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Loss of Agricultural Land in the Irrigation Districts of the State of Mexico and Urban Growth Patterns

Pérdida de superficie agrícola en los distritos de riego del Estado de México y patrones de crecimiento urbano

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Abstract. In this paper we analyze the agricultural loss in the irrigation districts (ID) of the State of Mexico and identify the patterns of urban growth. The methodology was with mixed approach combined quantitative, qualitative, and spatial methods. Images from the sentinel-2 satellite from the years 2016 and 2022 and the vector layer of plots from 2010 were processed and analyzed to identify total or partial urbanized plots and to account for the loss of agricultural area. Also, urban growth patterns in the ID were identified and interviews were conducted with key stakeholders to learn about their expectations about agricultural land loss due to urbanization. The results show urban growth in all ID, with the greatest loss of agricultural area at the ID closest to Mexico City. The general rate of urban growth surface was of 0.7, with the highest loss percentage in the ID 088 Chiconautla and 073 La Concepción. Finally, five patterns of urban growth were identified and analyzed. Urbanization is a continuous process which will continue in next years, so it is important to plan it based on the growth patterns and characteristics of each ID.

Keywords: urban growth, agricultural land conversion, remote sensing, GIS, land use change.

Resumen. El crecimiento de la población mundial demanda más espacio para viviendas y a la vez mayor disponibilidad de alimentos, lo que afecta de manera directa y continua la superficie de tierra dedicada a la agricultura. En este contexto, la pérdida de superficie agrícola se relaciona con la tasa de crecimiento urbano y, por tanto, con el crecimiento poblacional, por lo que el entendimiento de la relación de dicha pérdida de superficie con la expansión urbana es importante para predecir los impactos de la urbanización en la agricultura. A pesar de existir un panorama desalentador en la pérdida de superficie agrícola, Rimal *et al.* señalan que la gestión adecuada del crecimiento urbano puede reducir las pérdidas de tierras agrícolas. Sin embargo, es necesario conocer la configuración y el comportamiento espacial de cada lugar para un mayor entendimiento de la expansión urbana y generar una mejor planificación territorial.

Los objetivos de esta investigación fueron cuantificar y analizar el crecimiento de superficie urbana en los distritos de riego del estado de México del 2010 al 2022 en dos subperiodos 2010-2016 y 2016-2022 e identificar los patrones de crecimiento urbano presentes; así como conocer las expectativas de actores clave sobre los factores que influyen en el cambio de uso de suelo de agrícola a urbano.

La superficie con uso o vocación agropecuaria en México fue de 88.4 millones de hectáreas, mientras en el Estado de

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México esta superficie fue de 1.1 millones de hectáreas, de acuerdo con el censo agropecuario de 2022. Sin embargo, espacialmente es difícil delimitar toda la superficie agrícola y es posible confundir parcelas agrícolas con otro tipo se suelo. Por ello esta investigación utiliza los datos de los DR del Estado de México cuya información considera sólo aquellas parcelas que son o fueron de uso agrícola. El área de estudio comprende las parcelas de los cinco DR que se ubican en la parte norte del Estado de México: 033 Estado de México, 044 Jilotepec, 073 La Concepción, 088 Chiconautla, 096 Arroyozarco.

La metodología aplicada combina un enfoque mixto de métodos cuantitativos, cualitativos y espaciales. Se procesaron y analizaron imágenes del satélite Sentinel-2 de los años 2016 y 2022 y la capa vectorial de parcelas del 2010 para identificar parcelas total o parcialmente urbanizadas y contabilizar la pérdida de superficie agrícola. El procesamiento de las imágenes se realizó con el software QGIS (v. 3.16).

También se identificaron los patrones de crecimiento urbano dentro de los DR y se realizaron entrevistas a actores clave para conocer sus percepciones y expectativas con respecto a la pérdida de superficie agrícola por urbanización.

Los resultados muestran crecimiento urbano en todos los DR, sin embargo, el porcentaje de pérdida de la superficie agrícola varía de acuerdo con la cercanía de cada distrito a las ciudades y zona metropolitana de la Ciudad de México. Se encontró una tasa general de crecimiento de superficie urbana de 0.7 durante el periodo 2016-2022; los DR con la mayor tasa de crecimiento urbano fueron el DR 044 Jilotepec y DR 088 Chiconautla.

A pesar de que los distritos están dentro del mismo estado y las condiciones socioeconómicas pudieran ser parecidas, los resultados muestran diferentes patrones de crecimiento urbano dentro de cada distrito. Los patrones de crecimiento urbano encontrados son: crecimiento urbano cercano a vialidades, crecimiento urbano por construcción de infraestructura, crecimiento urbano cercano a zonas metropolitanas, crecimiento disperso y crecimiento por desarrollo industrial.

Complementando el análisis espacial, los resultados de las entrevistas a actores clave permitieron identificar los posibles factores que más influyen en el cambio de uso de suelo agrícola a urbano. Los actores entrevistados coinciden que los principales factores explicativos del crecimiento urbano son la cercanía a las ciudades, la construcción de vialidades, infraestructura o zonas industriales, y el incremento de las cuotas de luz de los pozos para el riego, lo que sugiere que, en general, el crecimiento poblacional y la satisfacción de las necesidades conduce al requerimiento de más tierra que se reduce principalmente de la superficie agrícola. Por otro lado, los principales factores explicativos que inhiben el cambio de uso de suelo son la rentabilidad de la actividad agrícola, la edad avanzada de los titulares de la tierra y el apego de los agricultores a la agricultura.

La urbanización es un proceso complejo y continuo que perdurará en los próximos años, por lo que es importante establecer un proceso de planificación ordenado con base en los patrones de crecimiento y características de cada DR. Por otro lado, es importante intensificar e innovar para hacer más eficiente la producción en las zonas agrícolas, maximizando la productividad con mayores rendimientos y sistemas de producción más eficientes con el uso de los recursos disponibles.

Palabras clave: expansión urbana, conversión de tierra agrícola, sensores remotos, SIG, cambio de uso de suelo

INTRODUCTION

Population growth around the world demands more space for housing and greater food availability. These factors directly and continuously affect the area dedicated to agriculture; on the one hand, the growing population requires greater food production to meet their needs, and on the other, the availability of farming land is reduced due to the expansion of urban areas, particularly in peri-urban areas. Therefore, agricultural land is threatened by fragmentation and dispersed urban development in many countries (Azadi *et al.*, 2011; Rimal *et al.*, 2018).

The loss of agricultural land is related to the rate of urban growth — and, therefore, population growth — so loss of agricultural land involves a shift from rural to urban landscapes (Pham *et al.*, 2015; Rimal *et al.*, 2018). This loss of agricultural land is expected to increase in line with urban population growth (Pandey and Seto, 2015) due to the increased demand for land for housing and human activities (Salem *et al.*, 2020)· As the size of the land is fixed, the annual population growth will involve greater demand for accommodation and competition for land to meet various needs (Ziem Bonye *et al.*, 2021).

Understanding the relationship of agricultural land loss to urban areas is important for predicting the impacts of urbanization on agriculture (Pham *et al.*, 2015). A smaller area of agricultural land can reduce the availability of agricultural products and food supplies for the population. In this sense, uncontrolled urbanization and ineffective land-use planning systems affect food security (Ziem Bonye *et al.*, 2021). These processes and their impacts have been observed in other parts of the world; for example, K. Shi *et al.* (2016) reported a positive correlation between the decrease in grain production and the significant loss of agricultural land in developed areas of China. This reduction in agricultural production could be prevented with strategies that promote the intensification of agricultural production by implementing new technological packages and innovations in production systems.

The loss of agricultural land due to urbanization affects not only agriculture and fresh food production, but also environmental sustainability, climate, hydrology, and habitats, impacting biological diversity (Bhatta, 2010; Pandey *et al.*, 2018; Radwan *et al.*, 2019)spatial analysis, uncertainty modeling and geo-visualization. Fazal (2000) concluded that fertile agricultural land is destroyed that cannot be reclaimed, and the canals that previously transported water to agricultural areas are invaded and used to dispose of garbage and waste in India. Separately, Vargas and Magaña (2020) concluded that rapid urban growth in Mexico has increased the frequency of intense heat and rainfall events.

The main factors derived from urban growth and driving the loss of agricultural land in Egypt include rapid population growth, the economic value of land, speculation about the real estate market, fragmentation of agricultural land, and the road network (Salem et al., 2020).

Despite the current discouraging scenario regarding the loss of agricultural area, Rimal et al. (2018) have pointed out that proper urban growth management can reduce agricultural land losses relative to historical trends even under increased population growth and urbanization. However, it is necessary to know the configuration and spatial behavior of each place to better understand urban expansion and improve territorial planning (Spieth et al., 2014).

In Mexico, no studies have been conducted on the loss of agricultural areas in zones currently dedicated to food production, such as irrigation districts (IDs). In addition, human activities exert environmental and social pressures, including the demand for water for household and commercial uses, which affects the exploitation of aquifers and other water sources in the Valley of Mexico (Graizbord and González Granillo, 2019)Mexico City, the country's capital, exhibited unprecedented demographic growth and physical expansion involving numerous local government jurisdictions transcending the historical city limits. The resulting spatial distribution of population and location of economic activities in a complex metropolitan structure generated direct and indirect pressures on the Mexico Valley environment and beyond. Comprising the metropolitan area, a set of weak municipalities impose an apparent insurmountable barrier to transcend roles and a traditional institutional structure. Most, if not all, metropolitan municipalities have shown limited capabilities to respond to what seems to be the cross-cutting character of these trends that require coordinated multisectorial and multiscale management solutions. This article analyzes the impact of those processes and explores the scope (challenges and opportunities. Therefore, studying the urbanization of agricultural plots of IDs in Estado de México is essential.

In Mexico, the agricultural area with irrigation infrastructure comprises 6.7 million hectares, with 3.3 million corresponding to the 86 irrigation districts. IDs are projects developed by the federal government since 1926, including water storage, direct derivations, pumping plants, wells, and canals (CONAGUA, 2022). The volume of water for irrigation in each ID is set each year according to the availability of supply sources.

Based on the above, the objectives of this study were to quantify and analyze the growth of urban areas in irrigation districts of Estado de México from 2010 to 2022, divided into the subperiods 2010–2016 and 2016–2022, identify urban growth patterns, and know the expectations of key actors about factors that influence the conversion of agricultural land use to urban use. In addition, this study analyzed the implications of urban growth on the configuration of the different sectors, as well as the problems and consequences derived from the urbanization of agricultural plots. After the introduction, this article briefly describes the methodology, then delineates the results of urbanization and loss of agricultural area in the IRs and the identified urban growth patterns, and finally outlines the conclusions.

METHODOLOGY

Study Area

According to INEGI's 2022 agricultural census, the area suitable or used for agriculture was 88.4 million ha in Mexico and 1.1 million ha in Estado de México (INEGI, 2023). However, spatially delimiting the entire agricultural area is complex, as agricultural plots can be misidentified as a different land-use type. For this reason, this study used data for Estado de México IDs considering only plots that are or were dedicated to agricultural uses.

The study area includes the plots of the five IDs located in the northern part of Estado de México (Table 1): 033 Estado de México, 044 Jilotepec, 073 La Concepción, 088 Chiconautla, 096 Arroyozarco (Figure 1). ID 033 Estado de México belongs to the Lerma-Santiago-Pacific basin and the other four to the Valley of Mexico basin. This irrigated area of Estado de México is dedicated to

Table 1. Overview of Estado de México's IDs (2010–2020)

	Main crops	Municipalities	Area (km²)	Agricultural and forest area, 2016 (km²)	Population size, 2010 (No. of inhabitants)	Population size, 2020 (No. of inhabitants)	Population density, 2016 (inhabitants /km²)	Population density, 2020 (inhabitants /km²)	Population growth rate, 2010–2020 (%)
ID 033 Estado de México	Corn, ryegrass, forage oats, grain wheat, greenhouse tomato, and rose bush	Temascalcingo	362.34	140.55	62 695	66 414	173	183	6
		Atlacomulco	257.89	109.03	93 718	109 384	363	424	17
		Jocotitlán	277.35	173.35	61 204	69 264	221	250	13
ID 044 Jilotepec	Grain corn, ryegrass, forage oats, associated fruit trees, and greenhouse tomatoes	Jilotepec	586.2	329.7	83 755	87 671	143	150	5
		Soyaniquilpan de Juárez	128.64	68.47	11 798	14 323	92	111	21
ID 073 La Concepción	Alfalfa, fodder corn, grain corn, potatoes, and greenhouse tomatoes	Cuautitlán Izcalli	26.23	17.50	140 059	555 163	5340	21 165	296
		Teoloyucán	53.6	5.76	63 115	65 459	1178	1221	4
		Tepotzotlán	188.22	65.79	88 559	103 696	471	551	17
ID 088 Chiconoutla	Forage corn, fodder oats, alfalfa, grain corn, greenhouse tomatoes, and other forage plants	Tonanitla	9.04	5.94	10 216	14 883	1130	1646	46
		Tecámac	156.97	49.18	364 579	547 503	2323	3488	50
ID 096 Arroyozarco	Corn grain, forage oats, ryegrass, and greenhouse tomatoes	Aculco	453.74	271.17	44 823	49 266	99	109	10
		Polotitlán	126.69	83.84	13 002	14 985	103	118	15

Source: own elaboration with data from INEGI (2017, 2022) and CONAGUA (2019).

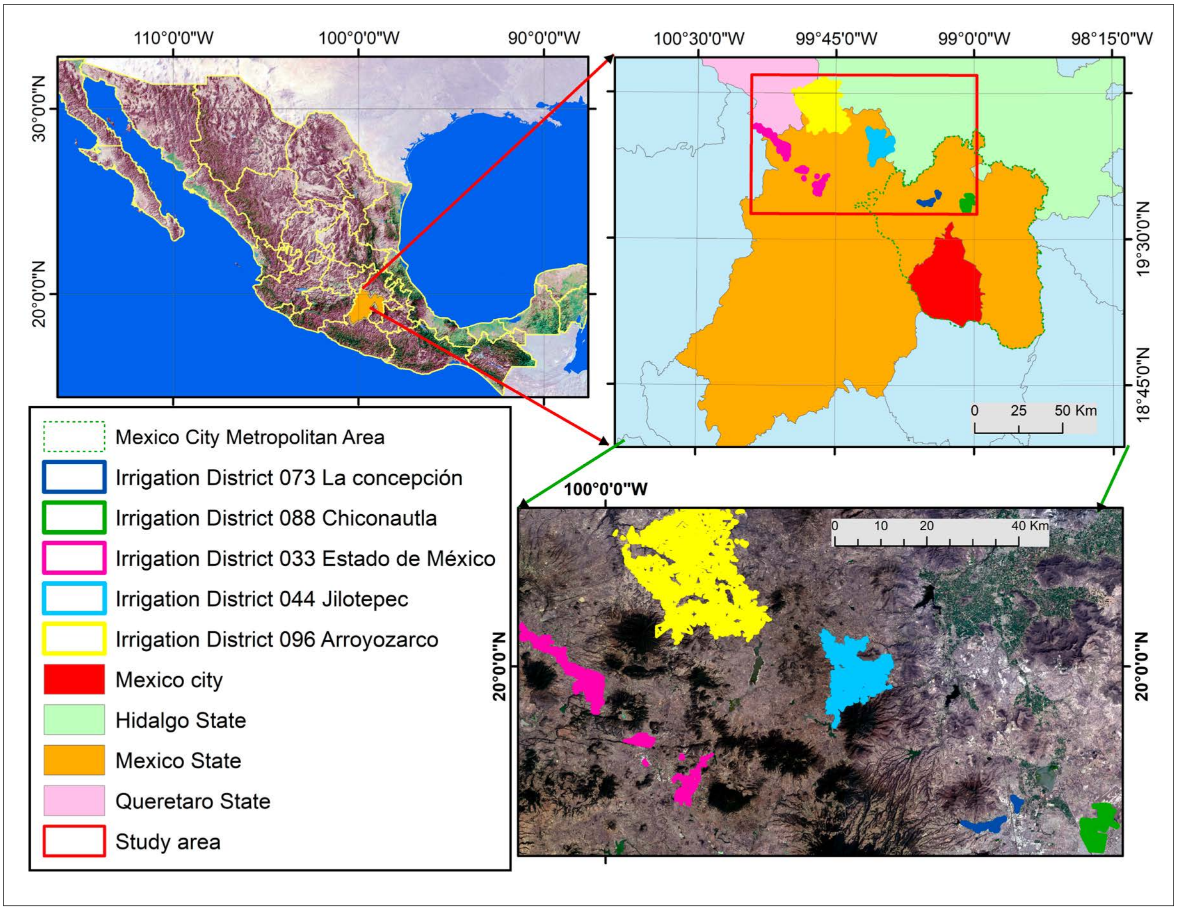

Figure 1. Location of the study area. Source: own elaboration.

agriculture as it has the essential water resource for production. The total area of the five IDs in the study area is 52,986 ha. It is worth mentioning that ID 073 La Concepción and ID 088 Chiconautla are located in the Valley of Mexico metropolitan area, which has historically maintained an accelerated urban growth; ID 096 Arroyozarco includes plots in the states of Hidalgo and Querétaro; and ID 033 Estado de México has plots in the state of Querétaro.

Data

Satellite imagery analysis is a reliable and valuable tool in urban territorial studies, as these images can be used to detect changes in the Earth's surface and update urban information, identifying newly constructed areas and urban expansion (Fazal, 2000; Heider et al., 2018). This study used images from the European Space Agency's Sentinel-2 satellite for 2016 and 2022, downloaded from the European Space Agency's Copernicus open-access center (ESA, 2022); 2016 images were obtained in 1C format, so they were processed with Sen2Cor software to transform them into 2A format with atmospheric correction.

The Sentinel images have 13 bands with wavelengths of 0.44 μm (coastal aerosol) to 2.19 μm (shortwave infrared); four bands have 10 m spatial resolution, six bands 20 m, and three 60 m. Three images were used to cover the study area: 14QLH, 14 QMH, and 14QMG. The urbanized area in the IDs was quantified in shapefiles provided by the

National Water Commission (CONAGUA, after the name in Spanish) with plots for the year 2010.

Three semi-structured interviews with CONAGUA operational personnel were held to collect information from the actors' perspectives on experiences and expectations related to land-use change in the IDs, the drivers of urbanization, and its effect on agricultural activities. Additionally, a tour of ID plots was carried out to observe the state of agricultural activities and urban/industrial development in the territory. As pointed out by Hernández-Sampieri and Mendoza-Torres (2014), this qualitative approach aims to complement and elaborate on the results of the quantitative analysis obtained from the analysis of satellite images, enriching the research with the interviewed actors' perspectives, opinions, and comments regarding the perception of the loss of agricultural area.

Processing and Analysis of Images and Interviews

Each band was clipped to cover the area of the shapefiles of the IDs analyzed. Subsequently, a mosaic was constructed with the three images that make up the total area. All image processing was done with the software QGIS (v. 3.16).

All ID plots from the 2010 shapefiles were used to identify those where agriculture was converted to urban uses. Each plot in the 2016 and 2022 images was visually examined to determine whether the plot was still dedicated to agriculture or had been partially or totally urbanized; in some cases, the change in land use was validated using Google Earth images. Finally, the agricultural area for 2016 and 2022 was quantified to determine the change and loss in the agricultural area relative to the baseline year 2010 calculated based on the CONAGUA plot shapefiles. Then, the urban area growth rate between 2016 and 2022 was estimated using the following equation (L. Shi *et al.*, 2019):

$$Ar = \frac{A_{t2} - A_{t1}}{A_{t1}} \qquad \text{(Equation 1)}$$

where Ar is the urban area growth rate in 2016–2022, $At2$ is the urban area in 2022, and $At1$ is the urban area in 2016, with $At2 > At_1$.

The analysis of urban growth and the transformation of the ID plots in Estado de México is based on the visual examination of the superposition of plot shapefiles on satellite images. Similarly, a field trip was carried out to the areas most af 2fected by urbanization, where it was possible to observe the conversion of agricultural to urban or industrial use on the IR plots. Based on research in other countries, five major urban growth patterns were identified and analyzed in the plots of the Estado de México IDs studied.

The qualitative information was processed through a content analysis of the information provided by interviewees to categorize and contextualize the collected data, to know their expectations about possible drivers of land use change, and to determine which of them promote or inhibit urban growth in the Estado de México IDs. The field trip corroborated the information obtained from the spatial analysis of images and was complemented with information provided by interviewees. A methodological overview is illustrated in Figure 2.

Urbanization and Loss of Agricultural Land in IDs

In general, urban growth displacing agricultural areas was observed in all IDs (Table 2). However, the percentage of agricultural land loss varies according to the proximity of each district to cities and the Mexico City metropolitan area.

The IDs with the highest urban growth rate were ID 044 Jilotepec and ID 088 Chiconautla. However, ID 044 Jilotepec has a larger surface area, so, despite having the highest urban growth rate, the percentage of agricultural land loss is much lower than in ID 088 Chiconautla and ID 073 La Concepción, the latter with the greatest loss of surface area in both years evaluated. In 2010–2022, the ID with the greatest loss of agricultural area was ID 088. It is important to note that ID 088 and ID 073 are located within the Valley of Mexico metropolitan area. In addition, ID 088 is home to the Felipe Ángeles International Airport, and its construction has changed the land use of many plots that are now included in the airport project. ID 073 is the smallest ID in Estado de México;

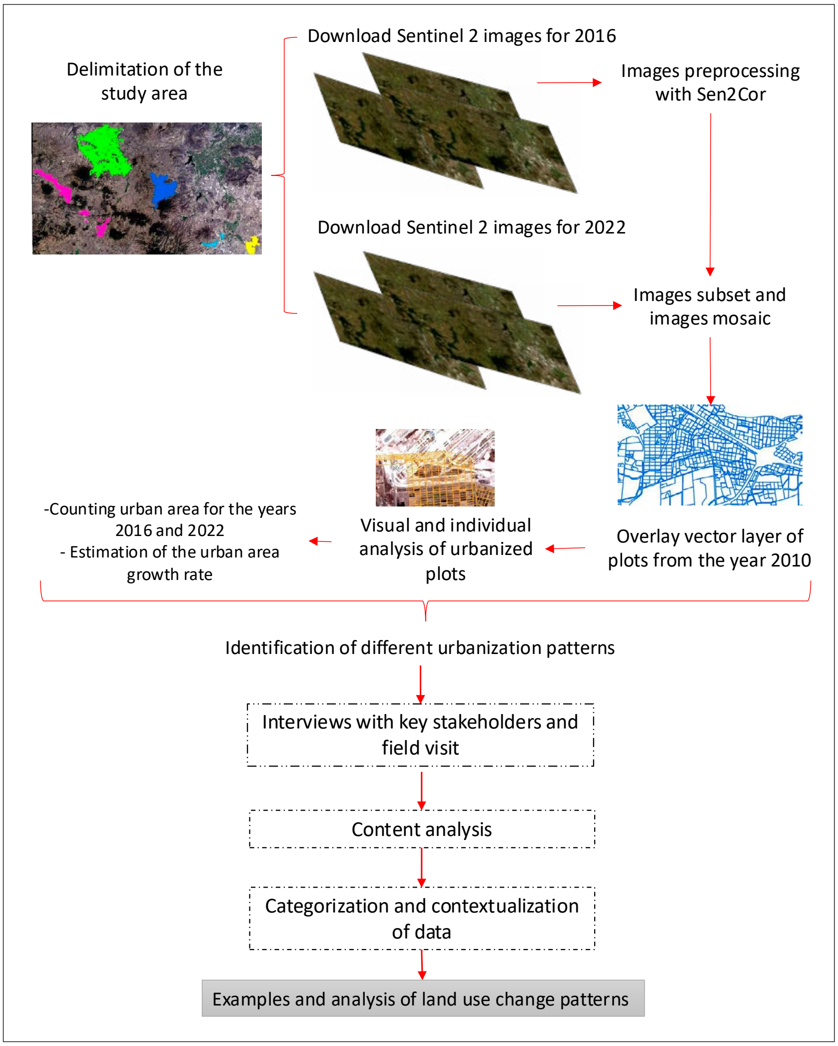

Figure 2. Methodological overview. Source: own elaboration.

approximately half of its surface area changed to urban use (47% of the total area) during the period 2010–2022 (Table 2).

ID 033 Estado de México shows the lowest percentage of conversion of agricultural land to urbanization. Finally, ID 096 Arroyozarco, with the largest surface area, showed the lowest urban growth rate, probably because it is the ID farthest from the Valley of Mexico metroopolitan area, with plots in the states of Hidalgo and Querétaro.

It should be noted that the results reported here differ from the CONAGUA statistics (CONAGUA, 2019) because our analysis considers plots that were agricultural in 2010 but currently have abandoned any agricultural activity. As these plots do not consume irrigation water but lack buildings, these plots are still considered agricultural land.

Urban Growth Patterns

Although the districts are located in the same state and the socioeconomic conditions may be similar, our results show different patterns of urban growth within each district, which, according to our analysis, are influenced by the proximity to Mexico City and the Valley of Mexico metropolitan area. The patterns of urbanization and loss of agricultural area found within the analyzed IDs are described and discussed below.

Table 2. Urbanized area in Estado de México IDs.

	Total agricultural area, 2010 (ha)	Urban area, 2016*		Urban area, 2022*		Urban growth rate, 2016–2022
		Ha.	% of the total area	Ha.	% of the total area	
DR033 Edomex	7591	49	0.65	69	0.91	0.40
Dr044 Jilotepec	9132	294	3.22	684	7.49	1.32
DR073 La Concepción	638	230	36.05	302	47.27	0.31
DR088 Chiconautla	3076	406	13.21	858	27.90	1.11
DR096 Arroyozarco	32 550	568	1.75	704	2.16	0.24
Total	52986	1548		2617		0.7

*Urbanized area relative to the total agricultural area in 2010.

Source: own elaboration.

Urban Growth Close to Roadways

Some studies have found that roads can directly or indirectly affect land-use patterns and distribution (Asadi et al., 2016), with greater urban growth in areas with greater road infrastructure (Cano Salinas et al., 2017). This type of growth is evident in plots close to a road of ID 096 Arroyo Zarco (Figure 3). Heider *et al.* (2018) argue that greater peri-urbanization near roadways allows access to cities or urban settlements. Therefore, it is expected that the construction of more communication routes, such as roads, will provide greater access and mobility to remote territories, which could accelerate the urbanization process starting in the land adjacent to the roads, increasing the proximity to services and the value of the land.

In addition to houses near roadways, this example shows the construction of warehouses, gas stations, and hotels as a result of greater movement of people from one place to another. The images show that land use in part of the plot changed to urban use and another part remains under agricultural use. However, urban growth will probably end up covering the entire plot and the conversion and fragmentation of cultivated land adjacent to roadways will be difficult to control, since roadways promote urban growth and, with it, urban invasion of agricultural land in the outskirts of metropolitan areas and small towns, as stressed by some authors (Salem et al., 2020).

Urban Growth due to Infrastructure Construction

According to Li (2012), drastic changes of land use occur mainly in areas with urban-rural interactions with accelerated population growth and high economic status. As a consequence of this economic growth and the easier mobility of people and goods, agricultural land is reduced in areas adjacent to infrastructure projects (Smidt *et al.*, 2018). Figure 4 shows an example of the loss of agricultural plots in ID 088 *Chiconautla* related to the construction of the Felipe Ángeles International Airport (AIFA, after its name in Spanish). The figure shows that the airport megaproject has been constructed on land previously dedicated to agriculture, similar to the case of the New Mexico City International Airport (NAICM) project, where urban growth displaced ejido land with crops (Romero-Padilla and Hernández-Juárez, 2023). Since the project has not yet been completed, it will likely require additional area, with plots adjacent to the airport

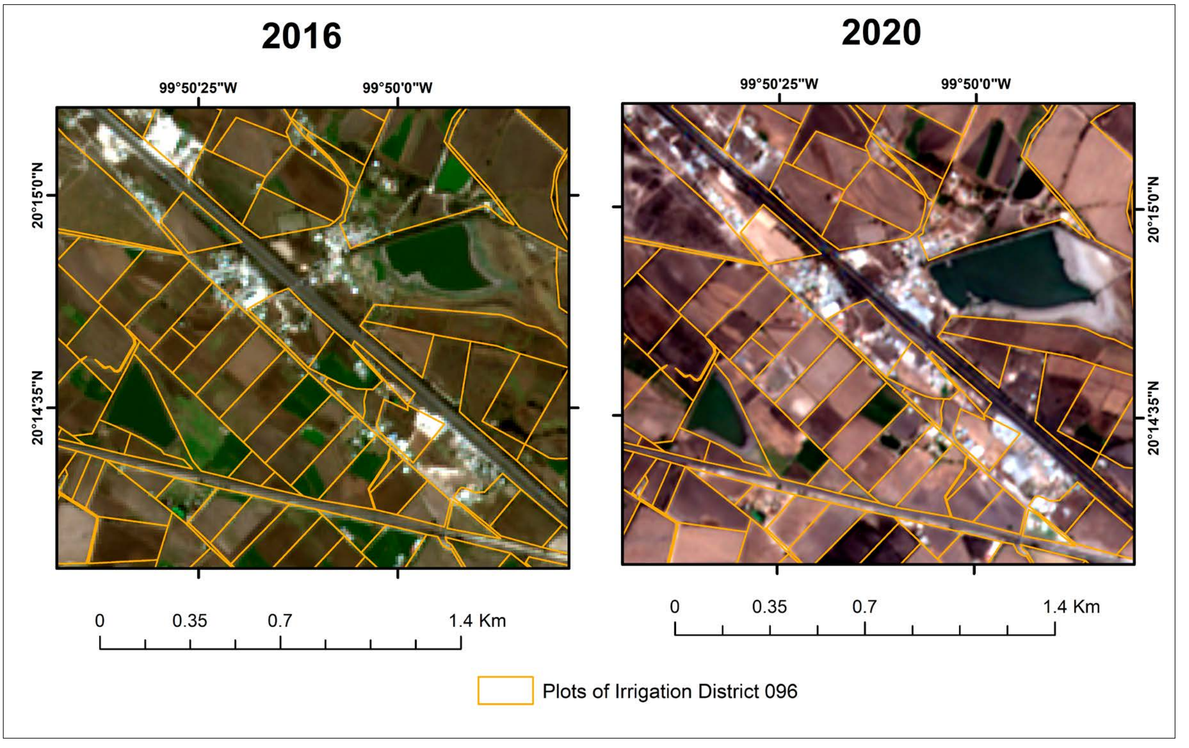

Figure 3. Urban growth near roadways, plots in ID 096 Arroyozarco. Source: own elaboration.

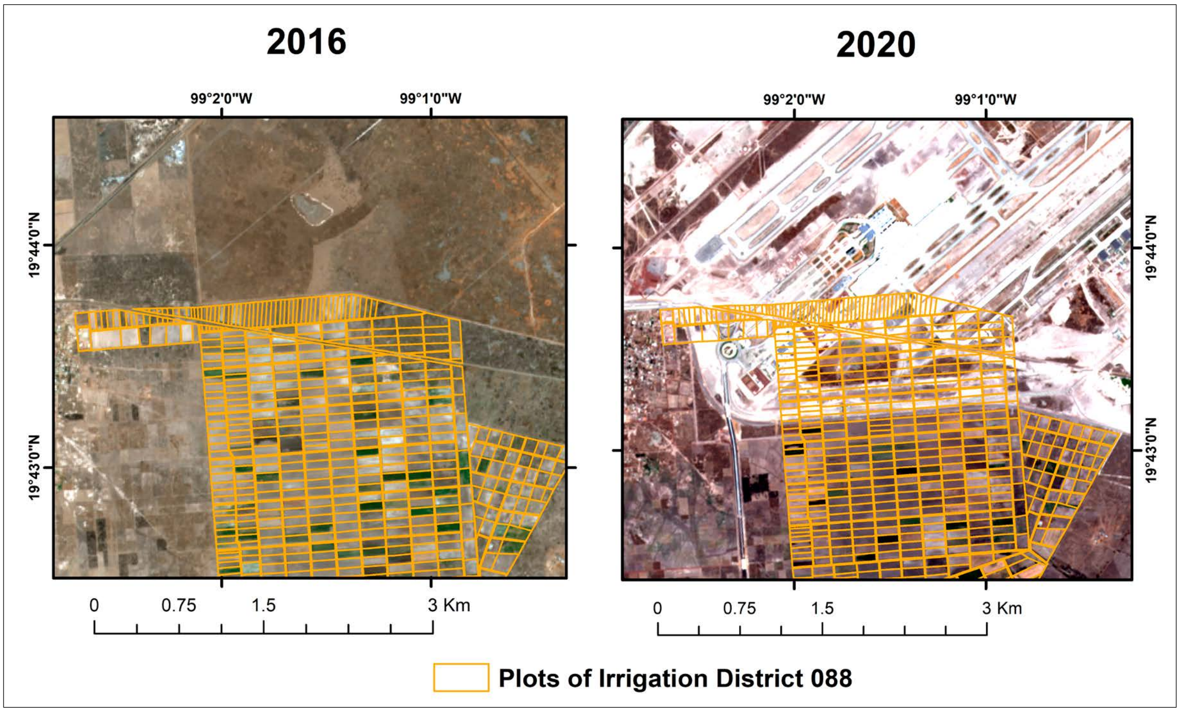

Figure 4. Urban growth due to infrastructure construction, plots of ID 088 Chiconautla. Source: own elaboration.

abandoning agricultural activities in response to the commerce/service needs of the people who use or work at the airport.

This example of urban growth derived from infrastructure is observed in the municipality of Tecámac, which, together with Cuatitlán Izcallli, is the municipality with the largest population; both municipalities are located north of Mexico City and have maintained an accelerated population growth. These municipalities still have agricultural plots with irrigation services; however, the urban area is expanding, and these plots will probably lose their agricultural vocation very soon. Consequently, as Fazal (2000) mentioned, the canals and tributaries that previously flowed through agricultural land will most likely be invaded and used for the disposal of garbage and waste.

Urban Growth Near Metropolitan Areas

In the metropolitan areas of Mexico, population growth will continue relentlessly, bringing with it the search for additional housing and service spaces to meet population needs, mainly near cities, leading to the loss of agricultural land on the outskirts. As indicated by Rimal et al. (2018), this urbanization is driven by interregional migration coupled with the growth of the local population, as areas near or within metropolitan areas offer greater job opportunities.

Figure 5 shows an example of urban growth in ID 077, located in the municipality of Tecámac within the Valley of Mexico metropolitan area. As indicated in Table 2, the IDs in this area had the highest percentage of urbanization and, consequently, losses of agricultural plots. As highlighted by Pandey and Seto (2015), in India, the highest loss of agricultural land occurs in areas adjacent to large cities. This growing urbanization towards peri-urban areas makes changes of land use unavoidable and impacts food production in periurban areas of developing countries, including Mexico (Ziem Bonye *et al.*, 2021).

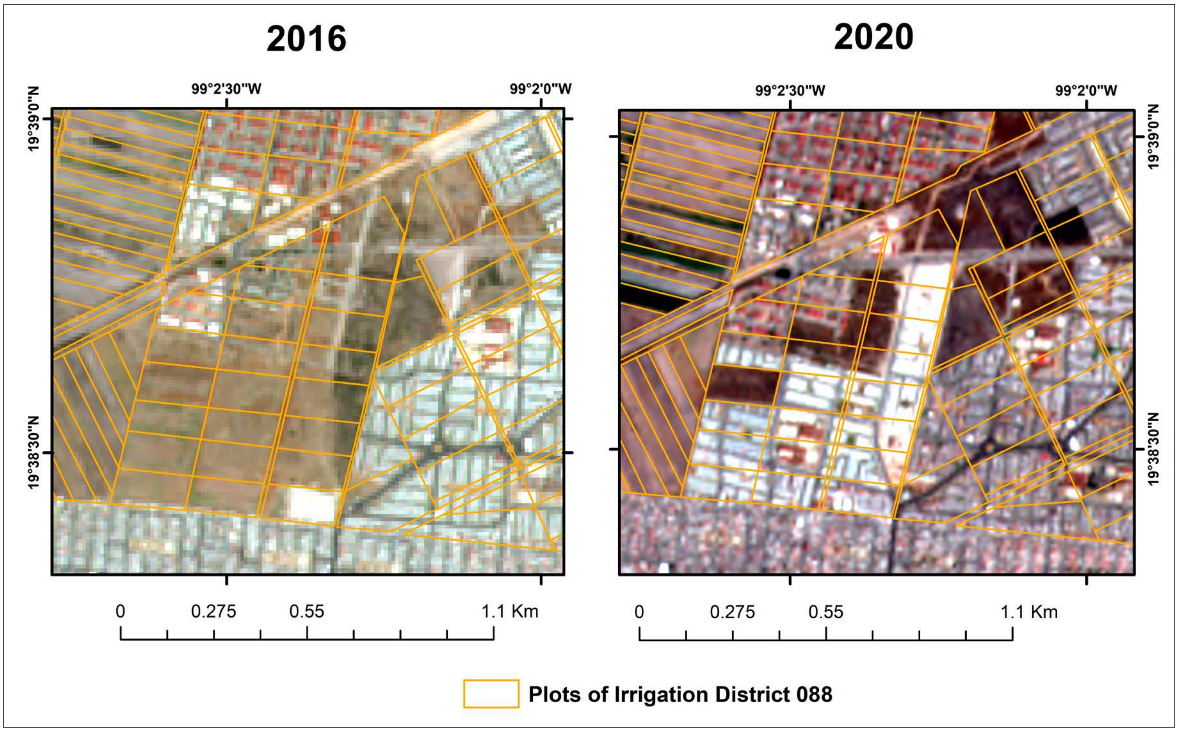

Figure 5. Urban growth adjacent to already established metropolitan areas, plots of ID 073 La Concepción. Source: own elaboration.

Disperse Growth

In IDs farther from cities, more dispersed urban growth was observed, associated with housing development within or near plots (Figure 6). Unlike IDs close to cities, this example of urban growth in more rural areas is characterized by spatial dispersal rather than concentration in major urban centers (Rimal et al., 2018), associated with population density in the municipalities where IDs are located. Figure 4 shows an example of this growth in ID 44 Jilotepec, which, together with ID 96 Arroyozarco, comprises the municipalities with the lowest population density in the study area.

Although it is slower than those mentioned above, this growth pattern could be of concern since, as noted by Inostroza et al. (2013), it shows an expanding trend with greater land consumption than in the 1990s, when population density was lower.

In the images, this pattern of urban growth appears as the distribution of small blocks scattered along agricultural land in the study area, corresponding to adjoining houses within plots. Consequently, adjacent plots can be fragmented and reduced in size, and, according to Orozco-Hernández *et al.* (2017), plot fragmentation and crop diversification compromise agricultural production in Estado de México. Although protected agriculture could be implemented on smaller plots under intensive production, it involves high costs that could be unaffordable to many producers. Furthermore, a more dispersed housing development makes installing basic services such as electricity, water, and drainage difficult compared to a more compact and organized growth.

Growth due to Industrial Development

The example of the recorded industrial growth pattern includes companies concentrated in ID 044 Jilotepec (Figure 7). While industrial areas can create jobs and sources of income for the population, providing a solid basis for economic

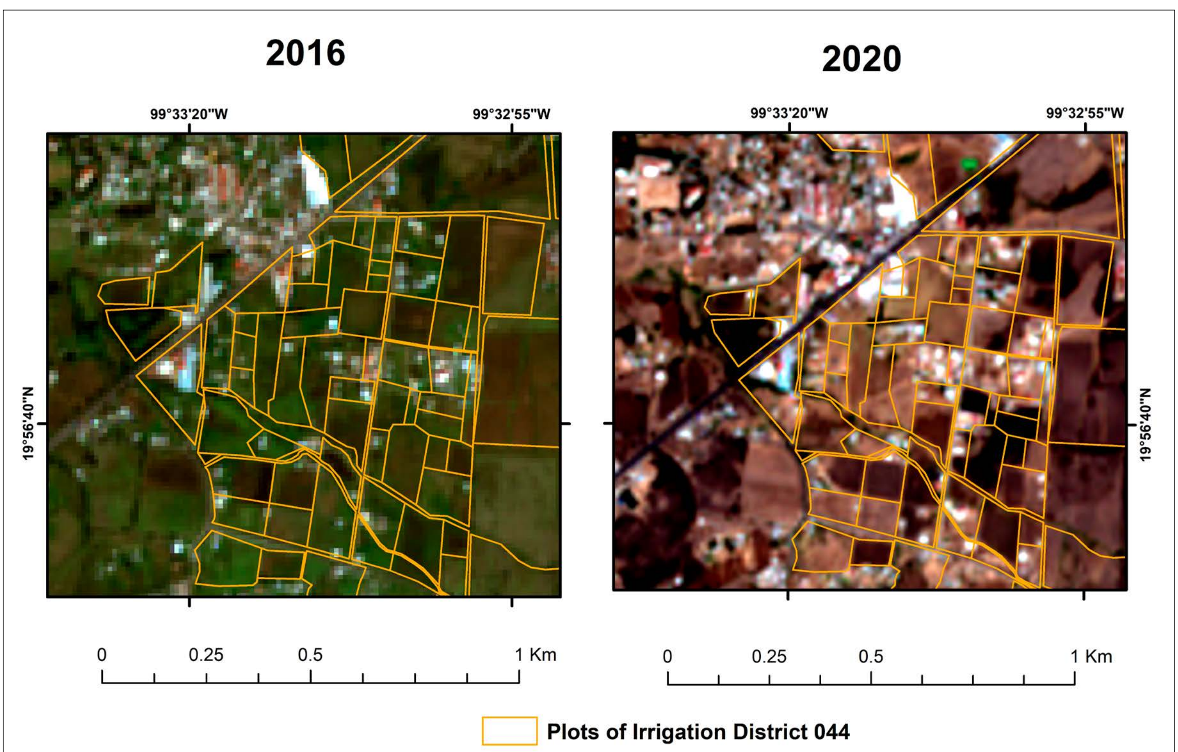

Figure 6. Disperse urban growth, plots of ID 44 Jilotepec. Source: own elaboration.

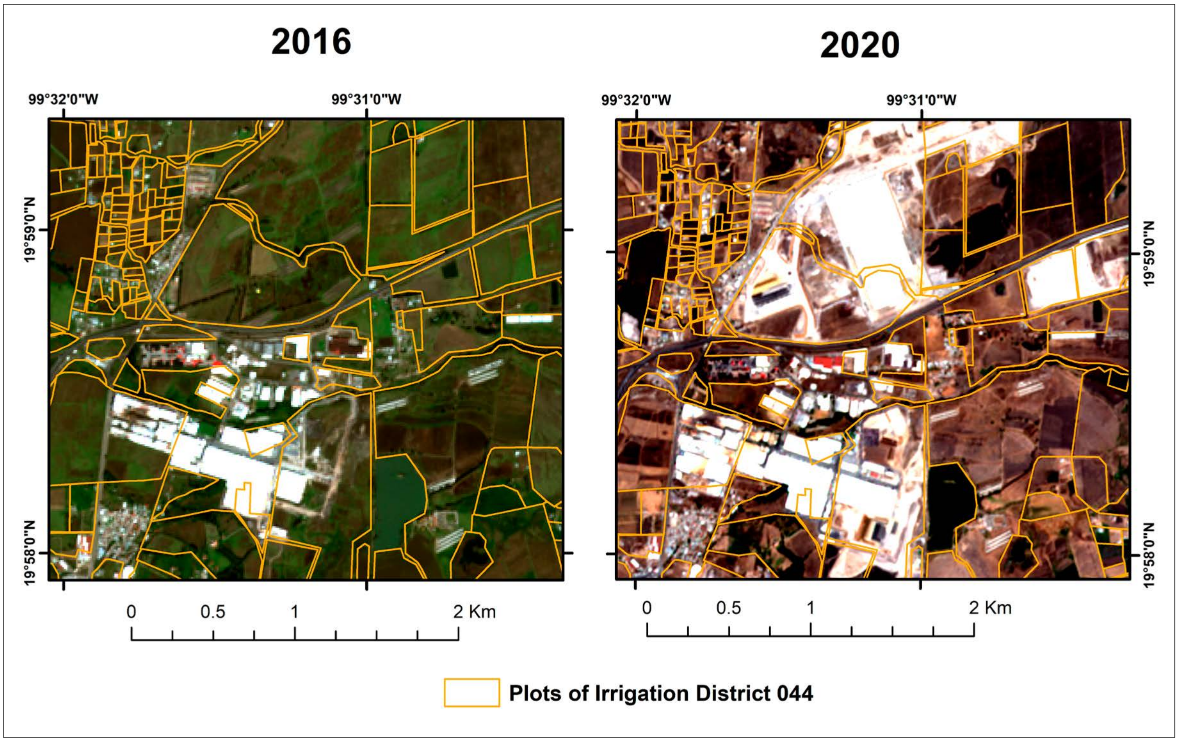

Figure 7. Urban growth due to industrial development in plots of ID 044 Jilotepec. Source: own elaboration.

development (Wu *et al.*, 2022), industrial growth can drastically convert the landscape from rural to urban by significantly reducing agricultural area and accelerating the urbanization of plots by fostering migration (Diaz Barriga, 1995).

Figure 7 shows the loss of agricultural plots due to vigorous industrial growth, evident in extensive constructions that require not only land but also resources and services, such as water, roadways, and drainage, among others (Azadi *et al.*, 2011). In this example, the industrial complex is strategically connected with roads that facilitate communication and transportation between warehouses and the main cities of Mexico.

What are the likely drivers of conversion from agricultural to urban land in IDs, according to the perception of local actors?

Population dynamics and growth have led to different forms of urbanization and territorial development that have contributed to shaping agriculture and rural areas. This study has shown various examples of urbanization in IR plots of Estado de México identified in satellite image analyses.

Complementing the spatial analysis, the semi-structured interviews with CONAGUA operational personnel facilitated the identification of the main drivers of the change from agricultural to urban land use. Figure 8 shows the main elements that drive or inhibit this change, as highlighted by interviewees. They agreed that proximity to cities is one of the main drivers of urbanization. This assertion is supported to some extent by the analysis of images, evidencing that the main driver of the urbanization of agricultural plots has been the proximity to Mexico City. The Valley of Mexico metropolitan area has been — and continues to be — a magnet of attraction for the population. In this area, they find greater job opportunities and demand housing spaces; consequently, the agricultural land adjacent to this area shows the fastest conversion of agricultural land to urban land uses.

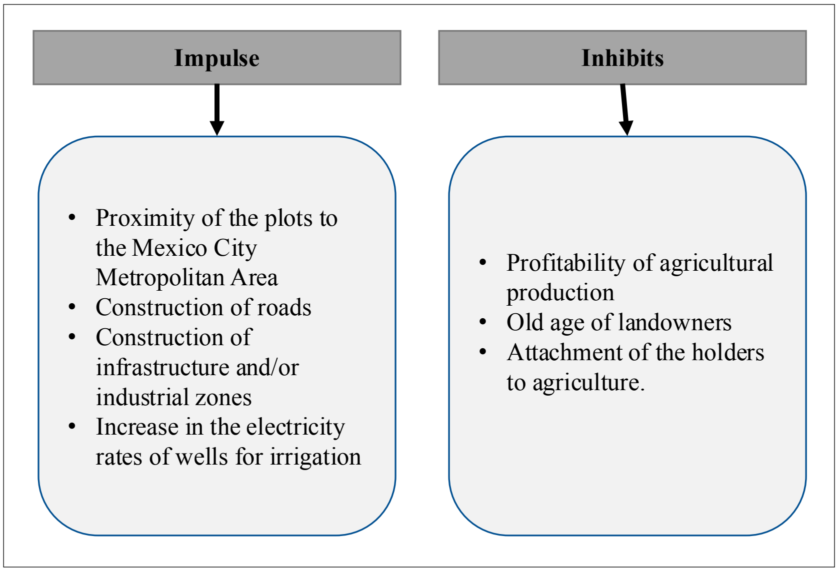

Figure 8. Factors identified by CONAGUA officials, which, in their perception, promote or inhibit the change from agricultural to urban use. Source: own elaboration.

Interviewees also agreed that a second driver of urbanization in the ID plots is the construction of roads related to the availability of services needed for population growth and distribution. The construction of communication roads directly or indirectly affects the urbanization of agricultural plots, directly when the road crosses the plot, and indirectly by fostering the urbanization of plots along the road. In this sense, the Texcoco and Santa Lucia airport projects have affected ID plots in Estado de México. This is an ongoing process since the Santa Lucía airport project includes plans to build a highway, which will directly affect plots of ID 088.

In addition to requiring mobility services, urban growth also involves services aiming to meet basic population needs; as a result, warehouses and factories are built to address this demand. In this sense, interviews with key actors and field tours of the IDs of Estado de México corroborated the construction of infrastructure and shopping centers on ID plots, affecting the ID Jilotepec, as mentioned above. These industrial zones are strategically located, with proximity and access to metropolitan areas of central Mexico for product distribution. This is consistent with Aguilar and Ward (2003), who stated that metropolitan urban expansion occurs towards the outskirts at the expense of adjacent rural areas, bringing with it the development of shopping centers and warehouses in more accessible areas. In addition to the change of land use in plots, an important aspect highlighted by the interviewees is the water required for industrial use, involving the competition between agriculture and industry for this resource.

Finally, the fifth driver of the conversion of agricultural to urban land use, as perceived by interviewees, is the higher cost of electricity related to water wells, which becomes more expensive as the number of people dedicated to agriculture decreases. As a result, farmers search for new sources of income and consider selling or renting their plots.

Even with an unfavorable scenario for agriculture facing urbanization, some factors can promote the continuity of agricultural activity. According to key informants, these factors are more related to the characteristics of production units, such as the attachment of producers to agriculture and the profitability of this activity. With greater profitability of agricultural activities, producers dedicate more time and investment to production. Under these conditions, they are less likely to seek sources of income outside agriculture because the opportunity cost of staying in agriculture is greater than the potential income from alternative activities. On the other hand, attachment to agriculture is related to the age of farmers. Older producers are generally more attached to the land and less willing to search for alternative sources of employment because they only have experience in agriculture; however, ensuring the continuity of agricultural activities seems to be challenging for younger generations.

What are the implications of urban growth on socioeconomic and environmental configuration?

The geographic space occupied by society is under continual change; thus, urbanization and change in land use have major implications for the environment and territory where societies develop. In Estado de México, the areas close to Mexico City and the metropolitan area have particularly experienced continuous urbanization (Romero-Padilla *et al.*, 2023). This transformation process, specifically in areas with agricultural potential, has significant social, economic, and environmental consequences. As a result of continuous urban growth, urban sustainability has been explored from a multidimensional perspective, considering environmental, economic, and social aspects (Vázquez Morán *et al.*, 2023). Some issues derived from urban expansion in the study area are discussed below.

Urbanization has detrimental effects on environmental sustainability and can influence soil degradation, water pollution, and biodiversity loss (Radwan et al., 2019). Weather conditions are becoming more extreme; these result from global warming, largely caused by population growth and its increasing demand for goods. This requires increasing natural resources to meet the population's needs. In this context, agriculture plays an important role in food production and supply of raw materials to address the new preferences of local inhabitants; however, urbanization of agricultural plots can reduce this production of food and raw materials.

While agriculture is indeed one of the activities that require high volumes of water, household areas, shopping centers, and industrial areas also require water, in addition to reducing water infiltration in the soil by adding an asphalt or concrete layer to buildings and roadways associated with urbanization. As a result, the volume of water in aquifers decreases, causing environmental and social issues as water is a vital resource. In this regard, in the construction of the Felipe Ángeles International Airport, ID 088 Chiconautla, Moreno Sánchez and Espejel Mena (2023) foresee the loss of biodiversity and water shortage in adjacent areas, since there are no nearby springs or aquifer recharge zones.

Likewise, population growth requires more housing space at the expense of agricultural or forest areas, which maintain vegetation and ecosystems that absorb carbon and mitigate greenhouse gas emissions. Urban growth reduces the area covered with vegetation and increases greenhouse gas emissions associated with construction and greater use of vehicles and transport, contributing to the rise in global temperature.

Economic issues derived from agricultural land loss can reduce agricultural production and affect food sustainability by increasing imports of agricultural products. This directly affects prices and, in extreme cases, can lead to inflation and unemployment. Furthermore, jobs can be lost in rural areas and promote migration to cities, increasing the demand for urban services, jobs, and housing. This brings new economic and social issues in cities, where it is more expensive to address the needs of immigrants and provide them with space and jobs.

A new form of rural-urban interaction or new rurality emerges alongside urban growth, where cities establish close links with rural localities. As Galindo Pérez *et al.* (2020) point out, these relationships are not only established between urban centers, but new relationships are being created between the city and the countryside, probably further promoting the change of land use in rural areas. An example of this new rural-urban relationship was observed in ID 96 Arroyozarco, where growth is more dispersed throughout the ID due to the ease of access and mobility from these homes to urban areas.

The social impacts and consequences of the conversion of agricultural to urban uses include the loss of cultural identity by changing the geographic space where rural populations used to live, as well as family conflicts over the sale of land whose value has increased due to urbanization.

Furthermore, even when farmers receive a payment for their land, the loss of their means of production causes a long-term loss of family income, leading to financial instability in rural families.

The land-use-change issue has also been reflected in conflicts during several government terms. An example is the social conflict due to the NAICM construction proposal, which led to a social movement involving farmer groups and became a political struggle. Although the construction of the Felipe Ángeles airport in ID 088 also triggered social unrest due to the sale of agricultural land, these social conflicts were minor, unlike those related to the NAICM (Moreno-Sánchez *et al.*, 2020).

Land-sale decisions, in addition to creating conflicts between rural communities and companies, also cause conflicts between farmers, with some choosing to sell their land and others deciding to keep it.

Factors Involved in Land-Use Change

Land-use change is caused by different economic, political, and social factors. Governments play a central role in modifying land-use plans when they approve the construction of industrial projects or when granting construction licenses to households in certain areas. The interviews with key actors highlighted the participation of the local government as a key aspect of the establishment of industrial zones on ID 044 Jilotepec, while in ID 088 Chiconautla, the federal and state governments authorized the conversion of agricultural land for the construction of the Felipe Ángeles International Airport.

The authorization of licenses for land-use changes involves real-estate and industrial companies requesting such licenses. These actors seek proximity to areas near roads and access to public services. In this sense, the proximity of Estado de México to several metropolitan areas and national transport hubs, such as the international airports established in the state, makes it an attractive area for industrial investment.

Despite the constant pressure on farmers about changes in land use and the perception of agriculture as a sector with lower economic income compared to other sectors, there have been demonstrations against the conversion of agriculture to urbanization in Estado de México. However, the lack of incentives to remain in agriculture and attractive land prices have weakened the resistance of farming communities to dedicate their land to agriculture.

CONCLUSIONS

The results allowed quantifying the loss of agricultural area in each ID and, as a consequence of spatial heterogeneity, we identified and analyzed five urban growth patterns in the study area. These patterns indicate that the main drivers of urban growth are the proximity to the metropolitan area, roads, and industrial zones, and the construction of infrastructure and industrial development. These findings suggest that, in general, population growth and the provision of basic services demand additional land at the expense of the agricultural area.

Urban growth was generally faster in IDs located within the Valley of Mexico metropolitan area. In this sense, proximity to cities and the construction of roads, industries, and infrastructure are all related to the loss of agricultural land, while the profitability of agricultural activity, the advanced age of farmers, and their attachment to agriculture restrain this loss.

Continued population growth will demand more housing space, so urbanization will persist. However, it is possible to plan urban growth to protect fertile agricultural land through effective planning or regulation. In addition, it is important to support the value of agriculture through sectoral policy instruments that encourage producers to remain in agricultural activity, mainly in areas with agricultural potential, such as the Estado de México IDs.

On the other hand, it is essential to intensify and innovate to increase the efficiency of agricultural production, maximize productivity with higher yields, and improve production systems with the available resources. Additionally, the efficiency of urban land use should be improved with better planning and structuring of urban areas, which would also facilitate access to basic services for the population.

REFERENCES

Aguilár, A. G., y Ward, P. M. (2003). Globalization, regional development, and mega-city expansion in Latin America: Analyzing Mexico City's peri-urban hinterland. *Cities*, *20*(1), 3–21. https://doi.org/10.1016/S0264-2751(02)00092-6

Asadi, A., Barati, A., Kalantari, K. y Odeh, I. (2016). Study of Relationship Between Roads Network Development and Agricultural Land Conversion in Iran NorthWest. *Int. J. Environ. Res.*, *10*(1), 51–58.

Azadi, H., Ho, P. y Hasfiati, L. (2011). Agricultural land conversion drivers: A comparison between less developed, developing and developed countries. *Land Degradation and Development*, *22*(6), 596–604. https://doi.org/10.1002/ldr.1037

Bhatta, B. (2010). Causes and Consequences of Urban Growth and Sprawl. In *Analysis ofUrban Growth and Sprawl from Remote Sensing Data* (pp. 17-36). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-05299-6_2

Cano Salinas, L., Rodríguez Laguna, R., Valdez Lazalde, J. R., Acevedo Sandoval, O. A., y Beltrán Hernández, R. I. (2017). Detección del crecimiento urbano en el estado de Hidalgo mediante imágenes Landsat. *Investigaciones Geográficas*, (92), 1–10. https://doi.org/10.14350/rig.52339

CONAGUA. (2019). Estadísticas agrícolas de los distritos de riego. Año agrícola 2017-2018. In *Secretaría del medio ambiente y recursos naturales*. http://www.gob.mx/cms/uploads/attachment/file/147019/ea2011-2012.pdf

CONAGUA. (2022). *Estadísticas del Agua en México 2021*. http://sina.conagua.gob.mx/publicaciones/EAM_2021.pdf

Diaz Barriga, M. (1995). The politics of urban expansion in Mexico City: a case study of ejido urbanization in the Ajusco Foothills, 1938-1990. *Urban Anthropology*, *24*(3–4), 363–396. https://www.jstor.org/stable/40553289

ESA. European Space Agency. (2022). *Copernicus Open Access Hub*. https://scihub.copernicus.eu/dhus/#/home

Fazal, S. (2000). Urban expansion and loss of agricultural land - a GIS based study of Saharanpur City, India. *Environment and Urbanization*, *12*(2), 133–149. https://doi.org/10.1177/095624780001200211

Galindo Pérez, M. C., Pérez Campuzano, E. y Suárez Lastra, M. (2020). Movilidad intrarregional en la región Centro de México, 2000-2015. *Investigaciones Geográficas*, (102), 0–2. https://doi.org/10.14350/rig.60093

Graizbord, B. y González Granillo, J. L. (2019). Urban Growth and Environmental Concerns: The Venture of the Greater Mexico City Metropolitan Area. *Politics and Policy*, *47*(1), 178–206. https://doi.org/10.1111/polp.12292

Heider, K., Lopez, J. M. R. y Scheffran, J. (2018). The potential of volunteered geographic information to investigate peri-urbanization in the conservation zone of Mexico City. *Environmental Monitoring and Assessment*, *190*(219), 1–17. https://doi.org/10.1007/s10661-018-6597-3

Hernández-Sampieri, R. y Mendoza-Torres, C. P. (2014). *Metodología de la investigación. Las rutas cuantitativa, cualitativa y mixta*. McGraw-Hill.

INEGI. (2023). *Resultados oportunos del Estado de México. Censo Agropecuario 2022*.

Inostroza, L., Baur, R. y Csaplovics, E. (2013). Urban sprawl and fragmentation in Latin America: A dynamic quantification and characterization of spatial patterns. *Journal of Environmental Management*, *115*, 87–97. https://doi.org/10.1016/j.jenvman.2012.11.007

Li, Y. (2012). Urban-rural interaction patterns and dynamic land use: Implications for urban-rural integration in China. *Regional Environmental Change*, *12*(4), 803–812. https://doi.org/10.1007/s10113-012-0295-4

Moreno-Sánchez, E., Velázquez-Martínez, M. de los Á. y Rivero-Hernéndez, M. (2020). Lo urbano y el conflicto social por la construcción del aeropuerto en Texcoco, Estado de México. *Boletín Científico Sapiens Research*, *10*(2), 68–75. https://www.srg.com.co/bcsr/index.php/bcsr%0A259,545

Moreno Sánchez, E. y Espejel Mena, J. (2023). La administración local y los megaproyectos. La percepción de la construcción del Aeropuerto Internacional Felipe Ángeles en México. *RIDE Revista Iberoamericana para la investigación y el desarrollo educativo*, *14*(27). https://doi.org/10.23913/ride.v14i27.1544

Orozco-Hernández, M. E., García-Fajardo, B., Álvarez-Arteaga, G., y Mireles-Lezama, P. (2017). Tendencias del sector agrícola, Estado de México Trends in agricultural sector, Estado de México. *Quivera*, *19*(1), 99–121. http://www.redalyc.org/pdf/401/40153531006.pdf

Pandey, B. y Seto, K. C. (2015). Urbanization and agricultural land loss in India: Comparing satellite estimates with census data. *Journal of Environmental Management*, *148*, 53–66. https://doi.org/10.1016/j.jenvman.2014.05.014

Pandey, B., Zhang, Q. y Seto, K. C. (2018). Time series analysis of satellite data to characterize multiple land use transitions: a case study of urban growth and agricultural land loss in India. *Journal of Land Use Science*, *13*(3), 221–237. https://doi.org/10.1080/1747423X.2018.1533042

Pham, V. C., Pham, T. T. H., Tong, T. H. A., Nguyen, T. T. H., y Pham, N. H. (2015). The conversion of agricultural land in the peri-urban areas of Hanoi (Vietnam): patterns in space and time. *Journal of Land Use Science*, *10*(2), 224–242. https://doi.org/10.1080/1747423X.2014.884643

Radwan, T. M., Blackburn, G. A., Whyatt, J. D. y Atkinson, P. M. (2019). Dramatic loss of agricultural land due to urban expansion threatens food security in the Nile Delta, Egypt. *Remote Sensing*, *11*(3), 1–20. https://doi.org/10.3390/rs11030332

Rimal, B., Zhang, L., Stork, N., Sloan, S. y Rijal, S. (2018). Urban expansion occurred at the expense of agricultural lands in the Tarai region of Nepal from 1989 to 2016. *Sustainability (Switzerland)*, *10*(5). https://doi.org/10.3390/su10051341

Romero-Padilla, A. y Hernández-Juárez, M. (2023). Cambio de uso de suelo por la construcción del NAICM en Texcoco, Estado de México. *REVISTA TERRA LATINOAMERICANA*, *41*, 1–15. https://doi.org/10.28940/terra.v41i0.1608

Romero-Padilla, A., Storie, J., Storie, C. D. y Espinosa Herrera, J. M. (2023). Urbanization in the Mexico City Metropolitan Area 1900–2020: Urban Dynamics and Driving Factors. *Cartographica: The International Journal for Geographic Information and Geovisualization*, *58*(4), 189–204. https://doi.org/10.3138/cart-2023-0008

Salem, M., Tsurusaki, N. y Divigalpitiya, P. (2020). Remote sensing-based detection of agricultural land losses around Greater Cairo since the Egyptian revolution of 2011. *Land Use Policy*, *97*(August 2019), 104744. https://doi.org/10.1016/j.landusepol.2020.104744

Shi, K., Chen, Y., Yu, B., Xu, T., Li, L., Huang, C., Liu, R., Chen, Z. y Wu, J. (2016). Urban expansion and agricultural land loss in China: A multiscale perspective. *Sustainability (Switzerland)*, *8*(8), 1–16. https://doi.org/10.3390/su8080790

Shi, L., Taubenböck, H., Zhang, Z., Liu, F. y Wurm, M. (2019). Urbanization in China from the end of 1980s until 2010–spatial dynamics and patterns of growth using EO-data. *International Journal of Digital Earth*, *12*(1), 78–94. https://doi.org/10.1080/17538947.2017.1400599

Smidt, S. J., Tayyebi, A., Kendall, A. D., Pijanowski, B. C. y Hyndman, D. W. (2018). Agricultural implications of providing soil-based constraints on urban expansion: Land use forecasts to 2050. *Journal of Environmental Management*, *217*, 677–689. https://doi.org/10.1016/j.jenvman.2018.03.042

Spieth, P., Schneckenberg, D. y Ricart, J. E. (2014). Business model innovation – state of the art and future challenges for the field. *R&D Management*, *44*(3), 237–247. https://doi.org/10.1111/radm.12071

Vargas, N. y Magaña, V. (2020). Climatic risk in the Mexico city metropolitan area due to urbanization. *Urban Climate*, *33*(100644). https://doi.org/10.1016/j.uclim.2020.100644

Vázquez Morán, I., Adame Martínez, S., Hernández Rejón, E. M. y Calderón Maya, J. R. (2023). Evaluación de la sostenibilidad urbana multidimensional de la Zona Metropolitana Puebla-Tlaxcala, México. *Investigaciones Geográficas*, *112*(112). https://doi.org/10.14350/rig.60785

Wu, X., Huang, Y. y Gao, J. (2022). Impact of industrial agglomeration on new-type urbanization: Evidence from Pearl River Delta urban agglomeration of China. *International Review of Economics and Finance*, *77*(October 2021), 312–325. https://doi.org/10.1016/j.iref.2021.10.002

Ziem Bonye, S., Yenglier Yiridomoh, G. y Derbile, E. K. (2021). 'Urban expansion and agricultural land use change in Ghana: Implications for peri-urban farmer household food security in Wa Municipality.' *International Journal of Urban Sustainable Development*, *13*(2), 383–399. https://doi.org/10.1080/19463138.2021.1915790