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MAPPING THE EXPANSION OF OIL PALM (*Elais guineensis* Jacq.) IN MEXICO — METHODOLOGY AND DEVELOPMENTS

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ABSTRACT

Oil palm (*Elais guineensis* Jacq.), a high-yielding oil-seed crop, is associated with multiple socio-environmental impacts. The Mexican oil palm sector is emerging and stands out for its dynamism. This paper presents hitherto unpublished maps to facilitate an independent, transparent and publicly accessible monitoring of the progression of this crop at national level. A first map, with data from 2014 to 2019, satisfactorily captures established plantations (94 % of the areas officially reported for Chiapas), even in very small plots (the area of the smallest polygon being only 330 m²). In the second, with data from 2016 to 2022, both the quality of the mapping and the coverage of cultivated areas increased (70 % of the officially reported planted areas), especially in Tabasco and Campeche, the states with the largest expansion of oil palm cultivation in the country since 2012. Comparing both maps with data on land use, vegetation and protected natural areas (PNAs) highlights the contribution of oil palm to the deforestation of more than 7500 ha of conservation-relevant habitats between 2014 and 2022 (5 % of the total oil palm area). The existence of large areas of oil palm in La Encrucijada Biosphere Reserve (Chiapas) and its presence in other PNAs is confirmed. High spatial resolution maps, such as the one presented here, are necessary for the calibration of surface and terrain models at the regional and global scales, which are used in environmental impact projections. Such projections can then advise public policies and conservation plans at the national level. This paper proposes alternatives for the verification and communication of statistical and spatial data, to support an informed debate on the benefits and impacts of oil palm in Mexico.

Keywords: mapping, geographic information systems, monitoring, Latin America, oil-seed crops, deforestation.

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INTRODUCTION

The contribution of oil palm (*Elais guineensis* Jacq.) to global oil-seed crop production grew from 3.2 % in 1961 to 37 % in 2020 (FAO, 2023). In 2020, 75.9 million Mg of palm oil were produced worldwide, with a production value of MXN 531 000 million (USD 30.1 billion). In 2021, 416.4 million Mg of fruit were produced globally, on an estimated total area of 28.9 million hectares. The high yield and versatility of palm oil, which is used primarily in the food, pharmaceutical and biofuel industries, explain the rapid expansion of the global oil palm sector (Furumo and Aide, 2017; SAGARPA, 2017). Global demand for palm oil has grown rapidly: between 2019 and 2020, global exports of this product grew by 13.7 % (OEC, 2023). Moreover, since 2020, the economic and geopolitical context (the war in Ukraine as catalyst) has hindered access to other oil-seed crops, particularly sunflower, increasing palm oil prices significantly (Statista Inc., 2023).

There is a deep controversy about the socio-environmental impacts of oil palm (de la Vega-Leinert *et al.*, 2021). Indeed, this crop is associated with high rates of deforestation, particularly in Asia (Vijay *et al.*, 2016). Currently, Latin America is the region with the highest rate of expansion of oil palm and the largest reserves of forest suitable for its cultivation (Furumo and Aide, 2017). Moreover, its cultivation requires the application of large amounts of agrochemicals (Comte *et al.*, 2012; Córdova-Sánchez *et al.*, 2017) that, coupled with the oil extraction process, causes significant impacts on soil, air, (ground) water and biodiversity (Kamyab *et al.*, 2018). To mitigate these impacts, possible strategies for the integrated management of agrochemicals (Shamala *et al.*, 2019) and mill effluents (Poh, 2020) are being explored. Recently, technical and systemic solutions embedded in the circular bioeconomy framework have been proposed to encourage more sustainable oil palm cultivation (Yeo *et al.*, 2020). The oil palm sector has also been linked to land concentration, foreignization and grabbing processes (Guereña and Zepeda, 2013), and its commodity chain is poorly regulated, despite important efforts within the framework of the round table on sustainable palm oil (Pacheco *et al.*, 2018). However, Castellanos-Navarrete *et al.* (2020) have illustrated different crop expansion trajectories in Latin America, depending on public agricultural policies, agrarian contexts and institutional capacity to enforce regulations. Accordingly, oil palm plays a complex role in growing regions, particularly for smallholders.

The first attempts to establish oil palm plantations in Mexico began in the 1950s in the state of Veracruz (Castellanos Navarrete, 2023). However, production only took off in the late 1990s in Chiapas and, more recently, in Tabasco and Campeche (SIAP, 2023). In 2021, Mexico cultivated oil palm on 122 882 ha, producing 1 600 559 Mg of fresh fruit and 320 112 Mg of crude palm oil. Simultaneously, it imported 441 275.73 Mg of palm oil, mainly from Costa Rica and Guatemala, with a value of USD 421.5 million (FEMEXPALMA, 2022). Although palm oil production capacity at the national level is rapidly increasing, its consumption is also growing at an accelerated rate. Currently, palm oil in Mexico mainly feeds the agroindustry, while attempts to initiate biodiesel production based on this crop have not been successful (Santacruz de León and Palacio Muñoz, 2018). Estimates on the capacity to cover domestic demand range from 42 (FEMEXPALMA, 2022) to 62 % (SAGARPA, 2017). Therefore, boosting national palm oil production to supply domestic needs and developing export capacity are explicit goals embedded within the national agricultural plan for the period between 2017 and 2030. However, the current administration of President López Obrador canceled subsidies for oil palm production, paving the way for a transformation led by the corporate palm sector, with extensive international investment (Agronomy Capital Advisors Limited, 2023).

Remote sensing has been used since the 1990s for the identification of crops and several of their characteristics (Xu *et al.*, 2020), including land cover maps, number of trees, crop structure, yield, etc. Both optical and radar satellites provide spatial data ranging from regional to national scale, while microwave data are often the most suitable for identification in humid tropical areas with high cloud cover. There are various methodologies to identify oil palm plantations using remote sensing data, encompassing visual (or manual), semi-automated, or fully automated detection methods. For example, Xu *et al.* (2020) used a combination of radar imagery (ALOS, PALSAR, ALOS-2, PALSAR-2 and MODIS) and optical satellites (Landsat and Google Earth), together with image classification and statistical methods, to detect changes and estimate annual crop area at 100 m resolution in Malaysia and Indonesia between 2001 and 2016, with an accuracy between 75.74 and 86.61 %.

Crop detection and monitoring using manual or semi-automated methodologies require large human resources and are, therefore, not sustainable in the long term. Semi-automated or fully automated methodologies make use of data-driven classification algorithms, but generate images that generally need to be subsequently verified by *in situ* data. Thus, resulting data do not achieve high accuracy at all spatial or temporal scales. In addition, automated methodologies vary in their capacity to distinguish primary forest from oil palm crops. Satellite imagery has served to analyze the type of land use change associated with oil palm cultivation. Unlike the trends observed in Southeast Asia, where oil palm has mainly replaced native forest, the loss of native forest in Latin America varies considerably depending on the region considered, both at national and subnational levels (Furumo and Aide, 2017). Furthermore, most of the recently-established oil palm plantations have replaced other crops in the agricultural frontier, although land use change from pastures is also important.

In Mexico, with the intention of promoting the cultivation of oil palm and analyzing the its socio-environmental impacts, several methodologies have been developed over the past decades to identify areas suitable for cultivation, as well as to locate and map plantations. These studies have been undertaken in governmental, academic, journalistic and civil society contexts; at local, state or national level, and with different degrees of public accessibility. At the beginning of this study, in 2019, despite the abundant official data and growing literature about this crop, an open-access map of oil palm plantations at national level could not be located in the public domain. Nevertheless, to carry out a thorough, contextualized and differentiated analysis of the benefits and impacts of oil palm cultivation in Mexico, it is essential to have complete and updated spatial data.

This article has a twofold goal: 1) to present an overview of spatial studies of oil palm in Mexico, and 2) to present methodological advances towards a mapping of this crop at national level. In the following sections, a summary of the contributions of previous oil palm mapping studies in Mexico is presented. The methodology developed in 2019 by Sandoval Vázquez *et al.* (2021 - version 1), based on current techniques for locating and mapping oil palm plantations at the national level, is also introduced. Oil palm crops were located and mapped using open-access satellite data in the period 2014-2019, with further modifications for the period 2016-2022 (version 1.1) (Sandoval Vázquez *et al.*, 2022). Emblematic results are selected to illustrate the benefits and methodological advances of the mapping. Finally, guidelines for monitoring the expansion of oil palm plantations in Mexico and for the spatial assessment of its socio-environmental impacts are proposed.

MAPPING OIL PALM IN MEXICO

At the national level, there are several mapping approaches for the visualization of information related to oil palm. Chronologically, the first available maps were produced to analyze the agroecological suitability for the cultivation of this crop in the country. Such maps have been mainly made by public institutions (e.g., the Ministry of Agriculture and Rural Development (SAGARPA); the National Institute of Forestry, Agriculture and Livestock Research (INIFAP); the Institute for Productive Reconversion and Tropical Agriculture (IRPAT)). Their primary goal is to define strategic regions to guide policies and programs that promote the cultivation of oil palm at federal or state levels. At first, these maps collate spatial data on climatic (obtained from meteorological stations), topographic and edaphic characteristics (obtained from local studies) to estimate crop production potential, as in the Agroecological Zones method defined by FAO (Aceves Navarro *et al.*, 2008). However, such maps are only available publicly at very low resolution, which prevents a detailed analysis by actors beyond the public institutions producing them. Further, different methodologies result in different zonifications and classifications so that the calculated areas suitable for oil palm cultivation vary significantly according to the source consulted (Table 1). This substantially prevents an appropriate comparison and evaluation of available data.

Despite these limitations, all estimates of areas suitable for oil palm cultivation in Mexico indicate the potential for a significant expansion of the area under cultivation (Table 1). For example, the area under oil palm cultivation in 2021 (122 882 ha, FEMEXPALMA, 2022) constituted only 5.9 % of the areas with good potential (INIFAP, 2006), and 17.9 % of the areas with high potential (INIFAP, 2012). The huge discrepancy between potential and actual area is another fundamental argument for the establishment of a mechanism to monitor the expansion of this crop in the country. One step in this direction is the development of a reliable and regularly updated mapping of oil palm cultivated areas.

To map the area actually containing oil palm crops, a first spatial analysis can link administrative units with statistical data directly related to this crop, such as planted area, fruit or oil production, exports and imports. While this type of visualization requires few technical mapping resources, it does not provide the precise location of the growing regions. In Mexico, this approach has been used to depict the emerging oil palm sector within the national context and to compare its growing importance at state or municipal level (Delgado Ramos *et al.*, 2013). A second analysis can identify and precisely locate oil palm plantations using geo-referenced data.

Table 1. Area suitable for oil palm cultivation in Mexico according to different official sources and suitability categorizations.†

	INIFAP (2006:14)		INIFAP (2012:70)		Argüello (2018)	
	Area (ha)	Suitability	Area (ha)	Suitability	Area (ha)	Suitability
			682 945	High		
National	2 080 000	Good				
	3 814 000	Average	2 668 845	Average		
			1 416	High		
Chiapas	560 000	Good				
	400 000	Average	235 288	Average		
			382 207	High		
Veracruz	520 000	Good				
	1 450 000	Average	796 045	Average		
			142 696	High	1 124 693	High
Tabasco	420 000	Good				
	430 000	Average	73 058	Average		
			8 698	High	739 176	High
Campeche	270 000	Good				
	950 000	Average	170 954	Average		
			147 928	High		
Other states	310 000	Good				
	580 000	Average	1 393 500	Average		

†Note the different suitability categorization depending on the source.

To this end, one can proceed empirically, using the global positioning system (GPS) to precisely locate palm-growing communities and plantations, oil palm natural dispersion processes, or infrastructure related to the palm oil industry (Fletes-Ocón and Bonnano, 2013; Trejo Sánchez *et al.*, 2018). To ensure systematic sampling, this method, nevertheless, requires significant resources in terms of time and personnel, so it is only used to cover specific regions.

Remote sensing methods and high-resolution satellite images combined with geographic information system (GIS) tools have driven an important transformation of spatial studies by allowing the generation of mapping information over larger areas in a short time. Oil palm plantation areas can thereby be mapped in great detail (Mata García, 2014; Castellanos-Navarrete, 2021). Until the early 2000s, free and open access to satellite images of sufficient resolution for the creation of oil palm plantation maps was limited. Moreover, it was necessary to have specific GIS equipment and specialized knowledge for the basic processing of satellite images. Nowadays, there are relatively easy-to-use online platforms that provide basic digital mapping tools, such as EarthExplorer (https://earthexplorer.usgs.gov/) or Google Earth (https://

www.google.es/intl/es/earth/), which is the most widely used platform. Further, geo-referenced datasets providing multi-variable information on crop areas enable the analysis of crop dynamics in relation to other socio-environmental processes. The diversity of existing efforts to map areas under oil palm cultivation in Mexico is illustrated below (Table 2).

Spatial studies on oil palm are performed for multiple purposes. For example, to analyze the evolution (e.g., establishment, intensification or abandonment) of cropland over time by comparing satellite images taken at different moments.

Table 2. Overview of spatial studies on oil palm in Mexico.

Authors	Oil palm cropland mapped in combination with	Scale / Focus region
Mata García, 2014		State (Veracruz)
Fletes-Ocón and Bonnano, 2013	Oil palm expansion sites Protected Natural Areas (PNA)	Municipal (Chiapas) / La Encrucijada Biosphere Reserve (EBR)
Trejo Sánchez *et al.*, 2018	Oil palm mills / PNA	Municipal (Chiapas) / EBR
Hernández-Rojas *et al.*, 2018	Vegetation cover Land use Comparison over time	Municipal Acapetua (Chiapas), Carmen (Campeche), Balancán (Tabasco), Mecayapan (Veracruz)
SIAP, 2018	Plots of land with oil palm / PNA	National, statewide, municipal
Berget *et al.*, 2021	Vegetation cover Land use Comparison over time	Ejido (Chiapas) Loma and Chajul (Marqués de Comillas)
Castellanos-Navarrete, 2021	Vegetation cover Land use Dispersion / PNA	Municipal (Chiapas) / EBR
Camacho-Valdez *et al.*, 2022	Vegetation cover Land use Aquatic ecosystems Comparison over time	Border area of the Usumacinta River Catchment (Mexico / Guatemala)
Muñoz *et al.*, 2021; EO Lab, 2023	Vegetation cover Land use Comparison over time	Municipal (Chiapas) Marqués de Comillas / Benemérito de las Américas (Chiapas)
de la Vega-Leinert *et al.*, 2021; Sandoval Vázquez *et al.*, 2021, 2022	Vegetation cover Land use Various environmental and socio-economic indicators Comparison over time	National, statewide, municipal

Also, to analyze the impacts of oil palm cropland on the biotic environment, especially on the vegetation cover (be it primary or montane forest; secondary or *acahual* forest; other natural vegetation types of high biodiversity, like shrubland; or aquatic ecosystems), and on crop and livestock production. It is also of interest to investigate the relationship between oil palm cropland evolution and other economic or geopolitical dimensions, such as transport or industrial infrastructure, international borders, cultivation of other monocultures, and to evaluate the potential socioeconomic impact of oil palm cropland expansion or contraction.

In Mexico, oil palm mappings have focused on the main production zones: the Soconusco and the Lacandón Jungle in Chiapas (Fletes-Ocón and Bonnano, 2013; Castellanos-Navarrete, 2021). However, recent studies have begun to explore different oil palm growing areas, especially in northern Chiapas, Tabasco and Campeche (Linares-Bravo *et al.*, 2017; Hernández-Rojas *et al.*, 2018; Isaac Márquez *et al.*, 2021). In the present study, a geo-referenced database is introduced, taking Sandoval *et al.*, 2021 as baseline. The resolution of this database allows evaluating oil palm cropland expansion, as well as the relationship between such expansion and governmental goals. This database can also be used as a reference for other territorial analyses identifying distinctive attributes or characteristics of oil palm production in Mexico, which allows the evaluation of its socioeconomic impacts.

MATERIALS AND METHODS

The methodology presented here was developed based on a literature review on oil palm cultivation in Mexico, mostly at local, municipal or state level (Núñez Hernández *et al.*, 2014; Mata García, 2014; SAGARPA, 2017; Hernández-Rojas *et al.*, 2018). This review also included Mexican governmental data from the Agri-Food Information System for Consultation (SIACON), developed by the Agri-Food and Fisheries Information Service (SIAP) and the Secretariat of Agriculture and Rural Development (SADER), using the list of Mexican municipalities where oil palm is cultivated. A second literature review focused on remote sensing techniques using raster data (e.g., aerial and satellite imagery) to identify the morphology of oil palm plants according to their state of maturity and cropland area (Yarak *et al.*, 2021; Rincón *et al.*, 2015).

The raster data used in this study correspond to the period 2014-2019 (version 1) (Sandoval Vázquez *et al.*, 2021) and, subsequently, to the period 2016-2022 (version 1.1) (Sandoval Vázquez *et al.*, 2022). Vectorization (creation of geo-referenced polygons, or vector data, from raster data) of the areas identified with oil palm plantations was achieved using geo-referenced satellite image mosaic servers (satellite and aerial imagery viewers).

To evaluate the dynamics of oil palm cultivation, oil palm cropland areas in version 1 that had been eliminated or displaced by another type of vegetation in version 1.1. were identified and marked. Therefore, version 1, with satellite images starting in 2014, creates a historical baseline of oil palm plantations that can be used to establish which plantations are still present and which have been abandoned or converted to other land uses in future data. All images that displayed oil palm cultivation areas meeting the following identification criteria were considered in the study: 1) be present in the municipalities and zones reported in official sources; and/or 2) display the characteristic shape of oil palm in any of its different levels of maturity.

In most cases, in order to allow a greater level of detail in the delimitation of oil palm areas and their vectorization, a height of less than 500 m and in no case greater than 1 km was chosen in the raster image viewers. The classification of oil palm crops was done manually with the support of various systematic sampling tools and techniques. Essentially, a block-coded grid (Figure 1) was projected onto the images using Phyton scripts (version 3.10), introduced in the geographic information systems ArcMap (version 10.5) and Quantum GIS (version 3.22). This method helped control the monitored areas, as it facilitated distinguishing between sectors reviewed and sectors pending verification. It also facilitated sampling small plantation areas with greater dispersion, and not only the most important areas (areas with a high concentration of easily identifiable crops).

For the location of oil palm croplands, Google Earth Pro was the main mosaic of raster satellite images used. When the identification of areas with oil palm crops in Google Earth was uncertain, we resorted to other Mexican geo-referenced raster image servers. For example, the online map service (Directorio de Sistemas de Control del SIAP, https://cmgs.gob.mx:31/PORTAL/) of SADER (formerly SAGARPA) and SIAP offers a set of standardized satellite images of higher quality (better image definition, contrast,

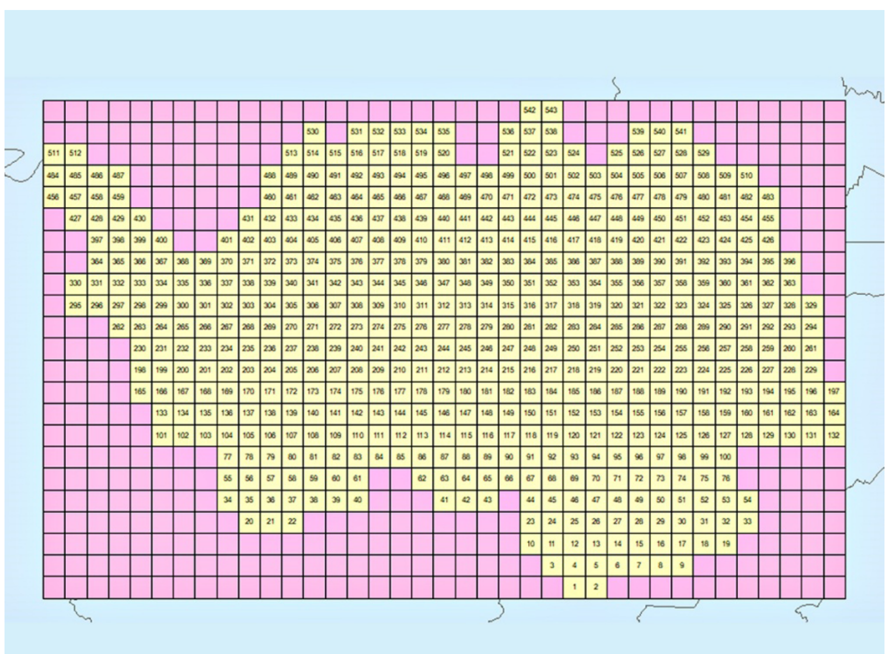

Figure 1. Example of systematic sampling, using the projection of a grid dividing the municipality of Acayucan, Veracruz (in yellow) into numbered sectors.

color, etc.) than those offered by Google Earth Pro in many areas. We did not consider areas where oil palm could be confused with other types of vegetation in the satellite images consulted. This generally occurred in areas with very young plants, which did not display (yet) the characteristic morphology of oil palm. It is important to note that the maps presented here have not been verified *in situ*. However, results from version 1.1 were compared with the oil palm polygons for the Lacandón Jungle (Chiapas) prepared by the General Coordination of Corridors and Biological Resources (CGCRB) and oil palm producers in the municipalities of Benemérito de las Américas and Marqués de Comillas, which are in the public domain (National Commission for the Knowledge and Use of Biodiversity, 2013). For the calculation of areas under oil palm cultivation, the UTM (Universal Transverse Mercator) projection for Zone 15 North was used.

In addition, territorial analyses were carried out, using the most updated governmental databases on environmental, socioeconomic and socio-political indicators at national level in the public domain (Table 3). These allowed the exploration of potential relationships between oil palm expansion and other phenomena and processes. For example, they allow the identification of changes in forest vegetation cover due to oil palm cultivation. For this purpose, the areas under oil palm cultivation in our version 1.1 maps were compared with the Land Use and Vegetation layers of series VI and VII of INEGI data (INEGI, 2017, 2018) to derive the type of vegetation prior to the establishment of oil palm plantations. Other interactions between oil palm and other socio-environmental aspects have been published by de la Vega-Leinert *et al.* (2021).

Table 3. Data types and sources used in the two mapping versions presented here (version 1: 2014-2019, version 1.1: 2016-2022).

Data type	Sources
Raster images	Google Earth Agricultural Area Estimation System (SIAP-SADER)
Oil palm strategic region	SAGARPA (2017)
Land use	Land Use and Vegetation layers of Series VI (2017) and VII (2018) of INEGI data (National Institute of Statistics and Geography)
Precipitation	CONAGUA (National Water Commission), INEGI, CONABIO (National Commission for the Knowledge and Use of Biodiversity)
Slope	Own creation based on INEGI Digital Elevation Models
Protected Natural Areas	CONANP (National Commission of Protected Natural Areas), INEGI
Priority terrestrial regions	CONABIO, INEGI

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Table 3. Continue

Data type	Sources
Priority hydrological regions	CONABIO, INEGI
Areas eligible for payments for environmental services	IDEFOR (Forest Spatial Data Infrastructure) by CONAFOR (National Forestry Commission of Mexico)
Municipal borders	INEGI
Roads and highways	INEGI
Urban centers	INEGI
Route of the Tren Maya	FONATUR (National Fund for Tourism Development)
Land under communal tenure	RAN (National Agricultural Registry)
Indigenous settlement	INEGI
Areas approved for the cultivation of transgenic soybeans	CIBIOGEM (Intersecretarial Commission on Bio-safety of Genetically Modified Organisms), CONA-CYT (National Council of Humanities Science and Technology)
Settlements within the area of the public program “Sembrando Vida”	Secretariat of Welfare

RESULTS AND DISCUSSION

Some important contributions of the mapping are illustrated below. First, using a block-coded grid facilitated the systematic detection of oil palm plantations, so that both large (2467 ha in the larger polygon) and small (330 m^2 in the smaller polygon) oil palm tree polygons in established plantations can be satisfactorily captured. This visualization also helps detect the particular importance of some municipalities for this crop, e.g., the municipality of Acayucan, Veracruz (Figure 2).

As a second contribution, a first verification of the version 1 map, using official data for the Lacandón Jungle region, confirmed the quality of the mapping approach. Indeed, a large number of errors were found in the often-outdated oil palm plantation polygons of the CGCRB archive. To incorporate the verified information into the version 1.1 map, a new file was created based on the updated raster images. The polygons that did not depict the presence of oil palm plantations were eliminated. The geometry of other polygons was corrected for their proper projection and measurement. Finally, new polygons were created whenever new plantations were found, particularly along the border between the municipalities of Maravilla Tenejapa and Ocosingo, and the municipality of Benemérito de las Américas (Figure 3).

The second version of the cartography demonstrates the dynamism of oil palm cultivation in the country. The 2019 oil palm polygons were updated according to more recent satellite images, and those polygons where plantations were no longer found were eliminated. Table 4 illustrates how the coverage of the mapping improved between the first and second versions.

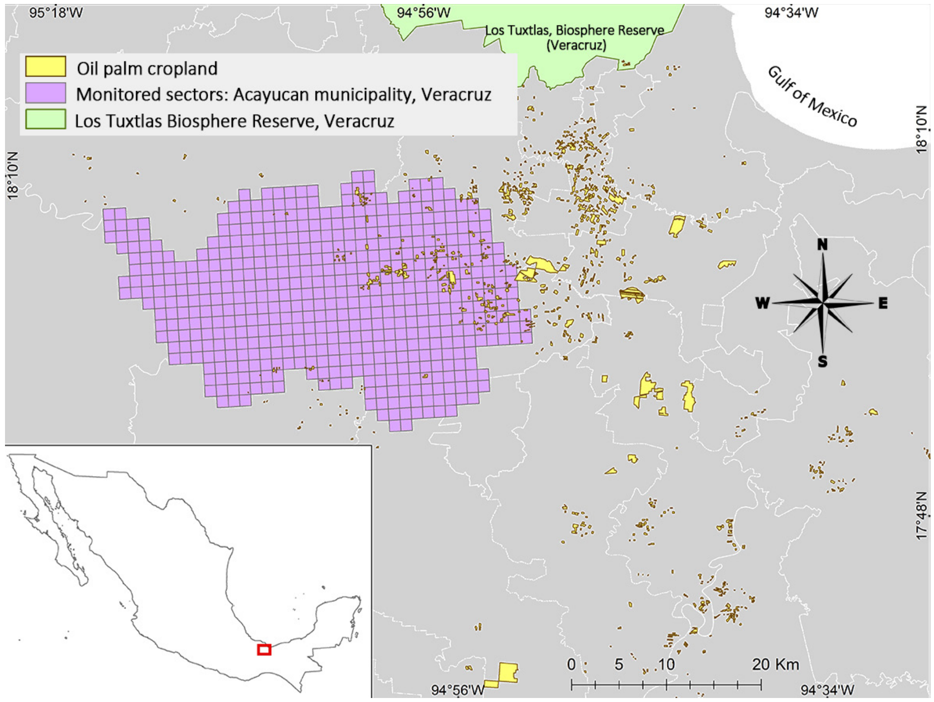

Figure 2. Example of the block-coded grid for the municipality of Acayucan, Veracruz.

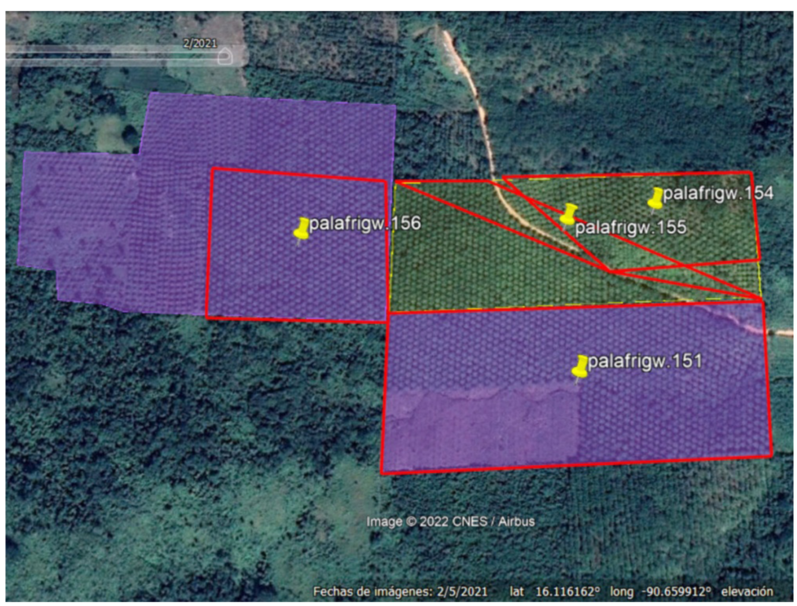

Figure 3. Example of outdated and incorrect polygons stemming from the CGCRB dataset (2013, in red; yellow dots represent their centroids). These polygons do not perfectly coincide with the oil palm areas identified using satellite images in the year 2021 (in purple).

Table 4. Comparison between mapped and reported areas under oil palm cultivation.

	Area mapped (ha)	Reported area under oil palm cultivation (ha) (SIAP, 2023; data from 2019)	% Mapped area / Reported area
Version 1, 2019			
National	62 057	108 690	57.1
Chiapas	42 972	45 435	94.6
Veracruz	6256	7201	86.9
Tabasco	7445	26 719	27.9
Campeche	5350	29 334	18.2
Version 1.1, 2022			
National	85 879	122 882	69.9
Chiapas	51 872	53 212	97.5
Veracruz	6663	9033	73.8
Tabasco	12 225	28 346	43.2
Campeche	15 054	32 291	46.6

Indeed, version 1 mapped 57.1 % of the areas planted according to official sources for 2019 (SIAP, 2023). The results are particularly reliable in Veracruz and Chiapas, two states with established plantations and where croplands tend to be older and oil palm morphology is easier to detect. However, this version displays large discrepancies for the states of Campeche and Tabasco, where the mapped areas fail to capture a large part of the areas under oil palm cultivation according to official sources. By refining the methodological approach in version 1.1, both the quality of the mapping and its coverage significantly increased. Approximately 70 % of the official areas under oil palm cultivation for 2021 were mapped. The observed discrepancy between mapped and reported areas was significantly reduced in the states of Campeche and Tabasco, and to a lesser extent in the state of Chiapas. On the contrary, in the case of Veracruz, this discrepancy increased.

Several elements may explain the discrepancies observed between reported and mapped areas. On the one hand, the present methodology does not sufficiently capture younger plantations, particularly if their establishment did not cause direct deforestation. In addition, publicly available satellite image repositories (in particular Google Earth) do not contain the most up-to-date images. This mainly affects the coverage in states characterized by recent oil palm expansion (i.e., Tabasco and Campeche in the first period, and Veracruz in the second period). The increase of more than 1800 ha reported by official sources in the state of Veracruz for 2021 could not be mapped satisfactorily, resulting in a reduced oil palm coverage for this state in the second mapping. Also, official statistics are compiled based on reports without *in situ* verification and are thus likely to contain inaccuracies caused, for example, by errors and delays in the reporting of plantation abandonment after, for example, weather-related damage.

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By relating the baseline oil palm crop coverage (version 1) with official data on forest cover (INEGI, 2017; 2018), it was identified that more than 5400 ha of forests and jungles had been lost to oil palm during the period from 2014 to 2019. This area corresponded to 4.97 % of the total oil palm cropland reported in 2019 (108 690 ha). This trend was confirmed in the second mapping (version 1.1) for the period between 2016 and 2022 (Figure 4). Cumulatively, approximately 7317.4 ha of forest cover (mainly secondary arboreal vegetation and high evergreen forest) was lost, which represents 5.95 % of the total area under oil palm cultivation between 2014 and 2022. Nevertheless, this deforestation only corresponds to the 9-year period of satellite image coverage considered (2014-2022), and does not reflect possible earlier deforestation.

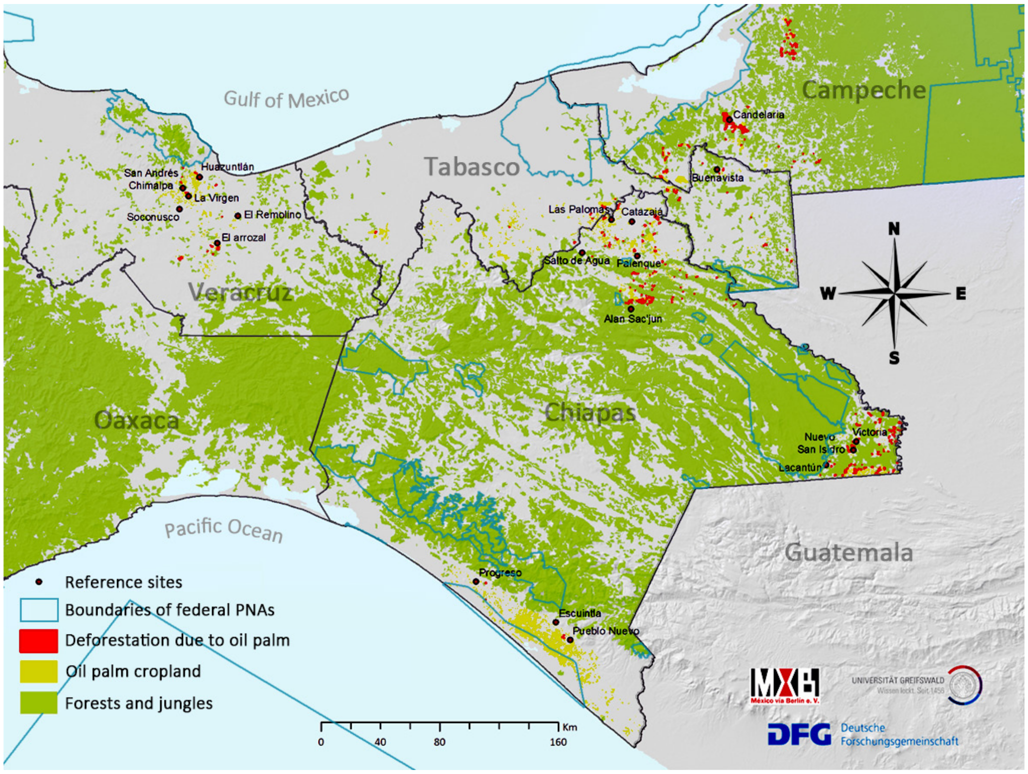

Figure 4. Deforestación por cultivo de palma aceitera en México entre 2014 y 2022, incluidos los límites de las ANP.

These results confirm previous studies documenting the increasing role of oil palm in deforestation (Bonilla-Moheno *et al*., 2012; Hernández-Rojas *et al*., 2018).

Deforestation related to oil palm cultivation during the period analyzed was concentrated in the regions of Marqués de Comillas, Benemérito de las Américas and Valle de Tulijá (Chiapas), as well as in the region of Candelaria (Campeche). In order to more precisely determine deforestation hotspots related to oil palm cultivation, a detailed long-term analysis is needed. This analysis would imply adequately defining the boundaries of the regions to be considered, as well as the calculation method used, in order to avoid over- or underestimations of deforestation. For example, if the municipal scale is chosen, it is necessary to calculate forest losses in percentages, in order to compare municipalities of different sizes (Hernández-Rojas *et al.*, 2018). However, for largely deforested areas, it would be more indicative to calculate deforestation in relation to the remaining forest cover of the specific entity studied.

Additionally, 7559 ha of oil palm were observed in PNAs, almost all of them in the state of Chiapas, mainly in the Encrucijada Biosphere Reserve (EBR), confirming previous mappings (Table 5). The EBR has been a focus of attention for academia, civil society and the media, as well as for governmental agencies, which have recently promoted efforts to control oil palm in this area.

Table 5. Areas under oil palm cultivation detected in PNAs in version 1.1.

PNA	PNA Type	Total area PNA (ha)	Area under oil palm cultivation in PNA (ha)
La Encrucijada (Chiapas)	Biosphere Reserve	144 868	7559
Palenque (Chiapas)	National Park	1772	24
Los Tuxtlas (Veracruz)	Biosphere Reserve	155 122	3

However, the presence of oil palm plantations was also detected in Palenque's National Park and the Tuxtlas Biosphere Reserve in Veracruz. It should be noted that this last information had been reported by witnesses from peasant organizations in the region but had not been evidenced in existing mappings. The next step in the analysis will be to locate oil palm cultivation precisely in relation to the zoning of the PNAs under consideration, in order to assess the extent to which oil palm cultivation is compatible with the regulations and conservation objectives declared in their management plans. Similar evaluations already exist for the EBR (Castellanos-Navarrete, 2021; Navarro and Santiago, 2021), although they present different interpretations and conclusions on the socio-environmental implications of oil palm cultivation in this PNA.

In general, limitations in the identification of land use change, as well as in the progression between different stages of crop development, result in biases in the modeling of forest dynamics, which can impact the calibration of global land surface and terrain models (LSMs). LSMs simulate plant growth, biomass density, crop yields, and fluxes of energy, nutrients, water and carbon, which are used to make projections of global climate impacts. While the importance of adequately representing oil palm as a distinct plant functional type (PFT) within LSMs is beginning to be recognized, models that incorporate this difference are often calibrated with data from a few plantations in Malaysia and Indonesia (Xu *et al*., 2021), highlighting the importance of knowing whether oil palm plantations in Mexico, and more generally Latin America, follow different behaviors than those in Southeast Asia.

Oil palm in Mexico, although still covering small areas compared to neighboring producing countries, is part of the profound transformation of the landscape in the south-southeast of the country. Through relational mapping, it is possible to investigate aspects associated with land use and natural resource management within the oil palm plantations, potential impacts on biodiversity, and the economic and social interference on pre-existing local or regional activities. These analyses contribute to answer questions such as: What are the economic, social and biocultural benefits and impacts of the expansion of oil palm plantations? Which population groups benefit or are primarily affected by this crop? To what extent does oil palm benefit from the previous expansion of the agricultural frontier? And how can detailed mapping of the dynamics of oil palm cultivation contribute to calibrating regional and global models of land use changes and associated socio-environmental impacts?

However, the mapping presented here retains a certain margin of inaccuracy and time lag, although the second version has overall improved the quality and coverage of areas under oil palm cultivation identified. To solve the limitations related to the use of remote sensing approaches, periodic *in situ* verification campaigns are recommended, both in the most dynamic regions of oil palm expansion, as well as in and around PNAs where oil palm has been detected. These could be carried out as part of governmental agricultural planning and data collection programs, in order to update existing agroecological zoning analyses. In academic and civil society contexts, *in situ* verification and the establishment and maintenance of monitoring programs are mainly constrained by the difficulty of securing adequate long-term funding. An alternative to explore is using small unmanned aircraft (i.e., drones) that facilitate high-resolution local-level data collection for spatial ecological analyses (Khokthong *et al*., 2019). This tool can be combined with participatory mapping in communities located in the vicinity of oil palm plantations, to help populations investigate any associated environmental impacts and to protect their territories (Vargas-Ramírez and Paneque-Gálvez, 2019).

Currently, a second update of the mapping is underway, which includes a broader verification of official geo-referenced databases at the national level. In addition, a freely accessible online digital platform is being built to make the results of these mappings widely visible and to explore interactive tools that allow *in situ* reporting changes in oil palm plantations (OBSAM, 2023). An important challenge in this latter case is to develop efficient and transparent verification mechanisms for such reporting. Additionally, it would be interesting to construct a publicly accessible and non-commercial central repository of geo-referenced databases and metadata on oil palm, which would facilitate cross-checking and analysis of socio-environmental impacts. The inventory of existing mappings presented here is a step in this direction. Taken together, these measures would constitute an important basis for the establishment of an independent monitoring of the progression and impacts of oil palm at the national level.

CONCLUSIONS

A detailed methodology for the first publicly accessible mapping of oil palm cultivation in Mexico was presented (Sandoval Vázquez *et al.*, 2022). Existing mappings, mainly focused on southern Chiapas, have been expanded to obtain nationwide coverage of oil palm cultivation. These results are essential for a systematic and comprehensive assessment of the spatial dynamics of oil palm cultivation and its socio-environmental impacts. The two versions of the mapping are registered in the digital platform Zenodo, and are publicly accessible and free of charge for non-commercial purposes.

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