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Article

Loss of agricultural soil from 2009-2024 in Celaya, Guanajuato

Andrés Mandujano-Bueno[1]
Juan Francisco Buenrostro-Rodríguez[2]
Micaela de la O-Olán[3]
Víctor Montero-Tavera[1,§]

1 Campo Experimental Bajío-INIFAP. Carretera Celaya-San Miguel de Allende km 6.5, Celaya, Guanajuato, México. CP. 38110. (mandujano.andrés@inifap.gob.mx).

2 CIMMYT. Carretera México-Veracruz km 45, El Batán, Texcoco, Estado de México, México. CP. 56237. (j.buenrostro@cgiar.org).

3 Campo Experimental Valle de México-INIFAP. Carretera Los Reyes-Texcoco km 13.5, Coatlinchán, Texcoco de Mora, Estado de México, México. CP. 56250. (delao.micaela@inifap.gob.mx).

Autor para correspondencia: montero.victor@inifap.gob.mx.

Abstract

Urban and industrial growth, along with the abandonment of agricultural land, reduces the area to produce food, which compromises the food security of the population. Establishing the dynamics of land-use change allows actions to be applied to mitigate its negative impact. The research aimed to determine the change in land use to estimate the magnitude of the reduction in agricultural land area in the municipality of Celaya, Guanajuato. To this end, the outlines of the municipal agricultural area from 2009 were updated over high-resolution images from the Google Earth Geographic Information System of 2024; of the resulting polygons, their water use condition was determined, and based on this, the potential impact on corn and bean production was calculated. The results show that in 15 years, Celaya has lost 4 647 agricultural hectares; 41% were destined for urban use, 20% for industry, 7% for roads, and 32% remain unused. The loss of agricultural land use was confirmed by the decrease in the visible atmospherically resistant index from 0.05 to -0.02. Most of the change in land use from agricultural to urban and industrial originates from well-based irrigation, while the change to disuse originates from rainfed land. The impact on agricultural production is the loss of almost 8 000 t of beans. Nevertheless, corn has increased its area sown by nearly 4 000 ha at the expense of reductions in other crops.

Keywords:

Phaseolus vulgaris L., *Zea mays* L., disuse of agricultural land, VARI.

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Introduction

The agricultural sector contributes to the economic development of a country. It represents between 4 and 25% of GDP, depending on the level of development. The growth of agriculture is two to four times more effective than that of other sectors in reducing the economic deprivation of the poorest, thereby reducing poverty while increasing the capacity to meet the basic nutritional and food needs of the population (Bautista *et al*., 2021; Banco Mundial, 2024).

However, all these benefits are at risk due to changes in agricultural land use to other uses. Industrial and urban growth, land abandonment due to migration, aging of producers, drought, high temperatures and loss of fertility are factors that reduce the area of farmland and food production (Espinosa *et al*., 2018; FAO, 2021; Maxwell, 2025).

The thriving industrial sector is crucial for the development of a modern economy, but it sometimes develops at the expense of the agricultural sector, from which it demands space for its facilities and areas for housing construction (Chuncho *et al*., 2021), thus driving the growth of the urban area and the demand for services such as water, electricity, food, recreation areas, schools and roads, among other satisfiers of subsistence and protection needs. Nonetheless, this expansion is carried out to a greater extent on agricultural land (Oropeza and Picazo, 2020).

On the other hand, the development of remote sensing systems, such as the freely available Landsat satellite images, enables the estimation of the greenness of the areas of interest through vegetation indices, such as the vegetation atmospherically resistant index (VARI) (Gitelson *et al*., 2022). The value of the vegetation index changes in direct proportion to the changes in the green masses in the region, mainly the areas allocated to agricultural production, pastures, and forest areas, whose modification dynamics over the years can be studied by remote systems that estimate their reflectance at the red, green, and blue (RGB) wavelengths.

In the municipality of Celaya and the other 45 municipalities of the state of Guanajuato, Paredes *et al*. (2011) carried out a study to update the agricultural land use chart in the period between 2006 and 2009; in this study, it was determined that, in 2009 in the municipality of Celaya, there were 26 932.45 ha of agricultural land, of which 10 565.22 ha were rainfed and 16 367.23 ha corresponded to irrigation in its different modalities. Taking this study as a starting point, this paper analyzed the change in agricultural land use to other uses that occurred in the municipal territory of Celaya, Guanajuato, from 2009 to 2024, and its impact on the production of two of the main crops: corn and beans.

Materials and methods

Study area

The study included the 55 460 ha (554.6 km^2) of the territory of Celaya, Guanajuato, which is located between the decimal geographic coordinates 20.37978-20.68586 and 100.91039-100.64537 at an altitude of 1 767 m (Municipio de Celaya, 2021). The Köppen-Geiger climate classification modified by García (2004) mentions that ‘the climate is warm and temperate with an average temperature of 18.3 °C. Compared to winter, summers have much more rainfall with precipitation of 689 mm’. The Köppen-Geiger climate classification identifies this climate pattern as belonging to the Cwa category. The desk work was conducted at the Bajío Experimental Field of the National Institute of Forestry, Agricultural, and Livestock Research (INIFAP), for its acronym in Spanish, from November 2023 to April 2024.

Image preparation and analysis

The study was based on the agricultural land use information layer of Paredes *et al*. (2011) with a scale of 1:10 000, which, for its construction, used digital orthophotos at the same scale and the INEGI base map with a scale of 1:50 000. This layer was transformed from shapefile format to KML format using the shp2kml application to be viewed and manipulated in the Geographic Information System (GIS) Google Earth Pro, version 7.3.6.9796.

Revista Mexicana de Ciencias Agrícolas
REMEXCA
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The outlines of the agricultural area were updated by directly digitizing on-screen over high-resolution satellite images with temporal coverage extending up to the year 2024. The scale used in the land-use change polygons of this study is 1:10 000. The visual scale of digitization (eye altitude in Google Earth) was 2.6 km, with a resolution of 0.3 to 0.6 m per pixel.

The land-use change polygons were created using the 'add polygon' tool, updated, classified, saved in KML format, and transformed into shapefile format with the GIS ArcMap 10.0 program, in which the coverages were transferred from the geographic coordinate system to the UTM projection, Datum WGS84 in zone 14 north; the areas were calculated in hectares, and the final maps were generated in order to create a layer, which was overlapped with the 2009 land-use cartography to determine to which moisture condition each of the polygons that changed use belonged, to finally quantify the area by source of moisture.

The growth of the urban area of the city of Celaya was estimated using the official boundaries contained in the municipal geostatistical frameworks (MGM, for its initialism in Spanish) of INEGI 2009 V3 and December 2023.

Classification of land-use change

The land-use change polygons were classified into four categories according to the change of each of the agricultural areas: a) to urban areas, which refers to places where buildings intended for housing are located; b) to disuse, which corresponds to agricultural areas that are in an obvious state of abandonment, that is, those with secondary vegetation and without evidence of furrows or cultivation or that historical images show that they have not been cultivated for more than five consecutive years; c) to industry, which are areas that were destined for the creation of industrial warehouses or parks; and d) to roads, which refers to areas currently occupied by streets, roads, and highways.

Vegetation index

The loss of agricultural land use was confirmed by estimating the greenness of triannual satellite photographs of the municipality of Celaya from 2009 to 2021 available in the Google Earth database. The date of each photograph was December 31 of the corresponding year (except for 2024, which was May 26); on this date, the winter crops (mainly wheat, oats, barley, and chickpeas) had already been established. The vegetation atmospheric resistance index (VARI) (Gitelson *et al*., 2022) was used. Its formula is the following:

$$VARI = \frac{G - R}{G + R - B}$$

Where: G, R and B represent the reflectance at red, green, and blue wavelengths, which was standardized over a forested area with no visible cover changes (Figure 1a).

Revista Mexicana de Ciencias Agrícolas

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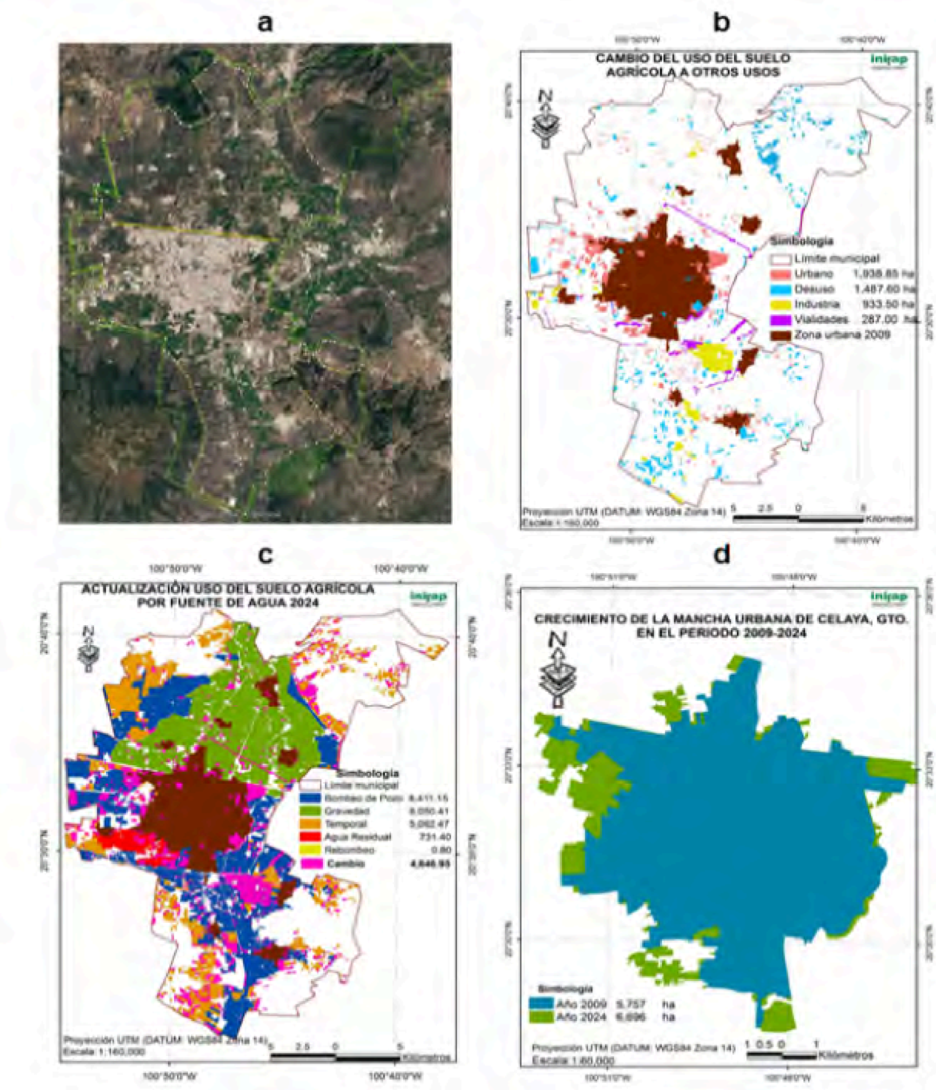
Figure 1. a) Areas for the study of the vegetation index. The green outline indicates the municipal boundaries, the yellow line delimits the north and south zones, the yellow outline is the area where the VARI was calculated, and the area shaded with green in the southeastern part was used as a control; b) change of land use where the destina tion of the change is indicated with different colors. Reduction of agricultural area; c) the different proportions of land-use change, when considering the source of water available for each property, are shown. Use of agricultural land by source of moisture, the change to non-agricultural uses is shown in pink; and d) the main growth poles of the city of Celaya are shown. Urban development in the western part stands out and growth of the city of Celaya (green).



The RGB reflectance values of this bounded area, and the VARI of this area in the image with the highest luminosity, the one from 2015, were used as a reference to standardize the reflectance of municipal agricultural areas in all images. To determine if there was a difference in the dynamics of land-use change between the south and north zones of the municipality, federal highway No. 45D, which divides the municipality in an east-west direction, was taken as the boundary (Figure 1a).

In each area, the VARI was calculated by delimiting a polygon that included agricultural areas and excluding the municipal capital, which is the largest urban concentration. The RGB reflectances of each image were calculated with the 'RGB measure' script of the scientific photography editing program ImageJ© (Schneider *et al*., 2012).

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Results and discussion

Both the cartography and the satellite images indicated that the forest areas remained without appreciable changes during the study period; on the other hand, the agricultural area decreased from 26 933.18 ha to 22 286.23 ha, that is, 4 646.95 ha over the last 15 years (Figure 1b). This loss is attributed to the growth of urban and industrial areas, the creation of new roads, and the abandonment of agricultural areas, mainly rainfed areas. Therefore, the average annual reduction rate of agricultural use areas is 309.8 ha.

The loss of agricultural area was mainly due to a change to urban use (Table 1), which was explained by a population increase of 52 700 inhabitants (INEGI, 2024) and the need for housing and services. A similar result was found when measuring land-use change in Zaachila, Oaxaca, where the authors found that human settlements gained 11.4% of territory from 1987 to 2020 (Pérez-Hernández *et al*., 2021).

Table 1. Agricultural areas in hectares that changed use by moisture conditions in the period 2009-20024 to which it belonged in 2009.

Change	Wastewater	Well pumping	Gravity	Rainfed	Total
Industrial	3.1	579.9	60.6	283.4	927.1
Urban	153.1	959.2	526.3	267.7	1 906.3
Roads	41	215	43.7	20.6	320.2
Disuse	10.6	399.9	66.5	1 016.4	1 493.3
Subtotal	207.7	2 154.1	697.1	1 588.1	4 646.9

The change from agricultural to industrial use is because Celaya is part of the Bajío industrial corridor, which extends from San Juan del Río (Querétaro) to Aguascalientes. This area is highly attractive for establishing industrial parks that occupy land suitable for agriculture. More worrying is the amount of agricultural land that fell into disuse (1 493 ha). The humidity regime to which the areas that changed use belong (Figure 1c), is broken down in Table 1; based on this, it was concluded that 46.4% are irrigated by well pumping, which are located near the urban centers of the municipality; 34.2% are rainfed areas, which are located to a greater extent in rural areas; 15% are gravity irrigated, and 4.5% are areas irrigated with wastewater.

In addition, the well-pumping regime contributed 62.5% of the land-use change to industrial use, 50% to urban use and 67.1% to roads (Table 1). In contrast, the largest proportion of the land-use change to disuse came from the rainfed regime (68.1%). These changes impact food production since the most productive lands, being closest to population centers and having a constant source of water, are used in the creation of services and satisfies not related to agricultural crops, whereas the less productive lands, which do not have a reliable water source, fall into disuse due to lack of profitability.

This aligns with Torres and Rojas (2018), who indicate that a country's food sovereignty is put at risk by the loss of land for food production. Another factor with a significant impact on the loss of agricultural land is the urban growth of the city of Celaya, which, in this work, was determined to be 950 ha (Figure 1d).

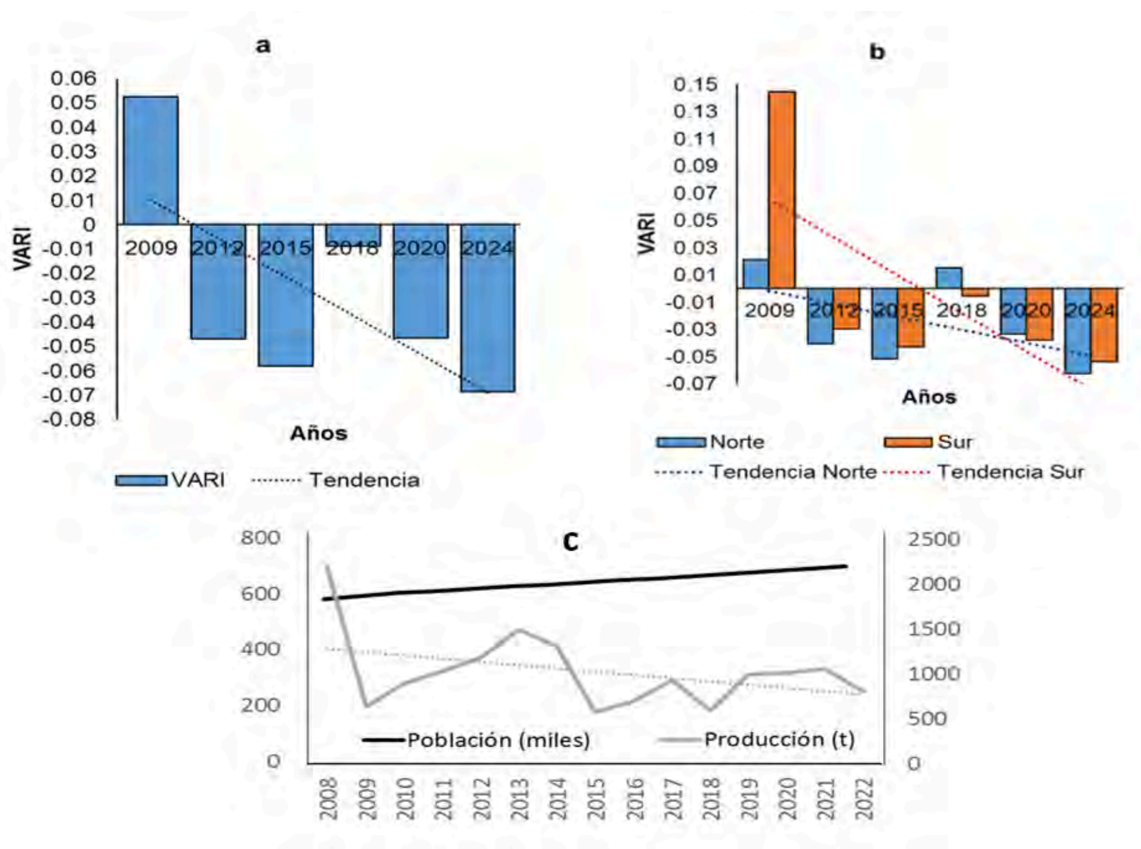
De Alba *et al*. (2020) systematized the information from 1980 to 2020 regarding land-use change in Mexico; they concluded that most studies focus on the reduction of the area of forest ecosystems for agricultural use, but there is very little information on the change of agricultural land use to other uses, which demonstrated the greater interest in forest ecosystem services than in food production. In addition, they demonstrated the lack of studies focused on the dynamics of land-use change in regions such as El Bajío, which are predominantly agricultural (Bonilla, 2024).

Hernández-Pérez *et al*. (2022); Hernández-Cavazos *et al*. (2024) studied land-use change in the center of Veracruz and Linares, Nuevo León, respectively and confirmed that forest land rapidly changes to agricultural land. In a more specific study, Adame *et al*. (2020) found that, from 1980 to

Revista Mexicana de Ciencias Agrícolas
DOI: https://doi.org/10.29312/remexca.v16i8.3866

2017, the eastern part of the urban metropolitan area of Toluca, State of Mexico, expanded at the expense of agricultural land, which decreased this land use by 35.74%; these results are consistent with the present work, since it also found a significant reduction of agricultural land due to the growth of urban area (Figure 2), but also identified losses of agricultural area primarily due to disuse.

Figure 2. a) Reduction of vegetation, mainly due to a change in agricultural land use, estimated using the VARI index; b) propensity for population increase in the municipality of Celaya from 2008 onwards and c) trend in the reduction of bean production from 2008 onwards in the same period (with data from Macrotrends, 2024).



Sandoval-García *et al*. (2021) also reported decreases in agricultural land of up to 8.4% in the Mixteca Alta region of Oaxaca due to disuse, primarily due to migration and lack of profitability. To date, no study in Mexico has described the change in land use in relation to the available water source. This information helps establish the dynamics of agricultural land loss in a region with a predominantly agricultural orientation more precisely.

Evolution of the vegetation index of the municipality of Celaya

The cartographic results were confirmed by estimating the VARI index. Figure 2a shows that the value of VARI of the entire municipality decreased abruptly from 2009 (0.04536) to 2015 (-0.05801), followed by a slight recovery in 2018 (-0.00876), possibly due to the state incentives granted to the agricultural area as of 2015; nevertheless, for 2020 and 2024, the VARI reached its minimum value (-0.06843). Jiménez Muñoz *et al*. (2009) compared the VARI with other procedures to obtain vegetation cover fractions, obtaining variations similar to those of the present work, with a standard error of only 8%, which makes it the best index for this type of study.

A similar result was obtained when estimating the VARI index in the north and south zones of Celaya (Figure 2b); however, the trend in the decrease of the index, represented by the dotted line, showed

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a more abrupt drop in the south zone. This drop in the VARI shows a decrease in greenness, which was caused by land that stopped being cultivated, particularly by land where winter crops were not established.

In the south zone, the steepest slope of the VARI is due to the growth of the urban area of the municipal capital, mainly to the establishment of the Honda automobile assembly plant, which occupied an area of more than 500 ha and drove great demand for new housing for its employees. Both the plant and the housing in the new housing developments were built at the expense of reducing the agricultural area originally intended for food production. On the other hand, the north zone has only suffered from the growth of urban centers, mainly in the municipal capital.

Impact of land-use change on food production

Overall, 3 059 ha (65.8%) of the agricultural areas that changed use are irrigated and 1 588 ha (34.2%) are rainfed. If the average production of beans and corn in the last 10 years in Guanajuato is considered (9.22 and 2.24 t ha^{-1} in irrigated and rainfed areas, respectively, for corn and 1.71 and 0.55 t ha^{-1}, respectively, for beans) (SIAP, 2014-2024), 31 000 t of corn and 8 000 t of beans would no longer be produced annually (Table 2). In contrast, according to the 2010 and 2020 Population and Housing Censuses, the number of inhabitants increased from 468 469 to 521 169 people (INEGI, 2024).

Table 2. Annual decrease in food production in the agricultural area changed use in the municipality of Celaya between 2009 and 2024.

Moisture condition	Area lost (ha)	Corn (t)	Beans (t)
Irrigated	3 059	28 214.8	6 836.5
Rainfed	1 588	2 717.2	879.8
Total	4 647	30 932.07	7 716.34

The municipal situation is complex as it has a larger population, but less land for food production. Given that the annual per capita consumption of beans is 9.9 kg (SAGARPA, 2017a), the reduction of the agricultural area would potentially impact the diets of 779 428 people; that is, the impact would extend beyond the municipality, as its current population is 542 000 inhabitants. Figure 2c showed the trend of population increase during the study period, accompanied by a simultaneous decline in bean production, mainly rainfed beans (Macrotrends, 2024).

If we consider that the per capita consumption of white corn per year is 196.4 kg (SAGARPA, 2017b), there would be a negative effect on the diet of 157 495 people. Nonetheless, the area allocated to corn production increased by just over 4 000 ha during the study period, and production increased by 10 000 t (SIAP, 2014-2024). This means that, in the context of reduction of agricultural areas due to land-use change, the area allocated to corn has increased, possibly due to government support to produce basic crops, at the expense of a reduction in the area allocated to other crops, such as vegetables.

Conclusions

The free-of-charge Geographic Information Systems, together with the VARI visible light vegetation index, are efficient in analyzing the dynamics of agricultural land use change in specific regions. In the municipality of Celaya, Guanajuato, changes in land use from agricultural to urban and to disuse are the leading agents in reducing the area designated for agricultural production.

The analysis of land-use change that considers the available water source reveals that the most productive lands, which have well water and are close to urban centers, are the greatest source of agricultural land loss. Of the lands that change use, 66% correspond to irrigated agricultural areas where food production is greater, which generates a significant risk and has a greater impact on the municipality’s food security. The information disseminated in this work contributed to updating and promoting the application of land and state planning plans.

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