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RESEARCH ARTICLE

Drought tolerance of Tének traditional agroecosystems: Towards mitigate the climate change effects

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ABSTRACT

Traditional agroecosystems (TA) are considered more resilient to climatic extremes due to higher crop diversity and agroecological approach. The TA of Tének were studied to evaluate their drought tolerance. Open-ended questionnaire surveys, field visits, and botanical collections, with the participation of local farmers, were considered. Cultivated plant diversity was analyzed using the Shannon-Wiener diversity index (H'), and the Morisita-Horn index (C_{MH}) in ten different agroecosystems in April and August. Remote sensing methods included the triangular greenness index (TGI). Additionally, normalized difference vegetation index (NDVI) and standardized precipitation index (SPI) were determined, covering the period from 2013 to 2022. The cultivated plant richness (P > 0.5382) and their abundance (P > 0.3622) did not change from April to August considering the total analyzed parcels. However, differences between types of agroecosystems were observed because higher diversity corresponded to managed jungle (*te'lom*) (H' = 1.5-1.7), and some parcels cultivated with maize (*milpa*) (H' = 1.02-1.54). Nevertheless, in August, lower similarity was observed in *milpa* (C_{MH} = 0.23-0.87) due to the absence of maize (*Zea mays* L.) and other herbaceous annual crops. Landscape interconnection can be affirmed with TGI correlations obtained by comparison of different TA. The negative SPI values were associated with a decrease of NDVI, but Tének polyculture agroecosystems maintained higher NDVI values compared to rainfed monocropping during the analyzed period. Tének polyculture agroecosystems exhibited higher drought tolerance, although maize and other herbaceous plants are susceptible to disappearing during prolonged drought events, thereby increasing food insecurity.

Key words: Food insecurity, NDVI-SPI relationship, remote sensing, TGI vegetation index, unmanned aerial vehicle.

INTRODUCTION

The indigenous communities of Mexico cultivate approximately 28 million hectares supported by agroecological approaches and conforming traditional agroecosystems. These traditional agroecosystems are distinguished by their extensive variety of cultivated crop species and their focus on agrobiodiversity conservation. The Tének are native people living in the Huasteca Region of San Luis Potosí, which is a subtropical area characterized by the presence of traditional agroecosystems, primarily managed under the slash-and-burn system. Tének agroecosystems are classified as follows: The *kalumlab*, those are the farmed backyards; the *te'lom* that consist of managed jungle; the *emm* is the area cultivated with maize (commonly named as *milpa*), and the *pakablom* is the area allocated for sugarcane production, among others. It is worth noting that these elements exist as a continuous mosaic of landscape units, interacting among them to create a unified system (Hernández et al., 2016).

Tének agroecosystems comprise a high heterogeneity of plants, which represent a substantial number of genetic resources, including approximately 84 species with 140 farmer-recognized variants. The most representative crops are maize, squash, and beans. The Tének agroecosystems have demonstrated their sustainability by maintaining productivity up to the present (Heindorf et al., 2019). The preservation of plant diversity by Tének farmers has endured despite the existence of political, social, and economic pressures. These farmers adapt, adjust, and introduce new species in response to ecological and economic considerations (Hernández et al., 2016).

These traditional agroecosystems are considered an ideal model for agricultural production (Toledo and Barrera-Bassols, 2017). Traditional agroecosystems are seen as more resilient to climatic extremes. This resilience stems from the combination of agricultural biodiversity and various agroecological practices, which help to mitigate the impacts of both biotic and abiotic disturbances. However, the Region periodically suffers prolonged droughts with devastating impacts on the agriculture and livestock, therefore, contributing to food insecurity. There are no previous reports on the study of this climatic phenomenon in the area, and their effects on cultivated crops. Taking these considerations into account and the relevance of the traditional agroecosystems for the Tének population, the objectives of this study were focused on characterizing the structure of cultivated plants in various Tének agroecosystems, conduct a comparative analysis of factors affecting crop production, quantify the relative diversity and abundance of crop species, and characterizing different parcels by remote sensing methods during a drought event.

MATERIALS AND METHODS

Study area

The data-gathering phase of this research was conducted in the indigenous communities of Tocoy (21°38'18.99" N, 98°52'14.98" W) and Xolol (21°38'0.99" N, 98°52'50.01" W), situated at 245 m a.s.l. in the municipality of San Antonio, San Luis Potosí, México. These two communities comprise 1061 and 233 people, and they are part of the ethnic Tének group (CONAPO, 2017). The climate type corresponds to a semi-warm wet group C. The average annual temperature is around 25.5 °C, with an average annual high of 31.6 °C and a low of 19.4 °C. Similarly, the rainy season occurs during the summer (90%-95%), while winter rainfall accounts for about 5% to 10%, and total annual precipitation fluctuates between 1000 and 2500 mm. The most representative vegetation includes tropical deciduous forest, and tropical rain forest. The main economic activity is traditional agriculture (INEGI, 2002; 2020).

Household questionnaires

The analysis of traditional agroecosystems (TA) involves open-ended questionnaire survey, field visits, and botanical collections of crops, with the participation of local farmers. To identify the issues affecting crop productivity, we applied a semi-structured questionnaire with a custom design to 30 farmers selected from both communities, utilizing a combination of purposive and random sampling techniques (Heindorf et al., 2019). The questionnaire consisted of 30 items associated with five principal topics: (1) Characteristics of the agricultural production system, (2) knowledge of pest and weeds, (3) agrochemical applications, (4) organic management practices, and (5) effects of climate phenomena experienced during the last years. The information gathered through the surveys was descriptively analyzed using the statistical software SPSS ver. 25.0 (IBM, Armonk, New York, USA) and the variables were compared between communities with the independent proportions test using the Epidat Statistical Program ver. 3.1 (Dirección Xeral de Saúde Pública, Xunta de Galicia, Santiago de Compostela, Spain, and Unit of Health Analysis and Information Systems of the Pan-American Health Organization, Washington D.C., USA).

Species diversity index

Simultaneously, the quadrat sampling method was used to quantify the relative diversity and abundance of cultivated plant species (Wohlgemuth et al., 2008), and the collected plants were taxonomically identified by taxonomist at the SLPM herbarium (http://slpm.uaslp.mx/), San Luis Potosí, Mexico, considering the works of

Rzedowski and Rzedowski (2005), among others. The procedure involved selecting ten plots to establish a 100 m^2 square area and counting all cultivated plants within ten randomly selected 1 m^2 quadrats. The selected plots from the communities of Tokoy (T) and Xolol (X) corresponded to four *milpa* (MT1, MT2, MX1 and MX2), two sugarcane (*Saccharum officinarum* L.) parcels (*pakablom*) (ST1 and SX1), two managed jungle (*te'lom*) (JX1 and JX2), one prickly pear (*Nopalea cochenillifera* (L.) Salm-Dyck) plot (NT1), and one pineapple (*Ananas comosus* (L.) Merr.) plot (PX1). The activities were performed in April and repeated in August, covering the agricultural production cycle of maize (*Zea mays* L.) for Tének communities. Additionally, this timeframe was chosen due to an unexpected drought event (CONAGUA, 2019). Data obtained from cultivated plants diversity from the selected plots were analyzed using Shannon-Wiener diversity index (H'), and Morisita-Horn index (C_{MH}). The indexes calculation and comparison were performed using the PAleontological STatistics software (PAST ver. 3.26) (Hammer et al., 2001).

Triangular greenness index

An unmanned aerial vehicle (UAV) Quadcopter, Phantom III Standard (SZ DJI Technology Co., Ltd., Shenzhen, China), equipped with a 12-megapixel RGB camera, was used for capturing images of the main agroecosystems identified: Three *milpa* plots (MT1, MT2, and MX1) and two *pakablom* plots (ST1 and SX1). Additionally, the contiguous jungle sections (*te'lom*) of each plot were analyzed (JMT1, JMT2, JMX1, JST1, and JSX1). Aerial photographs were captured at each study site at flight height of 30 m. Subsequently, the images were ortho-rectified using the OpenCV image library (Bradski, 2000). For each of these images, the Triangular greenness index (TGI) (De Ocampo et al., 2019) was calculated using a custom script written in the Python programming language (Rossum, 1995). The TGI estimates chlorophyll concentration in leaves and canopies based on the area of a triangle with three points: (480 nm, R_{480}), (550 nm, R_{550}), and (670 nm, R_{670}) (Hunt et al., 2013). The TGI provide quick and informative measurements about the state of health of the flora by estimating the photosynthetic activity through chlorophyll content, as higher values above 0.05 indicate the presence of photosynthetic activity (chlorophyll), while TGI values lower than 0.05 are likely the result of influences from biotic or abiotic factors (De Ocampo et al., 2019; Costa et al., 2020). Finally, TGI correlation values were obtained by comparing their corresponding histograms of captured images from different traditional agroecosystems (zones), for every pixel at each zone. In this way, it was possible to have quantitative measurements of the conditions of the studied areas based on a visible spectrum vegetation index.

Normalized difference vegetation index and standardized precipitation index

Four polygons composed of mixed cropping traditional agroecosystems (*milpa*, *pakablom*, and *te'lom*) were selected in the study area (Tocoy 1-2 and Xolol 1-2) and compared with another four polygons consisting of rainfed monocropping agroecosystems (Extensive 1-4) (Figure 1). The spectral data (Landsat Surface Reflectance) were obtained from Landsat-8 Satellite imagery and compiled from the US Geological Survey (Huete et al., 2002) at a spatial resolution of 250 × 250 m and monthly temporal resolution, covering the period from 2013 to 2022.

The normalized difference vegetation index (NDVI) is a normalized ratio of near infrared (NIR) and red (RED) bands (Huete et al., 2002), and it was calculated for the period from 2013 to 2022. The Climate Engine ver. 2.1. (2024) platform (http://climateengine.org) was utilized according to Huntington et al. (2017), and data visualization was conducted using ArcGIS (ver. 10.1) software (Environmental Systems Research Institute, Redlands, California, USA).

The standardized precipitation index (SPI) was calculated monthly according to the steps described in Edwards and McKee (1997). The SPI values were classified into seven different precipitation regimes: Extremely wet ($2.0 < SPI \leq Max$), very wet ($1.5 < SPI \leq 2.0$), moderately wet ($1.0 < SPI \leq 1.5$), normal precipitation ($-1.0 < SPI \leq 1.0$), moderately dry ($-1.5 < SPI \leq -1.0$), very dry ($-2.0 < SPI \leq -1.5$), and extremely dry ($Min \leq SPI \leq -2.0$) (Wang et al., 2018).

Figure 1. Polygons selected to perform a temporal analysis of Normalized Difference Vegetation Index (NDVI) and Standardized Precipitation Index (SPI) throughout the period from 2013 to 2022.

RESULTS

Characteristics of agroecosystems

The Tokoy and Xolol communities presented similar features. The survey results enable us to understand that the communities consist of small farm households and the parcels are tended by men and women with average ages of 53-57 yr old, indicating an aging process among landowners. The slash-and-burn agriculture farming method is mainly used, and land plots are smaller than 1 ha (80%). Sowing begins with the onset of rainfall, and the scheduling of harvest depends on the variability of the rainy season (water source), as they lack irrigation infrastructure. Sixty percent of the producers cultivate more than one crop species, and the total crop production is used for self-consumption. The principal cultivated crops are maize, and sugarcane. Fruit tree cultivation is less common (5% to 20%). People typically produce a single harvest per year, and farmers save seeds for planting the following season. Bartering is common among local producers. Farmers mentioned many vertebrate species feed on their crops (mammalians and birds), but only 56% identified insect pests and plant diseases as an agricultural problem. The respondents (16%) may use plant extracts, detergents, and lime S (calcium hydroxide + S) for pest control, and chemical pesticides are occasionally used (10%-40%). Weed management is primarily performed by manual removal (90%-95%) and occasionally with herbicides (5%-10%). Chemical fertilizers are rarely used (20%), with another organic source of nutrients being preferred (30%).

Abiotic stressors significantly contribute to the decline in maize and sugarcane yields, along with those of other annual crops. According to local farmers, high temperatures and droughts (80%-90%) consistently impact crop yields annually. Additionally, corn root lodging (60%-65%) was identified as an additional challenge during the windy rainy season. The consequent soil erosion was also noted as a prevalent problem (50%-90%), influencing the fallow period to range from 3 to 5 yr.

Species diversity and abundance

The results obtained from field visits and plant identification of studied agroecosystems exhibited a diverse array of herbaceous plant species, similar to results published by López et al. (2015), who documented the local edible plants of Tének communities. We identified 15 botanical families, with 22 different species recognized. Sixty-three percent of the identified herbaceous plants produce fruits and seeds, while the remaining 37% are plants whose edible parts are the leaves, stems, or roots. The herbaceous plants are grown from seeds (14 species) and exhibit high phenotypic variability, as well as good adaption to local edaphoclimatic conditions. Farmers employ vegetative propagation methods, but only sugarcane, vanilla, and pineapple were observed as established crops. Trees and palms were also observed in the studied agroecosystems, belonging to 16 botanical families, with 19 species identified. Trees and palms produce consumable fruits in 90% of cases, while the remaining 10%, the edible part are the flowers (*Erythrina americana* Mill.) or the vegetative primordial (*Sabal mexicana* Mart.). It is worth noting that herbaceous plants were always found coexisting with trees and/or palms, but the number of species observed per parcel ranged from 3 to 22 out of the total identified species (41 species).

The results obtained of the abundance (P > 0.3622) and richness (P > 0.5382) of cultivated plants considering the total number of analyzed parcels did not change drastically from April to August by effect of drought. The managed jungle (JX1, JX2) (*te'lom*) (H' = 1.5-1.7) and two *milpa* (MT1, MX1) (H' = 1.02-1.54) contained higher diversity, but monoculture plantations as sugarcane (H' = 0.09-0.79), pineapple (H' = 1.03) and prickly pear (H' = 0.50) exhibited lower diversity values (Table 1). Significant differences were observed between parcels because the diversity values decreased in August (second evaluation) due to the absence of maize and other herbaceous annual crops (*Cucurbita* spp., *Phaseolus vulgaris* L., and *Ipomoea dumosa* (Benth.), among others. Lower similarity (C_{MH} = 0.23-0.87) was observed in *milpa* (MT1, MT2, MX1, and MX2). The other agroecosystems showed higher similarity values (C_{MH} = > 0.96-1.00) because the vegetation structure did not change during the analyzed period (Table 1). During the course of this research, the drought event (CONAGUA, 2019) affected the survival of herbaceous annual crops. The most affected was the *milpa* agroecosystems. The managed jungle (*te'lom*) and sugarcane plots (*pakablom*) demonstrated resilience to the stressful conditions resulting from extended periods of rainfall absence.

Table 1. Diversity indexes of plant species cultivated in Tének traditional agroecosystems. Traditional agroecosystems: Area cultivated with maize (*emm* or milpa; MT1, MT2, MX1 and MX2), area allocated for sugarcane production, (*pakablom*; ST1 and SX1), managed jungle (*te'lom*; JX1 and JX2), area with prickly-pear (NT1) and pineapple parcel (PX1). **Significant differences (P< 0.01).

	MT1	MT2	MX1	MX2	ST1	SX1	JX1	JX2	NT1	PX1
					Shannon diversity index (H')					
April	1.02**	0.63**	1.37	0.50**	0.79**	0.09	1.50	1.67	0.34	1.03
August	0.39	0.00	1.54	0.00	0.26	0.09	1.50	1.73	0.50	0.76
					Morisita-Horn index (C_{MH})					
	0.88	0.42	0.26	0.23	0.87	1	0.99	0.96	0.98	0.97

Triangular greenness index

The traditional agroecosystems analyzed showed correlation values ranging from 0.7 and 0.95, indicating similar frequencies of TGI values between the milpa plots (*emm*), jungle managed (*te'lom*), and the sugarcane plots (*pakablom*) (Figure 2). However, the reduced vegetation cover observed in MT1, distinguishes it from the other plots, particularly with MT2 (0.5) (Figures 2 and 3). Likewise, there were strong correlation values observed among the jungle sections, ranging from 0.7 to 1.0. The highest values were noted between the jungle sections JMT1, JMT2, and JMX1. However, JST1 jungle section displayed a lower correlation (< 0.65) due to its lower TGI values (< 0.05), indicating reduced photosynthetic activity despite having similar vegetation cover. Padró et al. (2019) mention that RGB sensors present confusion in differentiating between the soil and dry vegetation, the reason for the high correlation (0.85) observed between MT1 and JST1, the first with lower vegetation cover and the second with predominately dry vegetation. Finally, when comparing the traditional agroecosystems with their adjacent jungle sections, correlation values ranging from 0.7 to 0.9 were obtained. The TGI algorithm allowed differentiating the plants with the highest concentration of chlorophyll and their spatial location (Figure 3).

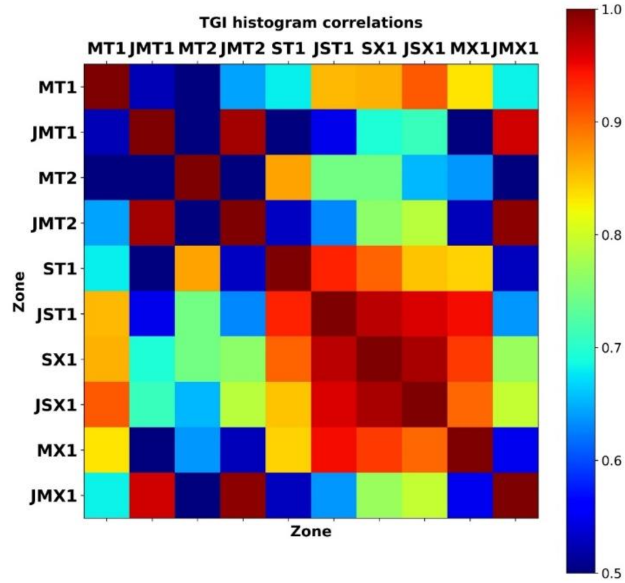

Figure 2. Triangular greenness index (TGI) correlations obtained by comparison of different traditional agroecosystems: Area cultivated with maize (*emm* or milpa; MT1, MT2 and MX1), area allocated for sugarcane production, (*pakablom*; ST1 and SX1); and their contiguous jungle (J) sections (*te'lom*; JMT1, JMT2, JST1, JSX1 and JMX1).

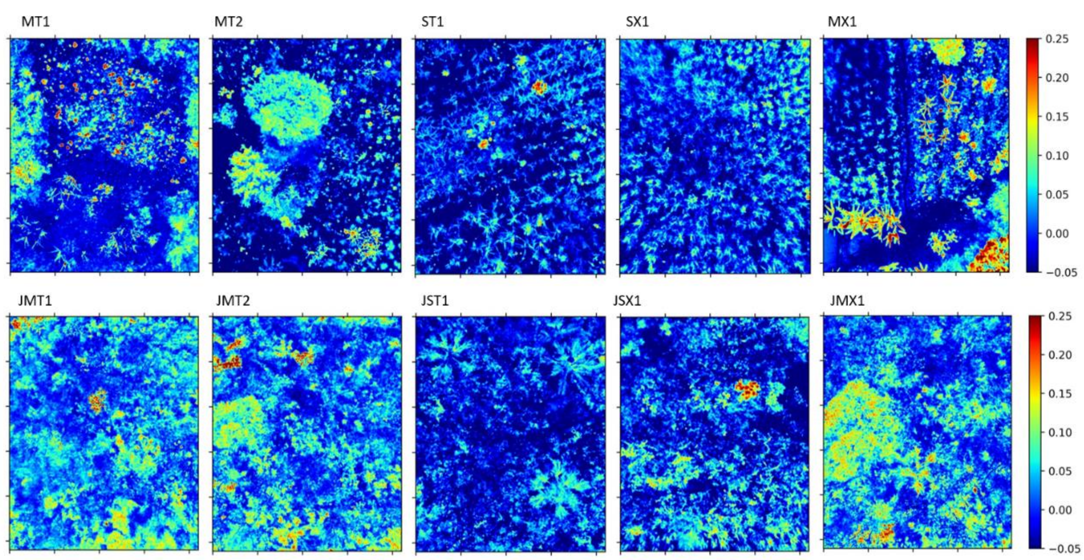

Figure 3. Triangular greenness index (TGI) frequency values observed from different traditional agroecosystems: Area cultivated with maize (*emm* or milpa; MT1, MT2 and MX1), area allocated for sugarcane production, (*pakablom*; ST1 and SX1); and their contiguous jungle (J) sections (*te'lom*; JMT1, JMT2, JST1, JSX1 and JMX1).

Normalized difference vegetation index (NDVI) and standardized precipitation index (SPI)

The results obtained from the analyzed period (2013-2022) showed an increase in the frequency of negative SPI values from 2019, but with a drought condition classified as "normal precipitation" (-1.00 < SPI ≤ 1.00), and only a few months as "moderately dry" (-1.50 < SPI ≤ -1.00) category. However, in previous years, the SPI predominately exhibited positive values, with some exceptions at the beginning of 2013 and the end of 2015.

It is important to highlight that the period 2015-2018 was the wettest, as several months exhibited a condition of “very wet” (1.50 < SPI ≤ 2.00) and “moderately wet” (1.00 < SPI ≤ 1.50) (Wang et al., 2018). Concerning the health vegetation associated with NDVI, negative variations in SPI induced a rapid decrease of NDVI, especially when SPI values are negative or near to zero. Years 2019 and 2022 maintained negative SPI values throughout the year, and consequently, the lower NDVI values. These years were registered with extreme drought conditions that affected agricultural activities in the geographical area analyzed (CONAGUA, 2019; 2024). The same behavior was observed during 2021, although the lower SPI values affected only half of the year.

The compared agriculture systems exhibited different NDVI behavior. Tének polyculture agroecosystems maintained higher NDVI values compared to rainfed monocropping (extensive agriculture) throughout the analyzed period (2013-2022), including the driest years (Figure 4). The higher NDVI values in Tének polyculture agroecosystems indicate greater drought tolerance to abiotic disturbances when environmental changes occur, as we addressed in 2019 using traditional methods previously described.

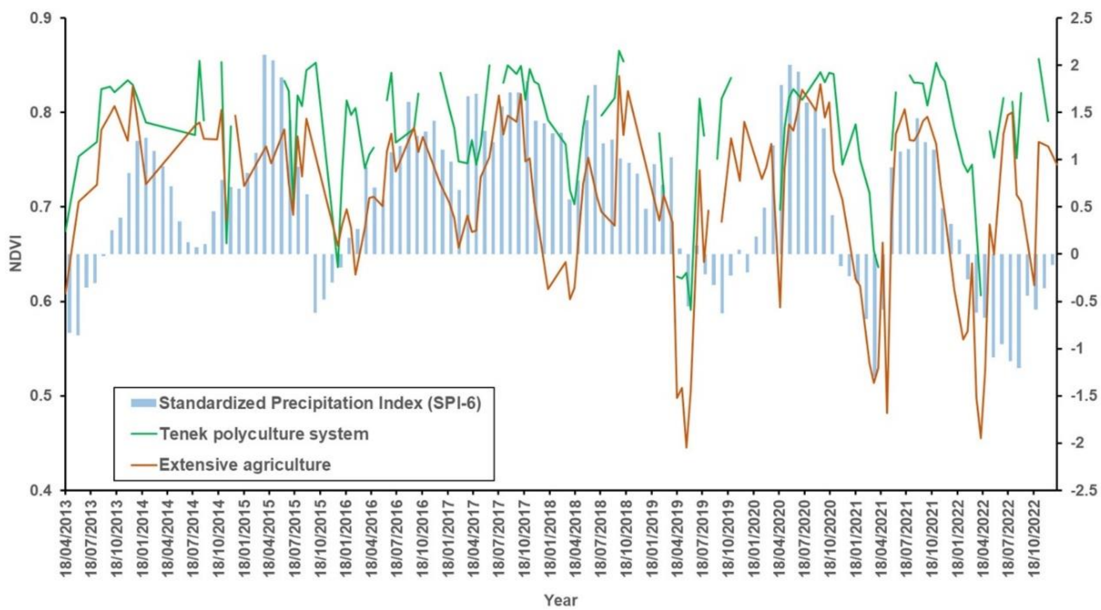

Figure 4. Normalized difference vegetation index (NDVI) and standardized precipitation index (SPI) throughout the period from 2013 to 2022.

DISCUSSION

Tének agroecosystems

Slash-and-burn agriculture is deeply associated with the sociocultural values of the Tének people. The tropical climate and agroecological features favor a high biodiversity of cultivated plants. The organic approach to crop management represents positive features of local agroecosystems. The milpa (*emm*) is the most important agroecosystems identified for Tének communities because it is the principal source of food, and the products harvested are mostly used for self-consumption. The managed jungle (*te'lom*) can provide additional food sources and other important ecological services (López et al., 2015; Heindorf et al., 2019). Regarding the richness of crop species, we observed higher variability among parcels (3 to 17 species per parcel), which is probably due to the tendency to incorporate monoculture practices, which are counterproductive and should be avoided. Sugarcane parcels (*pakablom*) are highly adapted to the local climatic conditions and can be harvested throughout the year for brown sugar production, which is commercialized only at local scale. Establishing tree fruit orchards and vanilla agroforestry production has huge potential, but specialized agronomic technical training focused on soil and water conservation measures is necessary.

The sustainability of slash-and-burn agriculture depends on the regeneration of forest resources, so long fallow periods (15 yr or more) are necessary to restore the soil's chemical and physical attributes (Lintemani et al., 2020). Additionally, large extensions of land are necessary to apply an effective fallow period (Pedroso et al., 2008). The Tének people mention that soil erosion becomes unproductive the parcels after 3 to 5 yr, corresponding to the fallow period mentioned by the interviewers. These situations highlight the importance of implementing soil conservation practices in the studied zones to reduce soil loss. Incorporating organic matter and using local cover crops (such as legumes) may represent viable alternatives to increase soil fertility and potentially enhance crop yields, while also reducing water loss due to evapotranspiration (Peterson et al., 2018).

It is important to mention that during the execution of the present study, the region experienced a severe drought (CONAGUA 2019). However, according to our observations, maize and other herbaceous species were more susceptible to disappearance in the evaluated agroecosystems, while other species withstood the prolonged drought periods [*Sabal mexicana* Mart., and *Nopalea cochenillifera*], and some species only showed yield reduction (sugarcane). However, the negative effects ultimately affected the Tének population because this adverse condition delayed crop planting, leading to considerable food losses. The drought and high temperatures affected all the municipalities of the Huasteca Potosina region; thus, food security was threatened, and the local economy required government intervention (SEGOB, 2019). Nonetheless, it is necessary to develop infrastructure for water resources management and introduce techniques aimed at reducing evapotranspiration to minimize the vulnerability induced by climatic factors in the region during drought periods. The Tének traditional agroecosystems exhibited features such as high diversity of crop species, low inputs associated with agroecological practices, resilience, and social solidarity. However, abiotic factors involved, such as high temperature, drought, heavy rainfall, and soil erosion, represent key constraints for improving crop productivity and increasing food insecurity.

Health vegetation and drought stress

Parcels with higher diversity of herbaceous plants and trees showed higher TGI frequencies. Jungle fractions also exhibited similar correlation values with other agroecosystems plots featuring higher plant richness and canopy cover. This suggests similarity in their spatial structure, vegetation cover, and photosynthetic activity, reflecting a cohesive mosaic of interconnected landscape (Hernández et al., 2016). However, plots with lower cover vegetation or predominantly dry vegetation displayed the lower TGI frequencies.

The use of unmanned aerial vehicle (UAV) coupled with RGB cameras provides real-time data about the plant's health status and soil coverage degree, which are necessary to evaluate the effectiveness of agricultural practices in mitigating the effects of climate change and maintaining agricultural productivity. Cameras with RGB sensors allow for characterization of parcels through the TGI algorithm without discriminating between vegetation types. Their low cost, higher resolution, and the possibility to perform low flight height make them ideal features (Carabassa et al., 2020).

The normalized difference vegetation index (NDVI) enables the distinction between healthy and stressed vegetation, serving as an indicator of vegetation-moisture condition. The standardized precipitation index (SPI) is multifaceted, allowing for drought monitoring across various time scales due to its ability to promptly react to precipitation pattern and different types of droughts. During a specific period, the SPI primarily mirrors the precipitation aspect for that timeframe (Wang et al., 2018). Indeed, the SPI has gained acceptance from the World Meteorological Organization (WMO) as the global standard meteorological drought index for more effective drought monitoring and early warning (Hayes et al., 2011). According to the processed satellite images, the Tének polyculture systems exhibited higher drought tolerance capacity thought the period analyzed, including the years with reports of severe drought events in 2019, and 2022 (CONAGUA, 2019; 2024). The extensive agricultural analyzed areas, composed of monocropping systems, showed lower drought tolerance during the same years. Furthermore, it is important to note that there is a tendency for an increase in the frequency of negative SPI values, which were associated with the progressive reduction of NDVI. Therefore, monocropping may exacerbate the drought impact in local rainfed agriculture.

Climate change is altering temperature and precipitation patterns, impacting both water availability and agricultural productivity. Understanding these climate shifts empowers farmers to adjust their farming practices and systems to mitigate adverse effects on food production. Climate change significantly affects traditional agroecosystems (TA), which rely on the rainy season. While the diversity of species cultivated in TA is crucial, some annual crops are highly vulnerable to extended droughts and elevated temperatures. Consequently, it is essential to develop infrastructure for water collection and storage, along with implementing cultural changes such as soil conservation techniques and avoiding slash-and-burn farming practices.

CONCLUSIONS

Tének traditional agroecosystems possess a rich biodiversity of cultivated plants and embrace an organic approach. Geospatial technology and unmanned aerial vehicles offer valuable insights into vegetation health. The Triangular greenness index enables us to assess vegetation health and land cover. Moreover, the normalized difference vegetation index and standardized precipitation index help identify the rising frequency of drier conditions in the studied area. Tének traditional agroecosystems have exhibited better drought tolerance over the analyzed period (2013-2022) compared with monocropping systems. However, extended drought conditions and high temperatures threaten the survival of maize and other herbaceous crops, which are crucial for maintaining food security for the Tének people.

Author contribution

Conceptualization: C.A.R.H., M.R.V.P. Methodology: C.A.R.H., L.M.G.O., J.A.S.H. Software: L.M.G.O., J.A.S.H. Validation: J.D.C.L. Formal analysis: C.A.R.H., M.R.V.P. Investigation: J.P.L.A. Resources: M.R.V.P., F.D.B. Data curation: J.A.S.H. Writing-original draft: C.A.R.H., M.R.V.P. Writing-review & editing: L.M.G.O., J.A.S.H., J.D.C.L. Supervision: M.R.V.P., Funding acquisition: M.R.V.P., F.D.B. All co-authors reviewed the final version and approved the manuscript before submission.

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