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Adaptation and biocultural conservation of traditional agroforestry systems in the Tehuacán Valley: access to resources and livelihoods strategies

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HIGHLIGHTS

- Traditional agroforestry systems (TAFS) are dynamic and highly adaptable to maintain biodiversity and peoples' livelihood.
- Access to natural resources is key to understand and act for agroecosystems analysis.
- Differentiated access to water and land drastically limits social adaptation.
- Integral assessment of social and environmental factors limiting TAFS is needed to understand their adaptation capacity.
- TAFS play a crucial role in sustainable food production and deserve strong actions for their conservation.

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ABSTRACT

Traditional agroforestry systems (TAFS) are important areas for conserving biodiversity, ecosystems benefits and biocultural heritage, outstandingly local knowledge, management techniques, and domestication processes. These systems have adapted to environmental, social, technological, and cultural changes throughout history. However, contemporary drastic socio-environmental changes as climate variability, economic inequality, migration, among others, have caused a productive crisis, with several consequences as productive land abandonment, threaten the sustainability of TAFS and vulnerating livelihoods. In such context, the question arises of what kind of adaptations are needed to face these changes, and how access to water and land, should be managed to improve adaptation of TAFS? The study analyzes TAFS in the Tehuacán Valley, a region with high biological and cultural diversity and early signs of agriculture in Mexico, where TAFS have remained active until present. The study analyzes the capacity of TAFS to conserve biodiversity and sustain local livelihoods, despite socio-environmental threats. It is based on a political ecology approach, which proposes that socio-ecological systems degradation is linked to unequal access to land and natural resources. Looking for an integral study of adaptations of TAFS to socio-environmental changes, this study combines qualitative and historical research methodology with quantitative methods evaluating plant diversity and spatial analysis. The study findings show that differentiated access to resources, water, land, and forest, is a key factor that limits adaptation of TAFS, impacting livelihood strategies, changing management patterns, and constraining social capacities for coping with socio-environmental changes. TAFS have significantly higher species richness than forests but lower diversity. The main contribution of the study is the methodological approach looking for an integral analysis of natural resources management and biocultural conservation in agroecosystems, and the identification of the unequal access to resources, as a keystone to understand and act for improving adaptive strategies of TAFS to socio-environmental changes.

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1. Introduction

An important prerequisite for sustainable management of agroecosystems is to procure their maintenance as integrated production systems capable of meeting the satisfaction of subsistence needs of local communities while keeping the ecosystems' balance (Vandermeer et al., 1998; Jácome, 1993; Perfecto and Vandermeer, 2008). Traditional Agroforestry Systems (TAFS) have called the attention of agroecologists because of their exceptional adaptive capacity to social-environmental changes throughout history and to favor a good balance between production and biodiversity conservation (Toledo and Barrera-Bassols, 2008; Altieri and Toledo, 2011; Moreno-Calles et al., 2016), providing ecosystem benefits (McNeely and Schroth, 2006; Jose, 2009; Assogbadjo et al., 2012) and both agricultural and forest products to the farmers (Moreno-Calles et al., 2013; Vallejo et al., 2019).

Global agriculture has progressively shifted towards intensified production systems, thus decreasing the area of TAFS and putting them at risk to disappear (Moreno-Calles et al., 2016; Nair et al., 2017; Santoro et al., 2020). However, some features of these systems support the initiative towards increasing their biocultural value and the great importance of maintaining, strengthening, and recovering them for a global strategy of sustainable agriculture (Altieri and Toledo, 2005). In this context, the impact of social and environmental changes on TAFS should be analyzed to identify those factors that influence their deterioration, put at risk their adaptation capacity, and the actions that are needed to conserve them. Particularly important is the study of the patterns of change in land use and management associated with the marginalization in access to resources—especially land and water—which have been identified as the main factors limiting the ability to cope with changes in farming activities worldwide (Blaikie and Brookfield, 1987).

Adaptations of systems as responses to threats from social and environmental changes have been extensively debated; this study takes into account two theoretical approaches for assessing a comprehensive understanding of social and ecological factors of adaptation capacities of TAFS. From a Social-Ecological Systems (SES) framework, agroecosystems' adaptations are commonly analyzed based on the management capacities or abilities of farmers to face shocks, reduce risks, and resist or recover from adversities (Altieri and Nicholls, 2013; Walker et al., 2004; Holling, 1978; Folke et al., 2002, 2003).

Adaptation in agroecosystem management is partly seen as a wide range of human interventions, including the use, conservation, and/or restoration of ecosystems (Casas et al., 2016a, 2016b). In other words, an expression of management and innovations toward promoting sustainable systems (Walker et al., 2004; Holling, 1978, 1986; Folke et al., 2002, 2003). Different forms of adaptation may allow the integration of livestock, agricultural, and forestry activities into the ecosystems without degrading them (Altieri and Hecht, 1990; Gliessman, 1990; Alcorn, 1993; Masera et al., 1999; Altieri, 2002; Gliessman et al., 2007). In these views adaptation and sustainability of social-ecological systems are not restricted to technical issues but consider multidimensional perspectives, including economic, political, social organization, and institutional aspects, among others.

The political ecology perspective emphasizes that capacities are socially constructed and contextual dependent on social relations, structures, and values as endogenous factors more than focusing on external factors (Wisner et al., 2004; Paavola and Adger, 2006). Adaptation is a social response relative to access to resources and the abilities of people to cope with risks or environmental hazards, in light of social differences and levels of vulnerability of populations; it has a multifactorial nature related to political and social power relations, resource use, and global economies influencing endogenous processes (Blaikie and Brookfield, 1987; Adger, 2003; Adger and Kelly, 1999; Smit and Wandel, 2006) In this perspective, ecosystem degradation is significantly influenced by social marginalization, therefore emphasizing the need to consider not only environmental changes as risks, but also structural, social, political, cultural, and economic vulnerabilities in the study of socio-environmental adaptation (Adger et al., 2009).

Access to natural resources is a key element that allows analyzing marginalization and that can be considered an endogenous factor influencing the adaptation capacity of agroecosystems and their managers (Norfolk, 2004; Berry, 1989; Peters, 2004) as it affects land use (McCusker and Carr, 2006; Eriksen and Lind, 2009) and the satisfaction of people' livelihood (Tittonell, 2014; Weltin et al., 2017). For some authors, the analysis of agroecosystems' degradation ought to incorporate the study of marginalization in access to resources, since it limits adaptive capacities (Blaikie and Brookfield, 1987), and the power that mediates access to natural resources (Berry, 1989; Adger et al., 2009; Yohe and Tol, 2002; Tittonell, 2014). In addition, it is important to analyze the forms of use and management of resources, and the social structures that constrain their distribution and access (Blaikie and Brookfield, 1987; Ribot, 1998; Ribot and Peluso, 2003). The control that powerful social groups have over access to resources drives marginalized groups to use unsuitable land, which leads to poverty and environmental degradation (Blaikie and Brookfield, 1987).

The limited access to natural resources and land has impacted both the farmers' livelihoods and agroecosystems management (Peters, 2004; Norfolk, 2004; Berry, 1989). And, as a response, the diversification of livelihoods and productive activities is a common adaptive subsistence strategy (Weltin et al., 2017; Frost and Mandondo, 1999). In this way, the factors affecting the agroecosystems' adaptations, should be analyzed at the landscape level (Tittonell, 2013; Dorward et al., 2009).

This study focuses on the Tehuacán Valley, located in central Mexico. It is an area recognized for its high biological and cultural richness (Dávila et al., 2002; Casas et al., 2016b). Particularly, the analysis focusses on the territory of Zapotitlán Salinas, which is known for its well-preserved ecosystems, includes different types of columnar cacti forests (where the dominant species may be: *Cephalocereus columna-trajani, Lemaireocereus hollianus, Cephalocereus tetetzo*, and rosetophylous plants including *Beaucarnea gracilis* and agaves) whose components coexist with TAFS (Hernández-Moreno et al., 2021). Agroforestry systems in the region show high adaptive capacity, in part due to efforts by local people who manage them based on their traditional knowledge and techniques despite the arid conditions and climate variability characterizing the ecosystems of the area. The regional TAFS has been documented to be effective to contribute to biodiversity conservation and the provision of livelihoods for local communities (Moreno-Calles et al., 2012,2013; Vallejo et al., 2015, Romero-Bautista et al., 2020).

The study analyzes meaningful social and environmental changes that have occurred in the study area seeking to identify which factors have affected or caused the loss of TAFS and which others have allowed their maintenance. The region is going through socio-environmental changes, socioeconomic transformations of productive activities, loss of government funding to farmers, consequently increasing impoverishment and migration, all of which are relevant factors impacting the agroecosystems dynamics. In addition, long-term social and economic changes, especially since the nineteenth century, have modified the local land use. Also, since the year 2000, climate changes are a matter of concern since the temperature has increased 2.5°–3.5° per decade and annual mean precipitation has decreased from 500 to 300 mm (CONAGUA-COTAS Tehuacán, 2017).

The main questions this research seeks to answer are: What factors have historically impacted the adaptation capacity of TAFS to socio-environmental changes? How access to resources, such as water and land, have impacted management adaptations of SAFTs? and What management and social responses are needed and possible to face socio-environmental changes? According to the benefits that have been documented about TAFS in the region, the hypothesis of the study are that adaptation in TAFS: 1) allows sustaining agroecological and socio-economic benefits persisting throughout time, showing different but permanent adaptation to changing conditions of marginalization and limited access to water and land, 2) The main factors affecting adaptation capacity of TAFS are the differential access of farmers to resources, as well as the different livelihood strategies, and combination of management techniques for coping with environmental changes.

Through an analysis that integrates both ecological and social aspects, this study examines adaptation of TAFS and households managing them, through decision-making processes on agroecosystem management for coping with limited access to land, water, and natural resources (Norfolk, 2004; Berry, 1989; Ribot and Peluso, 2003), and the farmers' livelihood components (Peters, 2004), considering these not only as a response to exogenous factors but also endogenous processes socially constructed (Blaikie and Brookfield, 1987).

The aim of the study is to analyze management adaptations of TAFS, attending to social and political factors that influence the decisions over agroecosystems. In this sense, the study focusses on three main aspects: access to natural resources, territorial management, and changes in productive activities and livelihoods, which impact agroecosystems management. To achieve these goals, the study explores the spatial distribution of TAFS and historical conditions of access to resources, land and water; also, how TAFS incorporate adaptive responses that allow biocultural conservation; and, finally, the social factors that influence adaptive management strategies of farmers.

2. Methods

2.1. Study area

The Tehuacán Valley, central Mexico, has geoecological conditions that harbor rich ecosystems and high diversity of flora and fauna (Rzedowski and Huerta, 1978; Dávila et al., 2002). It was declared as the Tehuacán-Cuicatlán Biosphere Reserve (TCBR) in 1998 (DOF, 1998) and included in the UNESCO's World Heritage List as a mixed, natural, and cultural heritage site (UNESCO, 2018). The Valley of Zapotitlán (Figure 1) is in this region. The municipality of Zapotitlán is 42,775 ha extent, with 8,495 inhabitants across 38 localities. Zapotitlán Salinas is the main town with 31% of the population (2,700 inhabitants; INEGI, 2015). Land tenure is communal, with 24,208.2 ha granted in 1964 as social property to the institution of Bienes Comunales de Zapotitlán Salinas (PHINA, 2016) (Figure 1).

The region has a semiarid climate with annual temperature averaging 15° to 25 °C and annual rainfall of 400–450 mm, but during episodes of severe drought, annual rainfall is 300–350 mm (Valiente-Banuet and Ezcurra, 1991). Heavy rains occur in the summer (SEMARNAT-UAM, 1997), 63% of precipitation from June to September.

2.2. Qualitative approaches to environmental subjects: historical and social perspectives

The study used an interdisciplinary approach to integrate social and ecological knowledge and explore social dimensions of conservation and resource management (Drury et al., 2011; Newing, 2010). Likewise, it develops a qualitative approach that allows a hermeneutic perspective for interpreting the actors' perspectives (Guba and Lincoln, 1994; Lincoln and Guba, 1985; Denzin and Lincoln, 2008) and carrying out a historical analysis of the productive activities in the territory and the community. It uses qualitative techniques, such as interviewing, snowball sampling and participant observation (Patton, 1990; Dewalt and DeWalt, 2002), informal conversations, semi-structured interviews, focus groups (Guber, 2001; Vela, 2001), and participatory mapping (Chambers, 2006; Rambaldi et al., 2006).

Fieldwork was conducted throughout eight visits to the community from January 2017 to February 2018. During these visits, a total of 90 gatherings were held with different participants, in which 77 semi-structured interviews with 68 local actors were conducted. Additionally, two meetings were organized as focus groups to document the community's organizational practices for territorial management and were made field trips to six rainfed agricultural areas with different access to land and water (springs, main river, run-off). The study documented the management style of 15 plots of traditional maize crops, 5 plots with crop reconversion to mezcal agave production, and three

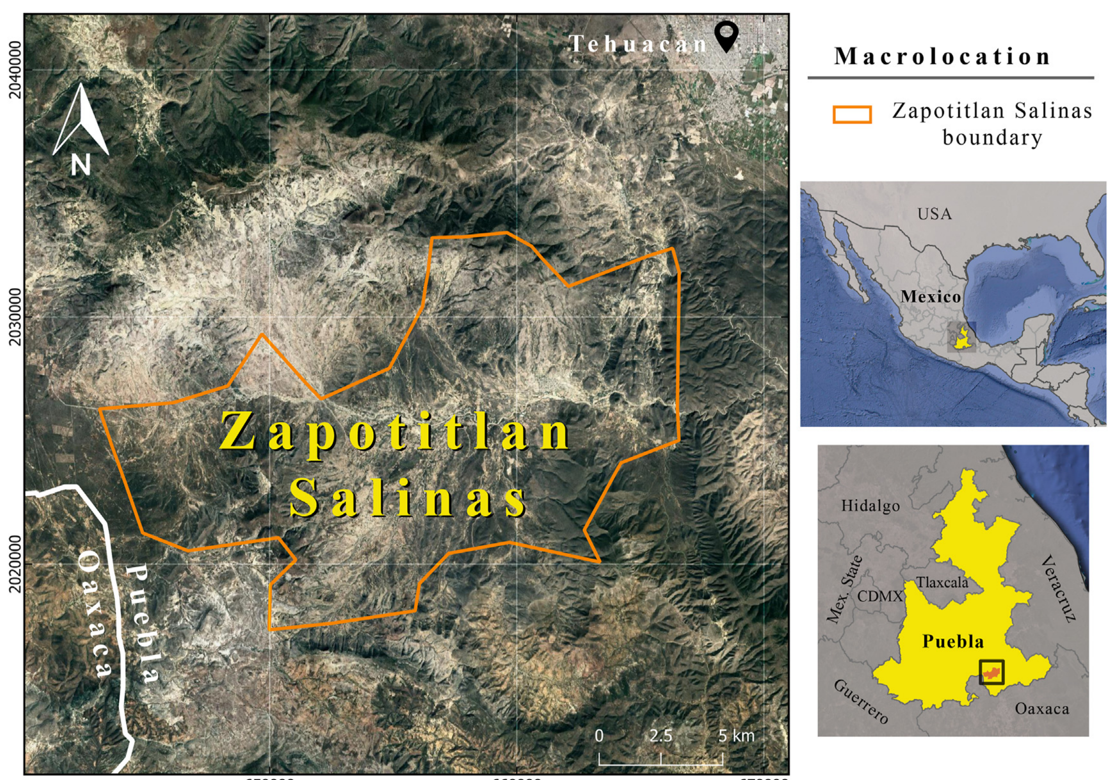

Figure 1. Study area.

with pulque agave. No ethical approvals were required for the study, but the consent of participants.

Three participatory-mapping workshops (Figure 2) were organized along with several trips across the territory, which included visits to plots and key spaces. Maps and field trips allowed calculating the community's perimeter, which was then used to carry out a visual interpretation of the high-resolution multispectral images from *Sentitel 2* satellite and the high-resolution RGB images from Google Earth Pro that were obtained through Qgis 3.10. Through this procedure, the terraced croplands and areas for conventional agriculture were identified and demarcated. Additionally, the data obtained in the workshops and the field trips was cross-checked to verify the information obtained from satellite images, which helped to mapping the agricultural, cattle raising, and salt extraction areas of Zapotitlán for 2018.

This study reviewed literature about the region and compiled press releases and archival notes (Land Commission Archive and General Agrarian Archive), with the purpose to analyze land conflicts, historical land delimitation, and territorial struggles. For processing qualitative data obtained from 77 interviews, ATLAS.ti 7 was used to classify the information and perform the interpretative analysis (Varguillas, 2006; Justicia, 2005). The study also codified and categorized the texts (Adler and Adler, 1987; Krippendorff, 1990) to interpret the narratives according to heuristic discourse categorization techniques (Saldaña, 2015).

2.3. Biodiversity conservation

The conservation capacity of TAFS was analyzed through vegetation sampling evaluating plant species richness, composition, and diversity in plots of five agricultural fields and five forest fields (Vallejo et al., 2015). Sampling was conducted in plots 50 m × 10 m (500 m2) subdivided into squares of 10 m × 10 m (100 m^2) in both TAFS and forest areas in each community. The study registered all the woody species; trees and shrubs were measured the height and crown spread and the trees were also measured for the diameter at breast height (DBH). All collected botanical material for identifying plant species in the laboratory "Manejo de Recusos Genéticos", UNAM.

Plant species richness, diversity and composition, biomass, height frequency, and the number of individual plants was calculated.

Figure 2. Land use of Zapotitlán Salinas.

Composition by the number of families, genera, and species, recording native species was also evaluated. Were calculated the *Importance Value Index* (IVI), as the sum of the percentage of relative frequency, abundance, and biomass of each species in the sampled area. Biomass was estimated using data on height (h), DBH, and diameters of tree canopy of each of the tree ($V = \pi/3h\ (r1^2 + r1r2 + r2^2$, R1 = stems radius, r2 = average of diameters of canopy) and shrub ($V = 4\pi/3\ ab^2$, a = major radius, b = ratio of canopy average) species, obtaining the biomass in m^2. The richness levels were measured with the Colwell's rarefaction method with *EstimateS* through Chao's nonparametric estimators (Colwell and Coddington, 1994; Gotelli and Colwell, 2001; Colwell, 2006).

Based on Jost (2006) and using the SPADE program (Chao and Shen, 2003), for each site the true diversity measure and the ${}^1D$ value (exponential of Shannon's entropy) were calculated. The ${}^1D$ value weights each species according to its abundance in the community, and hence, it can be interpreted as the number of 'common' species in the community (Jost, 2006; Jost, 2010).

3. Results

3.1. Social-environmental changes, and adaptation strategies on agroecosystem management

Zapotitlán Salinas is a community with a pre-Hispanic origin funded by the indigenous Ngiva indigenous people and conquered by the Spaniards in 1522 (Gerhard, 1977; Castelló n Huerta, 2007; Sepúlveda, 2006). Local populations have survived by basing their livelihoods on the use of local resources and the development of productive activities like agriculture and others that have changed throughout history, such as cattle raising, salt exploitation, onyx mining, and tourism. The social and environmental changes that straddle the region have posed a series of challenges to local people, who have had to adapt their production systems and livelihoods. These changes have influenced in turn changes in organizational structures to appropriate, distribute, and access territorial resources, which can be observed at the landscape level, where it can be seen in the footprints of long-range activities like agriculture.

Natural resource management across the region has been guided by productive trends that have been imposed by regional dynamics on the local territory. During the pre-Hispanic period, the use of plant, animal, mineral, and forest resources, along with salt springs, made possible the survival of hunters and gatherers and became the basis for a local agricultural subsistence economy until the colonial period (Castelló n Huerta, 2007; Neely and Castellón, 2003). Because of the region's dry conditions, water control was key for local survival. Adaptation of agriculture allowed local populations to settle down and consolidate their livelihoods (Castelló n Huerta, 2007; Cortés, 2009; Velázquez Soto et al., 2008).

Water availability has shaped the two types of landscapes in the territory: subterranean brine springs and freshwater streams (Neely and Huerta, 2014). Salt exploitation allowed direct use and trade, and freshwater allowed adaptations that led to agriculture for subsistence purposes (Enge and Whiteford, 1989; Neely and Castellón, 2003).

During the colonial period, the productive profile of the territory changed mainly because of the expansion of goat farming, which modified land use. The large flocks of goats that came from the Balsas River basin and the Pacific regions were established across the highlands of La Mesa, Chacateca, and the Mirador hills, amounting over 5000 goats (Dehouve, 1994; Martínez et al., 2011). This region was particularly important for the local economy, harboring five ranches dedicated to goat grazing, horse breeding, wild agave harvesting, and cultivation of green maguey (*Agave salmiana*) for pulque production, which are still local traditions.

The local cattle-raising elites sought to control territory and water, which led to the land grabbing of areas bordering the Zapotitlán river and springs that were later assigned to slaughterhouses and intensive agricultural zones (Henao, 1980). Land and water grabbing pushed other families to conditions of marginalization and to uneven access to resources. As a result, they were only able to have small rain-fed plots and complementary activities such as herding and salt extraction.

As a consequence of the Mexican Revolution between 1910 and 1917 and the Agrarian Reform initiated in the 1930s that gave guarantees to social property, under the figure of communities and ejidos, Zapotitlán Salinas received the communal property of land, as Bienes Comunales in 1964. In Zapotitlan, this process not only allowed the distribution of land among the peasants, but also finalized the economy of the haciendas and brought about productive changes. During the first quarter of the 20th century, the eradication of big *haciendas* led to a loss in the boom of livestock farming, which only continued with small and medium-sized producers that kept flocks of 50–500 heads. The decline of cattle raising impacted the local economy. However, this loss was compensated by mining with the expansion of onyx and baryte extraction, which gained economic momentum along with lime and salt (Lee, 2008). Furthermore, the establishment of over 100 workshops for producing and selling traditional craftworks was an addition to the livelihood of local people (Cortés, 2014). By the 1980s, the depletion of onyx led to the collapse of the local economy, pushing people to migrate to the USA (Lee, 2008, 2014; Cortés, 2009).

Since the 1990s, both the income that resulted from activities in the service sector in the city of Tehuacán (Martínez et al., 2011) and the remittances received by approximately 64% of the families (Lee, 2008) have been crucial to the local livelihood. Furthermore, governmental policies of biodiversity conservation have propelled new activities linked to ecotourism, which have modified the territorial dynamics—for example, the local families have invested in small businesses as complementary self-employment alternatives (Cortés, 2014; Zárate and Cortés, 2014).

Because agricultural, cattle-raising, and salt-extracting local activities yield little income and are vulnerable to social and environmental changes, they hardly allow for a surplus that could improve production or family businesses. Furthermore, as migration revealed the fragility of the local livelihoods, families have used livelihood diversification as a key strategy. Even though most of the families carry out activities in the territory, they complement their income with remote activities, which at the same time have contributed to the exploration of new productive options and local business ventures.

According to the above, agriculture's relevance within the community currently depends on the economic resources that result from supplementary activities, since the exacerbation of droughts and changes in production have increased the risk of crop loss. Farmers' decisions to continue cultivating land depend to a large extent on access to land and water. However, in Zapotitlán, agriculture depends not only on the natural availability of resources according to geoecological diversity (Cortés, 2014), but also on disputes between social groups over the appropriation and access to land, water, and resources.

3.2. TAFS in the Zapotitlán Valley: biodiversity conservation and differential control and access to land and water

Agroforestry management in Zapotitlán is a clear example of the community's ability to adapt to wild, arid land and mountainous terrain (Neely and Castellón, 2003; Hernández and Herrerías, 2004). However, the way in which productive zones are arranged in the landscape not only shows how the community has adapted to water scarcity but also demonstrates forms of social appropriation and control over strategic resources like land and water.

Adaptations of TAFS respond to two conditions: (1) climate variability of the arid ecosystems of the region, and (2) changes in productive activities and natural resource management. Both can be understood in the context of differential access to resources. To understand adaptations to ecosystems in agricultural management and spatial distribution of TAFS, it is important to characterize: (1) the development of water management systems designed to optimize water use, and (2) the use of native plants in agricultural areas that are linked to water retention and other culturally relevant purposes that are beneficial to the conservation of the environment.

Agricultural zones are differentiated according to the access to water, and the development of water management systems responds to adaptations to the topography of the Valley (Castelló n Huerta, 2007). Crop irrigation depends on both water inflows at different altitudes and humidity levels. While some lands benefit from access to abundant tributaries from springs and from the Salado River, others depend on rainfall as they receive water only from steep slopes and runoffs from hillsides.

Farmers classify the land in terms of their access to water: a) high-yield lands, which are near the Zapotitlán river or springs (Cosagüico, Soyalapa, Tilapa, La Huerta) and are the most productive; b) medium-yield lands, which are near tributaries of the Zapotitlán river; c) low-yield lands, which are rainfed lands located on the slopes of the hills and depend on ephemeral runoffs (Figure 3). Lands are also differentiated by their topography, soil types, levels of water erosion, and vegetation types; these differentiations influence the type of work for soil and water retention they perform.

The differentiation of agricultural zones is expressed in different forms of agroforestry and water management. In the most productive areas, water was available from springs. Water extraction was controlled by haciendas, which were granted to private owners until the 20th century. These lands were highly coveted and monopolized by large landowners during the 19th century. The most productive agricultural area was El Tablón, whose altitude and abundance of water from the Tilapa spring allowed intensified agriculture that provided abundant harvests for local marketing. This abundance even allowed the cultivation of fruit trees. However, the control of springs and construction of deep wells show the unequal access to water that persists until the present and has impacted agricultural enterprises.[1]

In the medium-yield lands, the construction of 4–5 m deep shallow wells allows the irrigation of fields near the main river to ensure harvests. However, the construction of wells, storage tanks, and water conduction systems with hoses of up to 5 km require investments, for which not all farmers have the resources to pay, even if they have land near the river.

The lowest yielding agricultural lands are rainfed. These lands are scattered throughout the Valley and located on the hillsides far from the urban area. Rainfed areas benefit from scarce water runoffs. To optimize them, farmers place vegetation to retain soil and moisture. Likewise, farmers construct water access and collection systems such as canals, edges, and jagüeyes, which are large mud cisterns of 15 m^2 and 1.5–2 m deep, designed to store water. Another technique to delimit the fields, used since pre-Hispanic times, is the construction of stone walls called coastal, which can last 15–30 years, and, in ancient times, they were built as collective work practice (Neely and Castellón, 2003; Neely et al., 2015). However, building them today is difficult and costly, and is rarely constructed now.

Farmers refer to rainfed agricultural areas as plains, where they use the technique of constructing semi-terraces or *melgas*[2] that are arranged in areas of 0.5–1 ha depending on the conditions of the terrain, which is generally heterogeneous and irregular. The practices that are still used within the construction of semi-terraces are based on agroforestry techniques designed to control erosion, retain water and delimit the land among 20 of the most mentioned reasons by villagers (Table 1). Under agroforestry management, *melgas* have maintained vegetation boundaries, living barriers, and natural edges, which are used to separate the semi-terraces and allow the staggered arrangement of the plots.

[1] There are 19 wells licenced to the municipality and 21 private wells for agricultural use. CONAGUA, Registro Público de Derechos de Agua (REPDA), 2017.

[2] *Melgas* is the local name that is usually used in the region to refer to agricultural plots.

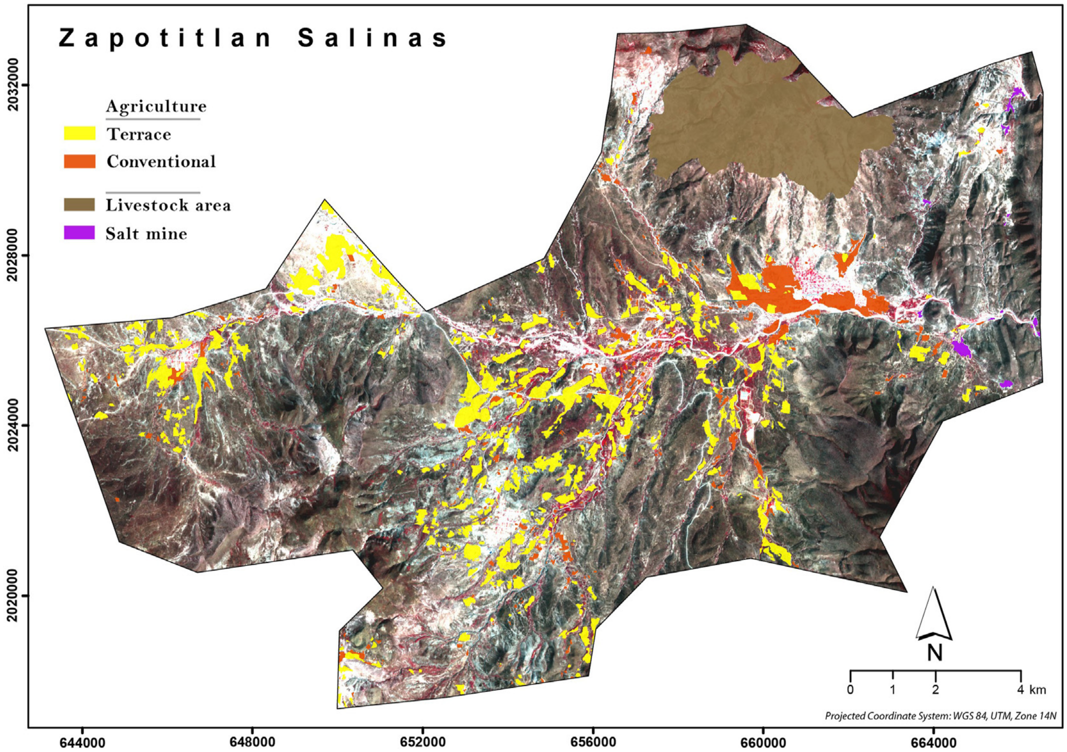

Figure 3. Photo of the agricultural terraces.

Semi-terraces are recognized as shelters of a high diversity of native forest species and associated fauna (Casas et al., 2007, Casas, 2014, 2016a; Moreno-Calles et al., 2012, 2016, Vallejo et al., 2014,2015). They contain fruits and other foods, firewood, medicines, and fodder. They also provide habitats for species of economic and cultural importance, such as the *cuchamá*, a caterpillar (*Paradirphia fumosa*) that is traditionally consumed in the region and has a high economic value. This caterpillar grows on the *Parkinsonia praecox* tree, a reason why this tree is valued and maintained in TAFS. Another edible animal that grows in the trees is the *cocopache*, which is a bug of the *Hemiptera* order. Likewise, native fruit trees are also maintained in the region because of their high levels of importance. For example, the *pitahaya* (*Hylocereus undatus*)—an epiphytic cactus that grows in the mesquites—the *xoconostle* (*Stenocereus stellatus*), the *garambullo* (*Myrtillocactus geometrizans*), and other xerophytic plants and wild vegetation have been protected for their gastronomic use, which offers high nutritional and cultural value.

A total of 48 species of trees and shrubs were recorded in TAFS, which belong to 15 families and 33 genera (Table 2). The number of woody species was on average 17.5 ± 5. The most important species based on their *Importance Value Index* (IVI) are *Prosopis laevigata*, *Viguiera dentata*, *Parkinsonia praecox*, *Cordia curassavica*, and *Verbesina neotenoriensis* (Appendix 1). On average, 95 individuals, with heights 1.5 m and 500 m^3 of biomass were recorded; and 18% of tree and shrub cover per plot was estimated. TAFS have significantly higher species richness than forests. However, the Shannon exponential index value differs statistically between wild forest and TAFS ($t = 6.0387$, $p = 2.62E\text{-}06$), TAFS having significantly lower diversity than forests (Figure 4). This is because in TAFS people favor species with utilitarian values, which are predominant in those plots.

Table 1. Reasons reported by people interviewed for maintaining TAFS and their ecosystem benefits.

Supplies	Regulation	Cultural	Sustenance or for support
Lumber	Erosion control	Aesthetic	Biotic Interactions
Firewood	Wind control	Ethical	Primary Production
Fruits	Water control	Spiritual	Nitrogen Fixation
Medicinal Ornamental	Moisture conservation	Ritual	
Tools	Shade	Communal rules	
Forage	Biological control		

According to the farmers, agricultural management begins with clearing the land. In the past, this was done with a *machete* – a labor tool used to knock down and arrange the borders of vegetation– but today, it is done with a plow. The introduction of the tractor in the 1980s increased the size of the plots but also diminished the islands and patches of vegetation conformed by trees and cacti that were preserved on the land.

The relevance of agroforestry practices is especially observable in rainfed agricultural land. The use of fertilizers and chemical inputs is somewhat uncommon in them, since they prefer animal manure and other organic matter as fertilizer. Furthermore, agroforestry practices have made it possible to preserve the traditional cultivation of corn, beans, and squash in *milpas* (cornfields) and the use of other food species. The cultivation of refined *milpas* in semi-terraces usually includes two or three varieties of corn within the same plot as a strategy to secure crops and test the resistance and quality of various seeds. For this process, farmers choose criollo or native corn seeds and use native drought-resistant varieties locally known as *bolita*, *vandeño* and *pepitilla* corn, which are distinguished based on the shape and size of the cobs. These seeds are selected and stored by the farmers. However, the crop failure of the last three decades has led them to purchase the seeds in markets in neighboring towns—such as in Chilac, Caltepec, Axusco, and San Juan Ixcaquixtla—where they obtain the native varieties of the region.

The preference for native seeds results from a common understanding of their high yield. Farmers argue that native seeds 'withstand more' the inclemency of drought and provide greater milpas—the cobs 'yield more', and tortillas and other foods have better flavor and consistency over other non-native varieties. In addition to corn, traditional milpa

Table 2. List of tree and shrub species present in the TAFS sampled.

Families	Species
Asparagaceae	*Agave marmorata* Roezl
	Agave salmiana Otto ex Salm-Dyck
	Agave sp.
Asteraceae	*Gymnosperma glutinosum* (Spreng.) Less.
	Montanoa grandiflora DC.
	Verbesina neotenoriensis B.L. Turner
	Viguiera dentata (Cav.) Spreng.
	Morfo1
Boraginaceae	*Cordia curassavica* (Jacq.) Roem. & Schult.
Bromeliaceae	*Hechtia sphaeroblasta* B.L. Rob.
Burseraceae	*Bursera schlechtendalii* Engl.
Cactaceae	*Cephalocereus columna-trajani* (Karw. ex Pfeiff.) K. Schum.
	Coryphantha pallida Britton & Rose
	Echinocactus platyacanthus Link & Otto
	Ferocactus latispinus (Haw.) Britton & Rose
	Mammillaria carnea Zucc. ex Pfeiff.
	Mammillaria haageana Pfeiff.
	Mammillaria sphacelata Mart.
	Opuntia ficus-indica (L.) Mill.
	Opuntia pilifera F.A.C. Weber
	Opuntia pubescens J.C. Wendl. ex Pfeiff.
	Opuntia sp.
	Lemaireocereus hollianus (F.A.C. Weber) Britton & Rose.
	Wilcoxia viperina (F.A.C. Weber) Britton & Rose
Cannabaceae	*Celtis pallida* Torr.
Convolvulaceae	*Ipomoea arborescens* (Humb. & Bonpl. ex Willd.) G. Don
Euphorbiaceae	*Euphorbia heterophylla* L.
	Euphorbia sp.
	Ricinus communis L.
Fabaceae	*Acacia angustifolia* (Lam.) Desf.
	Acacia farnesiana (L.) Willd.
	Acacia sp.
	Dalea carthagenensis (Jacq.) J.F. Macbr.
	Leucaena esculenta (Moc. & Sessé ex DC.) Benth.
	Mimosa luciana Barneby
	Mimosa sp.
	Parkinsonia praecox (Ruiz & Pav. ex Hook.) Hawkins
	Pithecellobium dulce (Roxb.) Benth.
	Prosopis laevigata (Humb. & Bonpl. ex Willd.) M.C. Johnst.
	Vachellia constricta (Benth.) Seigler & Ebinger
Malpighiaceae	*Galphimia glauca* Cav.
Phytolaccaceae	*Rivina humilis* L.
Simaroubaceae	*Castela tortuosa* Liebm.
Solanaceae	*Solanum nigrum* L.
	Solanum tridynamum Dunal
	Morfo 2
Verbenaceae	*Lantana achyranthifolia* Desf.
	Lippia graveolens Kunth.

cultivation includes a variety of beans. The most used are Flor de Mayo, Bayo, Amarillo, Pinto, Rojo, Enredador, and 7 Colores (a variety of red, yellow, white and pinto seeds). In addition to their nutritional benefits, beans improve the quality of the organic matter that is incorporated into the soil in the plots.

Local agriculture is low-yielding and destined only for subsistence. It does not provide surpluses of commercialization but can provide part of the families' food sustenance. The use of native vegetation on plots provides plant and animal resources that supplement livelihoods. Some farmers mention that they do not need to go to the bush to look for resources, for they obtain what they need from their plots.

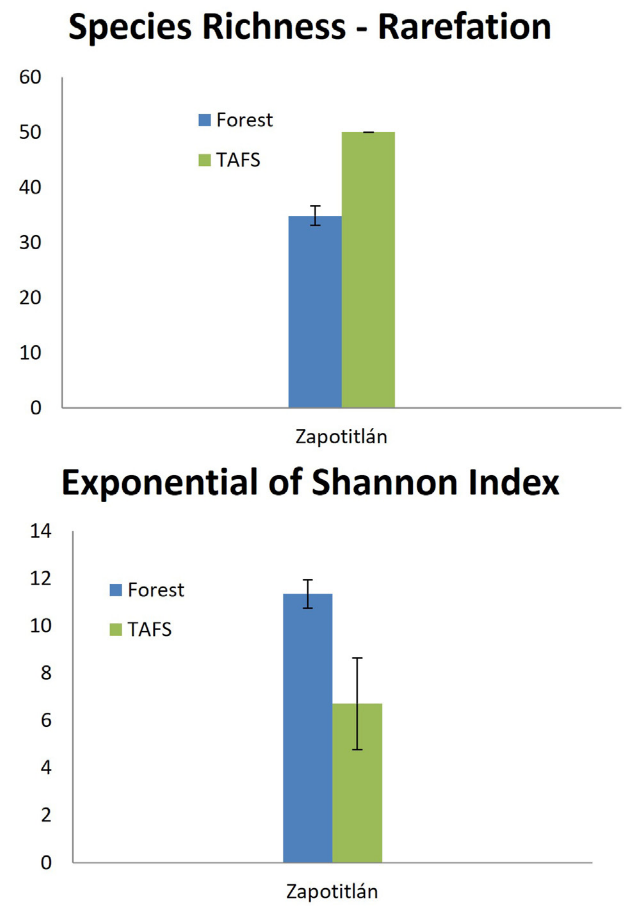

Figure 4. Species richness and diversity in TAFS (Traditional agroforestry systems) and surrounding forests.

The value of trees in the zone is measured by their number of uses and abundance in plots. The most valued trees in the zone are mesquite (*Prosopis laevigata*), guaje (*Leucaena esculenta*), lemon (*Citrus limón*), manteco (*Parkinsonia praecox*) and nopales (*Opuntia sp.*). *P. laevigata* is the tree with the highest number of uses. It is used for wind barriers, land alignment, fodder, firewood, and timber. In the branches of this tree grow pitahayas (*Hylocereus undatus*) and *cocopaches*. In addition, farmers use the forest to extract useful plants and insects with high gastronomic value in the region, which have been part of the local diet since pre-Hispanic times (Velázquez Soto et al., 2008; Casasola-González et al., 2013).

Agroforestry systems create a spatial arrangement that visibly shapes the landscape of the Zapotitlán Valley. The surroundings have been shaped by agroforestry management because of historical adaptation processes in relation to the availability of resources in the territory.

3.3. Unequal adaptations in the face of differential access to natural resources

The scenarios of climate variability and uncertain availability of natural resources that have occurred in the region in recent decades, and the imminent risk that these represent to farmers have led them to rethink their agricultural practices in different ways. In the town of Zapotitlán, many plots have been abandoned in the last 5–15 years even though the amount of deforested land available for agriculture has been more extensive than in other locations. The low rainfall that has been perceived for the last 10–15 years has led some farmers to gradually abandon agriculture. However, others insist on reinforcing their practices for water retention and storage or are considering the introduction of new drought-resistant crops.

The importance of agricultural work for farmers' lives greatly varies between inhabitants and localities across the region. Out of the 2,700 people of Zapotitlán Salinas, only 800 are *comuneros* (communal landowners), but only 400 of them continue farming. In the municipal head, a total of 80–100 farmers continues seeding, but only 30 to 40 (approximately 3%) consistently sow each year. In smaller and less urbanized communities, such as San Juan Raya, Las Ventas, and Colonia San Martín, agricultural activity is more relevant. There, about 150 community members (80% of all inhabitants approximately) continue farming every year. The difference in the importance of agriculture in the life of different communities is also the result of environmental conditions, because rainfed agricultural land is highly dependent on altitude, which influences the levels of precipitation and humidity. This is something that can be perceived in San Juan Raya, which has a higher altitude that allows more abundant rainfall and keeps higher moisture.

The options for adapting to new contexts are multiple. However, the ability to change depends on the conditions of each farmer. There are two factors for these processes of adaptation: a) access to agricultural land and water sources and b) availability of family livelihoods. For this reason, the abandonment of agricultural fields over the last 30 years should not only be explained in terms of a decrease in rainfall but is also linked to the farmers' interest and possibilities to respond to these changes regarding possible benefits.

Farmers believe that the "disinterest" to continue farming is mainly due to the high risk of crop loss. However, generational change and the shift in cultural perspectives also play a role. The labor and economic horizons of young generations that have migrated to the USA or other neighboring cities in search of work have also contributed to the loss of interest in farming (Lee, 2008). Consequently, they have also lost the knowledge associated with agricultural practices. Although young people's income—whether it comes from wages or remittances—makes up for shortfalls in the family's livelihood and makes it possible to invest in farming, it is parents or grandparents who are determined to carry out this work.

Likewise, the rights regarding land access and possession are relevant factors. The inequality surrounding access to resources constraints the number of benefits that a family may obtain from a territory and limits their ability to respond to changes. The lack of land ownership brings about disadvantages in investment, since it implies an extra cost for the rent and affects the interest people might have in agriculture. Farmers with limited investment capacities are unlikely to improve their infrastructure and are more exposed to the risks of losing their harvest. The most severe effects of this inequality are observed in rainfed plots: the plots of the most disadvantaged families are more neglected in attention to soil retention and water storage.

The decisions to determine which maintenance works are needed depend on the location of the plot and the type of water access it has. Even for those who own land, the inclemency of droughts is considered a high risk that families are not willing to assume. For those who decide to continue farming, it is key to invest resources to improve agricultural management, carry out hydraulic works, and/or modify the type of crops. As mentioned, the financial resources available for agriculture depend on the income received from complimentary activities for financial resources from government programs (PROAGRO and PROCODES[3]) that support the reconversion of drought-resistant crops.

[3] The promotion of agricultural productive reconversion by the Tehuacán-Culiacán Biosphere Reserve (TCBR), financed with PROCODES, is aimed at agave projects in plots and native fruit trees (such as pitahaya and xoconostle). The support consists of providing seedlings of two native agave species, papalometl (Agave potatorum), and pitzomel (Agave marmorata) for planting in plots.

In recent decades, some farmers have adopted the strategy of replacing corn with more drought-resistant crops, like mezcal agaves and native fruit trees, which are commercialized to obtain higher income. The trends in agriculture are oriented towards three types of cultivation: a) corn (in traditional milpas), b) mezcal agaves and native fruit trees, and c) vegetables and non-native fruit trees. Table 3 shows more information on the three types of agriculture and production trends. This typology is visualized spatially in the distribution of agricultural zones, which responds to the social disparity among producers.

Most of the rainfed areas are characterized by maize cultivated in the milpa system, which allows the preservation of agroforestry management. Farmers with land bordering the river can venture into other crops. In these areas, there is a higher percentage of conversion from milpa to agave and native fruit trees. Intensified greenhouse agriculture is practiced on land benefited from springs water, making it possible to grow vegetables and non-native fruit trees. The trends throughout the three groups show that conversion to crops other than corn, is of interest to those who have better land with access to water and greater investment resources. However, this is not yet a predominant trend among farmers. Most senior farmers continue to be rooted in the traditional milpa cultivation to complement their livelihoods. They depend on an annual intake of maize to complement their diet and are not prepared to switch to crops that would require 4–5 years to obtain benefits. Furthermore, they do not have the investment resources to undertake these changes.

The ability to continue farming depends not only on technical capacities to cope with environmental change, but also on social aspects such as access to land and water and the adjustments on family livelihoods. Farmers' responsiveness is bound to family livelihood strategies. In this way, the differences between the farmers' economic possibilities that persist to this day influence their assessment of needs and the number of benefits they receive from activities designed to prioritize the financial resources of families.

Although it is true that investment in agriculture has become an unattractive option, the valuations are not only economic. There are also cultural valuations, such as the entrenchment of traditional agriculture. Agricultural management and permanence of TAFS in Zapotitlán depend on the combination of multiple factors: access to land and water, available means of investment, cultural relevance, and family livelihood strategies. All these factors guide the current trends of agroecosystems in the territory.

4. -Discussion

This study provides elements that affirm the relevance of an integrated approach to assess the diverse factors of permanence and change in agroforestry management, especially access to resources and livelihoods. One of the main findings is that the agroforestry management of the milpa system is a response to conditions of marginal access to resources, land and water. Consequently, adaptations to social and environmental changes of TAFS respond to this differential access to resources. In fact, unequal access to resources can be observed in the spatial arrangement of TAFS in the territory.

4.1. Relation of adaptations in TAFS with territorial management and livelihoods

The development and adaptations of TAFS are related to the general management of territorial resources, and in turn, these aspects shape the integrated development of agroecosystems. Management dynamics in TAFS can be understood in relation to the territorial management and the livelihoods of local populations.

TAFS was formed by communities that settled in the region and had to adapt to the local arid conditions, which led to technical innovations (MacNeish, 1992; Smith, 1967). It has been suggested that the first forms of agriculture in prehistoric times emerged by promoting species in disturbed forest sites (MacNeish, 1967; Smith, 1967). The development

Table 3. Typology for categorizing agricultural production trends.

CRITERIA	GROUP 1: Traditional agriculture	GROUP 2: Agricultural Reconversion	GRUPO 3: Agricultural Intensification
Crop type	1 . Maize/corn 2 . Agave pulquero (green maguey)	1 . Agave for mezcal 2 . Native fruits trees	1 . Vegetables 2 . Non-native fruit trees
SYSTEM'S CHARACTERISTICS AND AGRICULTURAL MANAGEMENT			
Production orientation	Traditional milpa system (maize in association with beans and squash) Traditional cultivation of agave for pulque	Reconversion agriculture from milpa to cultivation of agave and native fruit trees.	Intensified agriculture through greenhouse farms for non-native vegetables and fruit trees
Management form	Agroforestry management system in smaller plots, between 1 to 3 ha with larger vegetation strips between crops. Usage of the 5 agroforestry management techniques.	Agroforestry management system in plots of 3–5 ha with smaller vegetation strips. Use of live barriers and agave borders.	Greenhouse system in plots of between 3 to 5 ha on land with very reduced vegetation strips. Diversified farm and monoculture farm.
Use of resources in the plot	Use of herbaceous plants and insects with nutritious qualities and collection of firewood for home-use	Collection of firewood for mezcal ovens (mezquite and manteco)	None
CONDITIONS OF ACCESS TO TERRITORIAL RESOURCES			
Access to land and location of grounds	Owned land, leased land, and farmland. Mostly on hillsides and in smaller quantities near river tributaries.	Owned land and farmland. Mostly near tributaries of the main river or springs.	Owned land. Mostly on the banks of the main river or near springs with ample water reserves.
Access to water and management works	Use of runoff water from hillsides. Implementation of water conduction and collection systems with jagüeyes, tanks and waterways.	Access to water tributaries of the main river. Construction of wells for water collection and storage, and conduction paths for irrigation systems.	Access to springs or tributaries of the main river. Construction of wells and conduction paths for irrigation systems.
FAMILY LIVELIHOODS CONDITIONS			
Family economy type	Subsistence economy. Production oriented to annual family self-consumption and small-scale sales.	Family economy that is focused on self-consumption and selling of small-scale products in local markets.	Commercial economy focused on the selling of products in regional markets
Type of associated work	Family work, especially for older adults and, to a lesser extent, for young people.	Family work involving middle aged adults and young day labourers.	Labor from young and middle-aged day labourers.
financing-related activities	1. Agricultural programs. 2. Family activities: livestock, salt mines, handicrafts, and services. 3. Remittances	1) Remittances 2) Family activities: livestock, salt mines, handicrafts, and services. 3) Agricultural programs	1. Foreign investors 2. Remittances
Linked government programs for financing	PROAGRO PROMAC PIMAF Siniestro agropecuario	PROCODES	SDR
PERSPECTIVES ASSOCIATED WITH AGRICULTURAL ORIENTATION			
Reasons associated with agricultural orientation	Family subsistence perspective: economic complement, cultural roots and economic support from government programs.	Vision of a family business oriented towards the local market: Pursuit of crop improvement for higher yields and drought resistance.	Family business vision oriented towards the regional market: Vegetable food production with a regional growth perspective.
Access to water and management works	Weather readings (cabañuelas), agricultural festivals, safeguarding or purchase of native seeds, transplanting of plants from plot to orchard.	Transplanting and purchase of native plants, agaves and fruit trees	Purchase of non-native plants for intensive production

of agriculture in the region is the result of innovations and adaptations to the environment, which imply the deliberate arrangement of the elements of natural systems to ease the appropriation of their components (Casas and Vallejo, 2019). The use of diverse resources strengthened the survival of the population and shaped agroecosystems into landscape units based on integrated management of the territory. In this case study, agroforestry adaptations result from the historical interaction of the inhabitants with their environments and the appropriation of resources. However, this occurs according to the development of changes in social production relations associated with production systems.

The different spaces that TAFS have occupied in Zapotitlán show a continual rearrangement according to the rest of the productive activities in the territory. Such rearrangement responds to processes of adaptation to socio-environmental changes, not only to face adverse climatic events, but also changes in the appropriation and access to the territory's resources that impact agriculture and livelihoods. Tittonell (2014) argues that agroecosystems first emerge from the accumulation of activities that sustain livelihoods and are then modified in response to social and environmental changes, both of which are projected in the agricultural contexts.

The integration of agricultural spaces into ecosystems and TAFS adaptations are not only the result of an adjustment to the natural availability of resources in the territory. They also respond to broader productive dynamics that have configured marginal access to resources and livelihoods. In Zapotitlán, different types of agroecosystems are distributed in space, it is possible to distinguish spaces according to resource access. Land use responds to the unequal appropriation of resources and land, which has been used for highly profitable activities such as cattle ranching and intensified agriculture, which have caused differentiated access to resources and environmental degradation.

According to Dorward et al. (2009), differences in livelihood are determined by differential access to natural resources and how livelihood activities are articulated. In cases in which agriculture has high commercial potential, it can finance other activities. Conversely, where there is low potential, external activities can increase their means to support agricultural activity. In Zapotitlán, investment in agriculture has been sustained through the income that results from investments in other family productive activities. However, farmers with scarce resources seek to maintain as much as possible resources in their plots, such as native plants.

Tittonell (2013) found that the most relevant decisions regarding the adaptation of agroecosystems not only depend on biological conditions but are also influenced by sociocultural circumstances. Throughout his work in South Africa, he has shown how productive diversification and livelihood supplementation are part of the response to numerous shocks affecting rural communities; people regulate cycles of self-organized

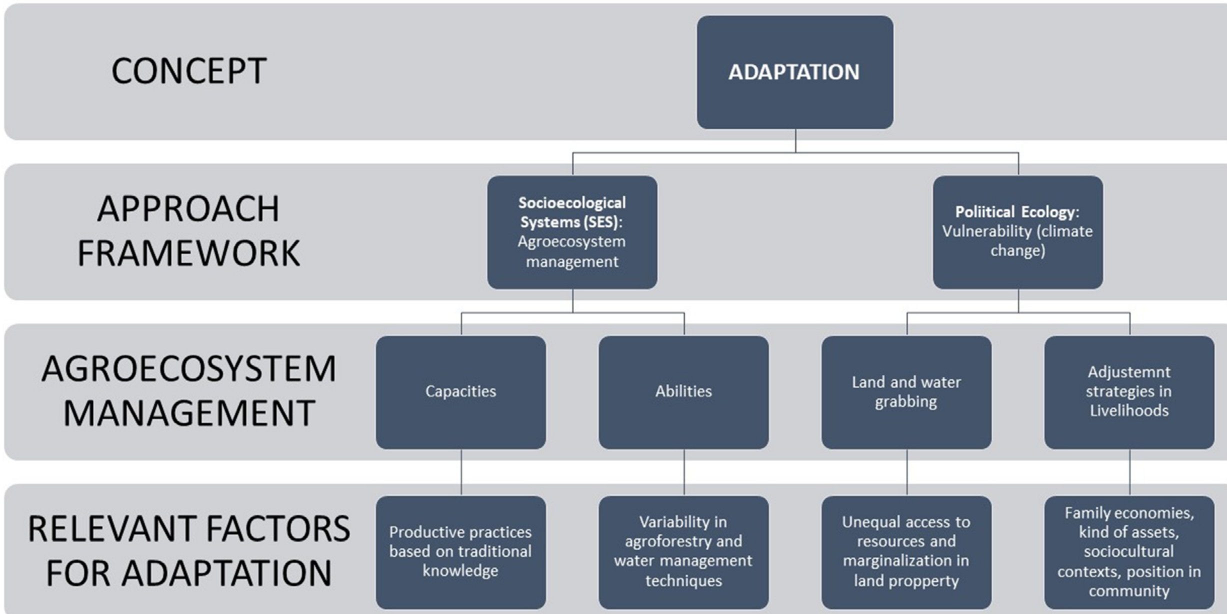

Figure 5. Conceptual framework for adaptation in traditional agroforestry systems.

adaptation to prevent economic collapse in households and constitute adaptive mechanisms of agroecosystems.

In this way, the strategies of livelihood complementarity are relevant in allowing the permanence of TAFS since they provide the means for the subsistence of families and the conservation of the ecosystems. However, the adaptation of TAFS in Zapotitlán occurs under conditions of inequity in access to resources and fragility in livelihoods, which make it difficult for some farmers to face changes, and as a result, repeatedly opt to abandon agriculture. In this regard, Eriksen and Lind (2009) suggest that unequal access to resources causes winners and losers in the adaptation process by reproducing inequities, as the most vulnerable have fewer possibilities of making changes in their livelihoods.

4.2. *Differential access and unequal adaptations in TAFS management*

Agroforestry adaptations in TAFS management in Zapotitlán demonstrate that there are differentiated capacities for coping with changes, and that the key factor influencing such capacity is the unequal access to resources, land and water. Differentiated land distribution across the region set the tone for the development of agroforestry management adaptations in disadvantaged agricultural areas. In rainfed lands, the preservation of vegetation areas to retain water and soil allowed harvests and benefited agricultural spaces and ecosystems by conserving forest areas.

The advantages of TAFS have been widely documented. They not only increase crop resistance to droughts but also benefit productivity and allow using several products. Furthermore, their assimilation into ecosystems enables ecological processes that increase their ability to conserve biodiversity (Jose and Bardhan, 2012; Montagnini, 2020; Torralba et al., 2016).

Although TAFS remain to the present and have social and ecological advantages over their counterparts, they are not exempt from threats, or deterioration risks. Differences in agroforestry management show the persistent disparity among farmers and their ability to face environmental changes. Local elites that have access to water sources have implemented irrigation systems and moved towards intensification of agriculture through fertilizers, agrochemicals, and machinery, which have led them to increase the area of open land and reduce vegetation spaces thus causing environmental impacts (Vallejo et al., 2014,2015).

In contrast, small farmers who have been marginalized from well-irrigated land developed other water management techniques to cope with climate variability. This shows how the monopolization of land and water sources causes the difference between agricultural productive spaces. As Blaikie and Brookfield (1987) argue that the adaptations made by groups that monopolize resources constrain the ability of other farmers to adapt, by marginalizing them from access to resources and forcing them to use less privileged lands with greater exposure to crop erosion and fertility loss. As Adger et al. (2006) said, inequalities in resource distribution result in *limits to adaptation*.

Deterioration of agroecosystems leads to social marginalization and contributes to low adaptive capacities, in this sense analysis of adaptations must address such inequity (Adger et al., 2006). While agroforestry management in Zapotitlán is expressed as an adaptive response linked to historical conditions of marginal access to land and water resources, agricultural abandonment, and soil deterioration.

In Zapotitlán, even though TAFS prove to be highly adaptive systems, they are maintained by the impoverishing farmers, for whom maintaining agriculture is relevant to their livelihoods; this effort is manifested in the persistence of promoting alternative crops to milpa. In sum, agroforestry management constitutes an adaptive response to conditions of marginality and differential access to resources. Since the capacity to adapt to environmental changes and pressures may be limited by the cultural and political conditions of different social groups—including their relationships, values, and institutions—agreeing with Adger et al. (2009), adaptation processes are limited and reproduce inequalities. Therefore, adaptation processes should be analyzed in relation to conflicts in the distribution of and access to resources (Figure 5).

5. Conclusions

This case study demonstrates that, while adaptation of TAFS depends on management techniques and knowledge, it also relies on two other key conditions that need to be considered: differential access to land and resources and strategies of livelihood diversification strategies. The study provides an innovative perspective for analyzing TAFS through elements of analysis from political ecology and the notion of *adaptation* used in the conceptual framework of social-ecological systems. It suggests the importance of considering adaptation in terms of social differentiation and marginalization in access to resources, since these are determining factors that shape adaptive responses to socio-environmental changes.

The adaptation of agroecosystems to socio-environmental changes is related to social differentiation. In conditions of marginal access, certain groups have better possibilities to adapt than others. It is therefore pertinent to study the differentiated structures between social groups, in correspondence to decisions about agricultural adaptations.

Marginality conditions drive disadvantaged social groups to a greater interest in preserving agroforestry techniques due to the productive and livelihood benefits. At the same time, the valuations of the farmers who maintain the SAFTS entail a greater tendency to preserve the forest areas, due to the benefits provided by the diversity of resources that they take advantage of. This favors the conservation of ecosystems while maintaining local knowledge about the management of agroecosystems.

The study shows that adaptations in agroforestry management depend not only on technical capacities or traditional knowledge, but also depend on social, political, and cultural factors that constrain those adaptations. For an integral understanding of the dynamism of TAFS, the study emphasizes the importance of analyzing the adaptation of agroecosystems by considering both environmental and social contexts.

6. Publication ethics

This investigation was conducted under the statutes of Code Ethic for research, the Action-Research and ethno-scientific collaboration of Latin America (2016). The participants were informed about the objectives and activities developed throughout the research and gave permission for the development of fieldwork in the community and territory of Zapotitlán Salinas, Puebla, which was carried out with respect towards the people and the environment.

Declarations

Author contribution statement

Paola Vázquez: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Alejandro Casas: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Mariana Vallejo: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Data availability statement

Data included in article/supp. material/referenced in article.

Declaration of interest's statement

The authors declare no conflict of interest.

Additional information

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