DYNAMICS OF CHANGES OF IRRIGATED CROPLANDS IN THE STATE OF GUANAJUATO, MEXICO.

Azucena Pérez-Vega[1]*, Yann Rene Ramos Arroyo[1], José Miguel Soria Ugalde[1], and Jean François Mas[2]

[1]University of Guanajuato, Department of Geomatics and Hydraulics, Guanajuato, Mexico
Av. Juárez 77, Col. Centro. C.P. 36000. Guanajuato, Gto * address: azu_pvega@hotmail.com

[2]Centro de Investigaciones en Geografía Ambiental, Universidad Nacional Autónoma de México, Morelia, México. jfmas@ciga.unam.mx

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ABSTRACT:

Irrigated agriculture requires extensive land areas and consumes high volumes of water. This study aims to determine and analyze the dynamics of irrigated croplands and their water consumption in Guanajuato State, located in the central region of Mexico. Guanajuato is among the Mexican states with the country's most considerable agricultural land extent, with more than half of its territory dedicated to agricultural activities.

The work offers an innovative approach by adding official statistical information on irrigated agriculture crops and geospatial data for a considerable period. First, land use and cover change patterns were studied using a multidate land cover cartographic database. We observed some reduction in irrigated areas due to urban expansion; nevertheless, most irrigated regions remained stable over time. After that, we computed the areal evolutions of ten main crops and their associated water consumption. We observed a slight contraction of irrigated agriculture. However, the most notorious changes in water consumption are due to changes in the types of crops and agricultural intensification can burden water scarcity.

1. INTRODUTION

Agriculture is a fundamental activity, for it provides food to man and livestock; however, it requires considerable amounts of natural resources such as extensive land surface areas and high volumes of water in the case of irrigated agriculture. Agriculture extension and livestock farming are the main modern human activities that modify the natural land covers (Noble and Dirzo, 1997; Coomes *et al*., 2008). These transformations are associated to processes of deforestation and fragmentation, which unavoidably bring an impoverishment of the natural resources (Lambin *et al*., 2001). The changes in natural land covers modify soil properties (structure and porosity), thus affecting infiltration and runoff, which alter the natural flow regimes and hydrological budgets.

The world population growth and consumption patterns in the wealthiest nations make it necessary to increase food production. Such augmentation brings an increment of deforested natural covers for agricultural purposes and an increment in water resources exploitation due to the conversion of rain-fed agricultural areas into irrigated ones.

Guanajuato is among the Mexican states with the highest percentage of transformed covers (around 60%). The historical evolution of Guanajuato's agricultural land can be traced back to pre-Hispanic times, but a significant increase in croplands occurred during the colonial period (Pérez-Vega, 2011). The agricultural activity served to feed the population dedicated to mining. These activities required fertile soil and energy provided by fuelwood and water flows (Meave et al., 2016).

In the 1930's Guanajuato developed an agroindustrial corridor. The prevailing agriculture in the 1950s was oriented to the production of basic grains with little technology, but horticulture grew a lot and required irrigated land and technology for flowering (Avella Alaminos, 1998). The main crops varied considerably during the last decades. Between the two decades from 1980 to 2000, the most important crops by cultivated surface were: corn, sorghum and bean. Sorghum, alfalfa and corn represented two thirds of the State's crop production between 2001 and 2002, occupying as much as 68% of the crop land located in the plains of Guanajuato, which with the advancement of cultivation techniques the rate of extension increased a little over 3,000 ha of new land per year (IEE, 2008).

According to the 2008 Environmental Report of Guanajuato State, the main crops were sorghum, alfalfa, and corn, that represented respectively, 23%, 21% and 19% of the crop production. The production of corn was considered not sufficient to satisfy the State's demand because a major part of it was exported. From 2000 to 2013, main crop was sorghum, but at present, its surface has been reduced by 46% according to the Agrifood and Fisheries Information Service (SIAP for its acronym in Spanish).

Irrigation agriculture amounts up to 33.4% of the total cultivated land of the 46 municipalities of Guanajuato, but t the most significant irrigated areas belong to only 5 municipalities: Pénjamo, Salamanca, Irapuato, Dolores Hidalgo y Valle de Santiago. On the other hand, in the municipalities of Santa Catarina, Atarjea, Tierra Blanca, Moroleón and Uriangato, the construction of irrigation systems is hindered by the irregular topographic conditions and the strong slopes (INEGI, 1997).

Regarding water resources management, groundwater supplies 70% of the state's water requirements and most of this water is used for agricultural activity. Because of the high consumption of groundwater all aquifers in the state register levels of overexploitation.

According to studies carried out by the state water commission of Guanajuato (CEAG, 2018), irrigation agriculture in Guanajuato consumes 2,741 million m^3 of water extracted from aquifers each year, representing 66% of the total volume used in this sector. The same study indicates a deficit between extraction and recharge of around 1,246 million m^3 per year. The efficiency in the use of water, as in the rest of the country, is estimated at 40%, that is, more than half (60%) of the volume of water extracted is wasted.

Due to the above reasons, irrigation agriculture faces several supply issues to meet water crop demands. Therefore,a more efficient water resources management is needed, including a more precise identification of the areas where the water table levels are decreasing rapidly. In this context, it is essential to highlight that modern irrigation technology should continue to be adopted since they decrease water losses by up to 60% compared to traditional techniques (CEAG, 2018).

Currently, the overexploitation and drawdown of groundwater resources which are unvaluable for crop irrigation, face problematic situations that can be accurately monitored and analyzed using a geoinformatics approach to identify tendencies and patterns in time and space.

We considered it important to study and analyze the changes generated by agricultural activities from a geospatial approach for a better understanding of the factors involved in overexploitation of groundwater resources by irrigation agriculture. Such an approach enables us to analyze the water consumption of certain crops considering water availability over the territory.

This study aims to determine and analyze the dynamics and trajectory of the changes in the irrigated agricultural areas and to establish the water consumption relationship with different cultivated crops in the State of Guanajuato during the period from 2002 to 2014.

2. STUDY AREA

The State of Guanajuato is located in the central part of the Mexican Federative Republic. Among 32 federative entities, it is the 22nd largest; despite that, it is the 6th most densely populated. This State is an economic node connecting the country's three largest cities: Mexico City, Guadalajara, and Monterrey.

Figure 1. Location of the State of Guanajuato (in red).

3. MATERIALS

The inputs used in this study are spatial-temporal data derived from land use/cover cartography and statistical census. We used the Land Use and Vegetation cartography Series III, IV, V y VI, scale 1/250,000 from INEGI, agricultural production data from SIAP (https://nube.siap.gob.mx/cierreagricola/) and the software programs DINAMICA EGO and R.

The information about the change processes was extracted from maps of land use and vegetation of INEGI. These maps constitute the official cartography for Mexico on a scale 1/250,000. They were constructed systematically, and for that reason, the different maps from the series are consistent in scale and regarding the classification system. The original categories corresponding to different types of agricultural activity were grouped either as irrigated or rain-fed agriculture (Table 2). The superposition of series V (2011) and VI (2014) showed a geometric consistency. Maps belonging to series III and IV required geometric and labelling corrections (Pérez-Vega et al., 2020).

4. METHODS

4.1 Rates of change

The absolute annual rate of change is the difference of the areas corresponding to two different dates divided by the number of years between the dates and expressed as hectares/year. The relative rate of change was estimated with the equation proposed by FAO (1996) to estimate rates of deforestation as shown in equation (1):

$$t = \left(1 - \frac{S_1 - S_2}{S_1}\right)^{\frac{1}{n}} - 1 \quad (1)$$

Where: t = rate of change
S1 and S2 = areas in the first and second dates
n = number of years between both dates

This rate expresses the proportion of land area that changes for one year. If multiplied by 100, t can be expressed in percentage. For both absolute and relative rates, positive values indicate an increase in the land cover area and a negative value a decrease.
The information about the processes of change was extracted from maps of land use and vegetation of INEGI. The maps are constructed in a systematic way and for that reason different map series are consistent among them in scale and regarding the classification system.

The superposition of maps was carried out to obtain the changes of agricultural surfaces for three consecutive periods: 2002-2007, 2007-2011 and 2011-2014, by means of the DINAMICA EGO free software package (Soares-Filho et al., 2002).

4.2 Sequences of change and processes of change

In social sciences, analyzing the sequence of social events is a common methodology of studying life and career trajectories (Abbot, 1983) because it enables researchers to determine trajectory patterns considering all the states experienced. Mas et al. (2019) applied this approach to analyze the sequence of land use and land cover categories. The representation of such change sequences helps to detect the main patterns and processes of land change and can be focused on a set of categories (e.g., agriculture).

Identifying the processes of change allows identifying the patterns and tendencies of the main types of transformation processes to understand the landscape dynamics due to the agricultural activity. For instance, the sequence “Forest-Agriculture-Agriculture-Secondary Forest-Secondary Forest-Secondary Forest” is completely different from “Forest-Agriculture-Agriculture-Agriculture-Agriculture-Agriculture”. The first one corresponds to a slash and burn agricultural system where forest is cleared to establish an agriculture plot for a few years and abandoned, while the second one describes a more permanent agricultural system.

4.3 Estimation of consumptive water use

As a first attempt to get a broad picture of the water use in the State of Guanajuato, we mapped the municipal area of irrigated agriculture over time using INEGI cartography. As a following step, we estimated consumptive water use (CWU) according to the definition of Falkenmark and Lannerstad (2005). It has the same meaning as "water depletion" which considers the water removed from a basin unavailable for further use (Molden, 1997). For crop production, CWU refers to "evapotranspiration", which represents the total evaporative use of a crop during its growth period (Liu et al., 2009).

The principal crops were identified and their respective area in each municipality was obtained from the SIAP database for 2007, 2014 and 2021. In order to estimate evapotranspiration of croplands, the Blaney-Criddle method (1950) was used because it is accurate enough and only requires temperature data as shown in equation (2).

$$ETc = \mathrm{Kc}\Sigma\, p \cdot (0.457 \cdot Tmean + 8.128) \quad (2)$$

Where:
Etc = crop evapotranspiration (mm)
$Tmean$ = mean daily temperature
p = mean daily annual daytime hours
Kc = crop coefficient.

The mean daily percentage (p) of annual daytime hours was calculated using linear extrapolation using the latitude of the centroid of each municipality. We obtained the temperature from climatological stations' data for 1981-2010. As possible, we chose stations giving a good representation of the climatic conditions of irrigated areas in each of the municipalities.

5. RESULTS

5.1 Rates of change and Sequences of change

In Figure 2 (left), we can observe that irrigated agriculture and rain-fed agriculture areas cover around 650,000 and 800,000 ha. We can see that irrigation and rain-fed agriculture areas show noticeable decrements from years 2011 to 2014. Rain-fed agriculture reached the most significant absolute loss at an average rate of 4,932 ha per year (− 0.6 %/year), and irrigated agriculture presents an absolute loss up to 2,759 ha per year (rate of -0.4%/year).

Figure 2 (right portion) presents the more frequent sequences of land use cover involving agriculture categories for four dates spanning from 2002 to 2014. The rectangles heights are proportional to the area represented by the sequence and are ordered from bottom to top by decreasing frequency. The figure shows that the five first sequences represent 80% of all the changes. In the first sequence, the most critical transformation is
rain-fed agriculture converted to irrigated agriculture from 2002 to 2007. The following two sequences involve a loss of irrigated agriculture by conservation to rain-fed agriculture and human settlements.

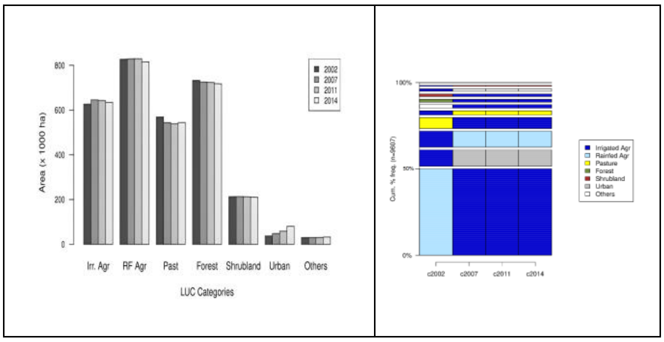

Figure 2. Area and pattern of change of the main land cover categories in Guanajuato.

5.2 Area of irrigated agriculture at the municipal level

In six municipalities the irrigation agriculture area covers more than 30,000 ha (areas indicated with intense orange and brown colors in figure 3a). The municipality of Pénjamo in the southwestern portion of the State (brown color) reached an extension of irrigated agriculture of 48,000 ha (Figure 3). A map of municipalities can be consulted in the supplementary material.

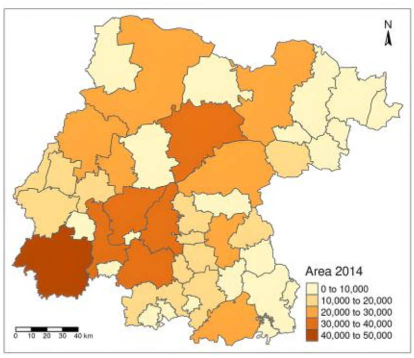

Figure 3. Irrigated agriculture areas (in hectares) (2014).

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The most remarkable increment in irrigated agricultural area during the 2002-2007 period concerns more than 8,000 ha (Municipality of Dolores Hidalgo, green solid color). Other municipalities showed increments between 4,000 to 6,000 ha and 2,000 to 4,000 ha (green tones). Several municipalities presented losses with low ranges between 0 to 2000 ha, except the municipality of Celaya (stronger orange color) that reached losses between 2,000 to 4,000 ha (Figure 4).

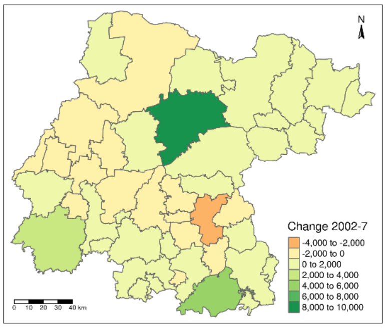

Figure 4. Change in irrigated agriculture from 2002 to 2007.

The changes occurring between 2007 and 2011 are mainly losses, ranging from 500 to 1,000 ha in almost half of the municipalities, reaching up to more than 2,500 ha lost (Salamanca Municipality intense red). The rest of the municipalities present increments of less than 500 ha (Figure 5).

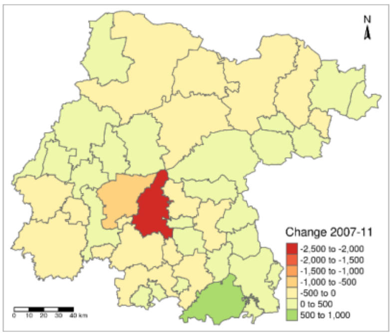

Figure 5. Change in irrigated agriculture from 2007 to 2011.

Lastly, in the 2011-2014 period, the loss of irrigated agricultural surfaces increased in almost 80% of the municipalities, most of them in low ranges from 0 to 500 ha, four of them between 500 and 1,500 ha, and only one to the southwest of the State reaches losses up to 2000 ha (Municipality of Pénjamo intense red color) The municipalities in light green present gain of less than 500 ha (Figure 6).

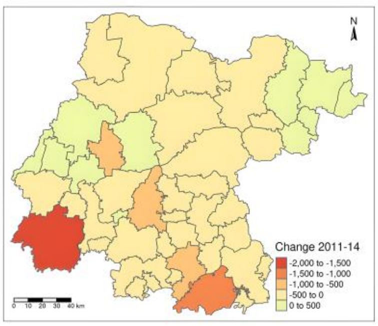

Figure 6. Change in irrigated agriculture from 2011 to 2014.

5.3 Estimated water consumption

The crops considered for this water consumption computing were alfalfa, asparagus, barley, beans, broccoli, corn, fodder oats, potatoes, sorghum and wheat for both autumn-winter and spring-summer cycles and permanent crops. These crops represented at least 82% of the total sown area over the entire period. We used crop coefficient from Allen et al. (1998), Angeles Hernández et al., 2017 and INIFAP, 2001.

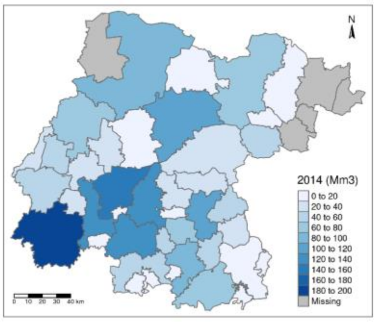

Figure 7. Water Consumption (million m^3) (2014).

Figure 7 and 8 show the estimated water consumption for the ten main crops in the years 2014 and 2021. The spatial distribution does not correspond strictly with figure 3, which represents irrigated area because in the water consumption calculation we also consider the spatial heterogeneity of mean temperature of each municipality and the type of crops. For example, growing alfalfa in a municipality with higher temperatures has a higher water consumption.

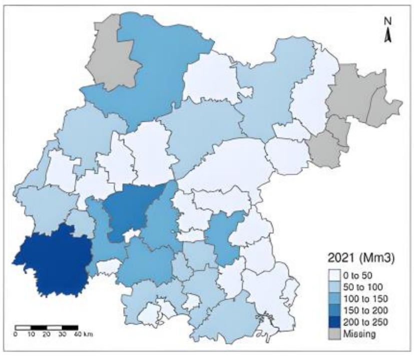

Figure 8. Water Consumption (million m^3) (2021).

Figure 8 clearly shows how two municipalities presented high decreases in water consumption with ranges between -80 to -60 Mm3 (Salamanca and Celaya with intense blue colours). Until 2003, Celaya was the largest producer of alfalfa (10,900 ha), but in recent years (2015), its area has shown a significant decrease of up to 49%.

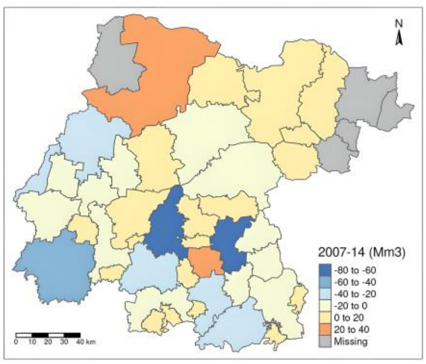

Figure 9. Change in water consumption (million m^3) from 2007 to 2014.

In Figures 9 and 10, the decrease and increase in water consumption observed in the municipality of Pénjamo (extreme southwest of the state) during the periods 2007-2014 and 2014-2021 are due to changes in the proportion of the three dominant crops: corn, sorghum and wheat. In the first period, corn and wheat areas decreased; in the second, corn increased and sorghum decreased, the latter requiring less water than corn.

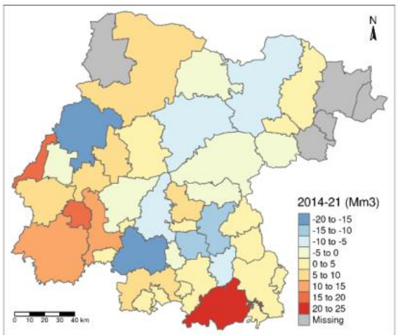

Figure 10. Change in water consumption (million m^3) from 2014 to 2021.

6. DISCUSSION

For a long time 1970 to 2000, the predominant crops in the State of Guanajuato were: corn, sorghum, beans, and wheat (Soto and Soto, 2003), when corn self-sufficiency was considered a food priority. After the year 2000, sorghum was the dominant crop, representing 23% of agricultural production until 2013, along with alfalfa with 21% of production, giving way to prioritizing feed for livestock and leaving corn with a representation of only 19% (SIAP, 2013).

New crops for exportation, such as broccoli, have been cultivated in recent years occupying surfaces of more than 22,000 ha in the State. In general, vegetable production has required significant areas in several municipalities where they were not previously cultivated. Currently, livestock feed crops continue to occupy important surfaces.

The dynamics of changes in irrigated agriculture maintain a close relationship with groundwater availability and, in some cases, keep circular sequences (Pérez-Vega et al., 2020). Irrigated and rainfed agriculture suffered a loss due to the displacement of urban growth. Urban areas are also threatened by the irregularity and scarcity of rainfall, which in 2019 and 2020 have left the lowest water supply levels in the dams, affecting the production of irrigated agriculture supplied by the State's dams (El sol de León, 2020).

The areas of irrigated agriculture supplied by deeper groundwater present a social dynamic: the landowners are dispossessed by large agricultural companies, which have enough capital to afford the electricity consumption to extract water at greater depths (personal communication forest rangers, 2017).

Agriculture has a dynamic character, where commercial crops establish a predominant trend and farmers face severe difficulties in meeting the demands of the international market. Agricultural production in the lowlands of Guanajuato is controlled by more than 80% by transnational food companies such as Purina, Bachoco, and Anderson, who are large hoarders of the products of the agricultural sector (Soto and Soto, 2003). Export agriculture is concentrated in a small group of companies with economic networks whose only interest is financial capital (Navarro and Correa, 2016).

The change in water consumption (Figure 4 c and d) between 2007 and 2014 and 2014 and 2021 respectively are due to changes in the type of crop and their respective areas. These changes are more significant than changes in irrigated area. The variation of water consumption reached 30% for the 16 municipalities with more consumption in 2021.There are evident changes in crops with large water requirements, such as alfalfa, which had a large area and then showed a substantial reduction to almost 50% of its area. This drastic reduction is due to the difficulty of extracting water at greater depths increasing electrical energy spending, a situation evidenced by Martínez Borrego (2015). However, in recent years, the significant increase in cultivation areas such as broccoli responds to the international demand for this crop (Martínez Borrego, 2015).

A concluding remark is that globalization of agriculture in the State of Guanajuato caused a slight contraction of agricultural areas and increased production. However, the most notorious changes concern the types of crops and their intensification and can even further burden water scarcity.
We consider it essential to study and analyze the changes generated by agricultural activities from a geospatial approach to understanding better the factors that intervene in irrigated agriculture's overexploitation of groundwater resources. This approach allows us to analyze the water consumption of certain crops considering the water availability in the territory.

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REFERENCES

Abbott, A. 1983. Sequences of Social Events: Concepts and Methods for the Analysis of Order in Social Processes. Historical Methods: A *Journal of Quantitative and Interdisciplinary History*, 16, 129-147. doi: 10.1080/01615440.1983.10594107.

Allen, R.G., Pereira, L.S., Raes, D., & Smith, M. 1998. Crop evapotranspiration – Guidelines for computing crop water requirements, FAO Irrigation and drainage papers Vol. 56. Rome: FAO.

Ángeles Hernández, J.M., Trejo Segura, V., Unland Weiss, H., Olvera Salgado, D., & Carrillo Castillo, M. 2017. La eficiencia de aplicación y productividad del agua en los cultivos de trigo y cebada en el Distrito de Riego 011 "Alto Río Lerma", Guanajuato. III Congreso Nacional de Riego y Drenaje COMEII. Puebla, Mexico, November 28-30, 2017.

Avella Alaminos, I. 1998. Los inicios de la agroindustria transnacional de frutas y legumbres en el bajío. Carta Económica Regional, 62, 7-13. doi: 10.32870/cer.v0i62.7678.

Blaney, H.F., & Criddle, W.D. 1950. Determining Water Requirements in Irrigated Areas from Climatological and Irrigation Data, *Soil Conservation Service Technical Papers* Vol. 96. Washington, D.C.: US Department of Agriculture.

Comisión Estatal del Agua de Guanajuato 2018. Compendio del agua subterránea en Guanajuato. Guanajuato: Dirección General de Planeación-Dirección de Estudios y Monitoreo-Gobierno del Estado de Guanajuato.

Coomes, O.T., Grimard, F., Potvin, C., & Sima, P. 2008. The Fate of the tropical forest: Carbon or cattle? *Ecological Economics*, 65(2), 207-212. doi: 10.1016/j.ecolecon.2007.12.028.

Reyes. O. 2020. En crisis, niveles de presas en Guanajuato. El sol de León. https://www.elsoldeleon.com.mx/local/en-crisis-niveles-de-presas-en-guanajuato-mexico-agua-sequia-jose-francisco-gutierrez-michel-secretario-de-desarrollo-agroalimentario-y-rural-de-guanajuato-conagua-5855625.html.

Falkenmark, M., & Lannerstad, M. 2005. Consumptive water use to feed humanity‒curing a blind spot. *Hydrology and Earth System Sciences*, 9, 15-28. doi: 10.5194/hess-9-15-2005.

FAO (Food and Agriculture Organization of the United Nations). 1996. Forest Resources Assessment 1990: Survey of Tropical Forest Cover and Study of Change Processes, Forestry Papers Vol. 130. Rome.

Gabadinho, A., & Ritschard, G. 2013. Searching for Typical Life Trajectories Applied to Childbirth Histories. In Gendered Life Courses—Between Individualization and Standardization (Chapter 14, pp. 287–312). LIT: Vienna, Austria.

IEE (Instituto de Ecología del Estado) 1999. Ordenamiento Ecológico del Territorio del Estado de Guanajuato. Guanajuato: Gobierno de Guanajuato.

IEE (Instituto de Ecología del Estado) 2008. Informe Ambiental del Estado de Guanajuato. Guanajuato: Gobierno de Guanajuato.

INEGI (Instituto Nacional de Geografía e Informática). 1997. El Sector agropecuario en el estado de Guanajuato. Aguascalientes, Ags.: INEGI.

INIFAP (Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias) 2001. Requerimientos hídricos de especies anuales y perennes en las zonas media y altiplano de San Luis Potosí, Folleto técnico No. 12, 31 p.

Lambin, E.F., et al. 2001. The causes of land-use and land-cover change: moving beyond the myths. *Glob. Environ. Change*, 11, 261-269. doi: 10.1016/S0959-3780(01)00007-3.

Liu, J., Zehnder, A.J.B., & Yang, H. 2009. Global consumptive water use for crop production: The importance of green water and virtual water. *Water Resources Research*., 45 (5) 1-15, W05428. doi: 10.1029/2007WR006051.

Martínez Borrego, E. 2015. Agricultura, sustitución de cultivos y exportaciones en la zona metropolitana de León, Guanajuato, México. *Carta Económica Regional*, 116, 112-140. https://doi.org/10.32870/cer.v0i116.6143.

Martínez-Arredondo, J.C., Jofre Meléndez, R., Ortega Chávez, V.M., & Ramos Arroyo, Y.R. 2015. Descripción de La Variabilidad climática Normal (1951-2010) En La Cuenca Del río Guanajuato, Centro De México. *Acta Universitaria*, 25, 3-19.
Mas, J.-F., Nogueira de Vasconcelos, R., & Franca-Rocha, W. 2019. Analysis of High Temporal Resolution Land Use/Land Cover Trajectories. *Land*, 8(2)30, 1-19. doi: 10.3390/land8020030.

Meave J.A., Ibarra Manríquez, G., & Larson Guerra, J. 2016. “Capítulo 14. Vegetación: Panorama Histórico, Rasgos Generales y Patrones de Pérdida”, in Geografía de México: Una reflexión espacial contemporánea, eds. O. Moncada Maya and A. López López. (Instituto de Geografía, UNAM). Tomo I, 216-234.

Molden, D. 1997. Accounting for water use and productivity, System-Wide Initiative for Water Management Papers Vol. 1. Colombo: International Irrigation Management Institute.

Navarro Moreno, J.A., & Correa, M.O. 2016. “Capítulo 37. Las Actividades Agropecuarias y Forestales”, in Geografía de México: Una reflexión espacial contemporánea, eds. O. Moncada Maya and A. López López. (México: Instituto de Geografía UNAM). Tomo II, 581-595.

Noble, I.R., & Dirzo, R. 1997. Forests as Human-Dominated Ecosystems. *Science*, 277, 522-525. doi: 10.1126/science.277.5325.5.

Palacio-Prieto, J.L., et al. 2000. La condición actual de los recursos forestales en México: resultados del Inventario Forestal Nacional 2000. *Investigaciones Geográficas*, 1, 43. doi: 10.14350/rig.59131.

Pérez-Vega, A. 2011. “Contexto mundial, nacional y estatal de los cambios de uso y cubierta del suelo y escenarios a futuro”, In Guerrero, L.F., Rendon, T.J., Domínguez, C.A., Robles, J., Mendoza, L.E., Lengeling, M. (Editors) Primer Foro Internacional Interdisciplina y Espacios Sustentables. Universidad de Guanajuato, 481-484.

Pérez-Vega, A., Regil H.H., & Mas, J.-F. 2020. Degradación ambiental por procesos de cambios de uso y cubierta del suelo desde una perspectiva espacial en el estado de Guanajuato, México. *Investigaciones Geográficas*, 103, e60150. doi: 10.14350/rig.60150.

R Core Team. 2022. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/.

SIAP (Servicio de Información Agroalimentaria y Pesquera) 2013. Atlas Agroalimentario. México.

Soares-Filho, B.S., Coutinho Cerqueira, G., & Lopes Pennachin, C. 2002. DINAMICA-a stochastic cellular automata model designed to simulate the landscape dynamics in an Amazonian colonization frontier. *Ecological Modelling*, 154, 217-235. doi: 10.1016/S0304-3800(02)00059-5.

Soto M.C. y Soto M. A. 2003. “La agricultura comercial de los distritos de riego en México y su impacto en el desarrollo agrícola”. *Investigaciones Geográficas*. Boletín del Instituto de Geografía. UNAM. No. 50, 273-195.

Torres Guerrero, C.A., Gutiérrez Castorena, M.C., Ortiz Solorio, C.A., & Gutiérrez Castorena, E.V. 2016. Manejo agronómico de los Vertisoles en México: una revisión. *Terra Latinoamericana*, 34, 457-466.