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Is the Mayan Milpa Disappearing? Drivers of Swidden Agriculture Land Cover in the Yucatan Peninsula

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Abstract

The Mayan milpa is a traditional swidden agriculture that sustains food sovereignty, traditional knowledge, and agrobiodiversity among Mayan communities in the Yucatan Peninsula, Mexico. Recently, this millennial practice has declined due to the expansion of commercial monocultures and the transition from subsistence agriculture to service-based livelihoods, such as tourism. This study assessed current trends of Mayan milpa land cover and identified the main drivers associated with their decline or maintenance. Annual land cover classifications from 2018 to 2025 were conducted across two forest landscapes in the Yucatan Peninsula to estimate both the number of newly established plots and total milpa cover. Two binary logistic regression models identified factors associated with milpa decline using institutional geospatial datasets and farmer questionnaires. Results confirmed a generalized reduction in Mayan milpa land cover in both study areas: (1) in Zona Maya, Quintana Roo, with annual rates of − 8.5% in the number of new plots and − 11.0% in area; and (2) in Peto–Chikindzonot, Yucatán, with rates of − 4.3% and − 4.9%, respectively. Key agricultural and socioeconomic factors associated with this decline include tropical cyclone exposure, the *Sembrando Vida* federal agroforestry program, fertilizer use, disruptions related to the COVID-19 pandemic and high marginalization levels. In contrast, greater per-capita maize consumption, engagement in beekeeping, and a greater number of *ejidatarios* (community members with landholding rights) were associated with a lower likelihood of reduced land cover. The results provide vital information to guide policies and strategies that promote the conservation of this important traditional farming system.

INTRODUCTION

Slash and burn farming is a type of swidden agriculture in a forested mosaic landscape, defined as a sequential agroforestry system where short-term (2 to 3 years) cultivation in burned forest clearings are followed by a regenerating fallow period (Estrada-Medina and Álvarez-Rivera 2021; Moreno-Calles et al. 2013). Located mostly in the tropics, this farming system is practiced by over 250 million people worldwide (Metzger 2003) in 140 countries (Li and Nath 2024). In this context, swidden agriculture enhances agricultural production and food security, while promoting agrobiodiversity and resilience to climate change in the marginalized rural tropics (Jiang et al. 2022). Moreover, these agroforestry systems contribute to carbon storage and capture, they provide construction materials, preserve traditional ecological knowledge (TEK) and support the well-being of tropical forest inhabitants (Jacobi et al. 2025; Romero-Natale et al. 2024).

Slash and burn agriculture has often been blamed for tropical deforestation and its associated impacts on climate and biodiversity (Kurien et al. 2019; West et al. 2025; Zou et al. 2025). Shifting cultivation has been estimated to account for up to 24% of tree cover loss (Curtis et al. 2018) and 37% of forest fragmentation, with up to 61% occurring in the tropics (Zou et al. 2025). Although land use data distinguish temporary forest disturbance caused by shifting cultivation from permanent tree cover loss from commodity driven expansion, these estimates often perpetuate negative environmental and social misconceptions (Bruun and Hepp, 2023; Heinimann et al. 2017; West et al. 2025). This happens despite

criticism that the impacts of shifting cultivation on forest cover may be overestimated due to mapping complexities and classification errors (Brunn and Hepp 2023; Curtis et al. 2018). Contrarily, some authors claim that shifting cultivation practices are decreasing worldwide and transitioning to permanent agricultural systems (Martin et al. 2023; Pérez-García and del Castillo 2016). Swidden agriculture is declining due to loss of TEK, increasingly frequent and unpredictable extreme climatic events, and the misalignment of public policies and social programs with the needs of rural farming households (Jacobi et al. 2025).

Regional and local cases may show more nuanced impacts of swidden agriculture on forest cover and environmental services in the tropics. This type of agriculture in the Congo Basin, is identified as a forest loss and degradation driver, overtaking industrial logging (Tyukavina et al. 2018). In India's Western Ghats, it is linked to deforestation driven by population growth and rising consumption rates (Kunte and Bhat 2024). In the Brazilian Amazon, shortened fallow periods and increased slash and burn plots resulted in the homogenization of the forested landscape with secondary forest and primary forest loss (Metzger 2003). In the Peruvian Amazon, longer fallow cycles promoted benefits of secondary forest regeneration (Smith et al. 1999), but population pressures and insufficient landholdings for swidden agriculture can lead to poverty traps (Coomes et al. 2011). In the Himalaya, swidden agriculture has a vital role in the survival of indigenous culture and hill farmers livelihoods (Hazarika et al. 2024). Evidently, blanket generalizations of swidden agriculture impacts on forest landscapes could be misleading, requiring specific research coupled with effective remote sensing classification methods to develop effective conservation and sustainable rural development strategies and policies.

In the Yucatan Peninsula of Mexico, the Mayan milpa (MM), known locally as *kool* or *roza, tumba y quema* (slash, fell, and burn, SFB), is a swidden farming system within a pre-Hispanic biocultural landscape characterized by extensive forest cover, (Brokaw *et al.*, 2024; Ek-Dzib et al. 2012). Much of the forest on the Yucatan Peninsula today greatly owes its current structure and species composition to the milpa practices of ancient Mayan people dated back over 1,000 years ago (Brokaw *et al.* 2024). The SFB process of the MM begins around December, when the vegetation cover is cleared and trees are felled, allowing them to dry for months. Subsequently, in May, the dried biomass is burned before the rainy season. In June, farmers plant native maize (*Zea mays*) varieties, squash (*Cucurbita moschata*), and beans (*Phaseolus vulgaris, P. lunatus, and Vigna spp*.), along with other crops in smaller proportions (Ek-Dzib et al. 2012; Mateos-Maces et al. 2016). Maize is harvested between October and November and stored for year-round consumption. After one to three farming cycles, the site enters a fallow period of approximately 12 years (Gómez-Pompa 1987; Hartter et al. 2007).

The dynamics of milpa establishment, secondary succession and forest recovery within the agroforestry landscape of the Yucatan Peninsula are highly variable due differences in vegetation types, the area available per farmer, proximity to urban centers and transportation networks, population size, topography, and migratory movements (Ellis et al. 2020; Foster and Lawrence 2002; Hernández-Gómez and Ellis 2023; Huchin-Ochoa et al. 2022). Few studies have analyzed the dynamics of MM land cover in the region, often limiting analyses to local scales or conflating MM with commercial agriculture or other

milpa approaches that are replacing the traditional SFB practices, such as *roza-tumba-pica* (slash, fell, and mulch; SFM), continuous milpa (with high fertilizer use) and milpa associated with perennial crops (e.g., *Sembrando Vida* plots) (Álvarez-Rivera et al. 2026). For instance, in Peto, Yucatán, the number of MM plots increased from 1,054 to 1,963 between 1988 and 2003 (Daniels et al. 2008), attributed to agricultural subsidies; whereas in Felipe Carrillo Puerto, Quintana Roo, the number of deforested areas, including MM, decreased from 12,590 to 8,228 patches between 1993 and 2018 (Ellis et al. 2020), due to the abandonment of MM in favor of tourism-related activities. However, recent socio-political variables must also be considered in explaining current MM dynamics, such as the federal *Sembrando Vida* (Sowing Life) agroforestry program (Gómez-Rodríguez et al. 2023; Moure et al. 2024), government fertilizer distribution (Gobierno de México 2024a), and restrictions during the COVID-19 pandemic (Estrada-Ramírez et al. 2022).

In land use change studies, such as evaluating MM cover trends, drivers are classified as direct and indirect. Direct drivers refer to the immediate activities that replace forest cover (e.g., agricultural expansion, timber extraction, and urban infrastructure development). Indirect (or underlying) drivers correspond to the social and environmental proximate causes behind the direct drivers (e.g., economic, political and institutional, technological, cultural, and demographic factors) (Geist and Lambin 2002). Due to its diversified practices and fallow cycles, swidden agriculture is often hard to classify and distinguish from permanent cropping systems by small-scale producers (Curtis et al. 2018). Moreover, remote sensing methods to detect and map MM agriculture are riddled with accuracy challenges and uncertainty from regional to local scales (Hurni et al. 2013; Tola et al. 2025).

In Mexico, shifting cultivation systems have declined since the 1980s (Heinimann et al. 2017; Martin et al. 2023), mainly attributed to commercial agriculture expansion, timber extraction, and secondary forest recovery following agricultural abandonment (Bray et al. 2004; Martin et al. 2023). This transition has been driven by expectations of increased crop yields, incentive-based programs, privatization of communal lands, conservation policies, and rural migration (Ellis et al. 2020; Martin et al. 2023; Miteva et al. 2019; Moure et al. 2024; Wyman et al. 2007). Also in the Yucatan Peninsula, MM decline is led by factors such as livestock expansion, flood-prone soils, and proximity to Mennonite agricultural communities, which facilitate access to equipment, agrochemicals, and commercial seeds; promoting oilseed crops, and displacing MM to marginal lands (Porter-Bolland et al. 2007). Similar trends occur in other Mexican regions, where SFB based milpa has declined due to perennial crops, commercial farming, agrochemical, shortened fallow cycles, and youth migration (Bermeo et al. 2014; Pérez-García and del Castillo 2016). Since the 1980s, community forest management (CFM) and conservation programs have altered milpa dynamics by increasing plot density, shortening fallow periods, and encouraging transitions to more sedentary farming systems (Cuanalo-de la Cerda and Uicab-Covoh 2006; Morales-Valderrama 2004). Although strong ejido (communal landholding) organization can support MM persistence, high rural marginalization may instead drive land privatization and conversion to monocultures and cattle ranching, further reducing MM cover (Dalle et al. 2011; Morales-Barquero et al. 2014).

Assessing the status of MM at the landscape scale is vital for informing policies and programs that support food security and biocultural conservation across the Yucatan Peninsula. In recognition of its contributions to food security, agrobiodiversity, traditional knowledge, cultural diversity, and sustainable development, the Food and Agriculture Organization (FAO 2022) designated the MM as a Globally Important Agricultural Heritage System. This recognition has enhanced efforts by governments, institutions and civil society organizations to conserve and promote this system.

This study aimed to determine current land cover trends of the MM in the Yucatan Peninsula using annual metrics of number and area of newly established MM plots and identifying a set of underexplored drivers of topical importance (e.g., the COVID-19 contingency, agricultural support programs, and the *Sembrando Vida* program). A remote sensing method was developed to accurately identify and map the MM in the region. Trends in MM plot establishment between 2018 and 2025 were quantified through GIS analysis in two milpa-producing regions of the states of Quintana Roo and Yucatán, Mexico and drivers of MM land cover trends were identified using a binary logistic regression (BLR) model with georeferenced data and independent variables derived from institutional sources and field questionnaires applied to local farmers.

METHODS

Study area

The study area consists of two MM landscapes in the Yucatan Peninsula, Southeast Mexico (Fig. 1): (1) the *Zona Maya* (ZMQR) in Felipe Carrillo Puerto municipality in the state Quintana Roo and (2) the Peto and Chikindzonot municipalities (PCY) in the state Yucatán. Both are characterized by a warm sub-humid climate with summer rainfall (June to October), an average annual precipitation of 1,100 mm, and a mean annual temperature exceeding 22°C (García 1997). Specifically, ZMQR covers 345,746 ha (INEGI 2023a) and is located at elevations ranging from 80 to 275 masl. The dominant soil types include Cambisol, Gleysol, Leptosol, Luvisol, Nitisol, Phaeozem, and Vertisol, and the vegetation is predominantly medium stature semi-evergreen forest (INEGI 2021, 2024). The ZMQR study area has a population of 20,529 inhabitants distributed across 16 ejidos (Bernardino Cen, Betania, Chunhuas y sus Anexos, Dzulá y su Anexo Xhaas, Filomeno Mata, Kampokolché, Laguna Kaná, San Francisco Aké, San José, Tabi, Tihozuco, Tixcacal Guardia, Xmaben y Anexos, X-Pichil, X-Yatil, and Yaxley).

The PCY study area, with an area of 152,884 ha (INEGI 2023a), is situated between 25 and 60 m above sea level. Its soils include Cambisol, Leptosol, Luvisol, Phaeozem, and Vertisol, and it is characterized by low-stature subdeciduous forest (INEGI 2021, 2024). PCY has a population of 30,017 inhabitants distributed across 12 ejidos (Chan-Chichimilá, Chikindzonot, Ichmul, N.C.P.A. San Francisco de Asís, Papacal, Peto, Progresito, Reforma Agraria, Tixualahtun, X-Cabanché, Yaxkopil, and Expedz). In the ejido territories, MM agriculture is mainly found in the outskirts the villages (Rodríguez-Robayo et al. 2020). Likewise, in recent decades, ejidos have experienced population aging due to the migration of younger

residents to urban and tourist centers, resulting in a decline in rural labor availability (Busch and Geoghegan 2010; Serralta-Batun 2024), which means that those who still practice SFB, are the elders.

In the study area several ejidos practice CFM within designated permanent forest areas where selective logging of valuable woods is carried out for commercialization as roundwood or sawn timber (Navarro-Martínez et al. 2021). Some communities also reserve areas for conservation that generate income through carbon credit programs. As well, the vegetation in the fallow provides wood for the traditional Mayan constructions, and firewood purposes; it also serves as habitat for game and forage for bees (Balderas-Torres *et al.* 2015; Rodríguez-Robayo et al. 2020).

Recently, the *Tren Maya* railway network was constructed to enhance connectivity among the major cities in the peninsula, to strengthen the tourism sector, and to foster employment and small-scale service entrepreneurship for the growing workforce (Pasillas-López 2023). In 2019, the Mexican government launched the large-scale agroforestry program *Sembrando Vida*, which subsidizes the maintenance of timber and fruit trees on 2.5 ha plots located in municipalities with high social marginalization (Gómez-Rodríguez et al. 2023; Secretaría de Bienestar 2024). The program includes two modalities within each plot: (1) the Agroforestry System (SAF), which combines timber and fruit trees, and (2) the Milpa Intercropped with Fruit Trees (MIAF) system, which integrates maize, beans, and squash (the traditional milpa triad) between fruit tree rows (Gómez-Rodríguez et al. 2023), replacing the SFB process with the use of bio-inputs and manual clearing. During the COVID-19 pandemic, tourism activities, central to the economies of Quintana Roo and Yucatán, were severely affected by business closures and lockdowns. As a result, members of the economically active population employed in tourist cities had to return to their communities, many reengaging in subsistence agricultural activities (Nadal and Nazar-Beutelspacher 2023).

Remote Sensing

Classification and analysis of MM land cover

Sentinel-1 SAR GRD and Sentinel-2 Harmonized MSI imagery were processed in Google Earth Engine (GEE) to generate annual median composites (2017–2025) from images acquired during the SFB season (January–June; <12% cloud cover), when MM plots are established. Interannual change was determined by using differenced indices and raw bands from Sentinel-1 and Sentinel-2 images. For example, B3, B4, B8, dNBR, dNDVI, dNDWI (Sentinel-2) and VV, VH, NDIVV and NDIVH (Sentinel-1) were used to enhance the detection of recent clearings and burn scars (Dalle et al. 2011; Tyukavina et al. 2018). Annual Sentinel-2 dNBR, dNDVI, dNDWI and NIR–R–G composites were exported to QGIS 3.40.7, where newly established MM plots were visually delineated and ~ 25–30 training points were digitized. Additional samples from SICAMFOR (CCMSS, 2026) included 40–50 points for forest class and an additional 25–40 points for non-forest classes (urban areas, water bodies, and agricultural lands, including prior MM plots). Annual classifications were conducted in GEE using a Random Forest model with 200 trees (Prasad et al. 2006), classifying pixels into three categories (new milpas, non-forest, and forest) at 20 m

spatial resolution (Supplementary Material 1). Outputs were post-processed in QGIS to remove misclassified features (e.g., clouds, non-MM burn scars, floodplains, infrastructure), and polygons classified as new milpa < 0.3 ha or > 10 ha were excluded to reduce noise and eliminate large non MM agricultural clearings with aid of Sentinel-2 and high-resolution Google Earth imagery. Final MM polygons were used to calculate patch number, total area, and change rates (Puyravaud, 2003) for two triennia (2018–2020 and 2023–2025), reducing short-term variability and accounting for the 2–3 years SFB cycle. Accuracy was assessed using the AcATaMa plugin in QGIS (Olofsson et al. 2013, 2014), generating 120 stratified random reference points for 2025 (30 new milpas, 40 non-forest, 50 forest) to estimate user's, producer's, and overall accuracy.

Data soures for Statistical Modelling

We used data from three sources for subsequent spatial statistical analysis: 1) Rates of change in newly established milpa plots per ejido, derived from the remote sensing analysis described above; 2) Binary and numerical georeferenced data obtained from official government institutions; and 3) Numerical data on the proportion of farmers within each ejido exhibiting specific characteristics, derived from field questionnaires administered as part of this study.

Spatial data sources

A digital elevation model was acquired from the National Institute of Statistics and Geography (INEGI 2013) to derive elevation and terrain slope. Vector files of the national road network and human settlements (INEGI 2023a, 2023b) were used to calculate distances from roads and settlements. Data on the number of *ejidatarios* and *comuneros* (members with agricultural land use rights) and ejido area were gathered from the National Agrarian Registry (RAN 2024). The 2020 Social Marginalization Index for municipalities was obtained from the National Population Council (CONAPO 2021). Authorized Environmental Impact Assessments and Unified Technical Documents from the Ministry of Environment and Natural Resources (SEMARNAT) were used to identify and digitize permanent forest areas in ejidos practicing CFM. Annual precipitation and precipitation of the driest month were obtained from WorldClim (2017). Although georeferenced data from *Sembrando Vida* plots were unavailable, a low-resolution map of production units was digitized to identify participating ejidos (Secretaría de Bienestar 2024). All variables were standardized into logical and numerical formats (Supplementary Material 2).

Field survey data

Due to the absence of databases detailing the socioeconomic characteristics and agricultural practices at the ejido level, 198 questionnaires were conducted with farmers practicing the MM system between November 2023 and January 2025: 104 in the ZMQR and 94 in PCY. The snowball sampling method was employed (Atkinson and Flint 2001) to select MM farmers in each ejido. The questionnaire collected information on plot area, cropping cycles, years dedicated to MM, maize consumption and price per

household, and fallow duration, as well as practices such as beekeeping, and use of fertilizers, herbicides and pesticides. Questionnaires also collected data on local impacts from meteorological events (e.g., tropical cyclones, droughts, fires, and floods) and loss of production due to pests. Additionally, the instrument incorporated exogenous factors such as participation in *Sembrando Vida* and other agricultural subsidy programs, degree of milpa activities during the COVID-19 pandemic, local impact of economic inflation, and influence of the *Tren Maya* project in the ejidos (Supplementary Material 3). For each variable, means and ejido-level proportions were calculated and spatially assigned to ejido polygons in QGIS.

Statistical analysis

A total of 2,000 random points (1,000 per study area) were generated, extracted from the centroids of 300 × 300 m grid cells within both study areas (Morales-Barquero et al. 2014). These points were used to extract data from the independent variables derived from the georeferenced datasets and field questionnaires (Supplementary Material 2 and 3), as well as the rates of change in both the number and cover of newly established MM plots. Points west of Peto in PCY were excluded due to incomplete Sentinel-1 coverage, leaving 1,959 points (Supplementary Material 4).

Two BLR models were developed using the pROC package in RStudio (Supplementary Material 5) to identify independent variables (X_1, X_2… X_n) associated with the maintenance/increase or decline of the MM. The first model was based on the rate of change in the number of newly established MM plots, while the second model used the rate of change in the total cover of new MM plots, both models analyzed at the ejido level for both MM landscapes in the study area between the triennia 2018–2020 and 2023–2025. In both models, the dependent variable (Y) was binary, where a maintenance/increase trend was coded as 0, and a declining trend as 1.

To reduce multicollinearity among the predictor variables (Akinwande et al. 2015), a Variance Inflation Factor (VIF) analysis was conducted using the Car package in RStudio 2025.05.0 for both models. This procedure reduced the initial set of 40 variables (Supplementary Material 2 and 3) to 11 variables retained for analysis (Table 1).

The susceptibility to a decrease in MM within each ejido was expressed as:

$$P = \frac{1}{1 + e^{-z}}$$

Where *P* is the probability that the number or total area of MM plots decreases, *e* is the base of the natural logarithm (2.71828), and *z* is the equation. *P* was calculated for each sample and averaged by ejido to estimate susceptibility to reduction in the number and area of MM plots. Ejidos were subsequently classified into 10% intervals and mapped accordingly (Al-Kordi et al. 2025).

Table 1
Description of variables used in the binary logistic regression to identify drivers of Mayan milpa land cover in terms of the number and area of plots

Variable	Used in the model		Spatial unit
	Number of new milpa plots	Cover of new milpa plots	
Elevation[1]	Yes	Yes	Meters / pixel
Distance to towns and cities[2]	Yes	Yes	Meters / pixel
Number of ejidatarios[3]	Yes	Yes	Unit / Ejido
2020 Social Marginalization Index[4]	Yes	Yes	Index / Municipality
Participation in *Sembrando Vida* program[5]	Yes	Yes	Yes / No / Ejido
Weekly per-capita maize consumption[6]	Yes	No	kg/person / Ejido
Percentage of farmers engaged in beekeeping[6]	Yes	Yes	Percentage / Ejido
Percentage of farmers using fertilizer in Mayan milpa[6]	No	Yes	Percentage / Ejido
Percentage of farmers affected by cyclones[6]	Yes	No	Percentage / Ejido
Percentage of farmers receiving agricultural subsidies[6]	Yes	Yes	Percentage / Ejido
Percentage of farmers whose activities were affected by COVID-19[6]	Yes	No	Percentage / Ejido

1. Obtained from INEGI, 2013

2. Calculated from INEGI, 2023b

3. Obtained from RAN, 2024

4. Obtained from CONAPO, 2021

5. Obtained from Secretaría de Bienestar, 2024

6. Obtained from surveys

RESULTS

Milpa land cover

The accuracy assessment based on 120 points indicated an overall accuracy of 97% for the 2025 classification in ZMQR, with a producer's accuracy of 61% in the identification of new milpa plots. While in PCY, overall accuracy was 98% with a producer's accuracy of 79% for new milpa plots. In both regions, misclassification of new milpa plots occurred mainly with non-forest areas, such as previously established milpas and burned areas.

The analysis of changes in milpa land cover across both study areas revealed an initial peak in 2019 with 1,933 plots and 2,771 ha (1,296 plots and 1,895 ha in ZMQR; 637 plots and 875 ha in PCY), followed by a minimum in 2022 with 481 plots and 463 ha (267 plots and 230 ha in ZMQR; 214 plots and 232 ha in PCY), and a second peak in 2023 with 1,625 plots and 2,301 ha (1,091 plots and 1,526 ha in ZMQR; 534 plots and 774 ha in PCY) followed by a final decreasing trend in most ejidos with 684 plots and 750 ha in 2025 (227 plots and 208 ha in ZMQR; 457 plots and 542 ha in PCY; Fig. 2, Fig. 3). Most ejidos recorded fewer than 50 new plots annually, except for those exhibiting peaks: Tihozuco (mean 97), Xmaben y Anexos (mean 136) and X-Pichil (mean 56) in ZMQR, as well as Peto (mean 100), Chikindzonot (mean 102), and Expedz (mean 82) in PCY.

ZMQR MM plots fell annually (–8.57% in number, − 11.06% in cover). All the ejidos declined, particularly Betania (–28.4% in number, − 34.5% in cover). PCY also decreased (–4.34% in number, − 4.95% in cover). The N.C.P.A. San Francisco de Asís increases its MM plots number (+ 6.8%) and Chikindzonot in cover (+ 7.5%). In contrast, most ejidos showed a decline in MM, particularly Chan Chichimilá (–29.6% in number, − 30.9% in cover; Fig. 4).

Drivers of milpa land cover

The variables included in the BLR model showed low multicollinearity, with mean VIF values of 1.71 for the number of new MM plots model, and 1.22 for milpa surface model. Both BLR models shared most of the same 11 explanatory variables: ten were associated with reduction in the number of new plots and eight with a reduction in cover. Key variables common to both were meters above sea level, distance to towns and cities, number of ejidatarios, the 2020 social marginalization index, participation in the *Sembrando Vida* program, and the percentages of farmers engaged in beekeeping and percentage receiving agricultural subsidies (Table 2).

Less probability in the reduction of new milpa plots established were associated with beekeeping (7.9%), number of ejidatarios (2.4%) and maize consumption (1.6%); whereas crop damage caused by tropical cyclones (27.3%), the percentage of farmers receiving agricultural subsidies (20.2%) and participation in *Sembrando Vida* program (19.3%) were associated with a higher probability of milpa plot reduction. In terms of area occupied by MM, the percentage of farmers receiving agricultural subsidies (33.9%), participation in *Sembrando Vida* program (19.6%) and percentage of farmers using fertilizer (16%) increased the probability of reduced surface with milpa land cover; while beekeeping (6.1%) and number of ejidatarios (4.5%) was associated with a greater probability of increasing milpa surface in ejidos (Tables 2 and 3). Both models showed strong predictive performance (AUC = 0.98), above the baseline

(AUC = 0.5), effectively in predicting the probability of changes in milpa Maya land cover in the study areas.

Table 2
Binary logistic regression models for the reduction of the number and area of Mayan milpa plots

Metric	Variable	Estimate	Std. Error	Z Value	Pr(>|Z|)	Signif.
Number of new milpa plots	(Intercept)	-19.5894	1.9916	-9.8359	7.8804e-23	***
	elevation	0.1769	0.0256	6.9020	5.1268e-12	***
	distance to towns and cities	0.0002	6.2588e-05	3.7226	0.0001	***
	number of *ejidatarios*	-0.0053	0.0006	-7.7182	1.1796e-14	***
	2020 social marginalization index	0.0859	0.0175	4.9089	9.1554e-07	***
	participation in *Sembrando Vida* program	6.5840	0.3719	17.7007	4.1394e-70	***
	weekly per-capita maize consumption	-0.3490	0.1608	-2.1702	0.0299	*
	percentage of farmers engaged in beekeeping	-0.0809	0.0097	-8.3056	9.9264e-17	***
	percentage of farmers affected by cyclones cyclones	0.0930	0.0150	6.1808	6.3740e-10	***
	percentage of farmers receiving agricultural subsidies	0.0826	0.0062	13.1764	1.1991e-39	***
	percentage of farmers whose activities were affected by COVID-19	0.0201	0.0094	2.1387	0.0324	*
Null deviance: 1821 on 1958 degrees of freedom. Residual deviance: 638.2. AIC: 660.2. AUC = 0.981						
Area of new milpa plots	(Intercept)	-6.1536	2.4448	-2.5170	0.0118	.
	elevation	0.1204	0.0261	4.6100	4.0255e-06	***
	distance to towns and cities	0.0003	7.7813e-05	4.6472	3.3634e-06	***
	number of *ejidatarios*	-0.0084	0.0010	-8.2183	2.0627e-16	***
Signif. codes: '***' < 0.001; '**' < 0.01; '*' < 0.05; '.' < 0.1						

Metric	Variable	Estimate	Std. Error	Z Value	Pr(>|Z|)	Signif.
	2020 social marginalization index	0.0903	0.0193	4.6585	3.1851e-06	***
	participation in *Sembrando Vida* program	5.5419	0.3414	16.2292	2.3740e-24	***
	percentage of farmers engaged in beekeeping	-0.0523	0.0061	-8.5196	1.6004e-17	***
	percentage of farmers using fertilizer in Mayan milpa	0.0680	0.0092	7.3872	1.4987e-13	***
	percentage of farmers receiving agricultural subsidies	0.1151	0.0098	11.6427	2.4984e-31	***
Null deviance: 1636 on 1958 degrees of freedom. Residual deviance: 483.5. AIC: 501.5. AUC = 0.983						
Signif. codes: ‘***’ < 0.001; ‘**’ < 0.01; ‘*’ < 0.05; ‘.’ < 0.1						

Table 3
Contribution of each variable in the binary logistic regression model for the reduction of the number and area of Mayan milpa plots

Metric	Variable	Contribution	Percentage
Number of new milpa plots	percentage of farmers affected by cyclones	9.3060	27.36
	percentage of farmers receiving agricultural subsidies	6.8866	20.25
	participation in *Sembrando Vida* program	6.5840	19.36
	elevation	3.3611	9.88
	percentage of farmers engaged in beekeeping	-2.6940	7.92
	distance to towns and cities	2.0500	6.03
	percentage of farmers whose activities were affected by COVID-19	1.6815	4.94
	number of *ejidatarios*	-0.8183	2.41
	weekly per-capita maize consumption	-0.5585	1.64
	2020 social marginalization index	0.0704	0.21
Area of new milpa plots	percentage of farmers receiving agricultural subsidies	9.5958	33.95
	participation in *Sembrando Vida* program	5.5419	19.60
	percentage of farmers using fertilizer in Mayan milpa	4.5410	16.06
	distance to towns and cities	3.1818	11.25
	elevation	2.2894	8.10
	percentage of farmers engaged in beekeeping	-1.7438	6.16
	number of *ejidatarios*	-1.2964	4.58
	2020 social marginalization index	0.0740	0.26

The average ejido-level probability of a reduction in the number of MM plots shows that four ejidos in PCY have a probability below 50% (Fig. 5a), while all ejidos showed a probability above 90% for cover reduction (Fig. 5b). In ZMQR, all ejidos exhibited a probability greater than 90% of reduction in the number of plots except for two with values between 80% and 90% (Fig. 5c), whereas all ejidos showed a probability above 90% for cover reduction (Fig. 5d). Overall, the mean probability was 82% for number reduction and 99% for cover reduction.

DISCUSSION

Annual data on newly established MM plots are essential given the migratory and rotational nature of this system (Dalle et al. 2011; Mota-Cruz et al. 2025). Although there are issues with cloud cover in the tropics when using multispectral satellite imagery (e.g., Landsat TM, ETM+, and OLI, as well as Sentinel-2), in our study, this limitation was mitigated by integrating data from the Sentinel-1 SAR sensor which penetrates clouds and other problematic atmospheric phenomena. Unfortunately, the lack of Sentinel-1 imagery prior to 2017 prevents the evaluation of earlier trends when applying this method.

In ZMQR, MM increased between the 1990s and 2000s, followed by a decline during the following decade (Ellis et al. 2020; Hernández-Gómez and Ellis 2023); meanwhile in PCY the forest area has decreased, driven not only by MM establishment but also by the growth of urban areas and non-traditional SFB milpa variants (Daniels et al. 2008, Wyman et al. 2007). In the present study, between 2018 and 2025, MM land cover generally continued to decline in both study areas. However, a peak in MM was observed in 2019, likely associated with the launch of the *Sembrando Vida* program (Gómez-Rodríguez et al. 2023; Secretaría de Bienestar 2024). The decline in 2022 is related to the end of COVID-19 lockdowns, which reactivated economic activities across the region and prompted many temporary farmers to return to their urban workplaces or other off-farm labor (Hernández-Galindo et al. 2022). A second peak observed in 2023 coincides with the implementation of the *Fertilizantes para el Bienestar* (Fertilizers for Wellbeing; Gobierno de México 2024a), which provided free fertilizers to farmers. The subsequent decline in 2024–2025 may reflect the continued use of these fertilizers, which can extend cultivation cycles and reduce the need to establish new MM plots over subsequent years. For example, in Africa, where agricultural subsidies helped intensify farming, reducing deforestation and increasing income and production (Abman and Carney 2020; Holden 2019). However, in other cases, agricultural inputs have replaced swidden agriculture with commercial plantations (Martin et al. 2023).

The constant reduction in both the number of plots (–3.6% to − 4.2% annually) and land cover (–5.5% to − 5.6% annually) of MM between the 2018–2020 and 2023–2025 triennia appear to respond to multiple factors, including the implementation of government programs, climatic variability, shifts in livelihoods (e.g., toward monocultures and cattle ranching), loss of Mayan language, demographic growth, population aging and migration, which are leading to an overall decline in agricultural activity in rural areas (Álvarez-Rivera et al. 2026; Moreno-Calles et al. 2013; Serralta-Batun et al. 2024). In Peto, Daniels et al. (2008) reported an increase in milpa between the 1980s and 2000s, both in average plot size and number of plots; however, no distinction was made between SFB, SFM or continuous milpa systems which may have varied, the latter being more intensive and permanent cultivation strategies (Álvarez-Rivera et al. 2026; Estrada-Medina and Álvarez-Rivera 2021). This earlier increase may have been linked to the adoption of technological inputs and the implementation of the *Milpa Sin Quema* (no-burn milpa) program in Yucatán, which promoted the SFM system (Cuanalo-de la Cerda and Uicab-Covoh 2006; Estrada-Medina and Álvarez-Rivera 2021). In contrast, the present study identified a declining trend in MM in the municipality of Peto. Conversely, some ejidos in the municipality of Chikindzonot have continued their traditional farming practices. According to the farmers surveyed, this is because the soil is not suitable for sedentary milpa. Another possible factor behind the widespread reduction of milpa is the promotion of secondary and upper-secondary education during the 1990s and 2000s (Alcántara

2008), which contributed to a generational shift in educational attainment, reducing interest in agricultural work and encouraging younger generations to pursue service-oriented occupations outside the rural environment of their indigenous communities.

The *Sembrando Vida* program was implemented throughout the Yucatán Peninsula, and all selected ejidos in ZMQR accepted participation. In contrast, some ejidos in PCY initially rejected participation because they believed the program would reduce labor availability for MM management (Gómez-Rodríguez et al. 2023). However, after observing the program's financial benefits, these ejidos have become interested in participating. Overall, the agroforestry and tree planting program has resulted in many of their beneficiaries in either reducing the area devoted to MM or replacing it with the MIAF (Agroforestry Intercropping System). Consequently, the subsistence-oriented strategy of MM by ejidatarios is being replaced by *Sembrando Vida*, which is more profitable, nearly eleven times higher the annual payment provided by the *Producción para el Bienestar* (Production for Wellbeing) subsidy program for the same cultivated land surface (Gobierno de México 2024b, 2024c; Gómez-Rodríguez et al. 2023). Some beneficiaries have suspended the cultivation of the milpa triad within the MIAF system due to shading effects from intercropped fruit trees. In addition, due to youth outmigration, most milpa farmers are increasingly older adults (average age 56 years in surveys, SD = 13 years) who depend on external labor, typically from relatives or neighbors, but this labor supply has been absorbed by *Sembrando Vida* beneficiaries, whose higher wages have further constrained non-beneficiary farmers. The BLR models detected *Sembrando Vida* as a significant driver of MM reduction, reflecting the mechanisms described above. Relatedly, it is important to mention, that a bias may exist in identifying new MM plots in 2019 and 2020, as some may have actually been *Sembrando Vida* plots (Gómez-Rodríguez et al. 2023), that is, areas where vegetation has been cleared for MM plots but subsequently incorporated as *Sembrando Vida* plots.

Historically, agricultural subsidy programs (e.g., PROCAMPO and PROAGRO) have contributed to the technification of agriculture (Zarazúa et al. 2011), the abandonment of traditional agroforestry practices (Moffette and Alix-García 2024; Ramírez et al. 2023) and deforestation (Ellis et al. 2025). Despite this, milpa farmers perceive that subsidies help them maintain their milpa plots (e.g., covering labor costs for clearing and weeding) and supporting daily household expenses, particularly when subsistence production is insufficient. Some of the reasons for such shortfalls include prolonged droughts and crop predation by animals such as the coati (*Nasua narica*). The *Producción para el Bienestar* program provides subsidies to milpas of varying sizes (Gobierno de México 2024b), while the *Fertilizantes para el Bienestar* program, providing fertilizer to farmers (Gobierno de México 2024a), promoted the increasing use of agricultural inputs. According to some farmers surveyed in ZMQR, these fertilizers subsidies may be encouraging both new milpa producers and farmers who had previously abandoned cultivation to re-engage in MM practices. This contrasts with PCY, where fertilizers use has been common since the early 2000s (Cuanalo-de la Cerda and Uicab-Covoh 2006). In tropical regions, swidden agriculture is declining, particularly in Southeast Asia, sub-Saharan Africa and Central and South America, due government restrictions on fire use, soil degradation and non-agricultural employment (Arwida et al. 2024; Heinimann et al. 2017; Li and Nath 2024), projecting to disappear after 2060 (Heinimann et al. 2017). However,

agricultural policies give contrasting results. In Malawi and Zambia, agricultural subsidies reduce deforestation and increase agricultural production (Abman and Carney 2020; Holden 2019). Conversely, in Madagascar and Southeast Asia, the market for agricultural inputs promoted cycles of debt accumulation and farm production to pay off debt, which increased deforestation and rural migration (Arwida et al. 2024; Li et al. 2014).

The most widespread fire management strategy used on the Yucatan Peninsula is fire exclusion (Souza-Alonso et al. 2022), but accidental spread of fires from the milpa is still frequent, often leading to major forest fires. However, adoption of no-burn milpa was limited since fire management is deeply rooted in the cultural practices surrounding the MM (Álvarez-Rivera et al. 2026; Cuanalo-de la Cerda and Uicab-Covoh 2006; Estrada-Medina and Álvarez-Rivera 2021). Consequently, policies have focused on issuing agricultural burn permits through municipal governments, specifying preventive measures such as maintaining firebreaks (Gobierno del Estado de Quintana Roo 2014; Gobierno del Estado de Yucatán 2006). Notwithstanding, fire management practices do not rely solely on state regulation, but also on ejido rules and community agreements. The transmission of TEK on SFB practices, from older to younger milpa farmers, is essential for enhancing agricultural efficiency and preserving forest ecosystems (Bruun and Hepp 2023; Falkowski et al. 2023; Jouault 2018; Li et al. 2014; Nigh and Diemont 2013; Souza-Alonso et al. 2022).

BLR models demonstrated that that higher maize consumption was linked to greater persistence of the MM system, revealing the deep cultural connection between Maya communities and native maize preferences, central to TEK (e.g., rituals, local customs, and diets) (Rodríguez-Robayo et al. 2020). This is also reflected during the COVID-19 pandemic period, since maize consumption was recommended for its high nutritional value (e.g., vitamin A) to help mitigate public health impacts and co-morbidities (Mota-Cruz et al. 2025; Pérez-García and del Castillo 2016; Rodríguez-Robayo et al. 2020). Concurrently, the practice of MM emerged as an adaptive response to the loss of income caused by the lockdowns across the Yucatan Peninsula (Nadal and Nazar-Beutelspacher 2023).

Since milpa production is primarily intended for auto-consumption, some milpa farmers often diversify their milpa plots with beekeeping (both apiculture and meliponiculture) as a complementary source of income (Morales-Valderrama 2004). Beekeeping in MM landscapes is ideal since bees tend to forage across various successional stages of secondary vegetation during the fallow periods (Estrada-Medina and Álvarez-Rivera 2021; Romero-Natale et al. 2024). On the other hand, beekeeping is generally incompatible with the use of agrochemicals applied in commercial crops; favoring the continuation of the MM system by beekeepers (Gómez-González 2016).

The MM agroforestry farming system has often been labeled by the Mexican government as a driver of deforestation and forest degradation linked to fire use and extensive traditional land production, prompting sedentarization policies (Gobierno de Quintana Roo 2023). However, an alternative is to promote indigenous SFB farming systems by conserving valuable TEK on native seeds management, fire management and knowledge of vegetation age (Bruun and Hepp 2023; Rodríguez-Robayo et al. 2020).

Such knowledge could also help determine the optimal fallow period, thereby enhancing agricultural productivity, reducing weed proliferation, and increasing soil richness (Hauser and Norgrove 2013). The use of agricultural inputs in sedentary milpa systems can increase crop yields, but long-term dependence may lead to the erosion of TEK.

Considering the decrease in milpa land cover between 2018 and 2025, future studies could should also evaluate changes and trends in aboveground forest biomass (Ellis et al. 2020; Hernández-Gómez and Ellis, 2023) and evaluate the different fallow management practices and outcomes between both study areas. However, such an analysis would require a longer study period, since SFB type MM systems typically exhibit fallow cycles of about 20 years (Estrada-Medina and Álvarez-Rivera 2021; Mota-Cruz et al. 2025). The quantification of these dynamics would provide valuable insights into their impacts on forest cover and biomass dynamics or forest degradation processes resulting from shortened fallow cycles, in addition to their consequences on local communities.

CONCLUSION

This study determines that there is an overall decrease in the MM farming system on the Yucatan Peninsula. The results suggest several key drivers of decline or persistence of the MM. The most influential factors for MM decrease included: the federal programs such as *Sembrando Vida* and agricultural subsidies (e.g., *Producción para el Bienestar*), fertilizers use (including *Fertilizantes para el Bienestar* program), crop damage caused by tropical cyclones, social marginalization, socioeconomic effects of the COVID-19 pandemic, distance to towns and cities and the elevation. On the other hand, the factors that influenced the maintenance of MM were beekeeping activities, maize consumption and the number of ejidatarios. Some of these drivers are temporary, linked to health restrictions and government administrations, whereas others are deeply rooted in the livelihoods and cultural practices of farming communities.

In situ research with farmers, supported by surveys collecting information on agricultural, socioeconomic, and cultural practices, is essential to complement geospatial analysis and understanding of the local factors that shape the motivations of farming families to continue practicing this millennia-old agroforestry system. Finally, the estimation of MM plot dynamics provides a useful metric for evaluating programs and designing public policies aimed at its preservation, as well as for guiding civil society initiatives and community-based campaigns dedicated to sustaining this traditional practice.

DECLARATIONS

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Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this article.

Author Contribution

D.C.C. and E.A.E. wrote the main manuscript text. D.C.C. conducted the field interviews and performed the data analysis. E.S.R. and M.A.N.M. contributed to the development of the manuscript and critically reviewed it. All authors reviewed and approved the final manuscript.

Data Availability

All data supporting the findings of this study are available within the paper and its Supplementary Information.

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Figures

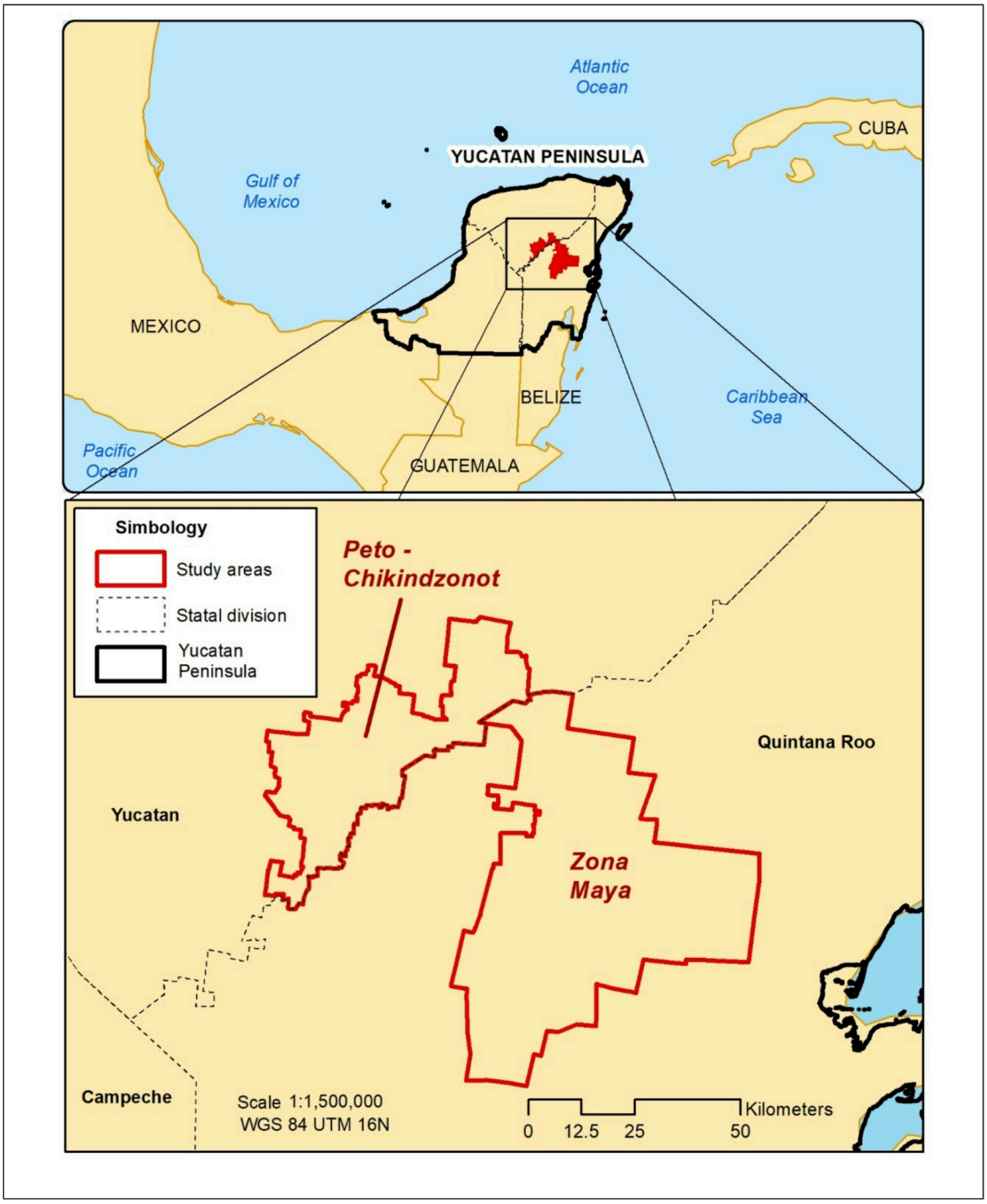


Figure 1

Location of the two Mayan milpa landscapes in the study area in the Yucatan Peninsula, Mexico

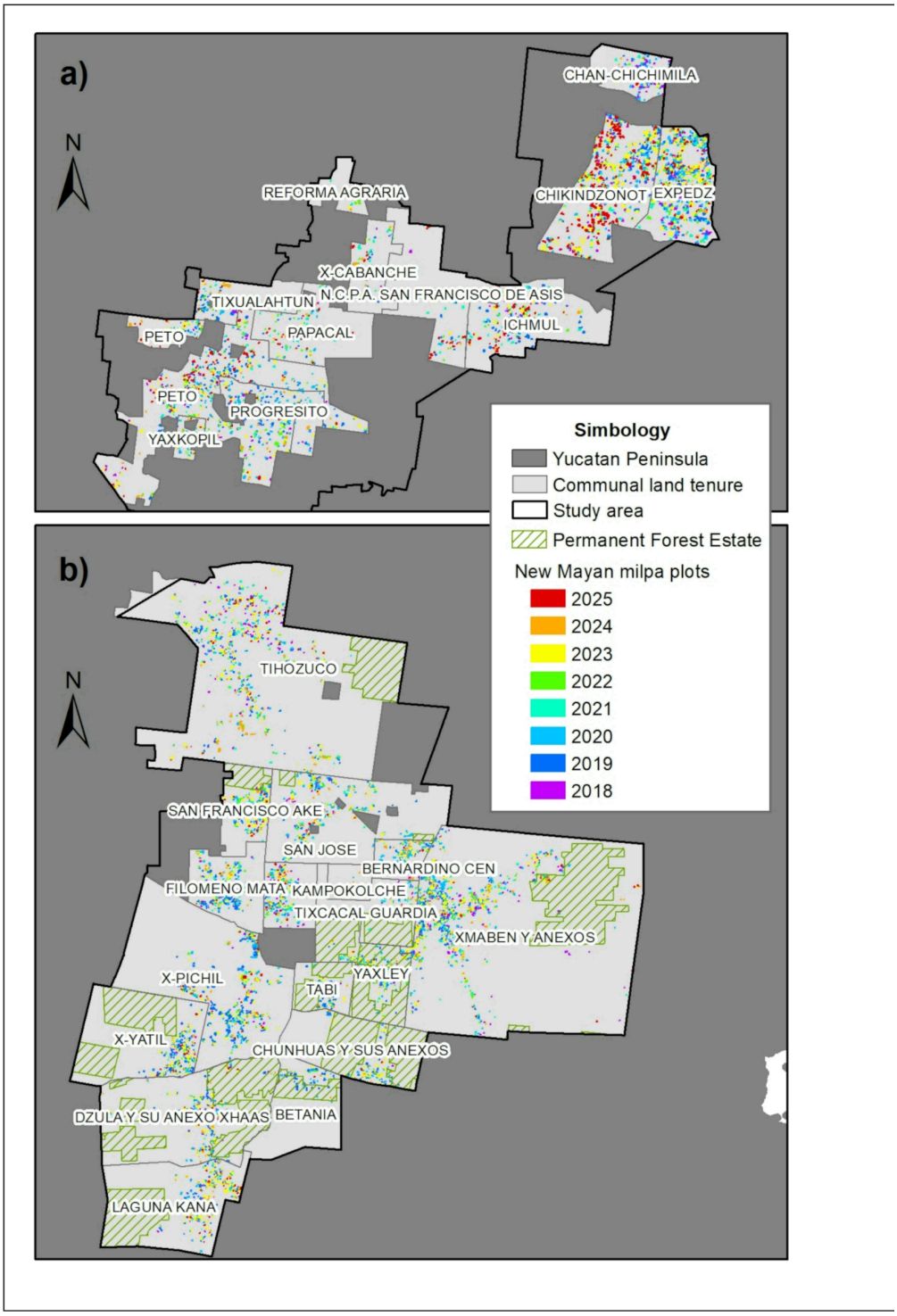


Figure 2

Mayan milpa plots during the period 2018–2025 in the Yucatan Peninsula study area: (a) Peto–Chikindzonot in Yucatán; (b) Zona Maya in Quintana Roo

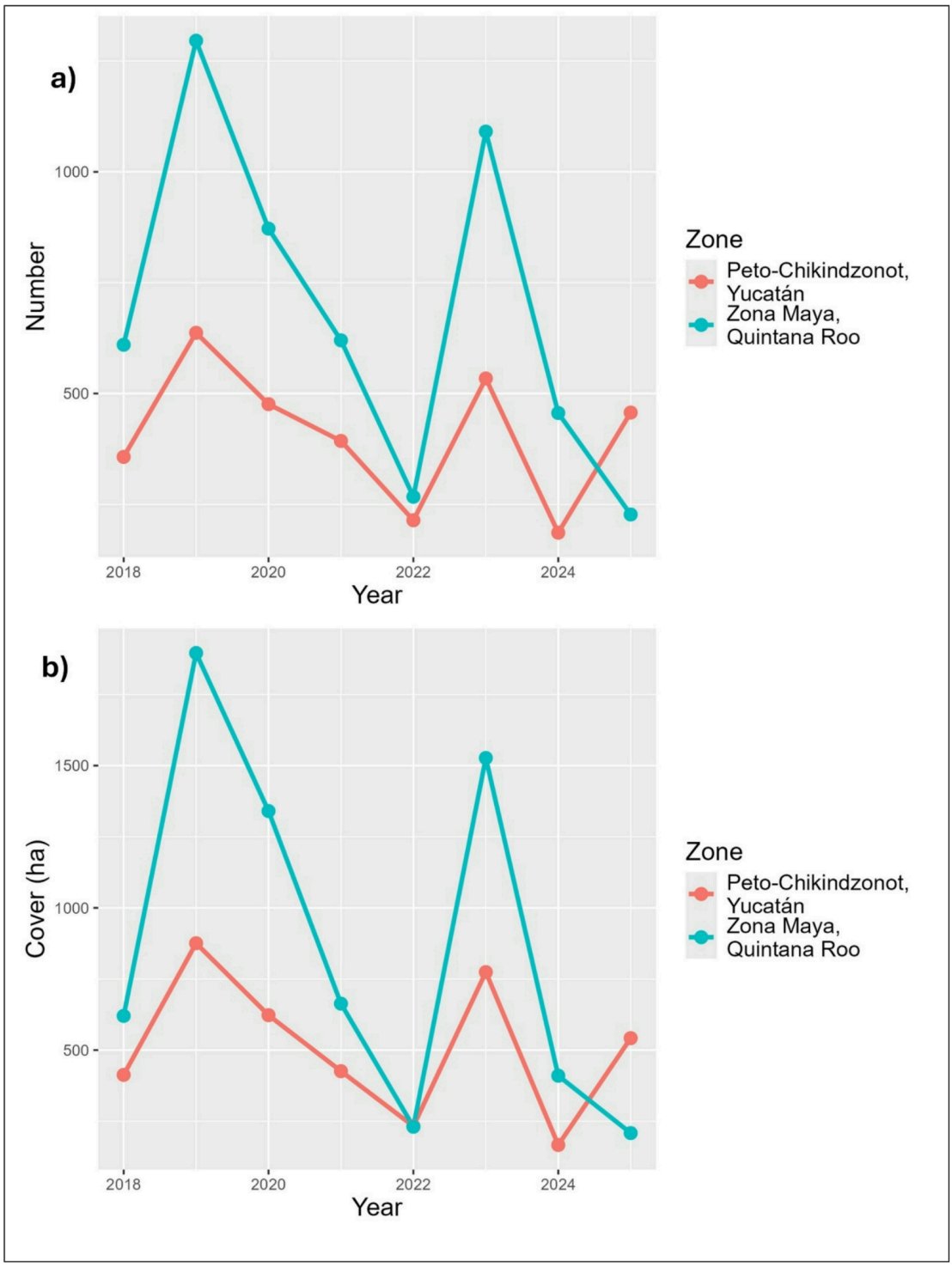


Figure 3

New Mayan milpa plots during the period 2018–2025 in Zona Maya in Quintana Roo and Peto–Chikindzonot in Yucatán: a) number and b) cover

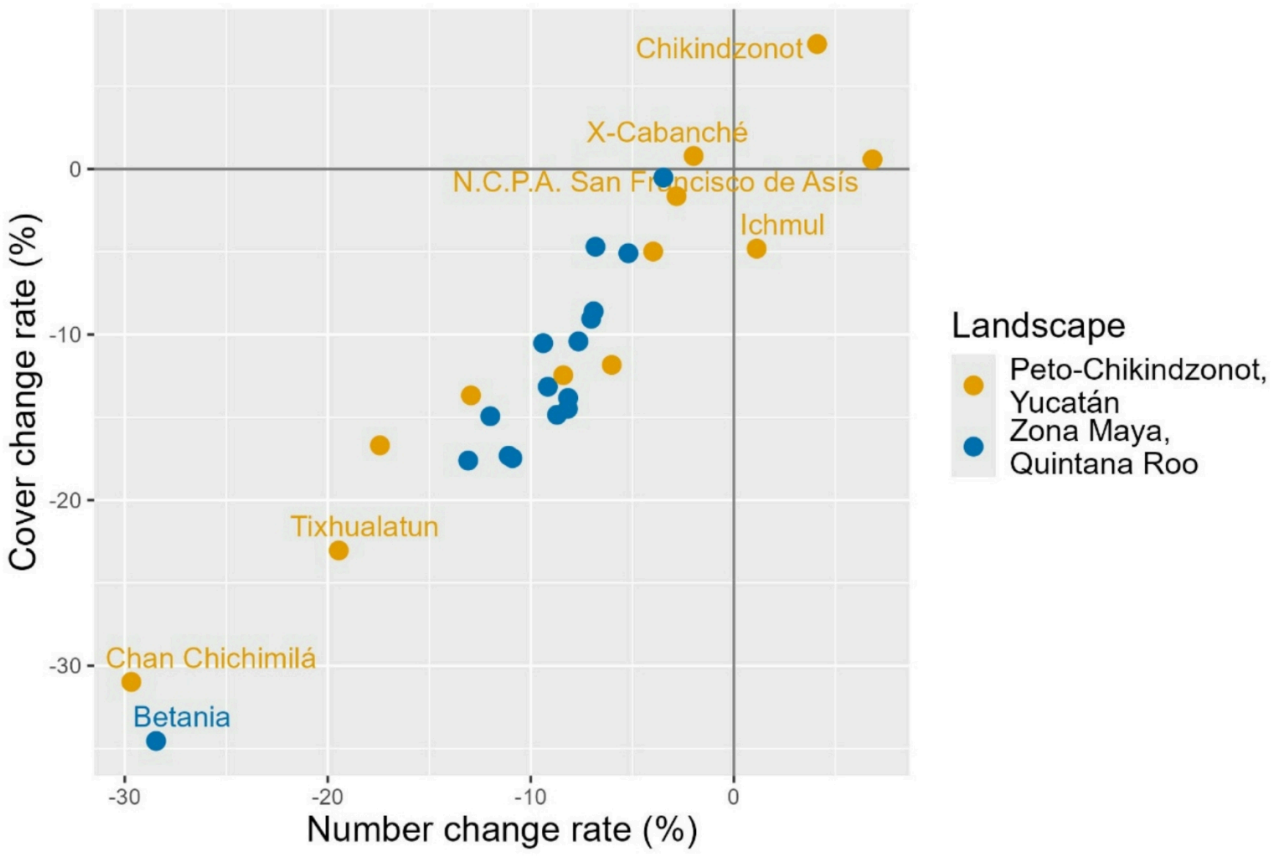


Figure 4

Rate of change in Mayan milpa cover between the triennia 2018–2020 and 2023–2025 in ejidos of Zona Maya in Quintana Roo and Peto–Chikindzonot in Yucatán

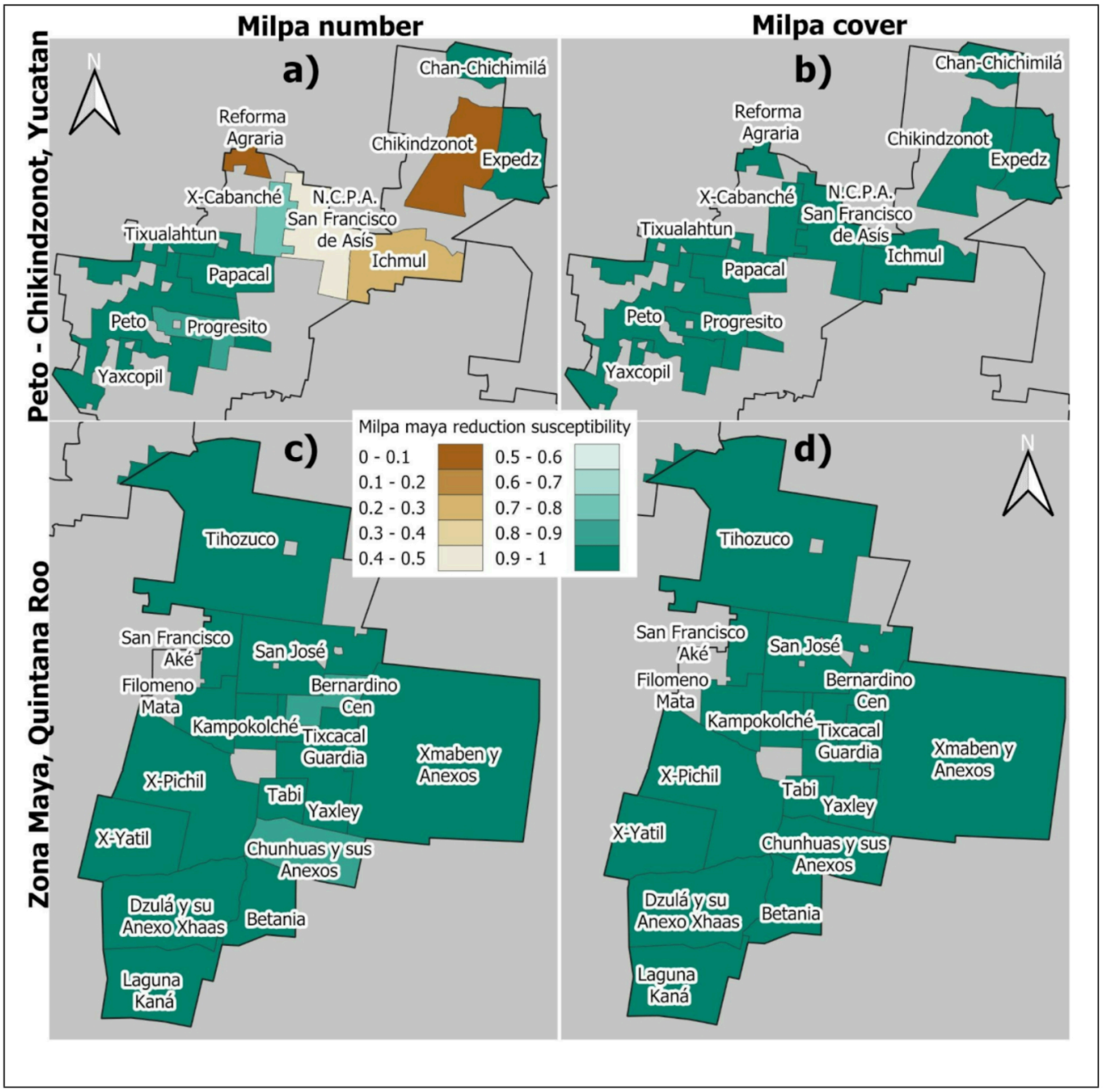


Figure 5

Probability of reduction in the number and cover of Mayan milpa in ejidos of ZMQR and PCY: (a) number of milpa plots in PCY; (b) milpa cover in PCY; (c) number of milpa plots in ZMQR; (d) milpa cover in ZMQR

Supplementary Files

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