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To cite this article: Sarah Hartman *et al* 2022 *Environ. Res. Lett.* **17** 115004

ENVIRONMENTAL RESEARCH
LETTERS

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OPEN ACCESS

RECEIVED
16 March 2022

REVISED
17 August 2022

ACCEPTED FOR PUBLICATION
17 October 2022

PUBLISHED
28 October 2022

LETTER

Mapping the expansion of berry greenhouses onto Michoacán's ejido lands, México

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Keywords: machine learning, greenhouse agriculture, remote sensing, mapping, agro-export, land tenure

Supplementary material for this article is available online

Abstract

Agricultural transformations have significantly contributed to the global market's year-round supply of capital-intensive greenhouse-grown crops. For instance, berry production in México is increasingly relying on greenhouse systems to meet the growing demand of international markets, particularly in the USA. It is still unclear to what extent these transformations are related to land tenure, as data on greenhouse distribution often do not exist, are incomplete, or lack spatial resolution. This paper presents a support vector machine learning algorithm tool to map greenhouse expansion using satellite images. The tool is applied to the major berry-growing region of Michoacán, México. Here agricultural areas are transforming to satisfy foreign demand for berries, altering local land and water resource use patterns. We use this tool and a unique land tenure dataset to investigate (a) the spatially explicit extent to which high-input commercial agriculture (mainly the production of berries) has expanded in this region since 1989; and (b) the extent to which smallholder (*ejidal*) land has been incorporated into the highly capitalized agro-export sector. We combine a national dataset on *ejidal* land (which includes both communal and parcel land) with geospatial agricultural data to quantify the land-use changes in six municipalities in the berry-growing region of Michoacán between 1989 and 2021. We find that the development of the greenhouse berry boom can be quantified and shown with spatially-explicit detail, growing from zero to over 9,500 ha over the period, using almost one-quarter of all regional agricultural land in 2020. We further find that the capital-intensive market-oriented berry industry has been widely integrated into smallholder *ejidal* lands, so much so that over half of greenhouses are found there.

1. Introduction

As the global population nears 8 billion people, Earth's natural resources are under immense pressure to supply food (Ramankutty *et al* 2018, IPCC 2019). In response, countries have increased their dependence on food trade, indirectly accessing foreign land and water resources (Allan 1996, Rulli *et al* 2013, D'Odorico *et al* 2014). The development of a globalized food system has been accompanied by agricultural intensification and expansion, including transitions to irrigated agriculture, use of high-yielding crops and fertilizers, incorporation of high-efficiency irrigation systems, and the proliferation of greenhouse farming (Hazell and Wood 2008, Mueller *et al* 2012, Sabir and Singh 2013, Laurance *et al* 2014). Capital-, input- and water-intensive greenhouse production stretches the globe, from Spain to Australia to México, increasingly supplying high-value crops like berries, tomatoes, lettuce, and peppers (Sabir and Singh 2013, Aguilar *et al* 2015).

With farming transitioning from open-air to greenhouses, research is needed to understand expanding greenhouse production and its impacts on local resource use and land management. In regions that have undergone rapid agrarian transformation over the last four decades, important questions arise with regards to by whom, to what extent, and on

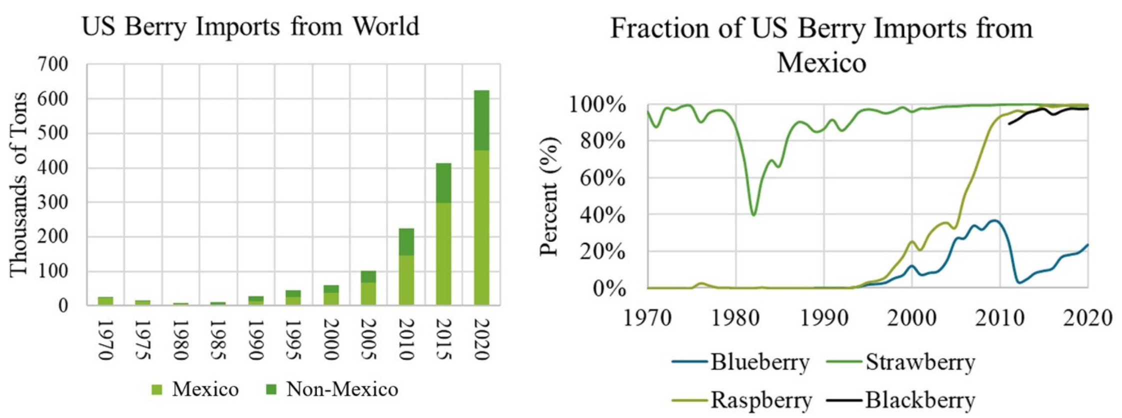

Figure 1. US berry imports from México and the world (left) and the fraction of global US berry imports from México between 1970 and 2020 (right), visualized using data from USDA FAS.

which lands this change has occurred. This article aims to answer the latter two questions. To this end, we developed a remote sensing, machine learning methodology to temporally and spatially map and quantify greenhouse expansion. In the following sections, we present, apply, and assess our methodology for the case of berry production in six municipalities situated in the heart of the 'Mexican berry boom' in the state of Michoacán, Western México, and combine it with a dataset of communal *ejido* land to measure intensification vis-à-vis land tenure. We conclude that this method has great potential to be used for quantifying agricultural intensification through greenhouse production worldwide.

2. México's berry boom

México has undergone an agricultural transformation to produce irrigated crops for the export market since at least the 1990s (González-Estrada 2016, Hartman *et al* 2021, Hoogesteger and Rivara 2021). These crops represent a significant virtual water transfer to the United States (US) and other world markets, often from over-exploited aquifers and watersheds (Hoogesteger 2018, Rosa *et al* 2019, Hartman *et al* 2021). In México, several specialized agro-export regions have developed including berries and avocado in Michoacán (Hartman *et al* 2021), broccoli and fresh vegetables in Guanajuato (Hoogesteger, 2017; Hoogesteger and Wester 2017), and tomatoes in Sinaloa.

In our case study, Zamora, Michoacán—the heart of México's berry industry (Alvarez del Toro 1985)—the strawberry boom began in the 1960s. Before then, strawberries occupied less than 20 ha—a small amount compared to the robust production of wheat, corn, and potato (Alvarez Del Toro 1985). In the 1960s, the area's first chilling facilities allowed for the conservation of export-oriented strawberries. US investors helped develop the Mexican industry, motivated by the fact that México could produce fresh strawberries in months that were unfavorable for US production (Feder 1981, González-Estrada 2016). Consequently, since the beginning of the US Department of Agriculture Foreign Agricultural Service (USDA FAS) global agricultural trade data, México has been the major player in supplying the US with fresh berries (USDA FAS 2021) (figure 1). Between 1970 and 2020, México supplied 92% of US strawberry imports from abroad. Since 2011, this has increased to 99%. US import of Mexican raspberries and blackberries began in the mid-1990s, averaging 98% and 95% of respective global fresh imports since 2011, making it the single most important player in an emerging market. Berry exports to the US represented 97% of México's global export in 2016 (CEDRSSA 2017).

México's modern-day industry was facilitated by agrarian policy liberalization and the North American Free Trade Agreement (NAFTA), signed in 1992 and enacted in 1994, which eliminated berry tariffs (NAFTA 1994, CEDRSSA 2017, Zlolinski 2018). While Michoacán farmers grew strawberries before reporting in the Servicio de Información Agroalimentaria y Pesquera (SIAP) database in 1980, the other berries were not grown until the neoliberal era of the 1980s–1990s (Chollett 2009, Kotz 2017, Hruska 2020). Michoacán started growing blackberries in 1992, followed by raspberries in 1996 (SIAP 2021(c)). Blueberries, which appeared in 2011, remain comparatively insignificant. Since 1980, berry production has increased by four orders of magnitude, driven by blackberries and raspberries since 2008 (SIAP 2021(c)). These berries are primarily grown under contract farming agreements with transnational corporations (Chollett 2009, González-Ramírez *et al* 2020).

Technological advances have driven the intensification of berry farms (Chollett 2009). This began with refrigeration and more recently involves patented berry varieties, drip irrigation, and protected agriculture (PA) (Comité de la Agroindustria y Productores de la Fresa AC (CONAFRESA) 2019). We use 'protected agriculture' (PA) and 'greenhouse' to refer to plastic used in the crop growing process, like plastic soil covering, tunnels, and shade cloths. This definition aligns with the Mexican government's definition (SIAP 2021(a)). Berry farmers primarily use groundwater for irrigation since it reduces the likelihood of introducing water-borne contaminants (CONAFRESA 2019) and because farmers can irrigate according to crop water demands. Drip irrigation allows for precise water and fertilizer application through fertigation. In strawberry, high-tech production reaches 70 tons ha^{-1} versus 26 tons ha^{-1} using traditional farming practices (SAGARPA 2016, González-Ramírez *et al* 2020).

3. A transforming land tenure system

In México, land is divided into private property and communal land tenure—denominated *ejido*. *Ejidal* lands are designated into three categories: common use, parcel, and residential (RAN 2021). *Ejidatarios,* the *ejido* members, collectively manage common use lands, usually being hills and forests whose resources are open to all *ejidatarios.* Contrastingly, parcels are owned and managed by individual *ejidatarios* and governed by *ejido* rules. These lands are generally used for individual cultivation and are considered individual property within the *ejido*.

Ejidal lands currently cover over half of México (Morett-Sanchez and Cosío-Ruiz 2017). The original *ejido* land tenure structure, which was based on usufruct land rights, transformed after 1992 (Assies 2008). Inspired by neoliberal ideology, in 1992, the Agrarian Reform culminated *ejidal* land reform and enabled resource privatization (Ley Agraria 1992). Then in 1993, the federal government established the *Programa de Certificación de Derechos Ejidales y Titulación de Solares Urbanos* (PROCEDE) to title *ejidal* land and enable *ejidal* land renting, division, and selling as private property (Secretaría de la Reforma Agraria 2006). It also enabled *ejido* dissolution.

In our study area, *ejidal* lands have been incorporated into berry production in three broad manners: (a) *Land transactions: ejidatarios* that have gone through PROCEDE sell their plots to outside investors (officially these lands are still registered as *ejido* but the owners are others). (b) *Long-term land rent*: agribusinesses offer long-term land rent contracts, usually for 10 years. These contracts often stipulate that the renter invests in developing infrastructure that reverts to the owner upon contract completion. Such contract farming agreements were documented as early as 1997 (Chollett 2009). (c) *Smallholders'* investments in PA: some capitalized *ejidatarios* have invested in PA either independently or through contract farming to enter lucrative markets. In all these cases, upfront investments must be made for the installation of groundwater wells, agricultural inputs, and labor.

Due to the peasant crisis in the 1990s, many *ejidatarios* went bankrupt, abandoning land production and moving towards cities or economic opportunities including labor migration to the US (Assies 2008, Hoogesteger and Rivara 2021). The economic importance of agriculture in rural livelihoods greatly decreased, reducing interest in and attachment to agricultural land and facilitating the above-mentioned processes. Resultingly, many *ejidatarios* now reap income from renting their land, some have additionally become laborers on their lands, and those that have invested in PA have become small business entrepreneurs. The increased seasonal and permanent labor demands of PA production have also attracted laborers throughout México similar to examples seen in Baja California (Zlolniski 2018) and Guanajuato (Hoogesteger and Massink, 2021).

4. Study site: the heart of the berry boom

Within the above-mentioned context, the question remains to what extent *ejidal* land and resources were and are presently integrated into the capital-intensive global berry market. While SIAP remains the primary source of publicly-available agricultural data, this data seems to have inaccuracies and lacks the spatial detail needed to analyze sub-municipal transformations. To fill this gap, we tested our PA identification methodology in six Michoacán municipalities that are the heart of the berry boom: Ixtlán, Jacona, Los Reyes, Peribán, Tangancícuaro, and Zamora (figure 2). These municipalities have the highest blackberry, strawberry, raspberry, and blueberry production, respectively, accounting for 71.6%, 42.3%, 21.6%, and 8.9% of national production (SIAP 2021c). The municipalities total 177 750 ha, with 53% of the land tenured as *ejido* or agrarian communities: 26% as common use, 20% as parcels, and 7% as residential (RAN 2021). The study site lays over two aquifers; both have been overused since 2013 in the north and since 2020 in the south (CONAGUA 2021).

In the municipalities, irrigated crops dominate agricultural output: sugar cane, strawberries, avocados (rainfed and irrigated), blackberries, and raspberries (SIAP 2021c). Perennials occupy 18% of the region, while seasonal crops occupy 10% (SIAP 2021c). Further, based on government-reported statistics, the area's greenhouses are used almost exclusively for berry production, excluding 3% used for tomato and cucumber (SIAP 2021a). We will assume that all detected greenhouses represent PA for berry production. Also, government statistics on PA are only available from 2015 onwards and largely underreport PA compared to this study and another Mexican PA study (Perilla and Mas 2019). See the supplementary information for a side-by-side comparison.

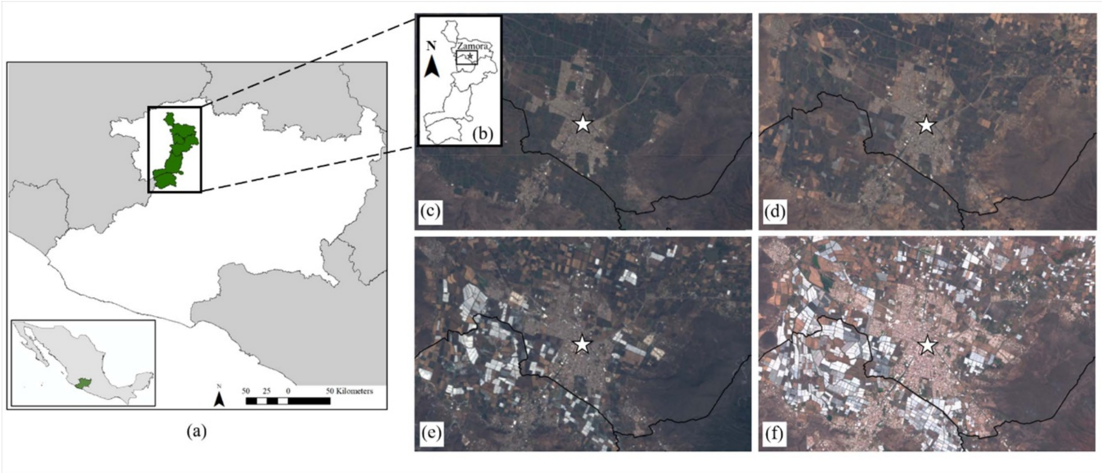

Figure 2. The six-municipality study site within Michoacán, México and corresponding satellite images from a sample area within the study site: (a) study site within México; (b) insert of study site with the principal city of Zamora starred and sample area boxed; 90th percentile true color composite using: (c) Landsat 5 image of 1989–1990; (d) Landsat 5 image of 1999–2000; (e) Landsat 5 image of 2009–2010; and (f) Sentinel 2 image of 2019–2020.

5. Methods

5.1. Greenhouse mapping

Greenhouse mapping is increasingly achieved using medium spatial resolution satellite imagery and supervised classification methods, including random forest classifiers, support vector machines (SVMs), and artificial neural networks (Peña-Barragán *et al* 2011, Novelli *et al* 2016, Li *et al* 2020). We chose to use SVMs due to their high performance in the binary classification of pixels (Peña-Barragán *et al* 2011, Gilbertson *et al* 2017).

We obtained the satellite data from Landsat 5 (TM) imagery for 1989–1990, 1999–2000, and 2009–2010, and Sentinel 2 imagery for 2015–2021. Each cycle is from August to August, for example, 1 August 2015–1 August 2016. The August cutoff aligns with the spring-summer and fall-winter harvesting periods, which were determined using SIAP harvesting data, and verified through discussions with farmers and the USDA FAS Mexican berry import dates (US Department of Agriculture Foreign Agricultural Service (USDA FAS) 2021, SIAP 2021b).

Satellite images were accessed and analyzed in Google Earth Engine (GEE). For Sentinel, images were filtered for less than 20% cloud coverage. While other studies have used a lower tolerance for clouds (Perilla and Mas 2019), we chose a higher tolerance to include more images thereby capturing more short-lived, non-permanent greenhouses (i.e. those established only before berry emergence). For Landsat 5, which has less temporal availability, we used all images and the Cloud Confidence bits to mask high cloud confidence and shadow confidence values.

Next, we reduced the collection to an annual composite based on 90th percentile band pixel values. This percentile improved the ability to capture short-lived greenhouses, which are not as well represented in a median or mean value. Then, we computed indexes that have previously been successful in improving greenhouse classifications and tested them for efficacy in our case. Ultimately, five indexes improved accuracy (table 1). They were calculated and used according to their specifications, excluding the normalized difference build-up index (NDBI) limit of the plastic greenhouse index (PGI) (Yang *et al* 2017). We used a modified PGI (MPGI) that does not assign a value to NDBI greater than 0.005 since applying this threshold worsened classification accuracy.

To reduce calculation time, we classified a subarea of the site by masking areas unlikely to have PA, including water features and elevations above 2600 m. Also, we applied a mask to the Sentinel images to exclude areas where the MPGI was not between −1 and 10, the range of values for 90th percentile MPGI for greenhouses, following (Yang *et al* 2017).

5.2. Classification and accuracy assessment

SVM classifications and accuracy assessments were conducted in GEE. We used a stratified random sampling of training polygons to select 1000 greenhouse and 5000 non-greenhouse points for classification (Perilla and Mas 2019). Following the methods of Gilbertson *et al* (2017), we chose a 3:2 sample split ratio classification for accuracy assessment. Both the validation and testing data were separate from the training data and each included 667 greenhouse and 3333 non-greenhouse points. Training, validation and, testing polygons were hand-generated in GEE where time-stamped high-resolution Google Earth Pro satellite images and on-the-ground-collected data from 2021 confirmed PA presence. SVM training years were selected based on the availability of high-resolution imagery in Google Earth Pro for validation. We also conducted a grid search for the best gamma and cost factors, with a gamma of 0.3 and

Table 1. Table of computed indexes that were used to improve classification accuracy, modified from Perilla and Mas (2019).

Index	Abbreviation	Equation	References
Normalized difference vegetation index	NDVI	$\frac{NIR-RED}{NIR+RED}$	Rouse *et al* (1974)
Normalized difference build-up index	NDBI	$\frac{SWIR1-NIR}{SWIR1+NIR}$	Zha *et al* (2003)
Normalized difference water index	NDWI	$\frac{GREEN-NIR}{GREEN+NIR}$	McFeeters (1996)
Modified plastic greenhouse index	MPGI	$\begin{cases} 0 & NDVI > 0.73 \\ 100^{*} & \frac{BLUE*(NIR-RED)}{1-mean(BLUE+GREEN+NIR)} \end{cases}$	Yang *et al* (2017)
Plastic-mulched landcover index	PMLI	$\frac{SWIR1-RED}{SWIR1+RED}$	Lu *et al* (2014)

a cost of 2500 providing the best validation accuracy (Hsu *et al* 2003). The default Radial Basis Function kernel was used.

Three SVMs were trained and tested: 2020–2021, with the learning applied to 2016–2021; 2015–2016; and 2009–2010, with the learning applied to 1999 and 1989. A separate SVM training was needed for 2015 to achieve acceptable accuracy given the limited availability of imagery in Sentinel 2A's first year in orbit and before Sentinel 2B's launch. Each SVM training used year-specific training and validation points. In all cases, testing accuracy exceeded 95%. The testing confusion matrices are available in the supplementary information.

5.3. Map analysis in ArcMap

Classified maps were exported for 1989, 1999, 2009, and 2015–2020. They were processed in ArcMap with the projection UTM13_WGS84, then combined with *ejidal* land tenure data (RAN 2021). Greenhouse areas were calculated for two scenarios: annual and maximum extent. The annual extent reflects the greenhouses for an August-to-August season. Contrastingly, the maximum extent represents the cumulative agricultural footprint of the greenhouse berry industry, generated by dissolving annual maps into one layer.

6. Results

6.1. Annual maps

Annual maps were generated for 9 years spanning 1989–2021. The maps for 1999, 2009, 2015, 2019, and 2020 are available in this publication. During this time, the region's agricultural landscape changed significantly (table 2 and figure 3). No PA is detected in 1989, representing a pre-NAFTA period when Mexican berry sales to the US were uniquely strawberries. PA first appeared then expanded in Zamora, Jacona, and Tangancícuaro between 1999 and 2009. It emerged rapidly in Ixtlán between 2009 and 2015 and gradually in Peribán and Los Reyes between 2009 and 2019.

By 1999, farms began adopting PA, totaling 189 ha and representing less than 1% of each municipality. The most PA was found in Jacona, then Zamora, with both centered around Zamora City. *Ejidal* parcels and non-*ejidal* land used PA. A greater amount was detected in parcels, but the distribution between *ejidal* and non-*ejidal* land varied by municipality. Sixty-six percent of Jacona's PA was on non-*ejidal* lands, with the remaining in *ejidal* parcels. While Zamora had the second-highest PA area, it had the largest *ejidal* land area using PA, at 44.8 ha.

Between 1999 and 2009, PA doubled annually, with Tangancícuaro and Zamora increasing the quickest. By 2009, PA covered 2390 ha, being greatest in Zamora. In all municipalities excluding Los Reyes, a higher area and a more significant fraction of land were from non-*ejidal* than from *ejidal*. In Los Reyes, PA on parcels outstripped non-*ejidal* PA. The ratio of non-*ejidal* to *ejidal* land remained steady at 66% non-*ejido* and 34% *ejidal* parcels.

Between 2009 and 2019, PA expansion slowed. However, more PA was brought into production during 2009–2019 than 1999–2009 for all municipalities and land tenures. The swiftest expansion occurred in less-developed Ixtlán and Peribán, which more than doubled annually. By 2019, Zamora had the greatest expanse of PA, covering 10% of the municipality, occupying 19% of non-*ejidal* land, 16% of *ejidal* parcels, and less than 1% of common use or dwelling lands. Jacona was similar—18% non-*ejidal* and 22% *ejidal* parcels.

PA was first detected on common-use lands in Tangancícuaro in 2015, reaching its maximum in 2020 (figure 4). This land directly borders other tenures previously developed with PA. According to the national registry, this common-use land is designated for agricultural and livestock purposes, being good-quality pastureland (RAN 2021). Thus, PA emergence indicates a transition away from the registered communal land use toward integration into the global berry industry.

For the entire study, common-use lands with PA have a government-designated use including agriculture, livestock, and forestry. However, not all lands designated for these uses have PA. PA is not found on the remaining common-use designations, including valuable perennial crops, biosphere reserves, and

Table 2. Harvest season PA (hectares) extent and average annual percent change for the previous decade by land tenure.

Area (hectares)	Total		Non-*ejido*		Parcel		Residential		Common use	
1989	—	—	—	—	—	—	—	—	—	—
1999	189.16	—	86.71	—	102.45	—	—	—	—	—
2009	2389.85	116%	1573.11	171%	816.74	70%	—	—	—	—
2019	9526.16	30%	4464.84	18%	4895.89	50%	7.57	—	157.85	—

Figure 3. Annual total PA per municipality by land tenure and *ejidal* land use designation.

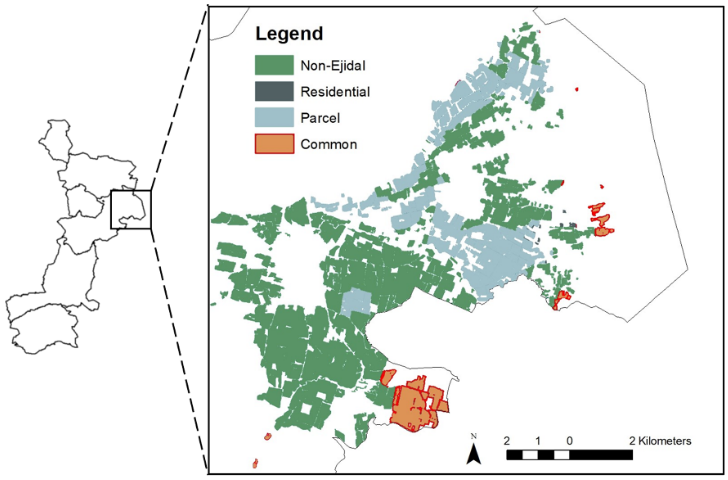

Figure 4. PA on common use lands in Tangancícuaro, outlined in red for emphasis. PA has emerged on parcel *ejidos* since the 2009–2010 harvest season.

recreation. Ultimately, the *ejido* assembly determines common-use land management and decides which lands can have PA, offering an indirect reflection on *ejidal* decisions (Secretaría de la Reforma Agraria 1992).

6.2. Maximum PA footprint

A maximum footprint map was also created. While it gives no perception of temporal trajectory, it displays the full spatial extent of PA. Between 1999 and 2021, the berry industry used 24% of all land in Jacona, 23%

Table 3. Area of study site municipalities and area of the maximum extent of detected PA by land tenure.

Area (hectares)	Ixtlán	Jacona	Los Reyes	Peribán	Tangancícuaro	Zamora
Total municipality	12 403.40	11 883.84	48 142.57	33 212.65	38 563.02	33 545.06
Total PA	1767.30	2804.03	1223.76	1466.46	4474.15	7834.65
Parcel	1269.04	1522.97	764.48	592.88	1080.07	5151.28
Common use	9.02	2.81	11.42	4.86	307.56	114.6
Residential	0.25	0.25	1.87	2.42	7.89	6.05
Non-*ejidal*	488.98	1277.99	445.99	866.31	3078.63	2562.73

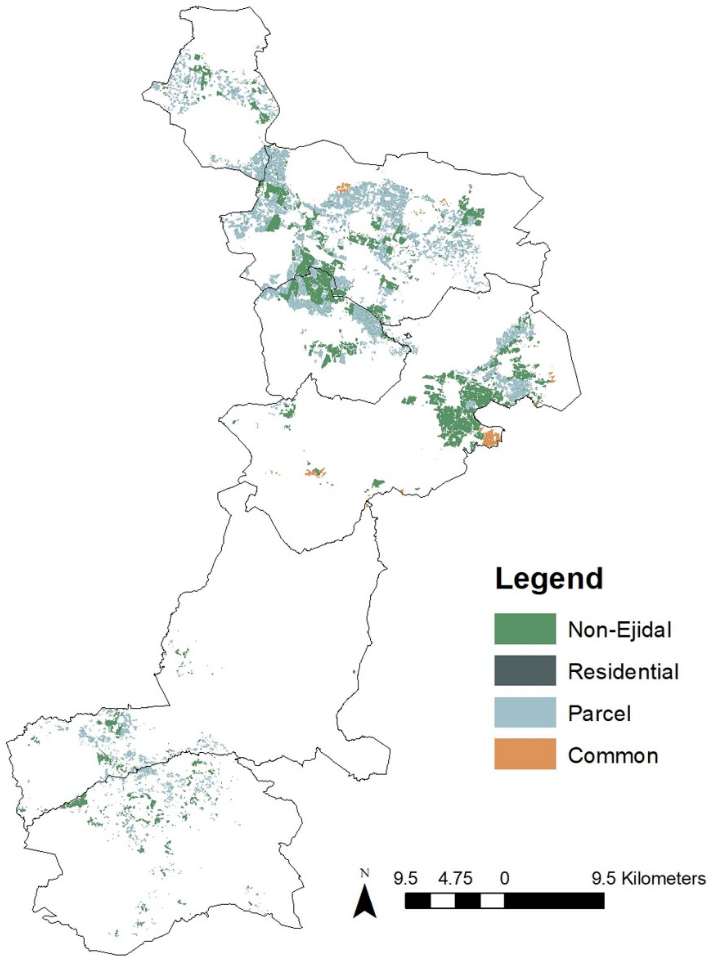

Figure 5. Map of the maximum extent of PA between 1989 and 2021 based on land tenure: non-*ejidal* or *ejidal* (including common use, parcel, and residential).

in Zamora, 14% in Ixtlán, 12% in Tangancícuaro and less than 5% in Peribán and Los Reyes. The footprint of detected PA is 19 570 ha, representing 11% of the study site, including non-cultivated areas (table 3 and figure 5). Of the PA, 10 849.7 ha are *ejidal* (6% of total area), and 8720.6 ha are non-*ejidal* (5% of total area). This is substantial considering the footprint of all crop production is 28% of the region in recent years (SIAP 2021c). Further, this is more than double the annual detected PA of 2019 (9526 ha) or 2020 (9465 ha). The difference may be due to land abandonment or field rotation.

Ejidal PA is concentrated in parcel land tenure. More than 97% of *ejidal* PA occurs on parcels, excluding in Tangancícuaro. For Zamora and Jacona, 44% of parcel land is PA. For Ixtlán, Tangancícuaro, Los Reyes, and Peribán; PA occupies 26%, 20%, 14%, and 12% of parcel lands, respectively. Contrastingly, less than 0.1% of PA occurs in *ejidal* residential zones. Tangancícuaro is the only municipality where more than 2% of the PA occurs on common-use-designated land. For this municipality, 7% of PA is on common-use land, representing 22% of PA's footprint on *ejidal* land (the fraction of PA on common-use land out of the total PA on *ejidal* land).

For non-*ejido* land only, PA occupies 41% of Zamora's non-*ejido* land, 33% of Jacona's, 24% of Tangancícuaro's, 17% of Ixtlán's, and less than 5% for Peribán's and Los Reyes'. Interestingly, a greater proportion of parcel lands have been used than non-*ejidal* lands in Ixtlán, Peribán and Los Reyes. For Jacona and Zamora, similar proportions of parcel and non-*ejidal* lands have been used. For Tangancícuaro, more non-*ejidal* than parcel lands are used.

7. Discussion

This study successfully measured PA expansion as a proxy to quantify market-oriented agriculture in six Michoacán municipalities, answering the questions of to what extent and on which lands the expansion occurred. Accordingly, this study (a) creates a historical reconstruction of agricultural expansion and intensification, (b) spatially quantifies the expansion, (c) augments limited but existing data, and (d) informs our understanding of how PA, especially for berries, has intensified and incorporated smallholder (*ejido*) land. The coupling of remote sensing and government data shows a high inclusion of formerly smallholder land into PA production. *Ejidal* parcels played a key role throughout the PA expansion process, being used comparably and, in some areas, more than non-*ejidal* lands. While a previous study (Beraud-Macías *et al* 2018) found that land-use change was most rapid during the PROCEDE *ejido* certification (1993–2006), this study shows that land conversion to PA was greater after certification. Post-2009 saw the largest growth of PA in all municipalities and land tenures, with growth facilitated by the 1992 land reforms that transformed the *ejido* tenure system.

Our results show that, even though berry production requires high upfront investment costs, extents of what used to be smallholder parcels have transformed into high-end PA production. The conversion of non-PA to PA land begs the question of what impact the transformation has had on Mexican food sovereignty given the displacement of local crops for berries grown primarily to supply foreign high-income markets (Soria Sánchez and Palacio Muñoz 2014, Rubio 2015, Carmona Silva *et al* 2020). This study's findings support research showing that Mexican export agriculture allows national and foreign investors to access cheap produce without 'paying the costs of damage to the environment and human health' (González 2019, p 183; see also Tetreault et al., 2021). This has led to heightened pressure on local aquifers, and, ultimately, unsustainable agricultural water use (Hartman *et al* 2021). It further points to processes of intensive agrarian change among smallholders and raises questions regarding changes in regional resource access. Some questions that remain unanswered, requiring further on-the-ground interdisciplinary investigation are: who is producing on the *ejidal* lands under PA? In what ways are smallholders engaging in market-oriented production? What impacts do these processes have on broader rural transformation, social differentiation, labor conditions, and sustainable resource use?

Methodologically the study could not overcome certain limitations. These include classic remote sensing challenges like the limited availability of low-cloud images and classification errors. Further, a single *ejido* that we visited and mapped on-site in Tangancícuaro was missing from the geospatial government dataset. Therefore, PA is overrepresented in Tangancícuaro's non-*ejidal* land calculation. After comparing the geospatial data to the National Agrarian Registry's written records, we confirmed that only the aforementioned *ejido* is missing for the region. Further, this study confirms SIAP berry data and suggests that SIAP underrepresents production (see supplementary information). Lastly, this study traced land-use change to PA but is unable to identify what was specifically produced where, who had access to and/or owned the *ejidal* lands over the years, or what socio-environmental impacts the registered changes have on the region's resources and people (see also Venot *et al* 2021). As such, we consider it a powerful proxy to remotely identify areas of agricultural intensification. Its further development has the potential to also deduce estimates of production, water use, and agricultural input use, however, this falls outside the scope of this paper.

8. Conclusion

México's prominence in the global berry industry, especially blackberry and raspberry, resulted from its rapid transformation into a high-tech berry grower. Between 1989 and 2021, farming technology spread through México, with new expanses of PA reflecting rapid market integration of private and *ejido* land. Long-term observation of six Michoacán municipalities shows a high inclusion of smallholder *ejidal* land into market-oriented production. Parcel lands have become a dominant contributor of natural resources to the berry industry, even as common use lands generally remain undeveloped. This raises important questions about what processes take place on the ground to spur this development.

Michoacán is an example of how globalization and agricultural intensification incorporate the world's common lands and the socio-ecological systems they support. With the long-term presence of PA on *ejidal* parcels, the international berry industry is accessing the natural endowments of formerly common property regime (CPR) lands through transnational contract farming. While CPRs are known for being suitable for the emergence of governance systems that are resilient to endogenous factors (Ostrom 1990), they have been proven to be vulnerable to exogenous drivers like land titling, international trade agreements, and global markets (Dell'Angelo *et al* 2017). In this case, the berry industry has integrated *ejidos*' CPRs into global markets, altering regional social, economic, and environmental realities.

While this analysis is grounded in the Mexican context, it can be applied more broadly. Despite its limitations, the methodology developed herein proved to be a powerful tool in capturing the rapid and widespread encroachment of capital-intensive PA upon smallholder *ejidal* parcels and non-*ejidal* land alike. With it, it lays the groundwork to map agricultural transformation towards PA, especially in places with a dearth of such data. As such, it is a valuable methodology to identify and assess PA expansion in data-limited places of the world, or to corroborate existing data.

Data availability statement

All data that support this study are included within the article (and any supplementary files).

The data that support the findings of this study are openly available at the following URL/DOI: https://drive.google.com/drive/u/0/folders/1P5QAoVCepjr16lkLMV5410TmCn1k5C3x. Cite as Hartman et al. (2022). Supplementary Data Files for Mapping the expansion of berry greenhouses onto Michoacán's ejido lands, México.

Acknowledgments

S H was supported by the National Science Foundation INFEWS Fellowship (#DGE-163374), the National Science Foundation Graduate Research Fellowships Program (#DGE-1752814), and the Berkeley Institute for International Studies Pre-Dissertation Grant. P D was funded by the USDA Hatch Multistate project (#W4190) capacity fund. The authors thank Professor Iryna Dronova (University of California, Berkeley) for guidance while developing the remote sensing methods used in this paper. Open access publication made possible in part by support from the Berkeley Research Impact Initiative (BRII) sponsored by the UC Berkeley Library.

Conflict of interest

The authors declare no conflict of interest.

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