



Spatial expansion of avocado in Mexico: Could the energy use of pruning residues offset orchard GHG emissions?

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Abstract

Avocado orchards (*Persea americana*) in Mexico are constantly being expanded to meet the increasing demand for the fruit in the national and international markets. The land-use change (LUC) caused by this expansion has numerous negative impacts, including greenhouse gas (GHG) emissions due to the loss of forest cover and the burning of pruning residues. To generate a comprehensive evaluation of this complex environmental issue, we calculate emissions from LUC and from residue burning between 1974 and 2017 at a local scale (1:20,000), and the energy potential of pruning residues was estimated as an alternative to revalue a waste product and mitigate the negative impacts of avocado cultivation. Our results show that land-use conversions emitted 390.5 GgCO₂, of which 91% came from conversions to avocado orchards. Emissions of GHG from biomass burning amounted to an additional 20.68 GgCO₂e released per year. Given that around 12,600 tons of dry avocado pruning residues are generated annually in the study region, their use for energy generation could replace 240 TJ/year of fossil fuels in rural industries and could mitigate around 31 GgCO₂e per year. This study provides decision-makers with a concrete example of how to establish multiple-impact strategies at local scales.

Keywords Avocado orchards · Biomass · Land-use change · Environmental impact · Pruning · Industrial biomass

1 Introduction

Globally, conventional agriculture generates negative environmental impacts (Ullah et al., 2020), including forest degradation and fragmentation, biodiversity loss, intensive pesticide use, air pollution (Sun & Dai, 2017), and greenhouse gas (GHG) emissions.

Direct GHG emissions from agriculture (Astier et al., 2014; IPCC, 2007; Lamb et al., 2016) account for 14 to 17% of global anthropogenic emissions (Maraseni & Qu, 2016). In addition, forestry and other land-use change (FOLU)¹ emissions, which are partly due to agricultural intensification is equally linked to climate change (Singh et al., 2020) and GHG emissions (Pradhan et al., 2019) of anthropogenic CO₂ emissions (IPCC: Climate Change, 2014). There is therefore a prevailing need to reduce the environmental impact of agriculture (Knapp & Heijden, 2018).

Perennial crops, particularly fruit orchards, are an important resource that generates numerous ecological and economic benefits (Xia et al., 2020), while also playing an important role in land use change (LUC). Their potential to mitigate environmental impacts through carbon sequestration and biofuel provision (Aguilera et al., 2015) have increasingly been explored: fruit orchards have been proposed as a strategy to increase CO₂ sinks, particularly in regions exposed to LUC (Paz et al., 2018), while the large amounts of biomass generated from fruit tree pruning (and agriculture in general) can be harnessed for energy purposes and other uses (Aguilera et al., 2015; Ledo et al., 2018).

Among the fruits cultivated in Mexico, avocado (*P. americana*) has particularly influenced LUC in the country (Ávila-Ortega, 2018; Bravo et al., 2019). Currently, Mexico is the main producer and exporter of avocado worldwide, growing more than two million tons per year (SIAP, 2022) in 224 thousand hectares (ha) of orchards (FAO, 2021). Production is mainly aimed at the international market (United States, Japan, the European Union, and China). Mexican avocado exports increased by 25% between 2015 and 2018 (COCONI, 2019) and are expected to continue increasing. The state of Michoacán is the country's main grower of avocado, representing 75% of the national production (SIAP, 2022). During the 2019–2020 season, 962 thousand tons of avocado were exported from Michoacán to the United States (APEAM, 2020), of which 97% corresponded to the Hass variety.

Avocado production is one of the main sources of income for the state of Michoacán (Bravo et al., 2019). It also drives formal job creation in the state, with employment in this sector increasing by 106% in the last decade. Avocado cultivation in Mexico generates 310 thousand direct jobs, as well as 78 thousand indirect jobs. It is estimated that 160 jobs are generated for every thousand tons harvested per year (SADER, 2020).

Despite the social and economic benefits of avocado cultivation, its fast-increasing production to meet international demand has contributed to the loss of temperate forests and other land-use changes, frequently without government approval. In Michoacán, temperate pine-oak forests have been cleared because avocado trees have the same climate requirements (Mas et al., 2017; Villanueva-Tomas & Zepeda-Anaya, 2016). As stated by Cho et al. (2021), approximately 20% of deforestation in Michoacán between 2001 and 2017 was associated with the expansion of avocado orchards. Moreover, areas traditionally dedicated to growing maize have been transformed into avocado orchards, leading to the disappearance of this agricultural system in almost all municipalities (Bravo et al., 2019).

Numerous studies have evaluated the negative impacts associated with avocado cultivation, including deforestation; effects on the hydrological system (Gomez-Tagle Chávez et al., 2019) (such as decreased infiltration, increased evapotranspiration, flow reduction in springs, contamination from the use of agrochemicals (Bravo et al., 2019), and modifications to water quantity and quality (Tapia et al., 2014)); biodiversity loss (Burgos et al.,

¹ Forestry and other land use (FOLU)—also referred to as LULUCF (land use, land use change and forestry)—is the subset of agriculture, forestry and other land use (AFOLU) emissions and removals of GHGs related to direct human-induced LULUCF activities (IPCC: Climate Change 2014).

2011; Villamil et al., 2018); and GHG emissions (Anaya & Burgos, 2015; Astier et al., 2014). To date, however, no studies have comprehensively analyzed the impacts of avocado orchards, considering the byproducts from crop management.

Pruning is an essential crop management process that consists of selectively removing parts or whole sections of plants. Avocado trees are pruned annually, generating substantial amounts of biomass that must be removed from the field as soon as possible to avoid the spread of pests (Contreras et al., 2020). These residues are commonly discarded through open burning, a practice that emits GHG and local pollutants. Considering the expected increase in avocado production (SIAP, 2022), the utilization of these pruning residues represents a potential strategy to mitigate emissions. So far, the emissions generated by the burning of pruning residues have not been quantified. A report by INECC-SEMARNAT (INECC-SEMARNAT, 2018a) quantifies the emissions from biomass burning in cultivated lands in Mexico, but these figures correspond to maize and wheat crops and do not include perennial crops (such as avocado). Some studies have estimated the emissions associated with LUC to avocado orchards. However, as Arneth et al. (2017) point out, land-cover simulation models underestimate CO₂ emissions from LUC because they do not consider processes such as tree felling and land-clearing for crop change. Better estimates of GHG emissions are fundamental for understanding the magnitude of the impacts of LUC.

Studies have looked at the energy balance and GHG emissions from fossil fuels in avocado orchard systems in Michoacán. Anaya and Burgos (2015) evaluated direct and indirect fossil fuel consumption in the avocado production chain, finding that fertilizer application represents the highest energy use (54.4% of the total), followed by the application of pesticides (39.9%), weed control (5.6%) and irrigation (0.2%). Astier et al. (2014) analyzed the energy balance and GHG emissions from orchards of avocados intended for export, finding that the average energy consumption was 56 GJ ha⁻¹ yr⁻¹ and that emissions reached 3.3 MgCO₂e ha⁻¹ yr⁻¹, with no significant differences between organic and conventional orchards. However, the aforementioned studies focus on the orchards and the fruit as a final product, and none have quantified the potential use of pruning residues for energy generation and mitigation of GHG emissions at a local scale, as suggested by Ledo et al. (2018). Nor have previous studies considered that product diversification in avocado orchards could compensate both the energy inputs and the GHG emissions.

Most studies that have analyzed the negative impacts of the expansion of avocado orchards have had a regional scope (Cho et al., 2021; Mas et al., 2017). Those that have studied LUC for avocado cultivation in Michoacán have done so at scales of 1:50,000 (Mas et al., 2017), 1:100,000 (Cho et al., 2021), and 1:250,000 (Ávila-Ortega, 2018). These spatial dimensions are suitable for generating diagnoses and perspectives at a macro level. However, when it comes to local decision-making and implementation of concrete land-use policies, an in-depth analysis is required at a scale that allows for greater cartographic detail. Therefore, a local-scale analysis of LUC is relevant for its capacity to observe detailed trends and impacts and avoid known undercounting errors in LUC estimates (Ávila-Ortega, 2018) by working at a local scale (1:20,000) and looking at a historical period of close to half a century.

In a highly complex world like today's, where the multiple interrelationships and feedbacks between socio-economic and environmental systems have become evident (such as climate change exacerbated by an economic system based on the intensive consumption of fossil fuels), the approach to solutions at the territorial level must be holistic and interdisciplinary. The purpose of this work is to contribute in this direction, considering many of the objectives from the UN 2030 Agenda, and proposing and evaluating comprehensive strategies for approaching and managing the territory, which enable decision makers to have

relevant inputs for land use planning processes. In particular, our objectives were: to characterize the agricultural production of the avocado crop, its management techniques and the specific practices in organic and conventional orchards; to carry out a historical-environmental analysis of the last four decades of land-use changes (through geographic information systems), and in particular, those promoted by the expansion of the agricultural frontier (for avocado cultivation); to quantify the climate impact of LUC and open burning of agricultural residues through GHG emissions; and finally, to evaluate the technical feasibility of using the woody residues of this multi-year crop as a renewable energy strategy that represents fossil fuel savings for producers in the region and mitigates climate change.

Our results are of fundamental importance for the development of policies that promote social and economic development in the context of decentralization.

2 Methods

The issue of land use for agriculture is analyzed from an interdisciplinary perspective. We first present a geospatial analysis of LUC between 1974 and 2017. The starting period was chosen as a baseline prior to the North American Free Trade Agreement of 1993 (Macías-Macías, 2011) and because no land use maps were previously available for this date, allowing this study to contribute to the environmental history of the region. Subsequently, we quantified GHG emissions from LUC and from the current management of agricultural waste, including avocado pruning residues. Finally, we evaluated the possible use of pruning residues as an alternative to revalue waste and mitigate the negative impacts resulting from orchard expansion and increased production of avocado.

2.1 Study area

The municipality of Tingambato (Fig. 1) is located at the north of the state of Michoacán (19°30' N, 101°51' W), with a mean elevation of 1898 m.a.s.l. Tingambato has a population of 15 thousand and it is dominated by mixed forests of oak, pine, cedar, and alder, as well as coniferous forests of pine, fir, and juniper. The climate is temperate, with a mean annual temperature of 16 °C and mean annual rainfall of 1000–1100 mm (CCA-UNAM, 2011), with rains occurring mostly from June to September.

It has an area of 189.9 km² and represents 0.32% of the state's surface. Agriculture of perennial crops is the prevailing land use and, to a lesser extent, forestry activities with pine and oak species. The predominant soil groups are andosols (74.4%), lithosols (8.8%), and vertisols (8.0%; (INEGI, 2007)). Tingambato produces almost 4% of the national avocado output.

2.2 Land-use change and greenhouse gas emissions

We analyzed the changes in land use that resulted from the expansion of avocado orchards in the study area. We then calculated GHG emissions from the loss of primary forest cover and the open burning of biomass.

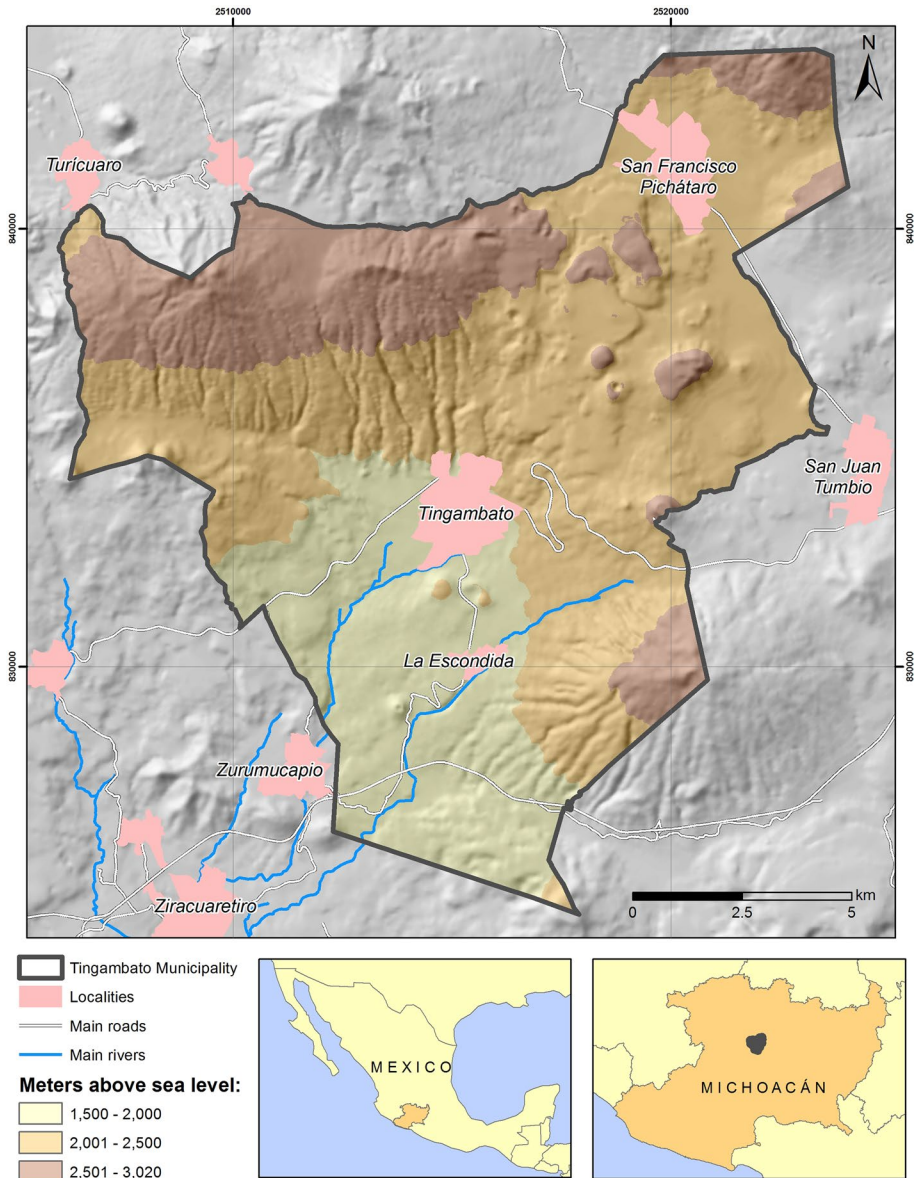


Fig. 1 Geographic location of the study area

2.3 Spatio-temporal dynamics

We used geospatial tools to study the evolution of land uses in the municipality of Tingambato between 1974 and 2017. For 2017, the land use map was made in ArcGIS 10.5 through photointerpretation of a 0.4 m resolution and GeoEye-1 image (Google Earth), following the technical procedure outlined by FAO (FAO, 2000; Palmer, 1998;) and used

Table 1 Land-use change matrix

			2017				
			Annual cropland	Perennial cropland	Forest	Grassland	Human settlements
			10	20	30	40	50
1974	Annual cropland	1	11	21	31	41	51
	Perennial cropland	2	12	22	32	42	52
	Forest	3	13	23	33	43	53
	Grassland	4	14	24	34	44	54
	Human settlements	5	15	25	35	45	55

in recent papers such as Cavalli et al. (2023). We used publicly available land use maps as cartographic references (INEGI, 2016; Mas et al., 2017). From these sources we extracted the following categories: forests, human-induced grasslands, human settlements, annual cropland, and perennial cropland. Data from SIAP (2022) show that avocado crops represented 99% of all perennial crops in 2017, so we treat them interchangeably here.

We then cartographically validated our classification following the guidelines for evaluation of thematic maps by Congalton (1988) and Stehman and Czaplewski (1998), assigning 50 verification points for each type of land use. For this, we incorporated the agricultural plot registry from the Local Board of Agricultural Health of Tingambato² (JLSV for its Spanish acronym) with their particular attributes (place name, landowner name, crop variety). We obtained a success rate of over 95%.

In order to generate the 1974 land-use map, we used aerial photographs from the archives of the National Institute of Statistics and Geography (INEGI for its Spanish acronym) with a working scale of 1:20,000 (see Fig. A1 in the supplementary material). These images were georeferenced and orthorectified using ArcGIS 10.5. In accordance with the independent photointerpretation criteria published by the Global Forest Resources Assessment of the FAO (FAO, 2000; Palmer, 1998;), we overlaid the 2017 land use classification described above to identify the changes that occurred between one point in time and the other, and we proceeded to digitalize.

For each year, the minimum mapping unit was established based on orchard-size data provided by JLSV, where the smallest plots have areas greater than 300 m². This is relevant because, for 2017, we identified more than 300 parcels scattered throughout the municipality with areas under one hectare, which in total add up to 114 ha. In 1974, on the other hand, 50 orchards were identified with a total area of 29 ha (see supplementary material for more information).

Land-use categories were then processed in raster format following the classification shown in Table 1. With these categories, we employed the method of cross-tabulation for

² This organization is audited by federal and state agencies, as well as the civil society. Its objectives include i) monitoring compliance with phytosanitary safety protocols during the harvesting process; ii) collecting fruit for dry matter testing; iii) verifying that the orchard complies with the Best Agricultural Practices program; iv) annually collating and updating the producer register; and v) maintaining a database of registered orchards (size, quantity, location, type, age, production).

the two years in question to identify the areas where a change in land-use occurs. As shown in Table 1, the diagonal indicates that land-use remains stable, while the rest indicates a conversion or change.

The values for each cell in the LUC matrix were determined using the calculate geometry tool in ArcGIS, while the percentages of LUC were calculated using Eq. 1, considering the area of the Tingambato municipality (19,000 ha) as a base. See detailed information in the supplementary material.

$$\%change = \frac{LUC\ surface * 100}{Total\ area\ of\ Tingambato} \quad (1)$$

2.4 Calculating emissions from land-use change

For the purposes of this study, we estimated emissions from LUC by assuming that the conversion from forest to cropland and grassland generates emissions (IPCC, 2006; Manrique & Franco, 2020; Pinillos et al., 2020) and that carbon capture occurs whenever there is a conversion from cropland or grasslands to forest (IPCC, 2006; Mackey et al., 2020; Rizinjirabake et al., 2019). Lands that maintained their cover throughout the study period are considered carbon sinks (INECC-SEMARNAT, 2018a, 2018b) (see Table A.3 in the supplementary material for more details about LUC dynamics). We applied the IPCC carbon stock difference methodology (IPCC, 2006) (Eq. 2) to estimate emissions from LUC, where changes in annual carbon stocks for each land use ($tC.year^{-1}$) are determined by the difference between carbon stocks at times 2 and 1, divided by the number of years elapsed between stocks (43 years in this case).

$$\Delta C = \sum_{ijk} \left(\frac{Ct2 - Ct1}{t2 - t1} \right)_{ijk} \quad (2)$$

where ΔC is the change in annual carbon stocks for each land use ($tC.year^{-1}$), $Ct1$ are the carbon stocks at time 1 (tC), and $Ct2$ are the carbon stocks at time 2 (tC).

Emissions of CO_2 are hence estimated as net changes to carbon stocks over time (FAO, 2015). Here, we assume that the changes in ecosystem carbon stocks occur mainly (but not exclusively) through an exchange of CO_2 between the planet's surface and the atmosphere (i.e. other carbon transfer processes such as leaching are assumed to be insignificant) (INECC-SEMARNAT, 2018a, 2018b). Therefore, CO_2 removals are transferred from the atmosphere to a reservoir (aboveground or belowground biomass, litter, soil, etc.) for each land use, while CO_2 emissions are transferred from a reservoir to the atmosphere. Removals of CO_2 are represented with a negative sign ($-$) and CO_2 emissions are positive ($+$) (IPCC, 2006).

We quantified changes to the main carbon stock reservoirs, aboveground biomass (AGB), and belowground biomass (BGB) in tons of oven-dried matter (tDM), holding all others constant (IPCC, 2006). These values were then converted to CO_2 based on the ratio of molecular weights. For native forests, we used the emission factors reported in the Second National Inventory of Forests and Soils (CONAFOR, Forestal y de Suelos., 2018) at a national scale. For other land-use categories in the study area, we used factors reported in previous studies as well as our own data (Table 2). The carbon fraction value of 0.48 is the mean obtained from a database of 47 values and is used by CONAFOR (2018).

Based on our estimates of areas where land use has changed or remained stable, we calculated CO_2 emissions from land-use conversions and CO_2 removals from land

Table 2 Carbon emission factors (CEF) by land-use type for aboveground biomass (AGB), belowground biomass (BGB), and total biomass (AGBt) reservoirs

Land use	AGB (t/ha)	R (adim)	BGB (t/ha)	AGBt (t/ha)	Carbon factor	CEF (tC/ha)
Primary forest (coniferous and broadleaf)	53.66 ^a	0.25 ^c	13.31	66.97	0.48	32.14
Annual cropland (maize)	4.37 ^b	0.10 ^f	0.44	4.81	0.48	2.31
Perennial cropland (avocado)	21.01 ^c	0.25 ^g	5.25	26.26	0.48	12.61
Grassland	2.70 ^d	0.18 ^h	0.49	3.19	0.48	1.53

^aAssuming coniferous and broadleaf primary forest (pine-oak)(CONAFOR: Segundo Inventario Nacional Forestal y de Suelos., 2018)

^bDefault value for arable land for temperate regions(IPCC, 2006)

^cWeight estimated in the study region with an average of 120 trees per ha, 12 years old

^dDefault value for grasslands in warm humid temperate regions(IPCC, 2006)

For R (adim) = ratio of belowground biomass to aboveground biomass, the values correspond to:

^eMean of all reported emission factors for all forest types in the country(SEMARNAT-INECC, 2017)

^fR of annual croplands(Ordóñez et al., 2008)

^gidem e(SEMARNAT-INECC, 2017)

^hR of grasslands(Jaramillo et al., 2003)

AGBt includes AGB and BGB (in tDM/ha)

remaining in a particular land-use category. Emissions of gases other than CO₂ are largely the product of microbiological processes (i.e. within the soil) and the combustion of organic materials (FAO, 2015; IPCC, 2003; Ravindranath & Ostwald, 2008). In the next section, we explain the process for estimating emissions of GHG other than CO₂ from burning.

2.5 Estimating emissions from biomass burning

Emissions from biomass combustion comprise mostly CO₂ but also include other GHG and polluting gases such as CO, CH₄, and NO_x, which originate from the incomplete combustion of the biofuel (FAO, 2015). Calculating emissions from GHG other than CO₂ depends on the speed of emission from a source directly into the atmosphere. Generally, this speed is determined by an emission factor for each gas by a unit corresponding to the generating activity. These activity data describe the magnitude of the action that produces GHG emissions or removals at a given time period and location (FAO, 2015; IPCC, 2006).

In order to quantify emissions from biomass burning, we considered the following: i) forest biomass removed to make way for new land use (50% is burned in situ); ii) residual biomass from annual agricultural crops, mainly maize (50% is burned in situ); iii) residual biomass from perennial crops (25% is burned in situ). For the last two conditions, we considered only those agricultural lands that remained under the same land-use category. For perennial avocado crops, the percentage of pruning residues burnt annually (Sagarpa, 2015) was estimated from interview data, as described in the next section. Estimates were made for each gas and land-use category using Eq. 3 (Eq. 2.27 of the IPCC (IPCC, 2006)). Emissions of CO₂ are considered neutral given that carbon released into the atmosphere is reabsorbed during the following growth cycle (IPCC, 2006), so we estimated emissions for CH₄ and N₂O in line with parameters for direct GHG (i.e. attributable to human activities) reported in national inventories (FAO, 2000; IPCC, 2006). Based on Ledo et al. (2018), we used global warming potential values over 100 years of 28 and 265 for CH₄ and N₂O, respectively, IPCC (2014).

$$L_{\text{fire}} = A * M_B * C_F * E_F * 10^{-3} \quad (3)$$

where L_{fire} = GHG emissions from burning (t); A = burned surface (ha), which corresponds to the surface that remains under the same land-use for the period of study for the case of agricultural residues; M_B = fuel mass available for combustion (ton ha⁻¹), considering only the AGB fraction for land-use conversions (detailed in Table 2); C_F = combustion factor, unitless; E_F = emission factor per g/kg of burned dry matter.

The amount of fuel that can be burned (M_B) is given by the burned surface and the density of fuel present on that surface, as well as by the type of fire. This value also considers the percentage of biomass that is destined for burning, since some of the material can have other uses. The combustion factor (C_F) is a measure of the proportion of the fuel that actually burns, which varies depending on the size and architecture of the fuel load, the moisture content of the fuel, and the type of fire. When data for M_B and C_F are not available, a default value can be used to represent the amount of fuel actually burned (the product of M_B and C_F ; (IPCC, 2006)). Table 3 contains these values, including N₂O and CH₄ emissions from biomass burning when converting cropland, grassland, and forests to other land use, as well as yearly burning of agricultural residues (both annual and perennial) on lands that remain under the same land use or were converted during the study period.

Table 3 Factors for estimating emissions from biomass burning

	A (ha)	M _B (t/ha)	C _F (adim) ^c	M _B * C _F	E _F CH ₄ (g/kg)	E _F N ₂ O (g/kg)
Emissions from land-use change						
Primary forest (coniferous and broadleaf – pine and oak)	3126.16	53.66 ^a	0.51	–	4.70 ^f	0.26 ^f
Annual crops (maize)	3750.26	4.37 ^b	0.51	–	2.70 ^g	0.07 ^g
Perennial crops (avocado)	66.20	21.01 ^c	0.51	–	6.10 ^h	0.06 ^h
Grassland	176.59	2.70 ^d	0.51	–	2.30 ⁱ	0.21 ⁱ
Emissions from agricultural residues in lands that remain under the same land use						
Annual crops (maize)	2025.40	–	–	10.00l	2.70 ^j	0.07 ^j
Perennial crops (avocado) (biomass)	3542.30	–	–	14.3m	6.10k	0.06k
Emissions from agricultural residues in the newly converted lands*						
Annual crops (maize)	43.2	–	–	10.00l	2.70 ^j	0.07 ^j
Perennial crops (avocado) (biomass)	4202.9	–	–	14.3m	6.10k	0.06k

Where: a–d = values from Table 2; e = default value for other forests in temperate regions, slash and burn (fire for land-clearing) or felling, wood removal and burning (fire for land-clearing; (IPCC, 2006)); f–k = default emission factors reported by the IPCC (IPCC, 2006) based on (Andreae & Merlet, 2001); l = default value for maize agricultural residues (post-harvest burning; (IPCC, 2006)) assuming that 100% of residues are burned; m = average default value for perennial shrub-like crops (IPCC, 2006; Sagarpa, 2015). * it is assumed that the lands were converted in year 1 of the study and therefore were subject to pruning (perennial crops) or generation of agricultural residues (annual crops)

2.6 Energy generation and mitigation potential from avocado pruning residues

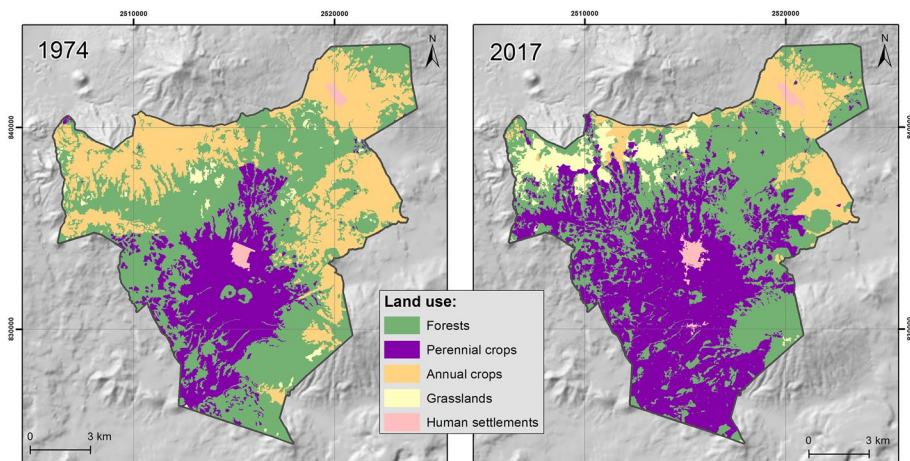
To qualitatively and quantitatively determine the amount of biomass generated by pruning, we conducted 40 semi-structured interviews with orchard managers, producers, and avocado pruners. These interviews allowed us to identify key variables, namely: the classification of orchards and pruning, orchard age, pruning frequency, amount of biomass obtained, and its current uses. Interviews were conducted at the JLSV. The amount of pruning residues generated per area unit was estimated from interview data and compared with data from the literature (Soria-González, 2019; Tauro et al., 2022). A mean value was estimated for all orchards and pruning methods used.

We estimated the energy potential of avocado pruning residues by multiplying the amount of annual pruning by their calorific value, following the methodology in Velázquez-Martí et al. (2018). The amount of annual pruning was obtained by multiplying the mean amount of pruning by the area covered by avocado orchards at the study site. The calorific value of a pruning residue sample, previously dried and crushed, was determined in a Parr 6100 calorimeter. The energy potential of avocado pruning residues was constrained by the fact that 50% of residues are incorporated into the soil and 25% have other uses (detailed information in the results section).

To analyze the potential for mitigation of GHG emissions, we estimated the amount of fossil fuels that could be substituted by biomass in Michoacán's industrial sector, as was done in Aguilera et al. (2015). The fossil fuels considered were selected according to Tauro et al. (2018), who contemplated that biomass could be economically competitive under current fuel oil and LPG prices. Here, we considered the following end-user

Table 4 Area destined to each land-use category in 1974 and 2017

Land-use category	1974	2017		Change Direction
	Area (ha)	Area (ha)	(%)	
Primary forest	8879.6	7880.2	5.43	Loss
Annual cropland	5784.4	2066.4	19.58	Gain
Perennial cropland	3949.2	7753.1	20.17	Gain
Grassland	236.5	1073.5	4.44	Gain
Human settlements	152.2	228.8	0.41	Gain

**Fig. 2** Land use in the Tingambato municipality for 1974 and 2017

costs within the national market: avocado pruning chips (2.0 USD/GJ), fuel oil (6.5 USD/GJ), and LPG (21.5 USD/GJ), the latter calculated based on data from PEMEX (2022).

The potential for mitigation of GHG emissions was obtained by multiplying the fuel savings from substituting fossil fuels for biomass by the carbon emission factors associated with each fossil fuel (IPCC, 2006). Emissions of CO₂ from biomass were considered neutral, in accordance with Tauro et al. (2018). We also calculated annual savings resulting from this substitution. Monetary calculations were made considering an exchange rate of 20 MXN = 1 USD.

3 Results and discussion

3.1 Land-use change between 1974 and 2017

Table 4 shows that forests were the predominant land-use category in 1974, occupying 46.7% of the area of the municipality, followed by annual agricultural crops (30%) and perennial crops (21%). By 2017, forests were still a dominant land use, although the total area they occupied had diminished to 41% while the area devoted to perennial crops doubled

(41%), mainly displacing annual cropland cover. Induced grasslands also increased to 6% by 2017, likely because of deforestation and the incidence of fires during previous years. Human settlements increased only slightly between the two years (0.4%), which can be attributed to low population growth and lack of infrastructure in the region (Fig. 2).

Forests and annual croplands lost 25% of their surface, while avocado orchards grew by more than 20% (Table 4). This value closely matches the 18% increase in the avocado cultivated area reported by FAO (2021) for the period analyzed. This shows that large areas of pine forests have been deforested to give way to avocado orchards, as stated by Garibay and Bocco (2011), generating GHG emissions that are quantified below, and representing a loss of primary forest and biodiversity. These numbers contrast sharply with the positions of different stakeholders in the sector, who do not consider that avocado promotes or generates deforestation (Cho et al., 2021).

The registry maintained by the JLSV of the Tingambato municipality lists a total of 2,370 avocado orchards covering an area of 4,500 ha in 2017. This value differs from the 7,753 ha estimated in Table 4, indicating that data are missing from the JLSV registry. Our data can therefore be useful to support the different organizations within the sector in planning and managing the distribution of orchards in the future. The values shown in Table 4 represent a significant contribution of this study toward a more precise estimate of the area occupied by avocado orchards at a local level.

Notable differences exist between results presented in academic publications and the values reported by official media. For example, Cho et al. (2021) calculated that there were 395,946 ha of avocado orchards in Michoacán in 2017, while Mas et al. (2017) estimated a total of 467,790 ha (15% greater). On the other hand, data from official sources such as SIAP (2022) indicate that, for the same year, 188,722 ha were cultivated with avocado in Michoacán (48% of the value estimated by Cho et al. (2021)). This divergence could have repercussions in the results obtained from land-use, environmental or socio-economic studies, for example, in the quantification of GHG emissions or the energy potential of pruning residues. It is necessary to normalize quantification methodologies.

3.2 Greenhouse gas emissions from land-use change

Based on the LUC analysis, 39% of the municipal area experienced some type of land-use change. About 5.3% of native coniferous and broadleaf forest cover was lost in the municipality between 1974 and 2017 (Table 4). This represented a loss of 1,556 tDM/year⁻¹ of aboveground and belowground biomass, releasing 117.8 GgCO₂e to the atmosphere. Considering that this type of forest has an average growth rate of 0.5 to 4 tDM/ha.year⁻¹ (IPCC, IPCC & IGES., 2003), and assuming even growth and conservation of the current forested area (7,880.2 ha), it would take between two and 17 years for the ecosystem to recover the amount of biomass that was lost. However, it is important to consider that forest growth within conserved sites is not unlimited, given that the carbon sequestration capacity of an ecosystem decreases as it reaches carrying capacity or climax (Keith et al., 2009). In addition, the consensus in ecology research is that each ecosystem represents a unique combination of biodiversity and biophysical characteristics (Kumar & Kumar, 2008; UNEP, 2019), rendering them irreplaceable and not interchangeable (Bordt & Saner, 2019; Mengist & Soromessa, 2019). This is particularly true for primary native forests. Therefore, the loss of primary forests by LUC to avocado orchards could be considered irreparable.

Table 5 Changes in surface area and related CO₂ emissions (positive sign) and removals (negative sign) for each land-use category

Land-use category (remaining/converted)	Area (ha)	CO ₂ (Gg)
Forestland (net)		- 717.2
Forests that remain	5805.4	- 684.2
Land converted to forests	2075.4	- 33.0
Annual Cropland (net)		- 12.2
Annual croplands that remain	2025.4	- 17.1
Land converted to annual croplands	43.2	5.0
Perennial cropland (net)		137.1
Perennial croplands that remain	3542.3	- 215.9
Land converted to perennial croplands	4202.9	353.0
Grassland (net)		28.5
Grasslands that remain	47.0	- 0.3
Land converted to grasslands	1023.7	28.8
Settlements (net)		3.8
Settlements that remain	151.9	0.0
Land converted to settlements	74.9	3.8

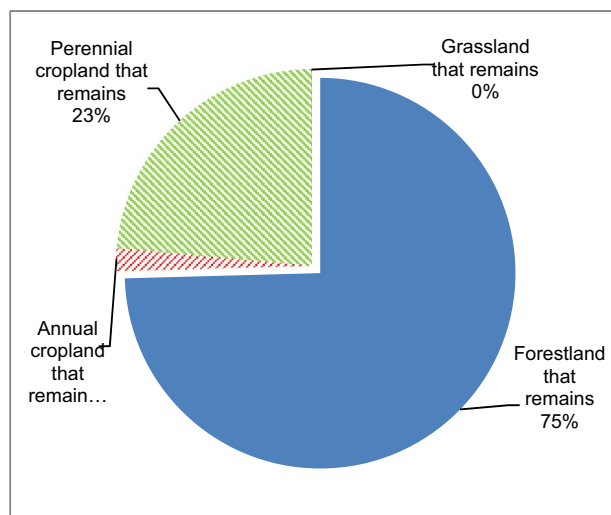
Fig. 3 Percentual contribution of each land-use category towards total carbon sequestration in Tingambato, considering lands that remained (no conversions) between 1974 and 2017

Table 5 shows the emissions and removals of GHG for each land-use category, detailing the total area that has remained under a given land-use (acting as a net carbon sink), and the land that has been converted to other uses (LUC), generating CO₂ emissions. Table A.3 in the supplementary material contains more details about the land-use dynamics.

Those areas that remained under a given land-use category throughout the study period, and that have remained until the time of writing (a total of 11,420 ha), have acted as net carbon sinks achieving total removals of -917.5 GgCO₂. As shown in Fig. 3, primary forests are the main carbon sinks, accounting for 75% of all GHG sequestration in the municipality. This represents only 0.66% of carbon sequestration in primary forests and forested lands in general at the national level (INECC-SEMARNAT, 2018a, 2018b).

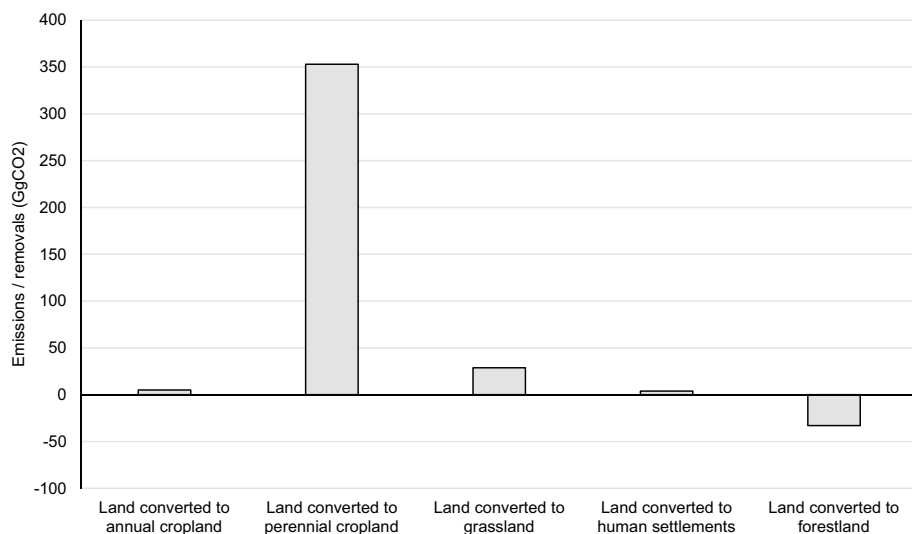


Fig. 4 Net contribution from each land-use conversion to CO₂ emissions (+) in Tingambato between 1974 and 2017. Conversions to forestland are assumed to represent CO₂ removals (–)

Total land-use conversions in the municipality (7,407.4 ha) have represented a loss of carbon stocks with a value of 390.5 GgCO₂e. This corresponds to nearly 2% of total emissions at the national level (INECC-SEMARNAT, 2018a, 2018b). Likewise, the municipality of Tingambato accounts for 3% of the total area that underwent land-use change in the country, while covering only 0.32% of the state's surface area. Figure 4 clearly shows that land-use conversions towards perennial cropland (avocado orchards) account for the vast majority (91%) of all GHG emissions in Tingambato. The fact that 70% of land converted to avocado orchards was previously forest, while 29% came from annual cropland and less than 1% from grasslands, indicates that avocado production has promoted local LUC processes (Garibay & Bocco, 2011).

When including land converted to forestland (which acts as a carbon sink but only represented 33 GgCO₂e of carbon sequestered over the entire study period) in the net balance of emissions and removals, net emissions resulted in 357.5 GgCO₂e. This corresponds to 8.32 GgCO₂e emitted per year during the 43-year period considered. Also considering the spatial dimension, this amounts to an emission rate of 43.8 MgCO₂e per hectare per year. As a useful comparison, the mean carbon footprint per inhabitant per year has been estimated at 3.7 MgCO₂e for the case of Mexico, which is less than the global average of 4.4 MgCO₂e (INECC-SEMARNAT, 2018b). The annual emissions generated from LUC by a single hectare in Tingambato are similar to the average emissions generated by 12 Mexican citizens during the same period. This implies that annual emissions from LUC in Tingambato correspond to those generated by 2,250 citizens of the municipality (15% of the total population) with an average consumption of resources and energy.

Table 6 Summary of total emissions generated by land-use change and biomass burning in Tingambato between 1974 and 2017

Emission source	GgCO ₂	GgCH ₄	GgN ₂ O	Total GgCO ₂ e
Land-use conversion (net balance) and biomass burning	357.52	12.06	6.08	375.67
Burning of residual biomass from annual crops		67.24	16.50	83.75
Burning of residual biomass from perennial crops		813.43	75.72	889.16
Total				1348.57
Emissions per year				31.36

3.3 Greenhouse gas emissions from biomass burning

Emissions from biomass burning for land-use conversion were 18.14 GgCO₂e (of which 66.5% correspond to CH₄ and the rest to N₂O). These emissions are produced only once, at the time of land-use conversion. The burning of forests accounted for 95% of these emissions. These values correspond to 7% of CH₄ and 8.8% of N₂O emissions from this category reported at a national level (INECC-SEMARNAT, 2018b).

For the case of emissions generated from the burning of agricultural residues, 90% came from avocado crop management and 10% from annual crops (mainly maize). Total emissions generated over the 43-year period were 972.9 GgCO₂e, representing an annual rate of 1.95 GgCO₂e for maize and 20.68 GgCO₂e for avocado.

It is important to note that we use the default biomass fuel value from the IPCC for crops (IPCC, 2006) (Table 3). In order to determine whether emissions from crops are being overestimated, we suggest evaluating emission factors for maize residues and avocado crops in the field under local conditions.

4 Summary of emissions associated with avocado production in Tingambato

Table 6 summarizes the net emissions generated from each of the two categories analyzed (land-use change and biomass burning), which add up to 31.36 GgCO₂e year⁻¹. Net land-use conversions accounted for 28% of total emissions, while the rest originated from burning residual biomass from avocado and maize crops. Considering the mean carbon footprint values for Mexico, these annual emissions are equivalent to those generated by more than half of the population of the municipality. In other words, the same impact on the atmosphere would have been achieved if the population of Tingambato had been 50% greater during the last four decades in terms of total emissions.

As stated by Kärkkäinen et al. (2020), net GHG emissions can be mitigated either through carbon sequestration by conserving or improving existing carbon stocks, or by diminishing emissions from gases other than CO₂. As highlighted by our results, the main avenue for mitigating emissions would be to conserve the primary forests that have remained unchanged, as well as reforestation (Calvin et al., 2016) and sustainable forest management (Pradhan et al., 2019). This single land use category is a carbon sink that accounted for 75% of all carbon sequestered in our study area. A second path toward reducing GHG emissions would be to limit the open burning of agricultural residues. In the case

of avocado pruning residues, which are woody biomasses, these could be used to substitute fossil fuels used in the state's industrial sector, as explained in the next section.

4.1 Energy generation from avocado pruning residues and potential mitigation of emissions

Interviewees reported that, although avocado trees can grow up to a height of 20 m, orchards in the region have employed various techniques during the last 10 years in order to limit their height to less than 7 m. This is said to facility harvesting, increase fruit production by allowing more air and light to enter the plant, improve tree health, and make pesticide application more efficient.

Based on interview data, we classified 72% of avocado orchards as small, with a mean area of 4.5 hectares and 470 trees per orchard. Young trees of around 20 years of age can be found in 60% of orchards. Regardless of age, all avocado trees are pruned, generating biomass residues. Different pruning techniques are used throughout the region and there is no uniform classification or standardized method. Producers select plants that require pruning based on their own experience with external advice. Consequently, we classified the pruning methods and the overall sizes of the branches obtained (Table 7).

The smallest branches, usually with diameters of under 5 cm, make up an estimated 50% of pruning residues and are usually crushed and incorporated into the soil (this carbon incorporated into the soil was not considered in the emissions balance). Branches with larger diameters do not have an established purpose: 25% of this biomass is burnt in the field, releasing GHG emissions as stated by Ledo et al. (2018), and the rest is given away or sold at very low prices in the informal market, mainly for packaging fabrication. Pruning residues from organic-certified orchards, often used as firewood, were not considered in this study as they represent only 2.5% of orchards in the study region.

Pruning may occur at any point during the year, though it is most commonly done between the months of November and February. According to the producers we interviewed, they are able to prune between 20 and 50 trees per day, depending on the type of pruning (rejuvenation or maintenance). From our interviews and the literature reviewed (Soria-González, 2019; Tauro et al., 2022) we estimate that the mean amount of dry biomass obtained from pruning in the study region is 13 t/ha (6.5 tDM/ha considering an average moisture content of 50%). This is higher than the value of 3 ton/ha reported by Fu et al. (Fu et al., 2020) for pruning residues from apple, citrus, pear, and peach trees in China. Other studies have also reported lower values, including Velázquez-Martí et al. (2011) for almond trees in Spain (1.3 tDM/ha), and for plum trees in Ecuador (2 tDM/ha; (Velázquez-Martí & Cazco-Logroño, 2018)). These differences may be due to the optimal climatic conditions in the study region which allow for a rapid growth rate of avocado trees, as reported by Barsimantov and Navia (2012), where larger amounts of biomass could be obtained by pruning.

From our LUC analysis, we can estimate the amount of pruning residues generated in the study region per year. Considering that the area dedicated to avocado orchards is 7,753 ha (Table 4) and that 25% of biomass residues can be used for energy purposes, this yields a total of 12,600 tDM per year. Given a mean calorific value of 19 MJ/tDM for these pruning residues, they represent an energy potential of nearly 240 TJ/year, which is equivalent to 2% of all fuel oil used in Mexico's industrial sector in 2020 (SENER, 2020).

Taking advantage of this energy potential and the corresponding diversification of the use of pruning residues would have positive impacts at a regional and national level.

Table 7 Classification and characteristics of the different pruning methods described by avocado producers in Tingambato

Classification	Pruning description	Characteristics	Type of biomass generated	Frequency
Renovation	Rejuvenation or change of variety	The crown or the entire tree is cut, leaving the trunk 1 or 2 m above the ground. Generally applied to diseased or unproductive trees, or when replacing plants	Branches of varying diameters and lengths, predominantly 20–40 cm in diameter	Every 10 years or more
Intensive maintenance	Tree shaping and thinning	Elimination of central branches, branches that cross over between trees and low branches that reach the ground	Branch diameters of under 20 cm	Annually after each harvest
Minor maintenance	Blunting	Also known as apex pruning, it is required to maintain tree height or remove smaller branches	Branch diameters under 3 cm	Annually

Source: own elaboration based on interview data and field visits

Garibay and Bocco (2011) suggested that this would decrease firewood extraction for domestic or small-industry use, thus avoiding forest degradation. However, it is important to note that local people prefer using oak wood for domestic tasks, while avocado wood is used mostly in brick kilns. This could still lead to a reduction in the open burning of biomass, as suggested by Mugica-Álvarez (2016).

Another potential benefit would come from the economic valuation of a byproduct of avocado production, namely pruning residues, which may constitute an attractive choice for farmers. As avocado prices fluctuate according to international demand, selling pruning residues could represent additional income for producers when avocado prices are low (Xia et al., 2020). Likewise, processing and treating pruning residues could generate new employment opportunities and higher incomes (Sagani et al., 2019; Torquati et al., 2016).

Additionally, as stated by Aguilar et al. (2015), the use of renewable resources such as pruning residues for energy generation contributes to lowering the emissions currently generated from fossil fuel use. Pruning residues could generate energy in different ways, including by conversion to ethanol (Contreras et al., 2020) or electricity generation (Contreras et al., 2020; Torquati et al., 2016). In Mexico, an immediate application for avocado pruning residues would be as substitutes for fossil fuels currently used in industrial boilers for thermal energy generation (i.e. public utilities users). At the national level, it would be possible to replace 240 TJ/year of fuel oil or LPG, which corresponds approximately to 6 million liters of fuel oil and 5 million kilograms (5 Gg) of LPG. Fuel substitution would mitigate between 25 and 31 GgCO₂e per year for LPG and fuel oil, respectively (significantly more than the 10.85 GgCO₂e emitted per year by land-use change and biomass burning).

As an example, we can consider the regional tequila industry, which has an increasing demand for biomass to substitute fuel oil or LPG use. The tequila production chain emits 1.1 kg CO₂e per liter of tequila (Centro Mario Molina (CMM) 2016). Substituting fuel oil for avocado pruning residues would mitigate 385 GgCO₂e per year or 5% of the emissions generated from fossil fuel use in this industry. Considering the costs of fuel oil and avocado chips (outlined above) the associated economic benefits are significant: considering that each 200 BHP boiler consumes approximately 1,200 tons of fuel oil per year, using wood chips to replace fuel oil would represent savings of over 375 thousand USD. In cases where LPG is used, savings could reach almost 1 million USD per year. The sale of avocado pruning residues to the tequila industry may also represent earnings of up to 500 thousand USD per year for avocado producers or sellers (12,600 tDM/year⁻¹).

Conventional orchard management practices require on average 56 GJ/ha of fossil fuel derivatives, which generate 3.3 MgCO₂e ha⁻¹ of GHG emissions (Astier et al., 2014). For the 7,753 hectares of avocado orchards in our study area, annual emissions from avocado production amount to 25.5 GgCO₂e. These emissions could be compensated using pruning residues for energy generation on an annual basis. Dividing the net energy potential obtained by the total area of avocado orchards, we obtain an energy potential of 31 GJ per hectare. This can balance the avocado production system and help to build a more sustainable industry.

In order to boost the energy use of avocado pruning residues to promote growth in low-income agriculture-dependent economies, they require a regulatory framework and biomass programs that are driven by sustainability (Nakamya, 2022). Participatory strategies should also be generated, including land-use planning for the fulfillment of multiple simultaneous objectives. Doing so requires consideration of the sector's organizational structure. Cho et al. (2021) suggest that the associations' vertical hierarchy (packers, exporters, importers, producers) plus the close relationships between these

associations and state government agencies, may allow goals to be set and their achievement to be closely monitored. The use of pruning residues should also be encouraged through public policies aimed at benefiting producers while considering their preferences and behaviors (Orduño-Torres et al., 2020). However, it is also important to consider the levels of resilience or opposition from local governments towards policy changes for environmental management, as discussed by Barsimantov and Navia (2012).

Mejia et al. (2022) observed potential new emerging hotspots of avocado expansion near the boundaries of the forest reserves of Michoacan, Mexico. It is important to highlight that any strategy that seeks to promote the use of pruning residues should prioritize and ensure the conservation of native forests, that serve as carbon sinks as well as producing numerous other ecosystem services. The case of Brazil is a relevant example, where emissions from LUC were successfully reduced in 2008 through the implementation of anti-deforestation policies (Calvin et al., 2016). In order to achieve similar success in stopping deforestation in the study region, it will be necessary to improve the integration, participation, and sharing of responsibilities between different government sectors, while strengthening local governance structures (Barsimantov & Navia-Antezana, 2012). An interesting option would be to increase the incentives for the owners of forested lands to conserve ecosystem services, thus balancing income inequality relative to avocado orchard owners (GFW, 2019). Conditions of insecurity and social conflict must be addressed to guarantee, among other things, the conservation of these diverse forests, Olivares-Martinez (2023).

Our proposed methods and findings can be used to generate information for policymakers to address inequality through strategic planning at the local level. This could be achieved through the methodology for structural proposed by CEPAL (CEPAL 2030), which covers all stages from project proposal through monitoring.

4.2 Challenges

The knowledge generated by the present study will allow agricultural producers, business owners, and policymakers to make more informed decisions aimed at reducing the negative impacts of avocado production. In order to improve our estimates and increase the impact of the results obtained, we propose further studies to address the following points:

- Characterize the physical and chemical properties of pruning residues.
- Calculate the economic variables that would affect the energy use of pruning residues, considering different end-use technologies.
- Estimate the logistical costs associated with using pruning residues as a biofuel, considering pruning seasonality and the time invested in the field.
- Analyze potential health impacts from the combustion of pruning residues through different end-use technologies.
- Evaluate the nutritional properties of pruning residues incorporated into the soil.
- Study the feasibility of generating carbon markets from the green energy use of pruning residues, in line with national GHG mitigation goals under the Paris Agreement.
- Generate a proposal for participatory action, involving the public and private sectors, aimed at improving the working conditions in orchards and promoting the use of residual biomass as a mitigation strategy.

5 Conclusion

This study uses an integrative approach to evaluate the consequences of land-use change as a result expansion of avocado orchards during the last four decades. We analyzed GHG emissions and energy balances generated both by LUC and the open burning of agricultural residues. With the information obtained, we estimated the potential use of avocado pruning residues for energy generation as a mitigation alternative in the study area.

This work shows that there is a growing trend towards LUC, where 25% of primary forests and annual croplands have been converted to perennial crops, consisting almost exclusively of avocado orchards. The area devoted to avocado cultivation increased by 20% between 1974 and 2017. This has generated GHG emissions due to the loss of carbon reservoirs, as well as from management activities such as burning forests for land clearing and the open burning of agricultural residues.

Considering the net balance of GHG removals and emissions from LUC, remaining forests have acted as carbon sinks, absorbing 717.2 GgCO₂ during the study period. On the other hand, the expansion of avocado orchards emitted more than 353 Gg of CO₂ (accounting for 91% of total LUC emissions) over the same period. Annual emissions generated by biomass burning for avocado production amounted to 20.68 GgCO₂e/year-1. Given that the overall area dedicated to avocado orchards has nearly doubled during the past four decades, total emissions from biomass burning under this management regime were 889.16 GgCO₂ during this period.

Against this backdrop, the use of avocado pruning residues for energy generation presents a technically and economically attractive alternative to replace fossil fuel use and mitigate GHG emissions, mainly by substituting fuel oil and LPG used in the country's industrial sector. We estimate that the amount of biomass obtained from pruning avocados (6.5 tDM/ha) could replace 2% of all fuel oil used in Mexico's industries. This would mitigate between 25 and 31 GgCO₂e per year, compensating for the emissions generated from the use of fossil fuel derivatives in current orchard management practices. This substitution would also accrue economic benefits. As a regional example, substituting fuel oil for wood chips from pruning residues in the tequila industry would represent annual savings of 375 thousand USD for every 1,200 tons of fuel oil used, while producers would stand to earn close to 500 thousand USD per year from the sale of 12,600 tDM year⁻¹ of residues.

Notwithstanding the potential regional economic, environmental, and social benefits of the use of pruning residues for energy generation, its successful implementation would require small producers to organize into groups or regions in order to facilitate harvesting and conditioning tasks. For future work, we suggest direct field measurements of the amount of pruning residues generated at the orchard scale, as well as studying the physico-chemical properties of these residues to evaluate their characteristics as a biofuel. Estimating the associated costs and analyzing social organization issues are also important points that must be addressed in the future.

Despite these limitations, this study provides a first estimate of the potential use of avocado pruning residues for energy generation as an alternative to mitigate GHG emissions from LUC. Our results can assist producers, social organizations, entrepreneurs, and decision-makers in energy planning, and could lead to the local implementation of public policies that promote the use of pruning residues by certified producers and prevent open biomass burning while ensuring and prioritizing the protection of native forests.

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Data availability All analyzed and processed data are presented in the manuscript or added in as supplementary information. Additional information and raw data sets can be provided by the author upon request.

Declarations

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

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