introduced in the third turn, provided players with USD 100 for each agriculture cell (whether traditional or mechanized), while the COP, introduced in the fifth turn, offered USD 250 per cell. The game director presented the COP before asking players if they were interested in giving part of the forest a conservation status, which would prohibit land use changes and firewood extraction. The subsidy was only introduced if at least three players agreed to the proposal. The AFP, introduced in the seventh turn, paid players USD 1000 if they allocated two cells to agroforestry management. The subsidy was not contingent on cells being adjacent to each other, ensuring players could place agroforestry on all the available soil types. This setup mirrored common situations where Maya farmers had to allocate their parcels across varying zones within their villages due to the scarcity of suitable agricultural land.

### 2.3. Field implementation

The game was played in three locations across the Yucatan Peninsula (Fig. 1) through participatory workshops with an average duration of three hours (Fig. 2B). During the first hour, we collected data from a total of 89 participants across 16 workshops to record the actual land management that served as a validation source (Table 1). As compensation for participation, each player was paid MXN 85 (Mexican pesos), equivalent to half a day's wages. The compensation amount was agreed with the local authorities during prospective visits. From the 16 workshops, 11 game sessions yielded full datasets for further analysis.

**Table 1**  
Summary of real-world land management across players (N = 89).

|   | Respondents | Average | Median | SE  | Min   | Max  |
|---|-------------|---------|--------|-----|-------|------|
| Household size                          | 89          | 4.4     | 4.0    | 0.2 | 1     | 9    |
| Managed land (ha)                       | 82          | 5.4     | 3.0    | 1.1 | 0.5   | 90   |
| Area, traditional agriculture (ha)      | 70          | 2.6     | 2.0    | 0.2 | 0.5   | 7.5  |
| Area, mechanized agriculture (ha)       | 21          | 6.5     | 5.0    | 0.8 | 1     | 20   |
| Managed paddocks (ha)                   | 7           | 14.1    | 4.5    | 2.8 | 0.5   | 70   |
| Managed agroforestry (ha)               | 14          | 2.8     | 2.5    | 0.3 | 2.5   | 6    |
| Yield, traditional agriculture (ton/ha) | 25          | 1.1     | 0.4    | 0.2 | 0.001 | 3    |
| Yield, mechanized agriculture (ton/ha)  | 18          | 5.1     | 4.5    | 0.6 | 0.5   | 11.6 |
| Agricultural subsidy uptake             | 64          | NA      | NA     | NA  | NA    | NA   |
| Conservation subsidy uptake             | 4           | NA      | NA     | NA  | NA    | NA   |
| Agroforestry subsidy uptake             | 19          | NA      | NA     | NA  | NA    | NA   |

SE: standard error; NA: not applicable

Participants were selected through a public call sponsored by the local government representing the visited communities. Dates for participation were coordinated with this representative, and invitation was open to household heads involved in agriculture. Each household was limited to one participant. In Location 1 and Location 3, we played the game in adjacent villages sharing territorial borders. The selection procedure served several purposes: 1) ensuring voluntary participation, 2) involving individuals engaged in land management, 3) obtaining local authority approval and adhering to their requirements, and 4) accommodating social distancing restrictions due to the COVID-19 pandemic, allowing for up to 8 participants per session. Players could consist of 1 or 2 participants, who were informed that they would play as a team to represent a single household's decisions.

We compiled the decisions of 44 players (18 female players/teams, 24 male players/teams, and 2 mixed-gender teams) throughout the eight turns of the game. Notably, the primary language in the visited communities was Maya, followed by Spanish. Consequently, some elderly participants faced challenges comprehending or expressing themselves in Spanish, the native language of the field-work team. To address this potential language barrier, we paired elderly participants with younger ones, enabling bidirectional interpretation (player-game director). This arrangement allowed the younger participants to assist in interpreting in both directions (player-game director). Due to the non-probabilistic participant selection approach and the formation of player teams, it was not feasible to examine in detail individual players' socioeconomic attributes as potential determinants of observed behavior.

In addition to the game director, four assistant facilitators coordinated all game sessions. At the commencement of each game turn, the game director introduced the specific rules for that turn, highlighting the available subsidies. Subsequently, following the rule presentation, the game players decided the number of cells and the desired land uses they wished to engage in. Players received corresponding tokens that represent the land uses and proceeded to select locations on the game board where they would place their land-use tokens (Fig. 2B). Players were allowed to communicate with other players in the session if they needed advice. On average, each turn lasted 15 minutes.

In instances where specific land uses incurred implementation costs, players were required to pay the necessary amount to the game facilitator prior to obtaining their corresponding tokens. At the end of each turn, players received the output products from their land uses and subsidies, if eligible (Fig. 3C). All players were instructed to mimic their real-world decisions within the context of the game's policy scenarios.

#### 2.4. Data analysis

The initial data analysis involved counting the number of players embracing each of the land uses in each turn. A database was built with each land use change throughout the 8 turns and the 11 game sessions. The proportion occupied by each land use was calculated based on the number of cells across all games, equal to 704 (11 game sessions times 64 cells). We also quantified the frequency of cells transitioning between different land uses. We used the analogous terminology to explain the change in land use: Turn = year, cell = ha.

We used a one-way ANOVA to analyze the change in deforestation rates before, during, and after the introduction of the forest conservation subsidy (Fig. S1). To analyze the association between soil type and land use, we performed a chi-square test. Finally, the associations between player location and gender and land use management was also explored. That is, the total cells played for each land use and player were aggregated across the 8 turns (Fig. S2) to conduct a one-way ANOVA test. A Tukey post hoc analysis was used to identify between-group differences.

We validated our results by comparing the game data on deforestation with actual deforestation that occurred between 2015–2020 in the three locations of the study area using land use and land cover data with 30 m resolution (CONABIO, 2020a, 2020b) (Fig. S3). While the pixel-by-pixel comparison makes little sense as the board game is highly

simplified in terms of landscape setting and rules, we focus on the land use patterns following the pattern-oriented modeling approach (Grimm et al., 2005). For example, we compared the average area managed per land use type (Fig. S3) in the game (traditional agriculture, mechanized agriculture, cattle raising, agroforestry) to the data collected on the players' actual land management (Table 1). We observed that the game gave a reasonable characterization of trends in deforestation, traditional agriculture and agroforestry, whereas the area managed by players for cattle raising and mechanized agriculture was slightly underestimated.

### 3. Results

#### 3.1. Qualitative observations and overall trends

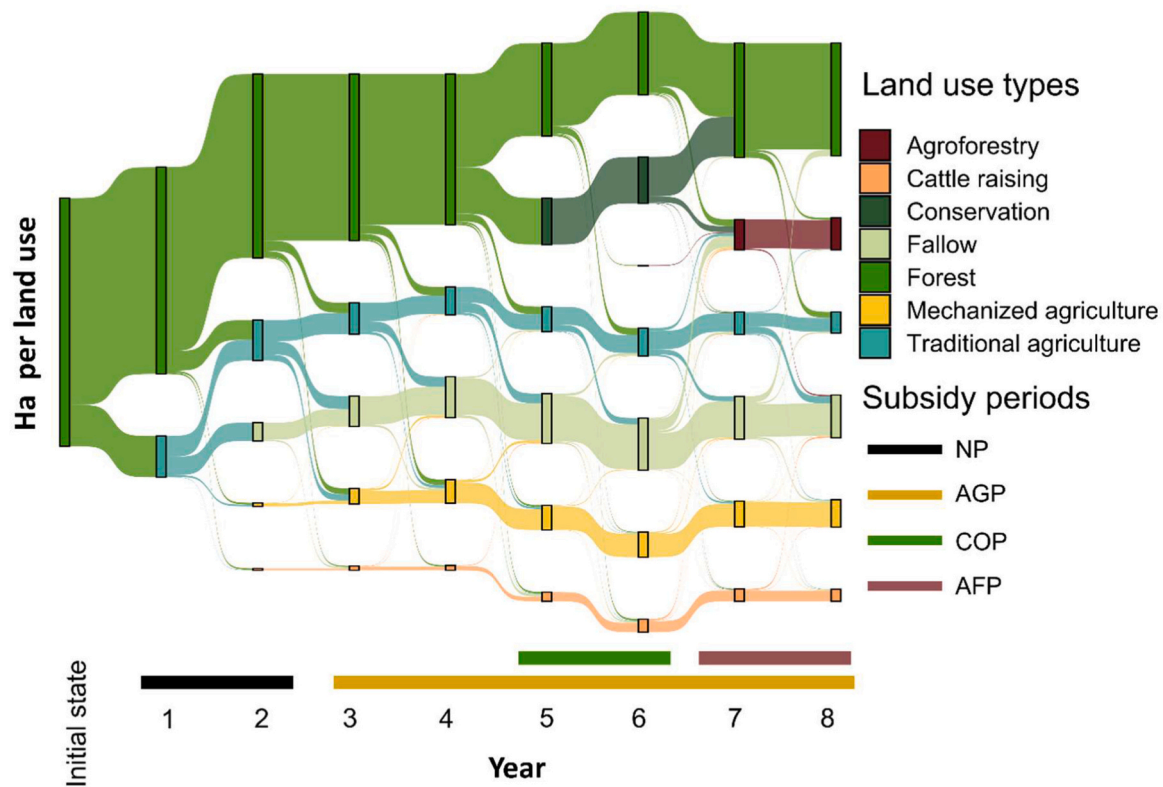
As no players opted for selective logging, we did not include it further analyses. Decisions on land management appeared individualistic, with sporadic knowledge sharing. For instance, players who recognized the positive impact of soil types on yields occasionally offered advice to other players regarding the placement of their land uses on the board.

Over the eight years of the game, land use extent and variety increased (Fig. 4), visibly affecting forest cover (Fig. 5A). By the end of the game, the forest cover had been reduced to 45% of the total area due to the expansion of agriculture, agroforestry, and cattle raising. During the burn-in period, 26% of the initial forest cover was lost. From the third year and onwards, forest cover was reduced by 5–8% per year, despite the conservation subsidy promoting forest protection. There was a significant difference in the deforestation rate between the four periods (with or without subsidies) (one-way ANOVA,  $p = 0.001$ ; Fig. S1).

Contrary to the anticipated transition from traditional to mechanized agriculture, players employed three distinct strategies concerning these two land uses: solely traditional agriculture, solely mechanized agriculture, and a combination of both. However, the frequencies of the strategies varied over time (Table S3). During the burn-in period, 89% of players on average opted exclusively for traditional agriculture strategies. In Year 3, with the onset of the agricultural subsidy, the number was reduced to 52% of players. For the rest of the game, 39% of players remained engaged in only traditional agriculture until the end of the game. The strategy of solely mechanized agriculture, absent during the burn-in period, gradually increased from being chosen by 16% of players in Year 3 to 30% in Year 8. The combined strategy of traditional and mechanized agriculture followed an initially increasing trend, starting at 16% of players in Year 2 and peaking at 39% in Year 4. Subsequently, this strategy experienced a declining trend, with only 25% of players adopting it in the final two years of the game.

We found significant differences ( $p < 0.01$ ) in the use of mechanized and traditional agriculture based on location, while forest conservation varied according to both location and gender. However, due to uneven gender distribution across locations, we couldn't definitively attribute these differences to either factor, as they were confounded. Male players were predominantly concentrated in Location 2 (66%), while female players were evenly distributed between Location 1 and Location 3. Specifically, Location 1 players engaged more in mechanized agriculture, whereas Location 2 and Location 3 players primarily practiced traditional agriculture (Fig. S2). Additionally, Location 2 players allocated fewer ha to conservation compared to players in Location 1 and Location 3. Furthermore, female players allocated more ha for conservation than their male counterparts.

Three key observations emerged from the game regarding fallow management: Firstly, there was a distinct upward trend in fallow area during the initial stages, primarily attributed to the yield decline after three years of using a cell for traditional agriculture. Secondly, players exhibited a respectful approach towards fallow cells utilized by their counterparts. They refrained from using their counterparts' previously employed cells to extend their own managed land. Lastly, we observed a reduction in the conversion of land use to fallow land within cells



**Fig. 4.** Eight years of land use changes in 11 game sessions (8 players in each, equaling 704 cells). Non-subsidy period (NP), agricultural subsidy period (AGP), conservation subsidy period (COP), agroforestry subsidy period (AFP).

occupied by mechanized agriculture when players were provided the choice of opting for permanent mechanized agriculture.

Finally, significant associations ( $p = 0.05$ ) between soil types and land uses were observed. For instance, conservation areas were predominantly located on flood-prone and stony soils, which are unsuitable for traditional and mechanized agriculture (Fig. 6B). Typically, players chose black soils for traditional agriculture and red soils for mechanized agriculture. However, occasional instances were noted where participants opted for different combinations of soil types and land uses. Also, the results indicated that forests on flood-prone and stony soils were less likely to undergo land use changes.

### 3.2. Stage 1: Burn-in period (non-subsidy period, years 1–2)

The burn-in period witnessed the rapid expansion of traditional agriculture, leading to a loss of 117 ha of the initial 704 ha of forest. In Year 1, 95% of players engaged in traditional agriculture (Fig. 6A). However, the related costs of mechanized agriculture, cattle raising, and agroforestry were too high for players to practice these land uses during the first year (Fig. 4). In the subsequent year, the remaining forest area decreased by additional 65 ha, with 56 ha attributed to traditional agriculture, 5 ha to mechanized agriculture, and 4 ha to cattle raising. Fallow land replaced 52 ha of the traditional agriculture from Year 1. By the end of the burn-in period (Year 2), all players had engaged in traditional agriculture, 16% in mechanized agriculture, and 11% in cattle raising. The increased adoption of mechanized agriculture and cattle raising was driven by players reinvesting their production surplus from Year 1 into these new land uses. None of the players showed interest in conservation or agroforestry during this burn-in period.

### 3.3. Stage 2: Agricultural subsidy period (years 3–4)

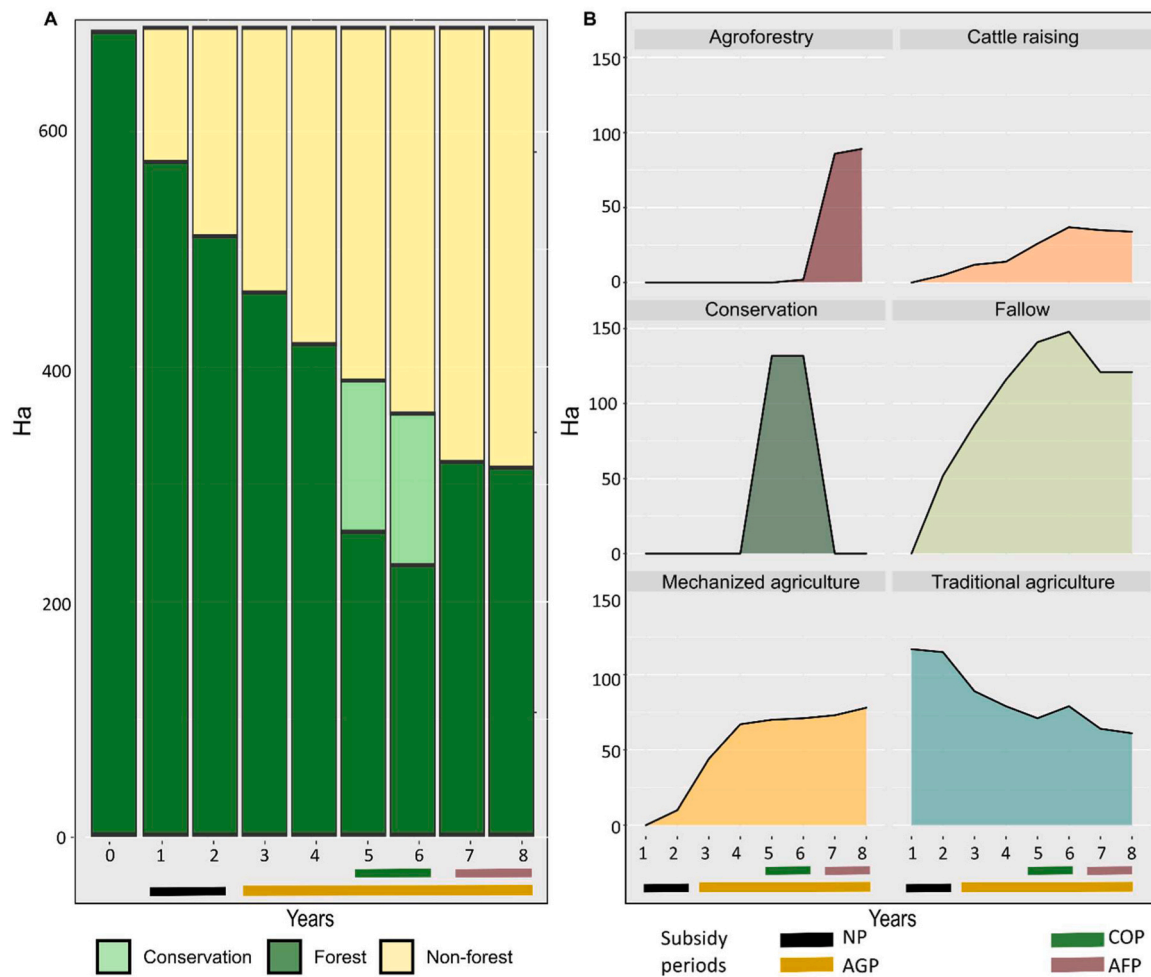
When the agricultural subsidy was introduced in Year 3, the forest cover was reduced by 49 ha, which accounted for 9% of the forest area

remaining at the end of Year 2. Traditional agriculture was the primary cause of deforestation, accounting for 29 ha, followed by mechanized agriculture, contributing to the deforestation of 17 ha, and cattle raising, which led to the loss of 3 ha. Traditional agriculture occupied 89 ha in Year 3, implying a decrease of 13% after the introduction of the agricultural subsidy. In contrast, mechanized agriculture expanded by 34 ha, reaching a total of 44 ha, 340% more compared to Year 2. Cattle raising remained relatively unchanged, only increasing from 5 to 12 ha. Fallow land replaced 37 ha of traditional agriculture and 1 ha of mechanized agriculture. Conversion from fallow to other land uses was rare, with only 4 ha of fallow land converted to cattle raising. The implementation of agricultural subsidies also resulted in changes in land use management, with 84% of players managing traditional agriculture and 48% managing mechanized agriculture (Fig. 6B).

At the end of this period (Year 4), forest cover decreased by another 45 ha, replaced by 25 ha of traditional agriculture, 16 ha of mechanized agriculture, and 4 ha of cattle raising. The conversion of forest to other land uses did not necessarily imply an expansion in those uses. For instance, in comparison to Year 3, traditional agriculture decreased by 10 ha in Year 4. This reduction was primarily due to the conversion of land from traditional agriculture to fallow (29 ha) and mechanized agriculture (8 ha), which exceeded the 27 ha converted to traditional agriculture from forest, mechanized agriculture (1 ha), and cattle raising (1 ha) in Year 4. Yet, mechanized agriculture increased to 67 ha, representing a gain of 23 ha or a 52% increase from the amount managed in Year 3. In contrast, cattle raising only increased by 2 ha compared to Year 3.

The conversion of fallow land to traditional agriculture, along with the replacement of 6 ha of mechanized agriculture and 1 ha of cattle raising, resulted in fallow land occupying 116 ha, 35% more than Year 3. The uptake of traditional agriculture continued to decrease, with only 77% of players managing it, while mechanized agriculture increased 61% and cattle raising 29%. Once again, conservation and agroforestry were not used by any player.





**Fig. 5.** Eight years of land cover and land use dynamics. Non-subsidy period (NP), agricultural subsidy period (AGP), conservation subsidy period (COP), agroforestry subsidy period (AFP).

**3.4. Stage 3: Conservation subsidy period (years 5–6)**

When introducing the conservation subsidy in Year 5, we observed that in one of the eleven game sessions players were reluctant to allocate forest land for conservation. However, 91% of players accepted the subsidy and allocated 132 ha of forest land, which accounted for 33% of the existing forest area for conservation. This trend continued until the end of the subsidy period, which was at the end of Year 6.

Deforestation continued, resulting in the loss of 32 ha of forest. Of these, 22 ha were converted to traditional agriculture, while mechanized agriculture and cattle raising claimed 5 ha each. Notably, conversion from forest to mechanized agriculture decreased compared to the previous year, but the conversion to traditional agriculture only dropped by 3 ha. As a result, both forms of agriculture now occupied the same proportional area, with each accounting for 10% of non-forest land use. Cattle raising, on the other hand, almost doubled, increasing by 12 ha. The players replaced 8 ha of fallow land with cattle raising, and the fallow area expanded to 141 ha, which was 21% more than the previous year. This expansion mostly occurred at the expense of traditional agriculture (Fig. 4).

In terms of uptake, three different paths were observed in Year 5. Traditional agriculture was managed by 73% of players, which is a minor reduction compared to the observed trend during AGP. Mechanized agriculture maintained the same level of participation as the previous year (61% of players), while 43% of players chose to manage cattle raising.

During Year 6, a total of 29 ha of forest were lost, with traditional

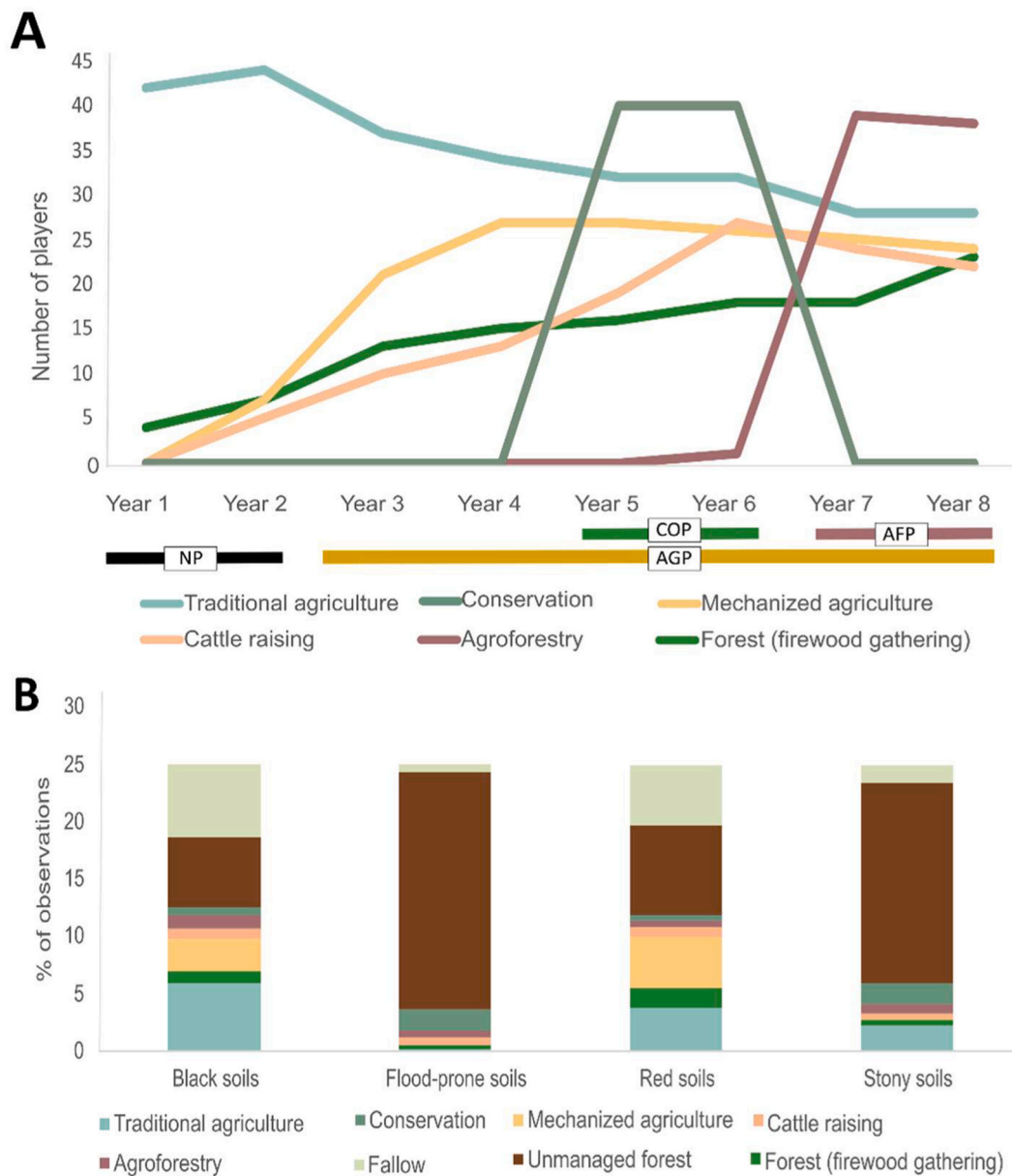
agriculture accounting for 20 ha, cattle raising for 5 ha, mechanized agriculture for 2 ha, and agroforestry 2 ha. The extent of traditional agriculture expanded by 8 ha, while mechanized agriculture increased by 1 ha. The most pronounced increase was observed in cattle raising, which expanded to occupy 37 ha, equivalent to 5% of all possible board cells.

At the end of the COP, the fallow area amounted to 148 ha, having replaced 18 ha of traditional agriculture and 2 ha of mechanized agriculture. Traditional agriculture remained the most popular among players (72%). However, participation in mechanized agriculture fell to 57%, while cattle raising increased to 61% and agroforestry to 2% of players. The highest land use diversity was observed in Year 6, presumably due to the increase in capital gained by combing the income from agricultural and conservation subsidies.

**3.5. Stage 4: Agroforestry subsidy (years 7–8)**

In Year 7, AGP began by all players with forest allocated for conservation purposes abandoning the conservation regulations, which resulted in 132 ha of conserved forest becoming available for land use change or firewood extraction. However, the introduction of the agroforestry subsidy caused a sudden increase in uptake and extent, with 89% of players managing agroforestry covering 86 ha (12% of the board cells). This upsurge was remarkable, representing a 3800% increase in uptake and a 4200% growth in coverage compared to the previous year.

The introduction of the agroforestry subsidy altered the deforestation trend, surprisingly replacing 36 ha of forest (Fig. 4), of which 17 ha



**Fig. 6.** Land use behavior trends. A) land use uptake per turn, B) percentage of observations where a land use was located on one of the four soil types across the eight turns/years. Note that, in A we present the land uses actively used by players to obtain products. In B, all land uses are presented.

had previously been allocated for conservation during COP, a higher amount than the 33 ha of fallow converted to agroforestry systems. Traditional agriculture replaced 4 ha of forest, while cattle raising replaced 3 ha, and mechanized agriculture 2 ha.

In Year 7, traditional agriculture decreased to 64 ha, cattle raising to 35 ha, and mechanized agriculture increased to 73 ha. The fallow area occupied 121 ha, with a 27 ha reduction due to agroforestry (33 ha), traditional agriculture (7 ha), cattle raising (1 ha), mechanized agriculture (1 ha), and 3 ha regrew as secondary forest. The introduction of the agroforestry subsidy resulted in reduced uptake rates, with 64% of players using traditional agriculture, 57% mechanized agriculture, and 54% cattle raising. This allowed players to allocate enough labor and capital to manage the mandatory 2 ha needed to receive the agroforestry subsidy.

At the end of this period, 320 ha (45%) of forest remained, and 34 players (77%) collected firewood from the forest. Traditional agriculture covered the smallest area, with 61 ha (9%) managed by 28 players (64%), corresponding to 16 fewer players than in the first turn, while

mechanized agriculture covered 78 ha (11%) managed by 24 players (54%), and cattle raising 34 ha (5%) managed by 22 players (50%). The fallow area remained unchanged, while agroforestry increased to 94 ha, managed by 38 players.

When AFP concluded in Year 8, the forest area was 5 ha smaller than the previous year. The game ended with a forest area that was 54% smaller than the initial area and 28% smaller than the area before introducing the first subsidy. Traditional agriculture occupied 61 ha and mechanized agriculture increased to 78 ha (representing 11% of the board), while cattle raising was reduced to 34 ha (5% of the board). The extent of these two land uses had remained relatively stable since Year 4 and Year 6. The fallow area remained the same as in the previous year, indicating an equilibrium between the amount of land that changed to and from fallow. Specifically, 29 ha of fallow land changed to forest (18 ha), mechanized agriculture (5 ha), traditional agriculture (4 ha), and cattle raising (2 ha), while 20 ha of traditional agriculture, agroforestry (4 ha), cattle raising (4 ha), and mechanized agriculture (1 ha) were replaced with fallow land.

In terms of uptake, only minor variations were observed. Cattle raising, mechanized agriculture, and agroforestry exhibited reductions to 50%, 54%, and 86% of players, respectively, while traditional agriculture remained at the same proportion of players as in Year 7.

## 4. Discussion

### 4.1. Continued deforestation despite conservation and agroforestry subsidies

Across the four periods of the game, forest was vulnerable to being converted into various agricultural land uses, including traditional agriculture, mechanized agriculture, cattle ranching, and even agroforestry. The expansion of traditional agriculture was the primary driver of forest loss throughout the game, aligning with the historical trends of deforestation in the Yucatan Peninsula (Díaz-Gallegos et al., 2010; Ellis et al., 2021, 2020, 2017a, 2015).

Converting forest land to traditional agriculture allowed players to obtain maize and firewood from the same land, reducing labor input (Table S1). As such, changing forest to traditional agriculture was a comparatively better option than obtaining separate benefits from the extraction of firewood in the existing forest or the continuation of traditional agriculture in an area already deforested. This process hinges on the game assumption that players have sufficient labor to convert forest to agriculture, and that they are willing to allocate labor to this task. In general, it will be less labor demanding to maintain a newly cleared plot in cultivation than clearing a new plot, but this is a trade-off with declining yields over time.

Although the introduction of mechanized agriculture is often promoted as a land sparing and forest conservation strategy (Ellis et al., 2017b; Pendrill et al., 2022), this was not the case during the game. Agricultural subsidies led to increased mechanized agriculture but did not stop deforestation. Earlier studies (e.g., Ellis et al., 2017b) argue that forest conservation in the Yucatan Peninsula requires a combination of land sparing and land sharing. Mechanized agriculture can boost yields on smaller land areas but has downsides like hindering wildlife mobility, reducing biodiversity, and impacting soil quality (Batey, 2009; Emami et al., 2018; Tenius Ribeiro et al., 2019). Agroforestry, a land-sharing option combining trees and crops, can support biodiversity and wildlife mobility but may slightly reduce crop yields (Montes-Londono, 2017; Perfecto and Vandermeer, 2008). Our game results suggest that combining strategies could be promising for Maya farmers, as players were prone to invest in diversified land use portfolios. However, our results show that traditional and new land uses drive deforestation differently. Traditional agriculture was associated with gradual deforestation, while mechanized agriculture and agroforestry led to rapid deforestation (Fig. 4). It is specially concerning that agroforestry replaced forest areas rather than being used for afforestation.

### 4.2. Subsidies reduce financial barriers to diversifying land use

The provision of subsidies effectively addressed the financial barriers associated with the implementation costs of various agricultural practices (Table S1). The subsidies enabled players to diversify their land use portfolios. The three subsidies in the game were associated with the increase in the extent of new land uses and the percentage of players embracing them. Similarly, real agri-environmental policies can encourage Maya farmers to adopt alternative land uses they might be hesitant or unable to embrace otherwise (Ellis et al., 2021; Kundu and Sheu, 2019; Shiferaw et al., 2009).

Implementation costs played an important financial and cognitive barrier for players to get involved in new land uses. This finding aligns with previous literature. For example, Mercer et al. (2005) found that the high implementation and maintenance costs of agroforestry were the main underlying reasons why attempting to introduce agroforestry in the Yucatan Peninsula failed.

Since the subsidies incentivize the adoption of certain land uses, revoking them would likely result in the abandonment of the promoted land uses. Ecosystem services programs have previously provided farmers with payments for their forest conservation effort (Ezzine-De-Blas et al., 2016; Gonçalves et al., 2018; Perevochtchikova, 2014). These financial subsidies have also enabled farmers to invest in other land uses (e.g., cattle raising and mechanized agriculture) and diversify their livelihoods. However, it is concerning that players appeared to abandon forest conservation once the external monetary benefits of the subsidy ceased. Furthermore, players frequently allocated forest conservation in areas unsuitable for agriculture, such as stony or flood-prone soils (Fig. 6C). Forest conservation on marginal lands, with little pressure for conversion and low opportunity costs remains a rational behavior during the implementation of forest conservation schemes (Wunder, 2007).

Also, some players adopted mechanized agriculture and agroforestry prior to the implementation of the respective subsidies. The inclusion of two ha of unsubsidized agroforestry in Year 6 could potentially be attributed to the players' awareness of the *Sembrando Vida* program and their ability to discern the underlying rule pattern of the game. This may have led them to anticipate compensation or subsidy for this particular land use for subsequent years. Nonetheless, alternative scenarios exist. For example, players might have been experimenting with diverse land uses to formulate an effective playing strategy or the possibility of unexamined factors, including an intrinsic interest in environmental preservation, personal affinity for the concept of an agroforestry system, or desire to engage in mechanized agriculture to increase maize yields.

### 4.3. Land use investments cause path dependency

Players who were able to cover the costs of management continuously used mechanized agriculture and cattle raising without the need for subsidies. Both land use types were introduced early on, but they never became dominant across the board. Instead, they persisted and expanded slowly over time. Two economic factors drove this land use path dependency. First, after becoming accustomed to receiving subsidies and generating profits, players were often reluctant to forgo this steady source of income. This can potentially be explained by the risk-averse and loss-averse attitude commonly found in smallholder farmers, i.e., people tend to avoid or minimize risks, uncertainties, and losses (Cartwright, 2018). Second, the high initial investments in cattle and/or renting of machinery makes it less likely that households will abandon the land uses, as that would result in stranded assets—or sunk costs (Sutherland et al., 2012; Thaler, 2016). We hypothesize that for cattle raising and mechanized agriculture, sunk costs can explain the observed path dependency (Conti et al., 2021; Thaler, 2016) (Fig. 2).

### 4.4. Serious games improve our understanding of land use behavior

Our game provided a stylized environment for studying Maya land systems, addressing the challenge of considering both biophysical (soil type, location) and socioeconomic (implementation costs, revenues per hectare) factors simultaneously (Feola, 2013). A key step was to distinguish between behavioral outcomes resulting from the game setup and those influenced by players' actions. For example, the initial deforestation in the first two turns was a result of the board's initial state being entirely covered by forest, which had to be replaced by agriculture to meet household needs. In contrast, the introduction of subsidies was the main factor affecting players' decision-making and land use outcomes after the burn-in period.

Compared to traditional questionnaire-based research, the utilization of serious games can offer a more authentic simulation of decision-making scenarios that closely resemble experimental research (Kong et al., 2021). These immersive games allow Maya farmers to engage in a series of controlled, interactive, and engaging activities related to land use decisions. In contrast to relying solely on self-reported land use decision behaviors, serious games can provide more precise and

accurate representations of realistic decision-making behaviors. Furthermore, serious games offer a unique opportunity to explore complex system dynamics, including path dependency, players' interactions and feedback processes, which can be difficult, if not impossible, to convey using a survey format.

However, serious games have limitations in terms of technical aspects and the range of achievable outcomes. The time-consuming workshop setup restricted participation due to limited availability of Maya farmers. Additionally, representing the complex interplay of physical and economic variables in the board game can be challenging. Our experience indicates that augmenting the complexity of game rules may lead to incomprehensibility or excessive cognitive load for players—which can hinder the game's capability to catch the major dynamics and key factors in land use decisions. Our inability to analyze socioeconomic characteristics limited our understanding of land use behavior variation across all players.

Modeling techniques within realistic scenarios can be employed to gain a deeper understanding of the real-world implications arising from our observed land use behaviors. Future work could combine geographic information systems (GIS) with agent-based models (ABMs) to construct scenarios that encompass a spectrum of social and ecological variables influencing land use decisions (Malczewski and Rinner, 2015; Pope and Gimblett, 2015; Villamor et al., 2014). GIS aids in the integration of geospatial data to establish the virtual environment, while ABMs could facilitate the representation of observed behaviors through simplified algorithms mimicking player decisions. For example, it could be explored how the land suitability for agricultural purposes affects deforestation within regions such as the Yucatan Peninsula. Such work is, however, out of the scope of this research.

Finally, the allocation of subsidies tailored to specific sectors should carefully consider farmers' behavioral patterns to mitigate potential spillover effects, especially related to deforestation and the displacement of traditional practices. For Maya households inclined to adopt new land uses, implementing measures to safeguard natural ecosystems alongside incentivized land use expansion becomes imperative. Further investigation is needed to explore innovative policy approaches. For example, a pertinent question arises about the effectiveness of introducing multisectoral subsidies or those targeting comprehensive portfolios encompassing both agricultural and forest-related practices in tandem. In conclusion, our study reveals the notable effects of agri-environmental subsidies on people's land use decisions. We advance existing knowledge on Indigenous farmers' land use decision-making by showing how land use transitions occur through a diversification process, where new land uses are integrated alongside established ones. The use of serious games is well suited to reveal such patterns – and the findings specifically highlight the need to consider path-dependency in existing theories on farmers' land use decision making (Meyfroidt et al., 2022, 2018).

#### CRediT authorship contribution statement

**Jepsen Martin Rudbeck:** Writing – review & editing, Supervision, Conceptualization. **Müller Daniel:** Writing – review & editing, Conceptualization. **Rasmussen Laura Vang:** Writing – review & editing, Supervision, Conceptualization. **Zhanli Sun:** Writing – review & editing, Conceptualization. **Alpuche Álvarez Yair Asael:** Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

#### Declaration of Competing Interest

None.

#### Data Availability

Data will be made available by the corresponding author upon request.

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#### Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.landusepol.2024.107067](https://doi.org/10.1016/j.landusepol.2024.107067).

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