



# Spatial patterns and determinants of avocado frontier dynamics in Mexico

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## Abstract

The surging demand for commodity crops has led to rapid and severe agricultural frontier expansion globally and has put producing regions increasingly under pressure. However, knowledge about spatial patterns of agricultural frontier dynamics, their leading spatial determinants, and socio-ecological trade-offs is often lacking, hindering contextualized decision making towards more sustainable food systems. Here, we used inventory data to map frontier dynamics of avocado production, a cash crop of increasing importance in global diets, for Michoacán, Mexico, before and after the implementation of the North American Free Trade Agreement (NAFTA). We compiled a set of environmental, accessibility and social variables and identified the leading determinants of avocado frontier expansion and their interactions using extreme gradient boosting. We predicted potential expansion patterns and assessed their impacts on areas important for biodiversity conservation. Avocado frontiers expanded more than tenfold from 12,909 ha (1974) to 152,493 ha (2011), particularly after NAFTA. Annual precipitation, distance to settlements, and land tenure were key factors explaining avocado expansion. Under favorable climatic and accessibility conditions, most avocado expansion occurred on private lands. Contrary, under suboptimal conditions, most avocado expansion occurred on communal lands. Large areas suitable for further avocado expansion overlapped with priority sites for restoration, highlighting an imminent conflict between conservation and economic revenues. This is the first analysis of avocado frontier dynamics and their spatial determinants across a major production region and our results provide entry points to implement government-based strategies to support small-scale farmers, mostly those on communal lands, while trying to minimize the socio-environmental impacts of avocado production.

**Keywords** Agricultural expansion · Globalization · Commodity frontiers · NAFTA · Extreme gradient boosting

## Introduction

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Food production and crop yields have been increasing globally for the last century, driven by the expansion and intensification of agricultural land (Foley et al., 2011). An accelerated expansion and intensification of agriculture for food production is expected in the future, following demands of an increasing population and changing consumption patterns (Crist et al., 2017; Pfister et al., 2011). Current agricultural production is a major driver of biodiversity loss due to land clearing, excessive water consumption, soil erosion, overuse of pesticides and fertilizers, and related air, soil, and water pollution (Geiger et al., 2010; Ren et al., 2018; Zabel et al., 2019). Also, climate change is expected to affect water supply for crop systems, increasing the pressure on natural ecosystems for food production (Ayala et al., 2016; Elliott et al., 2014).

The globalization of food systems has resulted in increased distances between production and consumption regions, making it difficult to establish linkages between food demand in any given place, and its environmental impacts along the supply chain (Lambin and Meyfroidt, 2011). Importing regions often export their environmental footprint to regions of agricultural production, encompassing land (Kastner et al., 2014; Laroche et al., 2020), water (Chen et al., 2018; Konar et al., 2011), or biodiversity (Lenzen et al., 2012).

Commodity crops produced for global export markets mainly originate from few low- and middle-income countries, such as Brazil, Indonesia, Congo, or Mexico, where agricultural frontier expansion is a major driver of land-use change (de Waroux et al., 2018; Gasparri and de Waroux, 2015; Ordway et al., 2017; Orozco-Ramirez et al., 2017). Moreover, large-scale deforestation due to the expansion of commodity crops (e.g. soybean, palm oil, cotton, or coffee) has been documented in several subtropical and tropical regions of South America, Southeast Asia, and sub-Saharan Africa (Laurance et al., 2014; Meyfroidt et al., 2013; Ordway et al., 2017). Such studies addressing frontier expansion dynamics have so far largely focused on major and widespread commodity crops and rather short time periods. Unfortunately, long-term frontier expansion dynamics of commodity crops with spatially concentrated production has been largely overlooked.

Avocados are a prime example of such overlooked cash crops. Avocado production is highly spatially concentrated with about 45% of the global production originating only in Mexico, thereof ~80% in a single state (SIAP, 2019). The most commonly traded avocado is the *Hass* variety. In Mexico, *Hass* avocados were first introduced around the 1960s and the expansion of monocultures of this variety for trade in local and national markets started in the municipality of Uruapan (Michoacán, Mexico) in the mid-1970s (Orozco and Bocco, 2012). The implementation of North American Free Trade Agreement (NAFTA) in 1994 boosted the agricultural sector and opened the market for fruit and vegetable exports from Mexico (Orozco-Ramirez et al. 2017). Since then, the international market for Mexican avocados has continued to grow and avocado expansion in producing regions has increased substantially as a response (Denvir et al., 2021). Besides the USA and Canada as main importers, avocados from Mexico are also traded to Japan, France, China, the Netherlands, UK, Spain, among others (SIAP 2019).

The surging global demand for avocados has resulted in an accelerated expansion and intensification of avocado production in Mexico over the past decades. Deforestation, high levels of water consumption, and environmental pollution due to the excessive use of fertilizers and pesticides are among the major environmental impacts

of this avocado boom (Atucha et al., 2013; Gonzalez-Esquível et al., 2015; Gonzalez, 2020). This phenomenon also had detrimental effects on small-scale farmers and has resulted in outmigration from rural areas (Orozco-Ramirez et al., 2017). Unfortunately, spatially explicit information on frontiers of avocado production, as well as knowledge about their main determinants and socio-ecological impacts is largely missing. Despite efforts to assess the potential spatial distribution of avocados and to identify suitable production areas using environmental factors and presence-only data in Colombia and across the Americas (Ramirez-Gil et al., 2019, 2018), no previous study has mapped avocado frontier dynamics in a spatially explicit way or assessed its leading spatial determinants for a production hotspot. Such information is key to address the social and environmental challenges posed by the increasing demands for agricultural commodities and to avoid undesirable future outcomes in such dynamic commodity frontier.

Our overarching goal was to map and understand frontier dynamics of avocado production in the state of Michoacán, Mexico, the dominant avocado producing region globally. We therefore used inventory data of avocado frontier expansion over 40 years, before and after NAFTA implementation. Subsequently, we used an optimized machine learning algorithm for gradient boosting to identify the most influential spatial determinants explaining frontier expansion patterns and assessed how their relative importance and interactions have changed over time. Finally, we predicted potential future expansion areas, which we overlaid with areas of conservation concern. Specifically, we addressed the following research questions:

1. Which are the most influential spatial determinants explaining frontier expansion patterns in Michoacán, Mexico, before and after the NAFTA agreement?
2. How have their relative importance and interactions changed over time?
3. What are the spatial patterns and environmental trade-offs of potential future avocado frontier expansion?

## Materials and methods

### Study area

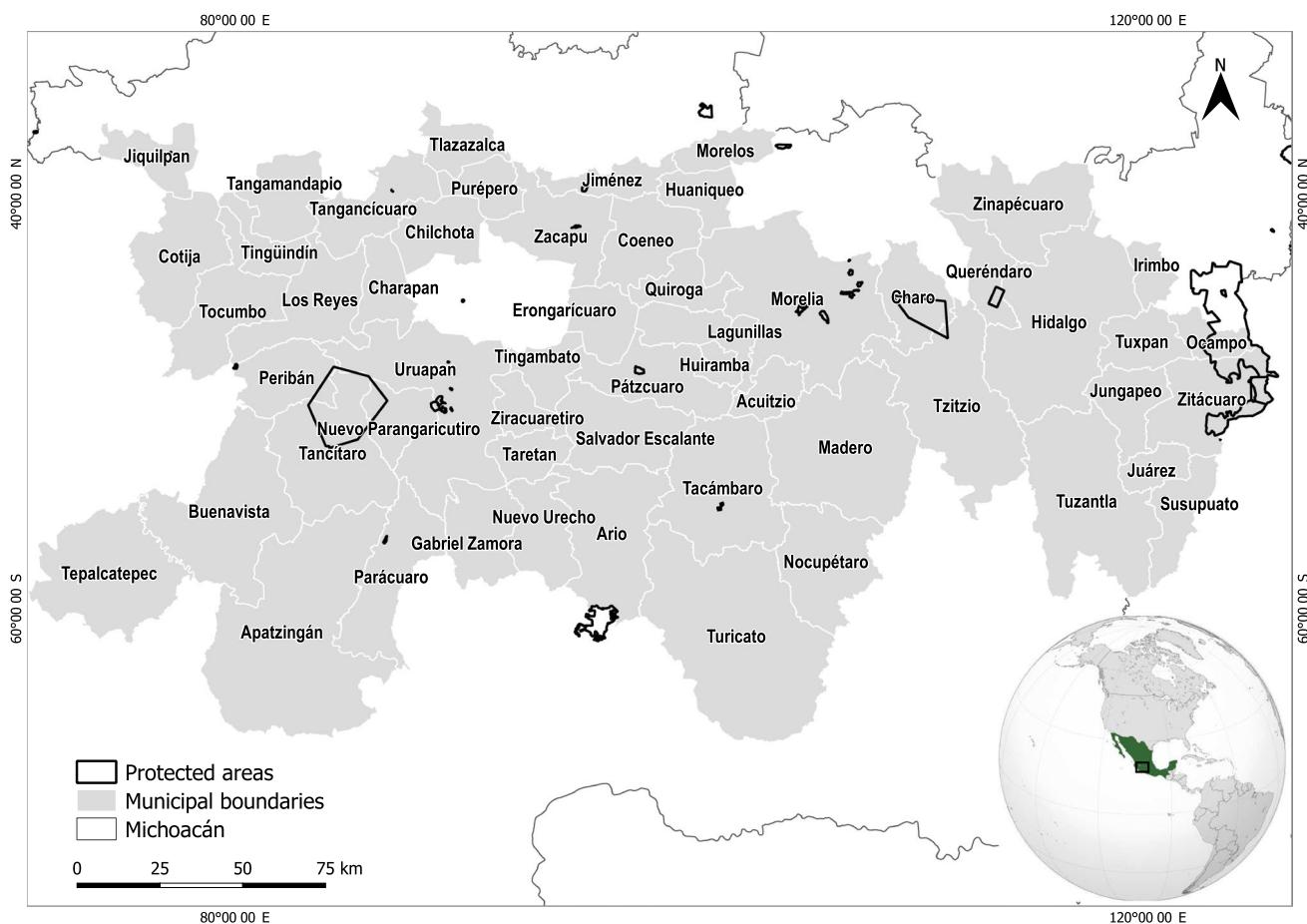
Avocado is a perennial crop currently cultivated in 28 out of 32 Mexican states, but only two states, Michoacán and Jalisco, account for almost 90% of Mexico's avocado production (SIAP, 2019). However, Michoacán is notably the largest producer, accounting for ~80% of the national production and ~86% of the total Mexican avocado exports

(Online Resource Text 1, Fig. 1). The avocado frontier in Michoacán, commonly known as the avocado belt, is located in the Trans-Mexican Volcanic Belt and the Balsas River Basin in central Mexico between  $18^{\circ}45'$  and  $20^{\circ}0'N$  and  $101^{\circ}47'$  and  $103^{\circ}13'W$  (Fig. 1). It spans across 61 municipalities, and 33 of them export the crop. Altitude across the avocado belt ranges from 1500 to 2400 m above sea level (masl). The climate is warm sub-humid with summer rainfall and annual mean temperatures between 10 and  $24^{\circ}C$ . Mean annual precipitation varies from 800 to 1600 mm. Typical landforms in this region are mountain ranges, hills, valleys, and plateaus, and predominant soils are Andosols and Luvisols covering ~ 80% of the area.

The avocado belt in Michoacán is the largest avocado producing region in the world as it provides optimal conditions for industrial-scale production. Avocados are native to Mexico and Central America and evidence suggests that Mexico is the center of origin and diversification of the species *Persea americana* (Galindo-Tovar et al., 2008). There are several varieties of this species differing in size, shape, texture, color, and flavor. The composition of the fruit depends on the variety, degree of ripeness, climatic conditions, soil

composition, and agricultural management practices. There is a great diversity of native avocado crops in Mexico, but only the *Hass* variety has been extensively cultivated and traded as the environmental and biophysical characteristics for growing this variety are ideal in the region and its fruit size, shelf-life, high yields, and year-round production are optimal for global commerce (Salazar-García et al., 2016).

Before NAFTA, *Hass* avocados produced in Michoacán were traded in local and national markets, and there was a very small number of exports mainly to France, Japan, Canada, and the UK (FAO, 2021). The accelerated increase in avocado exports was triggered by the implementation of NAFTA. After a series of tariffs and phytosanitary barriers enforced by the US government to prevent imports from Mexico in the early 1990s, the United States Department of Agriculture (USDA) began to lift the phytosanitary ban imposed on Mexican avocados during the period from 1997 to 2001 and opened its markets to imports from only the state of Michoacán, as no other state met the phytosanitary requirements. Since 2016, avocados from another state, Jalisco, were allowed to enter the US market. Tariff reductions from NAFTA and the end of the ban imposed by the



**Fig. 1** Study area located in the Trans-Mexican Volcanic Belt and the Balsas River Basin in the State of Michoacán, central Mexico

USDA favored avocado trade flow from Michoacán to the US, where consumption doubled in a 10-year period. The success of the avocado boom and its growing consumption in distant places has had severe impacts in the region, which are visible to a great extent due to the continued expansion of the avocado frontier and related socio-ecological impacts (Denvir et al., 2021).

## Avocado frontier inventory

To assess the spatial determinants of avocado frontier expansion stages before and after the implementation of the NAFTA agreement, we analyzed three time periods using the avocado frontier inventory available for years 1974, 1995, and 2011 (Morales and Cuevas, 2011; Morales Manilla et al., 2012). The avocado frontier inventory expands across the Trans-Mexican Volcanic Belt and the Balsas River Basin in the State of Michoacán (Fig. 1). It was generated for the years 1974, 1995, 2007, and 2011. The inventory for the year 1974 was generated through visual interpretation of aerial photographs provided by the National Institute of Statistics and Geography (INEGI) at a scale of 1:20,000. Avocado frontier inventory data for years 1995 and 2011 was updated through visual interpretation using orthophotos at a scale of 1:20,000 from INEGI and WorldView-2 satellite images with a spatial resolution of 0.5 m.

Considering that the first *Hass* avocado orchards were introduced in Michoacán around 1960, we used the period from 1960 to 1974 as our first study period, for which the latter year serves as the baseline of the avocado frontier inventory and includes all existing *Hass* avocado orchards until 1974 (Table 1). Our second period of analysis spans from 1974 to 1995 and represents a period during which *Hass* avocado monoculture expansion for local and national markets accelerated. Finally, we assessed avocado frontier expansion for the period 1995 to 2011, which coincides with the implementation of the NAFTA agreement and the further increase of avocado exports to international markets (Table 1). We used 2011 as our final year of analysis, marking the final year for which avocado frontier inventory data was available.

To match the spatial resolution of our spatial determinants (see “[Spatial determinants](#)”), we transformed the inventory maps from vector format into binary raster layers with a grid cell size of 100 m using nearest neighbor resampling. To generate our target variable, changes towards avocado orchards between 1974 and 1995 as well as 1995 and 2011, respectively, were labeled as *expansion*. Grid cells that did not change over time were labeled as *no expansion*.

## Spatial determinants

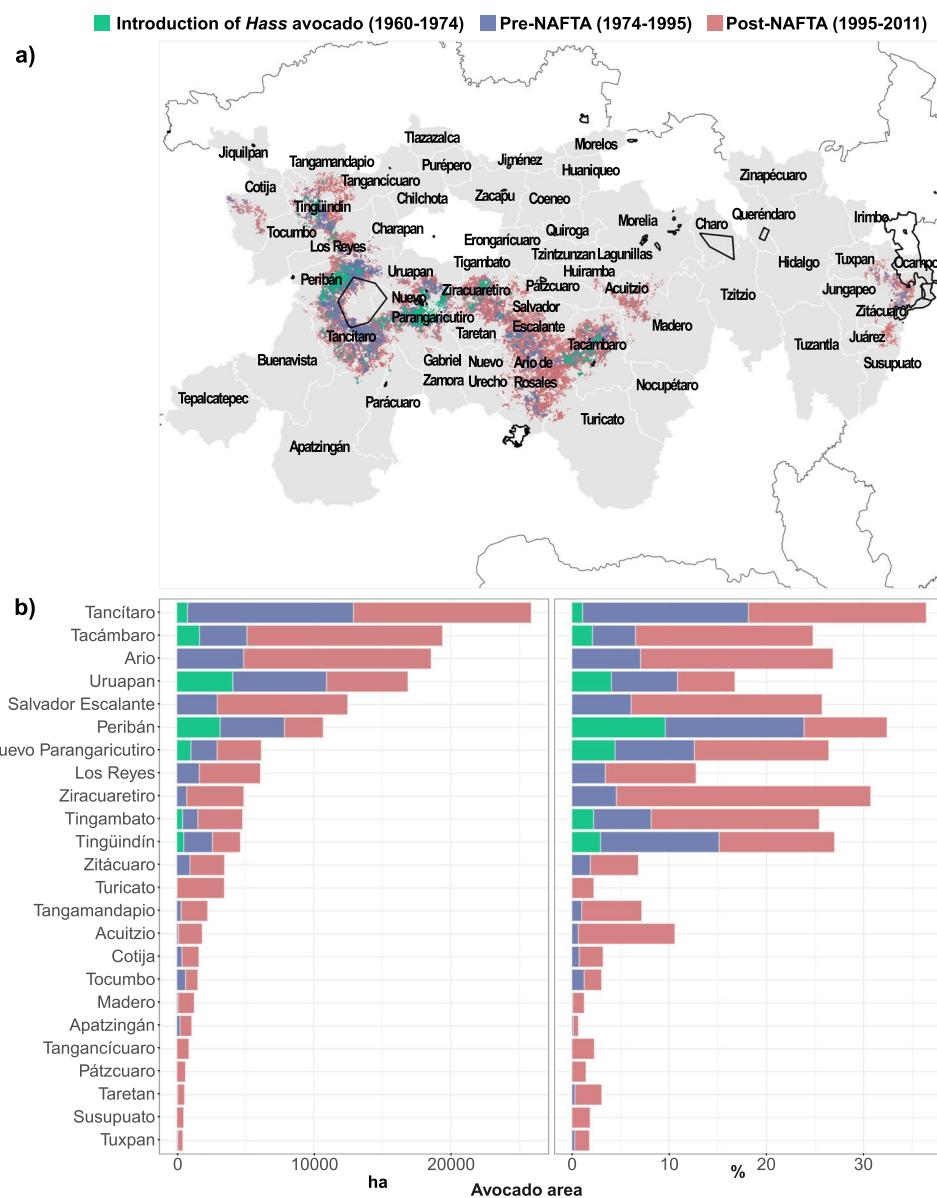
We identified 36 potential spatial determinants related to topography, climate, soil conditions, social factors and land accessibility from literature and based on the authors’ regional expertise (Online Resource Text 2). To account for collinearity among pairs of variables, we performed Spearman  $\rho$  correlation analysis and removed the variable with the lower correlation to the target variable for pairs with  $\rho > 0.6$  (Online Resource Fig. 2). Our final set consisted of 16 spatial determinants hypothesized to explain avocado frontier expansion, which we grouped into five categories: (1) bioclimatic conditions, (2) soil conditions, (3) terrain attributes, (4) social, and (5) land accessibility (Table 2).

Bioclimatic variables were available in raster format at ~ 90 m spatial resolution and terrain attributes were available at 30 m spatial resolution. We aggregated the respective layers to raster layers of 100 m spatial resolution using bilinear resampling. Soil data were available as raster layers at ~ 250 m spatial resolution, which we disaggregated to raster layers of 100 m spatial resolution without changing original grid cell values. Land accessibility variables were available as polyline data and we transformed these layers into raster format with 100 m spatial resolution. We incorporated distance to settlements as a static variable due to the lack of multitemporal datasets. We calculated Euclidean distances to roads, rivers, and human settlements. Protected Areas (PA) were incorporated as a binary layer, indicating presence (P) and absence (A) of PA. We also incorporated land tenure as a binary layer representing private (Pvt) or communal lands (C) (Table 2). All predictor variables were projected into Lambert Conformal Conic projection (datum WGS84).

**Table 1** Overview of the periods where relationships between avocado frontier expansion and environmental, land accessibility, and social spatial determinants were assessed

Period	Regime	Description
1960–1974	Introduction of <i>Hass</i> avocado	The period since first <i>Hass</i> avocado orchards were introduced in Mexico and before <i>Hass</i> monocultures expansion began
1974–1995	Pre-NAFTA	Avocado frontier expansion before the implementation of NAFTA, traded mostly in local and national markets
1995–2011	Post-NAFTA	Avocado frontier expansion after the implementation of NAFTA, lift of USDA ban to Mexican avocado exports, and rise of the avocado boom

**Fig. 2** Spatial patterns of frontier expansion for periods 1960–1974, 1974–1995, and 1995–2011 (a) and avocado area per municipality for periods 1960–1974, 1974–1995, and 1995–2011 (b)



## Extreme gradient boosting

We used extreme gradient boosting (XGBoost) to assess the relationships between avocado frontier expansion patterns, and their spatial determinants. XGBoost is a scalable, highly efficient, and flexible implementation of gradient boosting algorithms (detailed information in Online Resource Text 3) and is one of the fastest machine learning algorithms of gradient boosting (Chen and Guestrin, 2016). This algorithm incorporates multithreading and regularization to use more computational power and obtain more accurate predictions. As an extensible library, XGBoost allows users to define customized optimization objectives and evaluation metrics and incorporates features to perform cross-validation. To perform our analysis, we used the XGBoost implementation

in R (Chen et al., 2020). XGBoost provides a wide range of parameters for model optimization and fully leveraging its predictive performance.

We used the following parameters to build our models: (1) the *learning task and the corresponding learning objective (objective)*, determining the loss function to be used (in our case logistic regression for binary classification, returning predicted probabilities); (2) the *learning rate (eta)* or the step size shrinkage used to prevent overfitting; (3) the *maximum depth of a tree (max\_depth)*, controlling how deep each tree can grow during each boosting round; (4) the *subsample ratio of the training instance (subsample)*, determining the percentage of samples used per tree; (5) the *subsample ratio of columns when constructing each tree (colsample\_bytree)*, controlling the percentage of features

**Table 2** Spatial determinants of avocado frontier expansion

Group	Variable	Description	Unit	Scale/spatial resolution	Period/year	Source
Climatic conditions	Annual mean temperature	Annual mean temperature	°C	~90 m	1910–2009	Cuervo-Robayo et al. 2014
	Mean diurnal range	Mean diurnal range (Mean of monthly (max temp–min temp))	°C	~90 m	1910–2009	Cuervo-Robayo et al. 2014
	Annual precipitation	Annual precipitation	mm	~90 m	1910–2009	Cuervo-Robayo et al. 2014
	Precipitation of warmest quarter	Precipitation of warmest quarter	mm	~90 m	1910–2009	Cuervo-Robayo et al. 2014
	Aridity	Ratio of mean annual precipitation and mean annual potential evapotranspiration	Dimensionless	100 m	w/o year	Own calculation
Terrain attributes	Slope	Slope in percentage	%	100 m	n/a	Own calculation, INEGI 2017
Land accessibility	Distance to roads	Euclidean distance to roads	m	1: 50,000	n/a	IMT 1996, INEGI 2010, INEGI 2014
	Distance to rivers	Euclidean distance to rivers	m	1: 50,000	n/a	INEGI 2014
	Presence/absence of protected areas	Polygons of natural protected areas	Dimensionless	ranges from 1: 5000 to 1: 150,000,000	1974–2011	Conanp 2019
Social	Distance to settlements	Euclidean distance to settlements	m	30 m	2015	HRSL-CIESIN 2016
	Land tenure	Polygons of private or communal lands	Dimensionless	ranges from 1:100 to 1: 200,000	n/a	RAN 2019
Soil conditions	Type of soils	Classes of types of soil	Dimensionless	1:250,000	w/o year	INEGI 2007
	Bulk density	Bulk density of the fine earth fraction	kg/dm <sup>3</sup>	250 m	w/o year	de Sousa et al. 2020
	Cation exchange capacity	Cation exchange capacity of the soil	cmol(c)/kg	250 m	w/o year	de Sousa et al. 2020
	Sand	Proportion of sand particles (>0.05 mm) in the fine earth fraction	%	250 m	w/o year	de Sousa et al. 2020
	Soil organic content	Soil organic content for 0–30 cm topsoil layer	kg SOC/m <sup>2</sup>	250 m	1991–2010	Guevara et al. 2020

used per tree; (6) the *minimum loss reduction required to make a further partition (gamma)*, controlling node splits based on the expected reduction in the loss function after each split (Ogunleye and Wang, 2020; Su et al., 2018); (7) the *maximum delta step allowed for each tree's weight estimation (max\_delta\_step)* or the maximum step size that a leaf node can take, which is mostly used in logistic regressions using imbalanced data (Guo et al., 2018; Ogunleye and Wang, 2020; Song et al., 2016); and (8) the *number of rounds for boosting (nrounds)*, determining how many

decision trees are trained. For a detailed description of the tuning parameters, see Chen et al. (2020).

We converted our input data into a dense matrix (DMatrix) and fitted a model for each of the three study periods (1960–1974, 1974–1995, and 1995–2011) using a Bernoulli distribution. We conducted a hyper-parameter grid search to find the optimal parameter values to improve model performance (Table 3, Online Resource Table 1). We used 70% of the data for training and the remaining 30% for validation of each model (i.e., for each study period). To account for spatial autocorrelation in our data and to remove spatial

**Table 3** Summary of final parameter values for our XGBoost models

Hyperparameters								
Period	Regime	eta	max_depth	subsample	colsample_bytree	gamma	max_delta_step	nrounds
1960–1974	Introduction of <i>Hass</i> avocado	0.1	10	0.75	0.66	1	1	100
1974–1995	Pre-NAFTA	0.05	10	0.75	0.66	1	1	1000
1995–2011	Post-NAFTA	0.05	10	0.75	0.66	1	1	1000

sorting bias when performing cross-validation, we conducted pairwise distance sampling to our train and evaluation data. This method provides reliable model performance and prevents overfitting when using spatial machine learning approaches that do not account for spatial dependencies (Hijmans, 2012; Meyer et al., 2019). We performed tenfold cross-validation using the area under the curve (AUC) of the receiver operating characteristic (ROC) curve as evaluation metric. Additionally, we set XGBoost to randomly sample 75% of the training data during each model iteration. We applied a threshold value of 0.5 to classify the output probabilities into binary classes, where grid cells with predicted probability  $\geq 0.5$  were classified as expansion and values less than 0.5 were classified as no expansion.

To assess the goodness-of-fit of our models, we calculated the following evaluation metrics for binary classifications obtained from the confusion matrix: true positive rate (proportion of correctly identified positives), true negative rate (proportion of correctly identified negatives), balanced accuracy (sum of correctly identified positives and negatives over two), precision (proportion of correctly identified positives in relation to all observed positives), and prevalence (sum of true positives and false negatives over the sample size). We used the model for the 1995–2011 period to predict the probability of avocado frontier expansion for each grid cell in our study area. We selected this model to generate our final prediction as it better depicts the avocado expansion dynamics this region will likely continue to experience in the future. To estimate the areas of potential avocado expansion, we reclassified the predicted probabilities of expansion into suitable ( $\geq 0.7$ ), moderate ( $< 0.7$  and  $\geq 0.5$ ), and suboptimal areas ( $< 0.5$  and  $\geq 0.3$ ).

## Model interpretation

We used SHAP values, SHapley Additive exPlanations, to interpret model results (Lundberg et al., 2020; Lundberg and Lee, 2017). SHAP values provide a novel way for interpreting ensemble and deep learning models. It is based on Shapley values, a method from coalitional game theory

(Shapley, 1953). SHAP values explain the model's prediction by measuring the contribution of each observation for each variable (i.e., local explanations) and combining the local explanations to provide overall feature importance. Furthermore, SHAP values allow to capture local interaction effects and provide a consistent way of measuring hidden pairwise interaction relationships (Lundberg et al., 2020). A complete description and detailed mathematical explanation of SHAP's framework is provided by Lundberg and Lee (2017) and Lundberg et al. (2020). We visualized model results with SHAP feature importance plots, SHAP local explanations summary plots and maps, SHAP dependence plots showing the effect each feature has on the prediction of the model, and SHAP interaction effects plots using the R package SHAPforxgboost (Liu and Just, 2019) based on the implementation of SHAP in Python (Lundberg and Lee, 2017).

## Environmental impacts of frontier expansion

To explore trade-offs between avocado expansion and biodiversity, we compared spatial patterns of observed and potential expansion areas inside and outside (1) priority sites for biodiversity conservation (Urquiza-Haas et al. 2009; Conabio 2016), (2) important sites for crop wild relatives' (CWR) conservation (Tobón-Niedfeldt et al., 2021), and (3) priority sites for restoration (Tobón et al. 2017) (Online Resource Table 2). Priority sites for biodiversity conservation are based on biological data and their pressure factors and represent priority sites for conservation of terrestrial vulnerable species and habitats (Conabio, 2016; Urquiza-Haas et al., 2009). Important sites for CWR conservation in Mexico represent areas of high CWR species richness and integrate information on genetic diversity, CWR tolerance to human-modified habitats, and their extinction risks (Tobón-Niedfeldt et al., 2021). Priority sites for restoration integrate criteria and indicators on vegetation types, elevation zones, soil degradation, and fragmentation and represent areas of biological importance and restoration feasibility in Mexico (Tobon et al., 2017). First, we

calculated the sum of overlapping areas of avocado orchards in 2011 over each of the three conservation maps. Second, we reclassified the predicted probabilities of expansion into suitable ( $\geq 0.7$ ), moderate ( $< 0.7$  and  $\geq 0.5$ ), and suboptimal areas ( $< 0.5$  and  $\geq 0.3$ ) and calculated the sum of overlapping areas over each of the three conservation maps.

## Results

### Spatial determinants of avocado frontier expansion

We observed an accelerating avocado frontier expansion in Michoacán since 1974 (Fig. 2a). The extent of avocado orchards was 12,909 ha, 58,281 ha, and 152,493 ha in 1974, 1995, and 2011, respectively. Until 2011, only six municipalities accounted for ~ 68% (104,285 ha) of the total avocado production. In 1974, Peribán and Uruapan had the largest extent of avocado orchards, accounting for 3,166 ha and 4,091 ha, respectively (Fig. 2b). Tancítaro had an extent of 783 ha in 1974, but expanded its orchards to 12,899 ha in 1995, and up to 25,879 ha in 2011, thus becoming the largest avocado producing municipality in Michoacán (Fig. 2b).

Our models discriminated well between *expansion* and *no expansion* locations, resulting in high model fits (Table 4). Balanced accuracy and true positive rate were highest for the pre-NAFTA model (0.924), followed by the post-NAFTA model (0.907), and the introduction of *Hass* avocado model (0.889). Model precision was highest for the introduction of *Hass* avocado model, followed by the pre-NAFTA and post-NAFTA models.

For the introduction of *Hass* avocado period, the most important variables explaining avocado orchard expansion were annual precipitation, precipitation of warmest quarter, distance to roads, distance to settlements, and slope (Fig. 3a). SHAP summary plots show that the proximity to settlements and roads and high precipitation values, were positively related to the expansion of avocado orchards (Fig. 3b).

For the pre-NAFTA period, precipitation of warmest quarter, annual precipitation, distance to settlements, annual mean temperature, and land tenure were the most important variables explaining avocado frontier expansion (Fig. 3a). Likewise, for the post-NAFTA period, precipitation of

warmest quarter, annual precipitation, distance to settlements, land tenure, and annual mean temperature were the most important variables explaining avocado frontier expansion (Fig. 3a). For both periods, SHAP summary plots show that high precipitation and proximity to settlements were positively related to avocado frontier expansion (Fig. 3b). Also, private lands (Pvt) were positively related to expansion, whereas in communal lands (C) associated with negative SHAP values less expansion occurred (Fig. 3b).

SHAP dependence plots showed non-linear relationships for all spatial determinants of avocado expansion (Fig. 4). In addition, the SHAP local explanation maps allowed us to visualize the spatial distribution of the SHAP values, indicating regions where determinants had positive, neutral, or negative associations to the expansion of avocado orchards. During the introduction of *Hass* avocado period (1960–1974), annual precipitation beyond 1300 mm was positively related to the presence of avocados, whereas in areas with lower precipitation, the presence of avocados was less likely (Fig. 4a). We observed the same trend for precipitation of warmest quarter, with a distinct threshold at around 400 mm, beyond which precipitation was strongly positively related to the presence of avocado orchards. Locations within 400 m distance from settlements were positively related to the presence of avocado orchards (Fig. 4a). The areas with the strongest positive association between determinants and avocado orchard locations were mostly located in the central-western region of the avocado belt, mainly in the municipality of Uruapan (Fig. 4a).

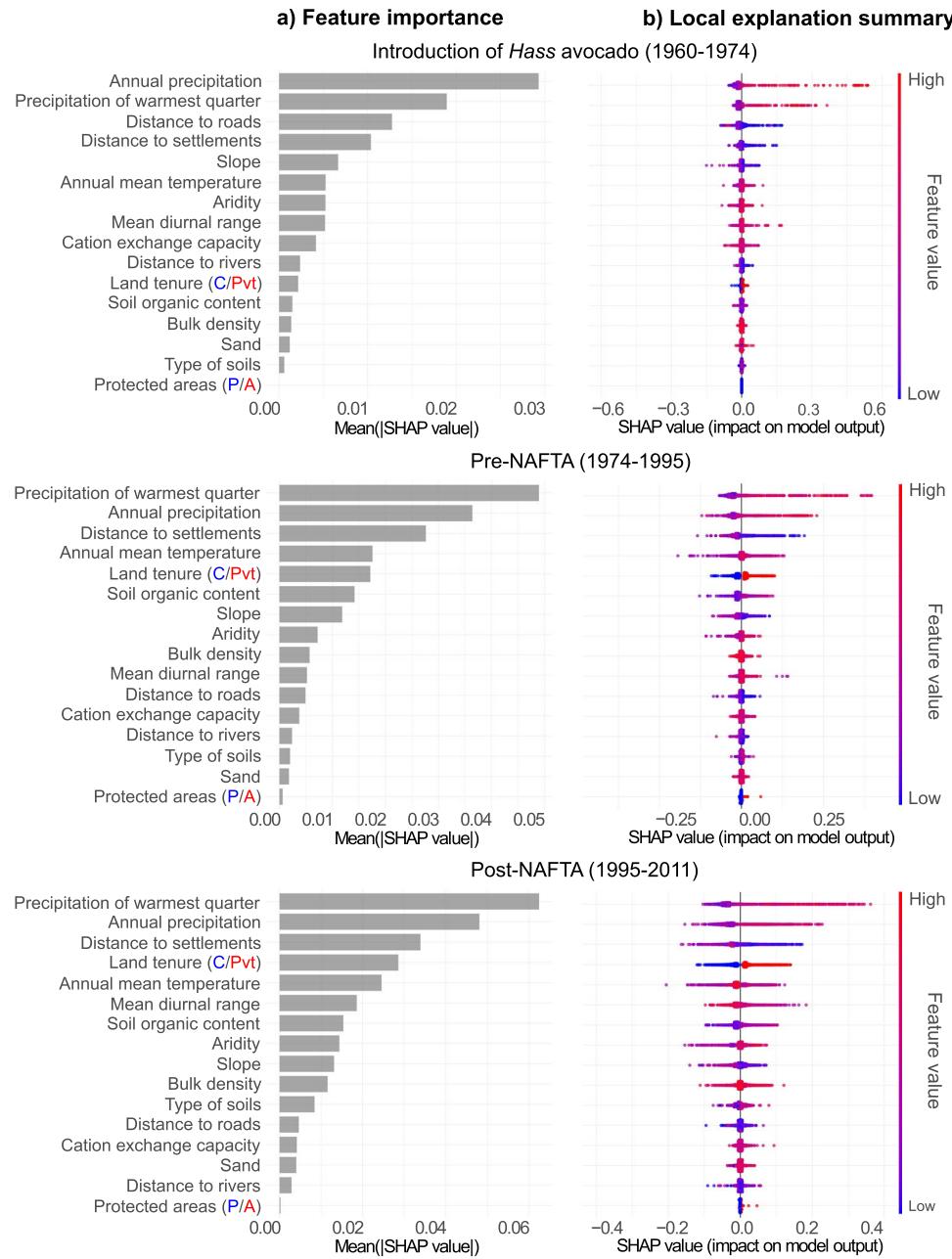
The general patterns of the relationships between spatial determinants and avocado orchard locations we found in the introduction of *Hass* avocado period remained relatively stable in the pre- and post-NAFTA periods. We observed a decrease in avocado frontier expansion at precipitation levels greater than 500 mm and 1400 mm and a slight increase of frontier expansion in areas further away from settlements (Fig. 4b, c). Areas with the strongest positive association between determinants and avocado frontier expansion extended into the central and western region of Michoacán during the pre-NAFTA period, most notably in the western part of the avocado belt in the municipalities of Tancítaro and Peribán (Fig. 4b). In contrast, these areas shifted to the central-southern and eastern

**Table 4** Goodness-of-fit measures for the predicted probability of avocado expansion

Evaluation metrics							
Period	Regime	AUC	Balanced accuracy	TPR	TNR	Precision	Prevalence
1960–1974	Introduction of <i>Hass</i> avocado	0.924	0.889	0.783	0.996	0.894	0.035
1974–1995	Pre-NAFTA	0.970	0.924	0.857	0.990	0.873	0.073
1995–2011	Post-NAFTA	0.962	0.907	0.837	0.976	0.817	0.110

TPR, true positive rate; TNR, true negative rate

**Fig. 3** **a** SHAP feature importance plots of mean absolute SHAP value for periods 1960–1974 (introduction of *Hass* avocado), 1974–1995 (pre-NAFTA), and 1995–2011 (post-NAFTA) and **b** SHAP local explanation summary plots where each dot corresponds to an individual observation. Y-axis shows each feature (i.e., spatial determinant) and x-axis displays SHAP values for each observation of each feature. Positive or negative SHAP values indicate whether the effect of a value is associated with a higher or lower than random probability of avocado expansion. Color represents the value of each determinant from low (blue) to high (red). Overlapping dots in y-axis show the distribution of SHAP values per determinant. Land tenure: communal lands (C); private lands (Pvt). Protected areas: presence (P); absence (A)



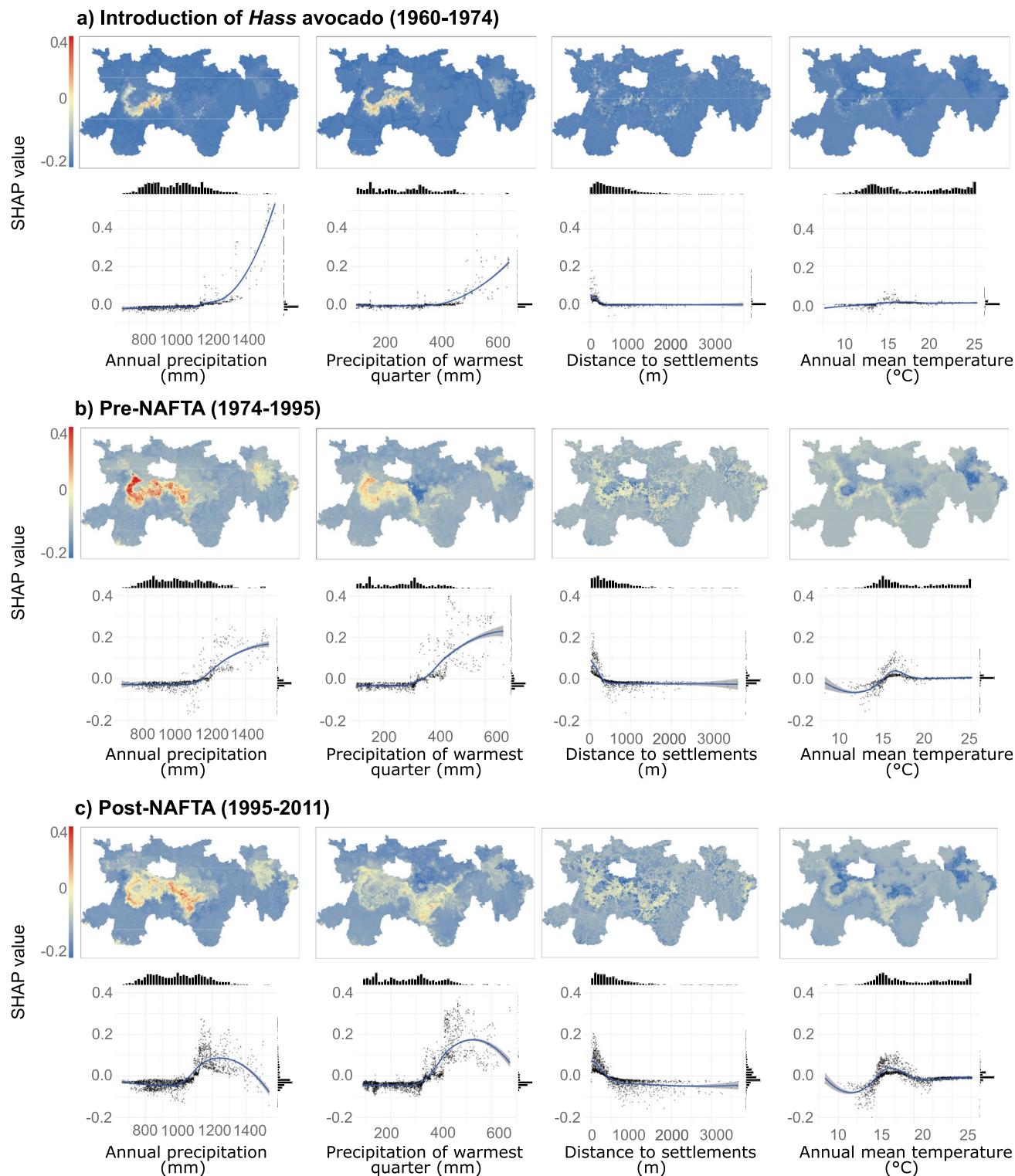
part of the avocado belt region during the post-NAFTA period, particularly into the municipalities of Salvador Escalante, Ario de Rosales, and Tacámbaro (Fig. 4c).

### Interaction effects of the spatial determinants of avocado frontier expansion

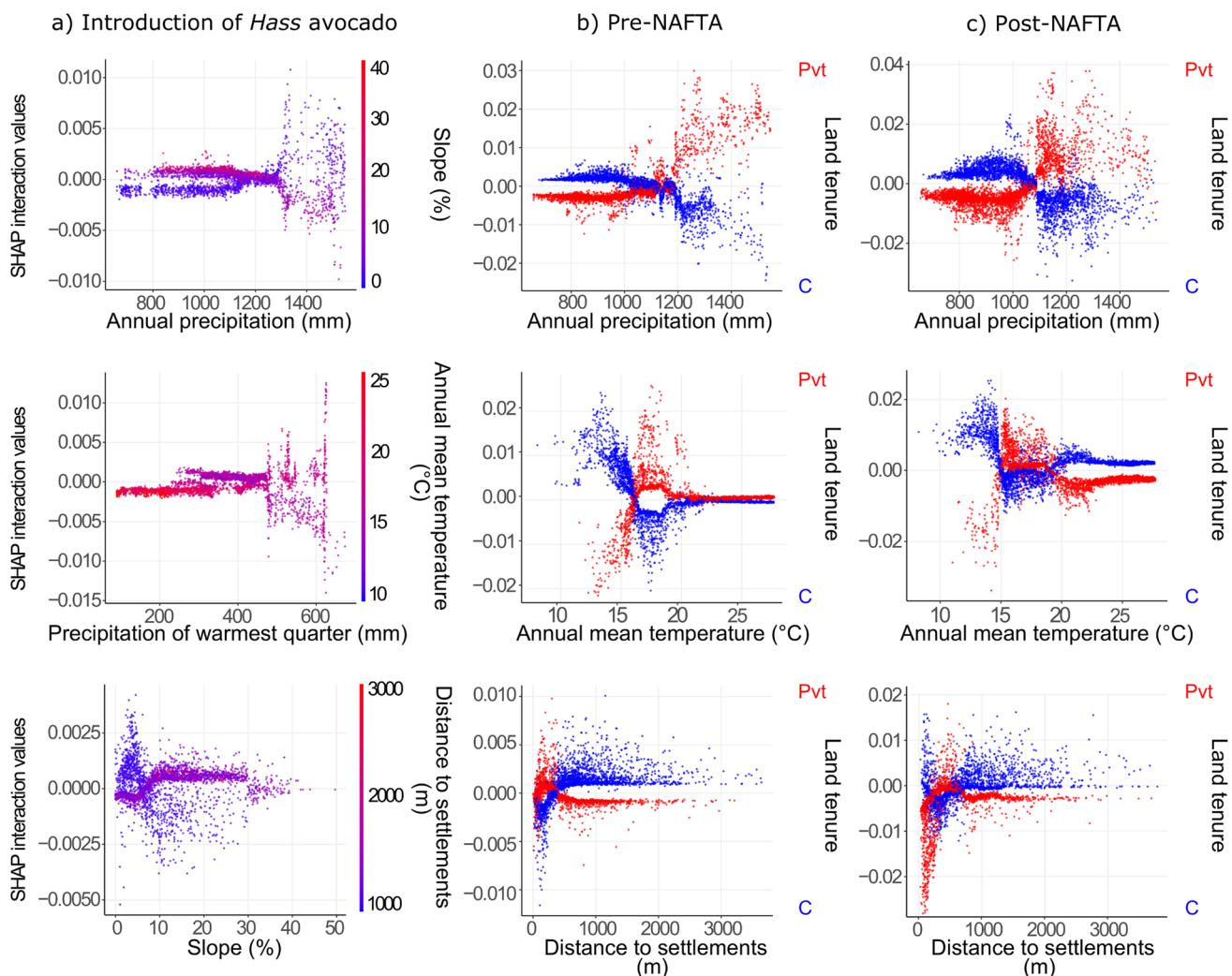
During the introduction of *Hass* avocado period, we found major interaction effects between annual precipitation and slope, precipitation of the warmest quarter and annual mean temperature, and slope and distance to settlements (Fig. 5a). Steep slopes with high annual precipitation and annual mean temperature greater than 20 °C were negatively related to the

presence of avocado orchards. Contrary, flat areas with high annual precipitation and annual mean temperature between 15 and 20 °C were positively related to the presence of avocado orchards (Fig. 5a).

During pre- and post-NAFTA periods, we observed interaction effects between land tenure and annual precipitation, annual mean temperature, and distance to settlements (Fig. 5b). During the pre-NAFTA period, private lands close to settlements and with high annual precipitation were positively related to avocado frontier expansion, whereas communal land areas located further away from settlements (> 300 m) and with less precipitation (< 1100 mm) showed an increased probability of avocado expansion. Furthermore,



**Fig. 4** SHAP dependence plots and spatial distribution of SHAP local values for the four most important variables explaining **a** avocado expansion during 1960–1974 (introduction of *Hass* avocado), **b** frontier expansion during 1974–1995 (pre-NAFTA), **c** and frontier expansion during 1995–2011 (post-NAFTA). The x-axis shows the distribution of each observation for each determinant and the y-axis shows the corresponding SHAP values. Histograms show the variable distribution along the x- and y-axis



**Fig. 5** SHAP dependence plots with interactions effects for **a** period 1960–1974 (introduction of *Hass* avocado), **b** period 1974–1995 (pre-NAFTA), and **c** period 1995–2011 (post-NAFTA). Positive or

negative SHAP interaction values indicate if the effect of a value is associated with a higher or lower than random probability of avocado expansion. C: communal lands; Pvt: private lands

avocado expansion on private lands showed strong interactions with annual mean temperature around optimal growing conditions (16–20 °C), while avocado expansion on communal lands was related to less suitable temperatures (11–16 °C).

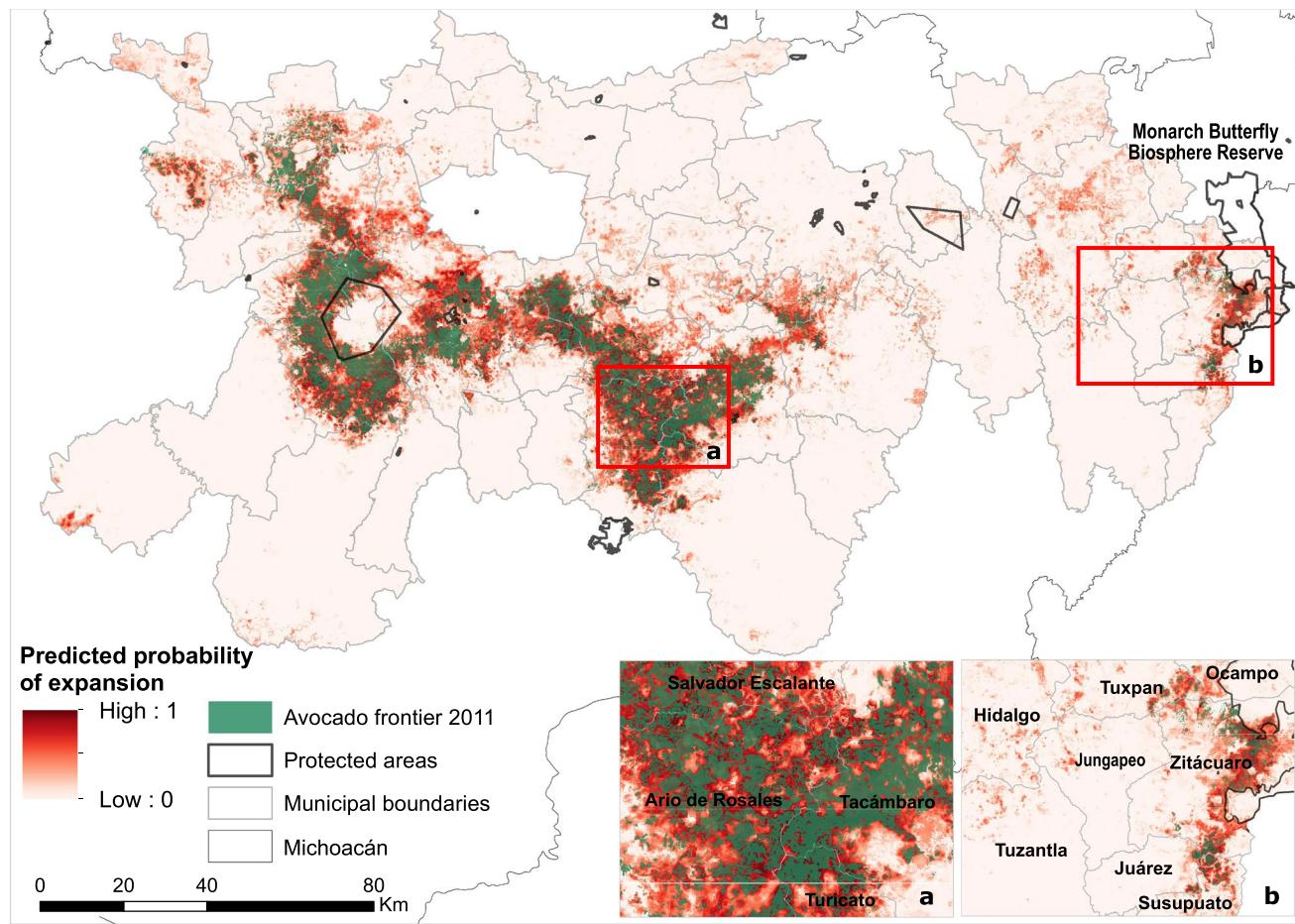
Interaction effects during the post-NAFTA period were similar to the pre-NAFTA period. Private lands with high values of annual precipitation and optimal annual mean temperature were positively related to avocado frontier expansion. However, the probability of expansion increased in areas with less suitable temperatures and with less precipitation on communal lands (Fig. 5c). In general, interaction effects revealed that private lands were more likely to be converted to avocado orchards given optimal environmental and accessibility conditions. On the contrary, communal lands under optimal environmental and accessibility conditions remained unaltered, as shown by negative SHAP

values. Moreover, communal lands under suboptimal conditions were more likely to be converted to avocado orchards than private lands under similar conditions.

### Prediction of potential areas for avocado frontier expansion

Areas of high predicted probabilities for new avocado orchard expansion were mostly located adjacent to existing orchards. However, we also observed potential new emerging hotspots of avocado expansion in the eastern part of the study area and near the boundaries of the Monarch Butterfly Biosphere Reserve, located in the municipalities of Zitácuaro and Ocampo (Fig. 6).

We observed a clear trend towards the expansion of new avocado orchards into climatically suboptimal areas



**Fig. 6** Predicted probability of avocado expansion. **a** Predicted avocado orchards adjacent to existing orchards and **b** predicted avocado expansion near the boundaries of the Monarch Butterfly Biosphere Reserve and new emerging hotspots in the eastern part of the study region

in terms of annual mean temperature and annual precipitation (Fig. 7). Avocado frontier expansion areas during the pre-NAFTA period appeared further away from settlements, roads, and rivers, and on steeper slopes. This expansion into less accessible and less climatically suitable areas slightly increased during the post-NAFTA period. We observed a continuation of these trends for potential avocado expansion in suitable areas (probability threshold  $\geq 0.7$ ), suggesting that future expansion areas will likely be displaced into more ecologically marginal regions.

In addition, using a probability threshold  $\geq 0.7$ , suitable areas for potential avocado expansion accounted for 11,827 ha. Furthermore, potential avocado expansion in moderate (threshold between  $< 0.7$  and  $\geq 0.5$ ) and suboptimal (threshold between  $< 0.5$  and  $\geq 0.3$ ) areas for production accounted for 27,617 ha and 62,192 ha, respectively.

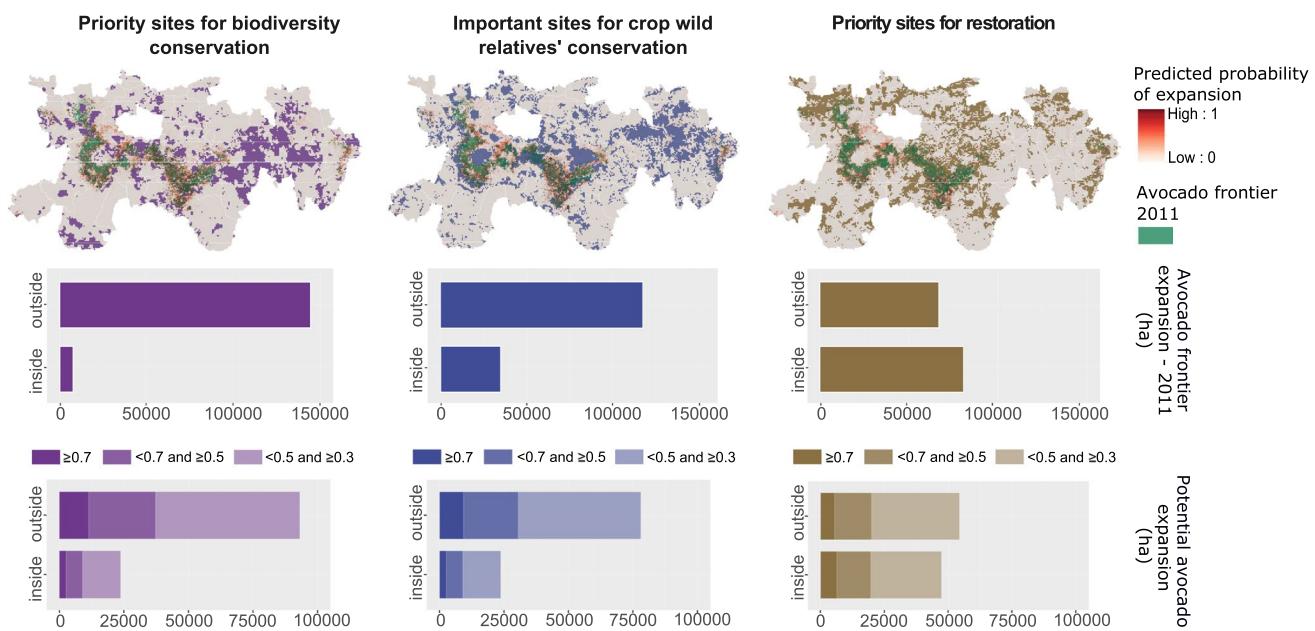
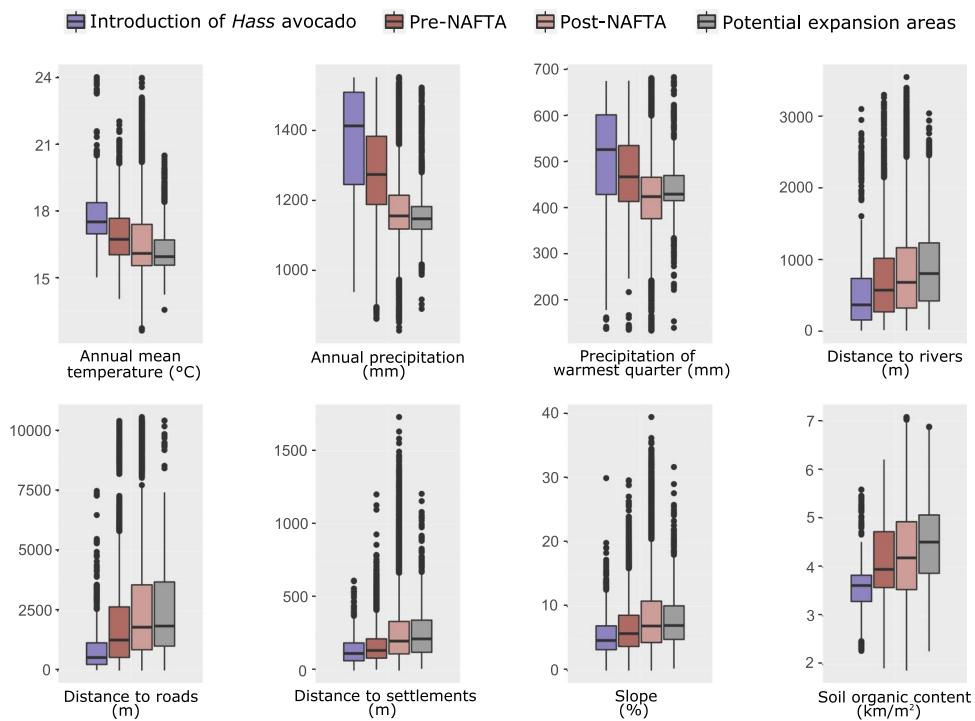
Most of the observed and potential avocado frontier expansion occurred mainly outside priority sites for biodiversity conservation and important sites for crop wild relatives' conservation (Fig. 8). The contrary occurred regarding

priority sites for restoration, as a larger expansion occurred inside compared to outside these sites.

## Discussion

We analyzed spatial patterns of avocado frontier expansion in Michoacán, Mexico, before and after the implementation of NAFTA and assessed how the relative importance and interactions of spatial determinants explaining these patterns have changed during a 40-year period of turbulent socioeconomic and political change in Mexico. Four major insights emerged from our analysis. First, avocado frontier expansion increased substantially across time and space, most strongly post-NAFTA. Second, the expansion of avocado orchards during 1960–1974 was mainly related to accessibility and environmental factors, i.e., annual precipitation, distance to roads, distance to settlements, and slope, whereas during pre- and post-NAFTA periods, land tenure and annual mean temperature were important factors in determining

**Fig. 7** Box plots of the main spatial determinants of avocado expansion during the introduction of *Hass* avocado (1960–1974), pre-NAFTA (1974–1995), and post-NAFTA (1995–2011) periods and for potential avocado expansion in suitable areas (probability threshold  $\geq 0.7$ )



**Fig. 8** Spatial patterns of observed avocado frontier expansion and potential expansion in suitable ( $\geq 0.7$ ), moderate ( $< 0.7 \text{ and } \geq 0.5$ ), and suboptimal areas ( $< 0.5 \text{ and } \geq 0.3$ ) inside and outside priority

sites for biodiversity conservation, important sites for crop wild relatives' conservation, and priority sites for restoration

frontier expansion. Third, potential future expansion areas are likely to shift into more marginal areas than currently, characterized by less precipitation, steeper slopes, and larger distances to settlements, roads, and rivers. This can result in less production potential and important economic repercussions for the livelihoods of small-scale farmers. Fourth,

potential future avocado expansion areas will likely entail substantial environmental trade-offs, due to encroachment on important areas for crop wild relatives' conservation, as well as on areas with high biological value and feasibility for ecological restoration. Considering the increasing demands for agricultural commodities that are rapidly transforming

the spatial patterns of land-use change in globalized production systems, our results facilitate a better understanding of frontier expansion dynamics of commodity crops.

### **Effects of environmental conditions and accessibility on avocado frontier expansion**

Distance to settlements was the major accessibility factor determining avocado expansion across the avocado belt in Michoacán during the three periods analyzed. Several studies have linked land-use change (e.g., deforestation for agricultural expansion) to more accessible, flat areas with high road and population density (Jakovac et al., 2017; Salonen et al., 2012; Verburg et al., 2014). Although we found that better accessibility increased the probability of avocado expansion, we also observed a clear trend towards the establishment of new avocado orchards in areas farther away from settlements, roads, and rivers, and with steeper slopes during pre- and post-NAFTA periods. This suggests that avocado frontier expansion is not only driving crop substitution and displacement of traditional crop systems distributed near settlements and local markets but also indicates that avocado orchards are expanding into more distant areas, resulting in pine-oak forest clearing in the region (Bravo-Espinosa et al., 2014). Displacement of shifting cultivation and replacement of forested areas driven by export-oriented crop production are processes observed also in other world regions, especially in Southeast Asia and sub-Saharan Africa, such as Vietnam (Meyfroidt et al., 2013), Congo (Ordway et al., 2017), or Cameroon (Ordway et al., 2019). Increased frontier expansion caused by global agricultural commodity booms can further lead to the marginalization of local small-scale farmers (Levers et al., 2021), negatively affecting their livelihoods by an increased vulnerability due to reduced productive potential and higher exposure to volatile and unstable global markets (Abid et al., 2016; Meyfroidt et al., 2014).

### **Effects of land tenure on avocado frontier expansion**

We found that avocado orchards during pre- and post-NAFTA periods expanded mostly in private lands. Moreover, private lands under optimal conditions were more likely to be converted to avocado orchards, whereas in communal lands, most avocado expansion occurred under suboptimal conditions. Lands under a communal regime are less likely to change towards avocado production, mainly because decisions over land use must be based on the consensus of the community, as opposed to private landowners that have individual agency over their land; therefore, new avocado orchards on communal lands tend to be established on areas that are less productive (i.e., suboptimal) and where there are fewer conflicts among community members. When lucrative activities are involved in communal land use planning, conflict among stakeholders

is the most common outcome (Perez-Llorente et al., 2019). It has been reported that land-use changes arise when communal lands are sold to both insiders or outsiders (DiGiano et al., 2013), especially as the reform of Article 27 of the Mexican Constitution in 1992 ended government obligations to redistribute land and authorized individualization and private titling of lands, which also disarticulated the social sector and affected land systems of communal property. The few well-organized communities in the region with strong governance have historically focused their resource management to forestry, preventing avocado expansion and land-use change in general, and thus protecting their natural resources and livelihoods (Barsimantov and Antezana, 2012; Orozco-Quintero and Davidson-Hunt, 2009).

However, for several communities throughout the avocado belt in Michoacán, avocado frontier expansion has resulted in profound land tenure regime changes, reigniting old conflicts over land titling, holding size, and land use (Barsimantov and Antezana, 2012). Moreover, post-NAFTA, economic incentives prompted by state and federal governments only favored large-scale commercial growers and agribusinesses, and small-scale farmers were increasingly left behind (Assies, 2008). The global avocado boom prompted by the implementation of NAFTA has increased and amplified the inequalities between large agribusinesses integrated into the global markets and local small-scale farmers facing land scarcity and lack of economic incentives (Orozco-Ramirez et al., 2017). This has further resulted in an increasing impoverishment of rural small-scale farmers, a disarticulation of local institutions, and has increased conflicts throughout the region (Ornelas, 2018). Such asymmetries in agency and power relations between actors were also observed in commodity frontiers in Argentina (de Waroux et al., 2018), Madagascar (Neimark et al., 2019), Laos (Junquera and Gret-Regamey, 2019; Ramcilovic-Suominen and Kotilainen, 2020), and Indonesia (Pichler, 2015), underlining the importance of land titling and land rights in global agricultural systems, which need to be considered in targeted and contextualized decision making.

### **Socio-environmental trade-offs and future development pathways**

Our results revealed substantial socio-environmental impacts of the ongoing avocado production in Mexico, and thus support previous findings showing that avocado production in Michoacán has triggered deforestation, illegal logging, and landownership conflicts (De la Vega-Rivera and Merino-Perez, 2021; Perez-Llorente et al., 2019). We showed that new avocado orchards expanded into increasingly less suitable areas throughout the study region since 1974, and we expect that this trend will likely continue in the future. This process of marginalization can result in poverty traps

for small-scale farmers (Barrett, 2008; Mastrangeli et al., 2019; Meyfroidt et al., 2013), increasing their vulnerability and impairing their ability to sustain their livelihoods. In addition, climate change trends modeled for the region are expected to negatively impact avocado production systems due to higher temperatures, lower precipitations, and more frequent extreme climate events (e.g., frosts and hail), further increasing the pressure on small-scale farmers (Charre-Medellín et al. 2021).

Although we observed that priority sites for biodiversity conservation were not strongly affected by past avocado frontier expansion, some important sites for crop wild relatives' conservation have been and will likely be transformed into avocado orchards. Moreover, our results revealed that the avocado frontier is likely to expand into sites with high restoration feasibility, thus reducing the possibilities of maintaining and restoring the biological diversity and ecological functions of those sites. Our findings identified ongoing and future hotspots of avocado expansion that could potentially compromise the long-term preservation of the region's biodiversity. For instance, the boundaries of protected areas — although effective — are already under high pressures, as well as several priority sites for biodiversity conservation and important sites for crop wild relatives' conservation (Sanchez et al., 2019).

According to official census data, the total land devoted to avocados in 2018 was 175,014 ha, corresponding to an increase of 22,521 ha since 2011 (SIAP, 2018). Following our results, using a probability threshold of  $\geq 0.7$ , suitable areas for potential avocado expansion only accounted for half of this area (11,827 ha). Yet, potential expansion in moderately suitable areas for production (threshold between  $< 0.7$  and  $\geq 0.5$ ) accounted for 27,617 ha. This suggests that avocado expansion in the past years likely occurred in both suitable and less suitable areas. Avocado production and exports are expected to continue in the future, which will likely result in further expanding avocado frontiers providing that areas for production — even under suboptimal conditions — are still available. Yet, this scenario could change anytime. For instance, NAFTA's transition into the United States–Mexico–Canada Agreement (USMCA) in 2018 raised concerns and increased tensions among the actors involved in the avocado industry. A potential hold-up in the ratification process was initially suggested, which would have put Mexico's food export markets at risk. In the longer-term, it could also be possible that growing environmental concerns affect avocado demand on a global scale. Despite these concerns, the avocado industry has overcome several instabilities, such as the COVID-19 pandemic, underlining the strength of its supply chain and collaboration strategies (Lopez-Ridaura et al., 2021).

However, the environmental footprint of global avocado consumption patterns continues to exert serious pressures

on local small-scale farmers, indigenous communities, and common property lands. A major concern is that as suitable lands for growing avocado become scarce, and the impacts on the environment are amplified, this system integrity can potentially be comprised. Moreover, these impacts can in turn be exacerbated in the future by reduced water availability, intense droughts, and higher susceptibility to pest invasions (Charre-Medellín et al. 2021; Chávez et al., 2019), by fluctuating market prices, changing consumer preferences, and by a fragile ecosystem facing a continuously more eroded genetic diversity of crops and crop wild relatives (Contreras-Toledo et al., 2018; Ford-Lloyd et al., 2011; Vincent et al., 2019).

## Limitations

In this study, we assessed the spatial patterns of avocado frontier expansion before and after NAFTA implementation based on environmental, land accessibility, and social factors determining that expansion. Aside from expansion, the intensification of land management is crucial to understand commodity frontier dynamics as both processes usually occur together in regions characterized by export-oriented crop production (Barretto et al., 2013; Byerlee et al., 2014; Varkkey et al., 2018; Zabel et al., 2019). In Michoacán, the increasing market demands, and rising prices have stimulated the continued expansion of the avocado frontier during the past three decades and have promoted land-use intensification to increase avocado yields to meet market demands. As land for agricultural expansion becomes scarce, agricultural intensification is likely to increase (Barretto et al., 2013; Lambin and Meyfroidt, 2011; Zabel et al., 2019). Evaluating the spatiotemporal patterns of land-use intensification across the entire avocado belt region was beyond the scope of this analysis due to major data gaps about system inputs (e.g., capital per land area, cropping frequency) and outputs (e.g., agricultural yields, production volumes). However, including intensification patterns and change trajectories in our analysis would have allowed us to further improve the understanding of land-system changes and the underlying factors in this dynamic commodity frontier region.

Context-specific studies linking local scale processes to global international trade dynamics by means of spatially explicit models are still rare, although they could greatly improve our understanding of how telecoupled systems interact (Friis et al., 2016; Gasparri et al., 2016; Yu et al., 2013). Here, we addressed a set of important environmental, land accessibility and social factors determining avocado expansion. Yet, a clear understanding of the local underlying factors driving conflicts and land-use change dynamics throughout the avocado belt is still necessary. Our analysis could be greatly improved by incorporating economic (e.g., market prices for agricultural

exports, export volumes, GDP growth, labor force), institutional (e.g., trade policies, domestic agricultural policies, trade tariffs changes), and other social (e.g., access to technology) drivers of avocado frontier expansion, which we could not incorporate due to data restrictions. Moreover, addressing flows, feedbacks, spillovers, and trade-offs along the avocado supply chain in a spatially explicit way and linking those processes to local land-use changes would offer an exciting opportunity to accurately quantify the environmental footprint of avocado production and to track the value chain from production to consumption (da Silva et al., 2021). Such approaches fall beyond the scope of the present study.

In this study, we assessed avocado frontier expansion for three periods using the avocado frontier inventory available for years 1974, 1995, and 2011. Yet, avocado production in Mexico and demand from elsewhere has continued to increase since then (Cho et al., 2021; Denvir et al., 2021). One key step towards more reliably assessing the impacts and trade-offs the avocado industry has left on this major production region is to generate an updated wall-to-wall version of the avocado inventory. This would allow validating the potential expansion areas predicted by our model against the actual avocado orchards currently found in Michoacán and in adjacent states such as Jalisco, a new and rising production hotspot. It would further allow for re-assessing the importance of spatial determinants explaining expansion patterns. Also, mapping settlement expansion since 1960 would allow to better capture settlement expansion dynamics, to refine our models' predictions, and to deepen our understanding of how this spatial determinant has influenced avocado expansion.

Finally, by using XGBoost and SHAP values, we were able to better understand the interaction effects between land tenure and environmental and accessibility variables, which thus allowed us to gain a unique insight into some underlying processes of this expanding frontier in central Mexico. As future research, it would be useful to integrate and compare the present results with other modeling approaches based on cellular automata (Soares et al., 2006) or other land allocation models that allow incorporating dynamic variables (Verburg et al., 2013).

## Implications

Landscape configuration reflects historical effects of land-use changes prompted by public policies. Avocado frontier expansion took place in a context of land policy and land tenure reforms in Mexico, but also as part of a wider context of agricultural development and trade policies (Assies, 2008). As such, the avocado industry has been shaped by context-specific circumstances and has been mediated by national and

global external forces. Our results further foster and support the discussion about the need for improving the representation of small-scale farmers in policies, regulations, and governance, and for strengthening communal land rights.

First, policies oriented towards increasing the integration of small-scale farmers into the agricultural sector are highly needed, as well as the design and implementation of strategies and incentives aimed at supporting small-scale farmers producing subsistence and domestic-oriented crops. Second, as avocado production is highly spatially concentrated, and communal lands are a key component for maintaining natural areas and avoiding conversion to avocado orchards, efforts to minimize the socio-ecological impacts of the international trade of avocado should focus on the reinforcement of communal land rights and local governance (Barsimantov and Antezana, 2012; Denvir et al., 2021). Such actions could improve the situation for the environment and small-scale farmers and could help to sustainably manage and protect biodiversity-rich areas currently at risk by expanding avocado frontiers (Sanchez et al., 2019). Third, government policy schemes could tax the environmental footprint of land converted to avocado orchards, potentially benefiting small-scale farmers already using degraded lands, over large ones clearing large areas of forests in regions with suitable environmental conditions. Fourth, the identification and mapping of supply chain actors and connections is crucial to accurately assess the environmental and social risks embedded in the production, consumption, and trade of agricultural commodities (Godar et al., 2016). Efforts to promote avocado supply-chain transparency and sustainability should focus on improving conventional regulatory frameworks and governance through multi-stakeholder initiatives (Cho et al., 2021).

Finally, fair and more equitable sharing of benefits arising from agricultural trade commodities, particularly among small-scale farmers, is essential to move towards more sustainable, efficient, and inclusive telecoupled food systems.

## Conclusion

Our study provides the first spatially explicit assessment of avocado frontier expansion dynamics and how the relative importance and interactions of a set of environmental, accessibility and social factors explaining its expansion have changed between 1974 and 2011, comprising the entire period of the global avocado boom. Our study showed that spatial patterns of avocado frontier expansion reflected the historical effects of land-use changes prompted by public policies and our model's predictions revealed that new potential expansion areas will likely shift into ecologically more marginal regions. Our methodological approach highlighted the potential of machine learning algorithms and new interpretability methods (e.g., SHAP values) for broadening

our understanding of complex socio-ecological systems. Our analysis can assist in better informing local small-scale farmers, producers, and stakeholders about the potential environmental and social costs of current production practices. Policies regulating land property rights and promoting the integration of local small-scale farmers into the agricultural sector and global markets can help to ensure more effective and equitable production systems and to improve sustainability and governance of agricultural supply chains.

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