Assessment of Census and Remote Sensing Data to Monitor Irrigated Agriculture in Mexico

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Keywords: Irrigated Agriculture, Evapotranspiration, Water, Remote Sensing.

Abstract: Irrigated agriculture faces imminent threats, such as escalating water scarcity and climate change impacts. Water scarcity is particularly crucial in countries such as Mexico, where approximately 41% of the land comprises arid and semi-arid zones. The study assesses the quality and consistency of monitoring irrigated agriculture in a municipality of the State of Guanajuato in central Mexico using agricultural census information and advanced remote sensing data from Landsat 8, MODIS, and ECOSTRESS. Preliminary analyses showcase the dominance of wheat and barley crops in Pénjamo, with MODIS time series effectively capturing crop growth dynamics. The study highlights the potential of remote sensing in estimating irrigated crop dynamics proportions and the associated water consumption at different scales.

1 INTRODUCTION

Irrigated agriculture is crucial to food and economic security in many countries worldwide. However, this practice has faced many significant challenges in recent decades that threaten its long-term sustainability. Two of the most pressing problems facing this sector are increasing water scarcity and the effects of climate change. The combination of these factors presents a worrying picture that demands a deeper and more detailed understanding of the dynamics of irrigated agriculture.

The National Commission of Arid Zones (CONAZA) reports that Mexico has around 41% arid and semi-arid zones. Water scarcity has emerged as a fundamental obstacle to irrigated agriculture in this context. As water demand increases for both agricultural and urban use, available water resources are reaching critical levels. This imbalance between water supply and demand raises crucial questions about the long-term viability of irrigated agriculture, which has historically relied heavily on water sources now threatened by overexploitation and climate variability (Madramootoo and Fyles, 2010). Climate change adds complexity to this problem, affecting precipitation patterns and increasing the frequency and intensity of extreme weather events (Hanjra and Qureshi, 2010).

In Mexico, the two agricultural cycles, autumn/winter and spring/summer, play a crucial role in the country's food production. During the autumn/winter, irrigated agriculture is relevant since rains are scarce and irrigation systems primarily depend on guaranteeing the necessary water supply for crops. In contrast, the spring/summer cycle coincides with the rainy season, which reduces the need for irrigation in certain regions (see Figure 1). Understanding the dynamics of irrigated agriculture and associated water consumption is crucial for efficient water resource management and climate change adaptation strategies. Addressing these challenges requires a multidisciplinary approach that integrates scientific, technological and policy knowledge to ensure the sustainability of irrigated agriculture in a changing environment. In this work, we will limit ourselves to evaluating some official census and remote sensing inputs to monitor irrigated agriculture in a municipality in central Mexico. The aim is to evaluate the quality and consistency of the information obtained from these various sources.

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Mas, J. and Pérez-Vega, A.
Assessment of Census and Remote Sensing Data to Monitor Irrigated Agriculture in Mexico.
DOI: 10.5220/0012701500003696

In *Proceedings of the 10th International Conference on Geographical Information Systems Theory, Applications and Management (GISTAM 2024)*, pages 181-186
ISBN: 978-989-758-694-1; ISSN: 2184-500X

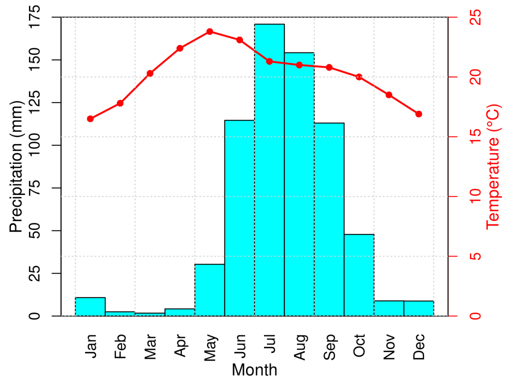

Figure 1: Ombro-thermal diagram of Pénjamo, Guanajuato. (Data obtained from CONAGUA https://smn.conagua.gob.mx).

2 STUDY AREA

The State of Guanajuato is located in central Mexico (Figure 2). 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). Nowadays, Guanajuato is among the Mexican states with the highest percentage of transformed covers (around 60%), including irrigated agriculture (21.5%), rain-fed agriculture (25.7%) and pasture (9.7%) (Palacios et al., 2000).

Figure 2: State of Guanajuato in Mexico (red polygon). The study area (Pénjamo) corresponds to the white square.

Regarding water resources management, groundwater supplies 70% of human needs; however, all aquifers in the state register levels of overexploitation. Most of the water is destined for agricultural activity. Water availability in the state is below scarcity, with 845 m^3/inhabitant/year, while the national average is 3,705 m^3/inhabitant/year (IEE, 2008).

3 MATERIAL

3.1 Agricultural Census and Climate Data

Data from the Agri-Food and Fisheries Information Service (SIAP) provide valuable information on agricultural activities in Mexico (http://infosiap.siap.gob.mx/gobmx/datosAbiertos.php). These open-access data are presented in tables and offer details on the cultivated, harvested and damaged areas by crop cycle and production mode (rain-fed / irrigation) and are grouped according to spatial units such as states, municipalities and irrigation districts (from 2003). The information provided by the SIAP offers a detailed vision of agriculture in Mexico during the last decades, facilitating agricultural sector decision-making (Pérez-Vega and Mas, 2023).

We also used data from the National Water Commission (CONAGUA) meteorological stations.

3.2 Cartography

We used the land use and vegetation map, scale 1:250,000 from INEGI, the official cartography and statistics agency of Mexico, to delimit the irrigation areas and a map of the municipalities (INEGI) to spatialize the agricultural census data.

3.3 Remote Sensing Data

We used Landsat 8 multispectral imagery. These images have nine spectral bands (spatial resolution of 30 meters), including a panchromatic band with 15 m resolution. The temporal resolution of 16 days and the existence of a historical collection with images with this spatial resolution since the 1980s facilitates the monitoring of changes in land cover and the detection of environmental phenomena over time.

The MOD13A1 product, version 6.1, derived from data collected by the MODIS (Moderate Resolution Imaging Spectroradiometer) sensor, focuses on global vegetation monitoring. It offers a spatial resolution of 500 meters, allowing evaluation of large-scale vegetation patterns with a frequency of 16 days since 2000. Among its notable features is the ability to calculate the Normalized Difference Vegetation Index (NDVI), a crucial metric for assessing the health and density of vegetation in different regions of the planet.

Another derivative product of the MODIS sensor is the MOD16A2 (version 6), explicitly designed to estimate water balance on a global scale. This product provides detailed information on evapotranspiration (ET) and water availability at the Earth's surface.

With a spatial resolution of 500 meters and for periods of 8 days, the MOD16A2 allows a detailed analysis of water consumption patterns at a regional level, thus contributing to the sustainable management of water resources.

The ECOSTRESS sensor (Ecosystem Spaceborne Thermal Radiometer Experiment on Space Station) has been developed to measure the temperature of the Earth's surface with high precision. The ECO3ETPTJPL product provides detailed data on Instantaneous Latent Heat Flux (W/m^2), which is directly related to evapotranspiration, at a spatial resolution of approximately 70 meters. This high resolution allows the study of specific phenomena at the local and regional level, providing valuable information to understand hydrological processes and the response of ecosystems to changes in water availability.

We used the Application for Extracting and Exploring Analysis Ready Samples (AppEEARS, available at https://appeears.earthdatacloud.nasa.gov/) tool to obtain ECOSTRESS evapotranspiration values. Climatic data were obtained and processed with the Climex program (Ángel Marqués-Mateu et al., 2023). We performed all other statistical analysis, mapping and graphing operations with the R program (R Core Team, 2021).

4 METHODS

4.1 Preliminary Analysis of Census Data

The SIAP data were analyzed to determine which municipalities have important irrigation areas (more than 10,000 ha) dominated by a single crop (more than 80%, during 2003-2023) and whether a change in dominant crop occurs. In this preliminary study, we sought a more straightforward case to avoid dealing with an area with different crops with different spectral responses and planting and harvesting schedules.

4.2 Analysis of Agricultural Dynamics and Estimation of the Sown Area

We prepared time series with MODIS (ET and NDVI, 2002-2023) and ECOSTRESS (Latent Heat Flux, 2018-2020) data. We selected 30 random points in irrigation areas and drew graphs showing the temporal variations of these variables, allowing us to observe the areas sown or not in the two cycles.

In the next step, we evaluated to what extent remote sensing data at different spatial resolutions allow evaluation of the sown area during the winter/autumn cycle. We computed the correlation coefficient between the sown area reported by the SIAP and indices obtained from the images as the sum of the NDVI and ET values in the irrigation areas during the autumn/winter cycle. An unmixing exercise of the MODIS images was also carried out to estimate the sown area obtained from the Landsat image for the same date.

To estimate the evapotranspiration of croplands, we used the Blaney-Criddle method (Blaney and Criddle, 1950) because it is accurate enough and only requires temperature data (Equation 1).

$$ET_c = K_c \sum p(0.457T_{mean} + 8.128) \qquad (1)$$

Where: Et_c is the crop evapotranspiration (mm), T_{mean} is the mean daily temperature, p is the mean daily percentage of annual daytime hours, and K_c is the crop coefficient.

We obtained the temperature from data from climatological stations for 1981-2010. We chose stations that best represented the climatic conditions of irrigated areas. We used crop coefficients from local and international sources (Allen et al., 1998; Ángeles Hernández et al., 2017; INIFAP, 2001). We compared these ET values with those obtained from the analysis of MODIS and ECOSTRESS images.

5 RESULTS

One municipality that met the search criteria was Pénjamo in the State of Guanajuato. The dominant irrigated crop (more than 80% during 2002-2014) was wheat, and from 2016, wheat and barley. The total irrigation area sown during 2003-2022 varied between 12,000 and 34,500 ha (autumn-winter cycle) and 18,000 and 37,000 ha (spring-summer cycle).

As shown in Figures 3 and 4, MODIS time series (NDVI and ET) allow crop growth to be clearly observed in both cycles.

The ECOSTRESS data obtained for the same points were very noisy. We observed very high latent flux values, which the uncertainty layer did not allow to eliminate (Figure 5).

The NDVI was calculated based on a Landsat 8 image from March 2, 2020, when the contrast between cultivated and non-cultivated areas appeared strongest. We determined visually that the value of 0.3 separated the areas with crops. The binary crop map obtained by thresholding indicates a cultivated area of 13,650 ha, while the SIAP reports a very close value (13,905 ha). The Landsat binary crop map was overlaid with the MODIS NDVI image of the same

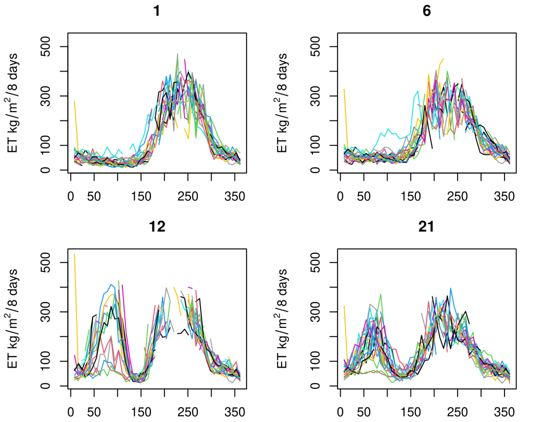

Figure 3: Variation of evapotranspiration (obtained from MODIS) over a year on some sampling points of the irrigation area of Pánjamo, Guanajuato. Each color represents a year on the period 2003-2022, time is shown as julian days.

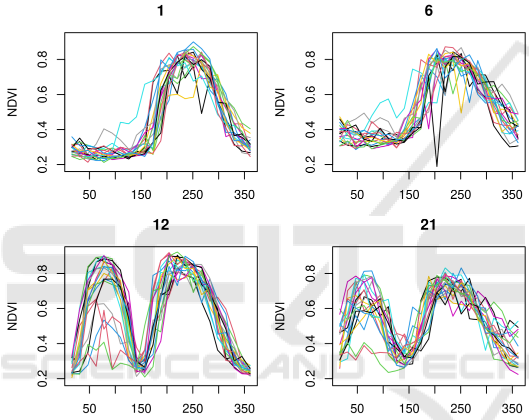

Figure 4: Variation of mean NDVI (obtained from MODIS) over a year on some sampling points of the irrigation area of Pánjamo, Guanajuato. Each color represents a year on the period 2003-2022, time is shown as julian days.

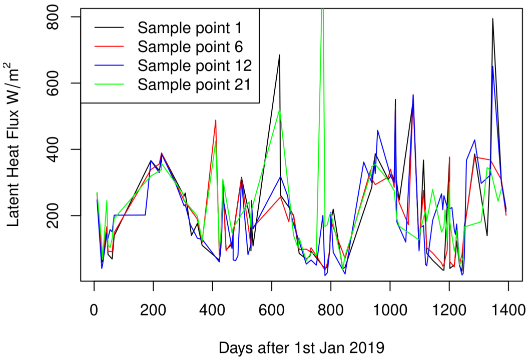

Figure 5: Variation of latent heat flux (obtained from ECOSTRESS) over 2019-2022 on the same sampling points of the irrigation area of Pánjamo, Guanajuato. Time is shown as julian days from 1st Jan. 2019.

period (MOD13A1_NDVI_2020_081), thus allowing the proportion of crops in each 500 m MODIS cell to be calculated. The correlation coefficient between NDVI and crop proportion was 0.85, which suggests that NDVI is a good indicator of crop proportion (Fig 6). We fitted a linear model to explain the crop ratio with the NDVI value. The model presented a good fit (Adjusted R-squared = 0.82).

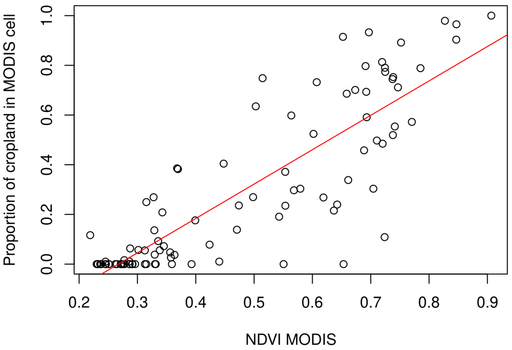

Figure 6: Relationship between the proportion of irrigated crop in coarse MODIS pixels and NDVI values.

We sought to estimate the relationship between the NDVI and ET values from MODIS on the one hand and the total area sown according to the SIAP during 2003-2022. To do this, we calculated the sum of each year's NDVI and ET values of the irrigation district cells. We evaluated the relationship between these values and the sown areas reported by the SIAP. Similarly, the unmixing model reported in the previous paragraph for each year (Figures 7, 8 and 9).

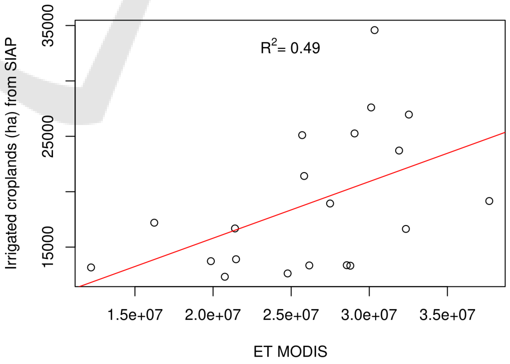

Figure 7: Relationship between the yearly swon irrigated area (autumn/winter cycle) during 2003-2022 from SIAP and the sum of MODIS ET values.

The best relationship was obtained using the evapotranspiration (R^2=0.49). However, it is not a strong relationship and does not allow us to estimate the snow-irrigated area accurately. These limitations have reported in the literature (Wu et al., 2022).

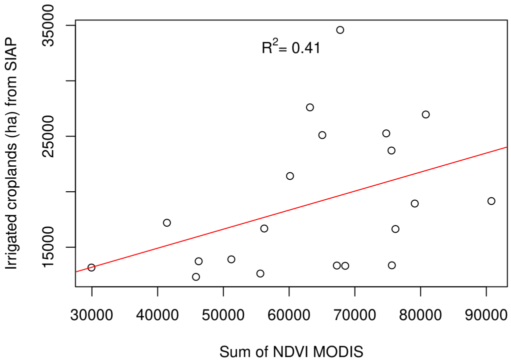

Figure 8: Relationship between the yearly swon irrigated area (autumn/winter cycle) during 2003-2022 from SIAP and the sum of MODIS NDVI values.

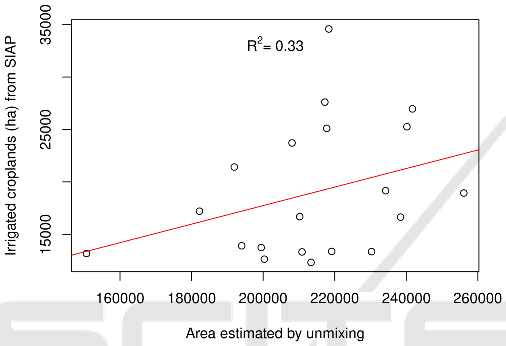

Figure 9: Relationship between the yearly swon irrigated area (autumn/winter cycle) during 2003-2022 from SIAP and the values obtained by unmixing MODIS NDVI values.

6 DISCUSSION AND CONCLUSION

This study focuses on evaluating the quality and consistency of information related to irrigated agriculture in the State of Guanajuato, Mexico, with a particular emphasis on the municipality of Pénjamo, located in the central part of Mexico. The methods include analysing agricultural census data, cartography, and remote sensing data from various sensors, such as Landsat 8, MODIS, and ECOSTRESS. The research specifically focused on Pénjamo due to its relevance in irrigated agriculture and the challenges posed by water scarcity in the region.

The results demonstrated the effectiveness of MODIS time series in clearly depicting crop growth in both cycles. However, ECOSTRESS data exhibited high noise levels, impacting the clarity of latent flux values. In the future, we will also use Sentinel-2 data, which presents high spatial and temporal resolution. Because different modalities of data can complement each other by combining their strengths and reducing their limitations, Multimodal remote sensing (MRS) methods are beneficial for crop monitoring and are gaining popularity (Karmakar et al., 2024).

The findings of this preliminary study provide valuable insights into the dynamics of irrigated agriculture. The effectiveness of MODIS time series in monitoring crop growth during different agricultural cycles highlights the utility of coarse remote sensing data in assessing irrigated agriculture over large extensions (e.g. the entire Mexican territory).

These findings contribute to the broader discussion on applying multidisciplinary approaches, combining agricultural census data, cartography, and remote sensing, to address the sustainability of irrigated agriculture in regions facing water scarcity and climate variability. The research underscores the importance of integrating different data sources and technologies to understand irrigated agriculture dynamics comprehensively. As water scarcity intensifies globally, the methods and insights presented in this study can inform policymakers in developing effective strategies for sustainable water resource management and climate change adaptation in irrigated agriculture.

ACKNOWLEDGEMENTS

This study was carried out within the scope of the PAPIIT-UNAM project (IN112823) entitled: *Azolvamiento y eutroficación en presas periurbanas de zonas templadas de México: contribuciones para su evaluación y prospección* and *Análisis de la Calidad, Cantidad, Gestión y Políticas Públicas ante escenarios de Cambio Climático en la Presa Solís, Guanajuato*, Dirección de Apoyo a la Investigación y el Posgrado, Universidad de Guanajuato).

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