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Back to the people: The role of community-based responses in shaping landscape trajectories in Oaxaca, Mexico

Ivan P. Novotny[a,b,*], Mariela H. Fuentes-Ponce[c], Pablo Tittonell[d,e,f], Santiago Lopez-Ridaura[g], Walter A.H. Rossing[b]

[a] *Doctorado en Ciencias Biológicas y de la Salud, Universidad Autónoma Metropolitana Xochimilco (UAM-X), Calzada del Hueso 1100, Col. Villa Quietud. 04960 México, D.F., Mexico*
[b] *Farming Systems Ecology, Plant Sciences Group, Wageningen University and Research, Droevendaalsesteeg 1, 6708 PB Wageningen, the Netherlands*
[c] *Departamento de Producción Agrícola y Animal. Universidad Autónoma Metropolitana Unidad Xochimilco, Calzada del Hueso 1100, Col. Villa Quietud. 04960 México, D.F., Mexico*
[d] *Agroecology, Environment and Systems Group, Instituto de Investigaciones Forestales y Agropecuarias de Bariloche (IFAB), INTA-CONICET, Modesta Victoria 4450 - CC 277 (8400), San Carlos de Bariloche, Río Negro, Argentina*
[e] *Agroécologie et Intensification Durable (AïDA), Centre de coopération Internationale en Recherche Agronomique pour le Développement (CIRAD), Université de Montpellier, 34000 Montpellier, France*
[f] *Groningen Institute of Evolutionary Life Sciences, Groningen University, PO Box 11103, 9700 CC Groningen, the Netherlands*
[g] *International Maize and Wheat Improvement Center, Sustainable Intensification and Socioeconomics programs, 06600 Mexico City, Mexico*

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A B S T R A C T

Land use change results from top-down drivers, such as policies, trade, and migration. Land use change may also result from community-based responses. In Mexico, rural communities govern most of the country's forests. This study aimed to assess how socio-economic and biophysical factors affected the landscape trajectories of rural communities in southern Mexico. It also aimed at evaluating the role of communities in landscape change. Land use change of 63 rural communities was analyzed for the years 1987 and 2017. Four land uses were distinguished: forest, shrubland, agriculture, and bare soil. Five groups of communities were identified according to their socio-economic and biophysical factors. Two groups located in areas with high slopes and elevated marginalization index values showed deforestation patterns. Two other groups, consisting of more than half of the municipalities assessed, showed reforestation trends. The final group did not reveal major changes in land use. Two municipalities with reforestation trends were selected for an in-depth analysis of how community-based responses impacted natural resource management and conservation. Through local assemblies, the population voted for regulations that increased the forest area and reduced the bare soil. There was no evidence that these regulations affected croplands. These results show how a combination of socio-economic and biophysical factors can affect landscape change, but it also shows the often overlooked role of communities as a relevant bottom-up driver of change.

1. Introduction

Land use changes are commonly considered to result from top-down drivers such as policies, trade, and migration (Lambin and Meyfroidt, 2011; Meyfroidt et al., 2013). Another strain of studies shows the role of communities in landscape planning and conservation, pointing to the relevance of dual governance systems by governments as well as communities (Baynes et al., 2015; Bixler, 2013; White and Martin, 2002). Social actors in communities and their goal-oriented perspectives can affect the degree to which land use changes will follow either a pathway towards natural resource conservation or depletion and degradation (e.g. overexploitation of forests, overgrazing, agricultural expansion and contamination of natural resources). The emerging pathway will influence resource availability and will ultimately determine the possibilities for the human development (Van der Ploeg, 2008).

At regional and larger scales, most of the landscape transformation is attributed to agricultural and urban expansion (Corona et al., 2016; Izquierdo et al., 2011; Lambin et al., 2003; Lambin and Meyfroidt,

* Corresponding author at: Calzada del Hueso 1100, Building W bis, 3rd floor, Office 314, Mexico City, Mexico.
E-mail addresses: ivanpnovotny@gmail.com (I.P. Novotny), mfponce@correo.xoc.uam.mx (M.H. Fuentes-Ponce), tittonell.pablo@inta.gob.ar (P. Tittonell), S.L.Ridaura@cgiar.org (S. Lopez-Ridaura), walter.rossing@wur.nl (W.A.H. Rossing).

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2011; Tapia-Armijos et al., 2015), biophysical conditions (e.g. soil type, geology, rainfall) (Bray et al., 2008) and global markets (Aide et al., 2012). Aide et al. (2012) observed how forest expansion in Mexico and Brazil was driven by demographic (e.g. population density, migration, municipality size) and environmental variables (precipitation, temperature, biome type). They also showed that in some areas high population density was associated with reforestation. More generally the same driver of change can lead to contrasting results. For instance, community marginalization is both negatively and positively correlated to deforestation (Mas and Cuevas, 2015), showing how landscape change is usually affected by a combination of drivers (Corona et al., 2016; Geist and Lambin, 2002). Thus, it is essential to study land use change in terms of multiple socio-economic, geographical, and environmental drivers.

Although top-down drivers are important, knowledge of local drivers enables a more complete assessment of landscape change. Local drivers shape the impact of community-based management on the landscape. Policies can enable community-based landscape management and offer incentives for their development. Carabias (2010) compiled 100 documented cases of community-based management in Mexico that were successful in elaborating a landscape plan for the municipalities to raise money from different government institutions.

A growing body of literature addresses the importance of giving more autonomy to communities by pointing out their efficacy in avoiding deforestation. In a meta-analysis of 69 cases around the world, Pagdee et al. (2006) associated factors like property rights, institutional arrangements, and community incentives and interests to the success of communities when managing their resources. Bray et al. (2008) found deforestation rates under community management to be similar to or marginally less than in strictly protected areas in Mexico and Guatemala. Ellis and Porter-Bolland (2008) found deforestation under community-based management to be very small even under conditions of high land pressure in the Yucatan peninsula, Mexico.

Another line of studies addresses the effect on forest regrowth of local migration patterns and the slowing of agricultural activities. For instance, Corona et al. (2016) observed an increase in forest area and a reduction in agricultural land between 1995 and 2006 in two communities in the southern part of Oaxaca, which they attributed to an increase in off-farm income and migration. In contrast, Cárdenas-Hernández and Gerritsen (2015) showed how livestock activities drove an indigenous community in the central-west region of Mexico to increase pastures at the expense of forest. In a study in the Argentinian Patagonian steppe, Gowda et al. (2012) concluded that deforestation was greater more close to roads, even under conditions favorable for seedling germination and survival. Since these studies were centered around forest, they usually did not contain detail on other land uses (e.g. agriculture and shared grasslands) that are especially important to communities relying on food production for self-consumption. All of these studies, except for the one from Cárdenas-Hernández and Gerritsen (2015), addressed large areas and several communities, making it difficult to assess in more detail the decision making processes and specificities of each community that led to landscape transformation.

Considering rough estimations from 1980, which still have not been revised, 80 % of the forest area in Mexico is situated within rural community territory (Bray and Merino-Pérez, 2007). This study examines the idea that local people are capable of understanding their environment, which entails temporal heterogeneities and biophysical conditions, and of drawing up action plans according to their realities (Zimmerer, 1994). This local agency goes beyond the structural characteristics of municipalities and leads to different landscape pathways. In this paper, land use change is studied at the levels of landscape and communities. Results contribute to the debate on the balance between landscape governance by higher government levels and by local communities.

This study focuses on a watershed in the state of Oaxaca, Mexico, that has been documented to have high deforestation rates (Velasquez, 2002), but at the same time has been showing local reforestation over the past decades (Aide et al., 2012). The first goal was to explore the diversity of land use trajectories among the communities under the influence of a set of common top-down drivers. The second goal was to explore community strategies for conserving natural resources. To address these goals two research questions were asked. First, what is the relation between land use change at the watershed level and socio-economic and environmental attributes of the constituent communities? Second, how has community decision making contributed to natural resource conservation? To answer the questions of this study, satellite images were used to assess regional landscape change over the past 30 years and distinguish groups of municipalities with similar response patterns along with their characteristics. A detailed analysis at the level of two communities is provided to understand the major local drivers that shaped the incumbent landscape by combining population and agricultural census data and workshops with former local government officials. Results are discussed in relation to consequences for effective community-based landscape management in general and in Mexico specifically, where most of the land is maintained by agrarian communities and *ejidos*.

2. Materials and methods

2.1. Land tenure systems

After the Mexican revolution and the proclamation of the Mexican constitution in 1917, rural communities were legally recognized as agrarian communities (conceded to indigenous people) or *ejidos* (conceded to petitioners who did or did not have a prior connection to the land granted to them) (Baynes et al., 2015). The *ejidos* and agrarian communities are regulated by internal rules that are voted by local assemblies and are enforced by the *ejido*'s commissariat and the common goods commissariat in agrarian communities (Procuraduría Agraria, Chapters I and V, 1992). The difference between the two types of communities relates to their origins (Rentería-Garita, 2011). According to article 99 of the Mexican Agrarian Law (Procuraduría Agraria, 1992), agrarian communities are formed when land is restituted to the community. *Ejidos*, on the other hand, are formed when a group of at least 20 landowners come together to establish a set of internal regulations (Article 90 of the Mexican Agrarian Law). Together, *ejidos* and agrarian communities cover 53 % of the land area in Mexico (Morett-Sánchez and Cosío-Ruiz, 2017). In both these communities, water bodies and forests belong to the community while cropland, orchards, and fallow land are usually privately owned (Merino-Perez, 2013), although exceptions may apply for water bodies relevant to the general public and for rainforests. These communities have autonomy in managing and protecting their land, subject to some restrictions. For instance, communities are not allowed to exploit wood unless an official government institution gives a concession to the community, in which the volume of wood to be exploited is specified (Madrid, 2008). To simplify, the term community will be used in the text to refer to agrarian communities and *ejidos*.

2.2. Case study area

The state of Oaxaca comprises 9.4 million ha. Around 1.6 million ha lies within *ejidos* and 5.8 million ha within *comunidades agrarias* (Morett-Sánchez and Cosío-Ruiz, 2017). The area with forest in Oaxaca covers 6.3 million ha, of which 5.0 million ha belong to *ejidos* or agrarian communities.

The Mixteca Alta is an ethnic-geographic region inhabited by indigenous communities called Mixtecs. It is located in a mountainous area at 1700–2600 m above sea level that extends from the northwest of Oaxaca to the south of Puebla. Rainfall mostly occurs between May and October (Mueller, Joyce, & Borejsza, 2012), with annual precipitation

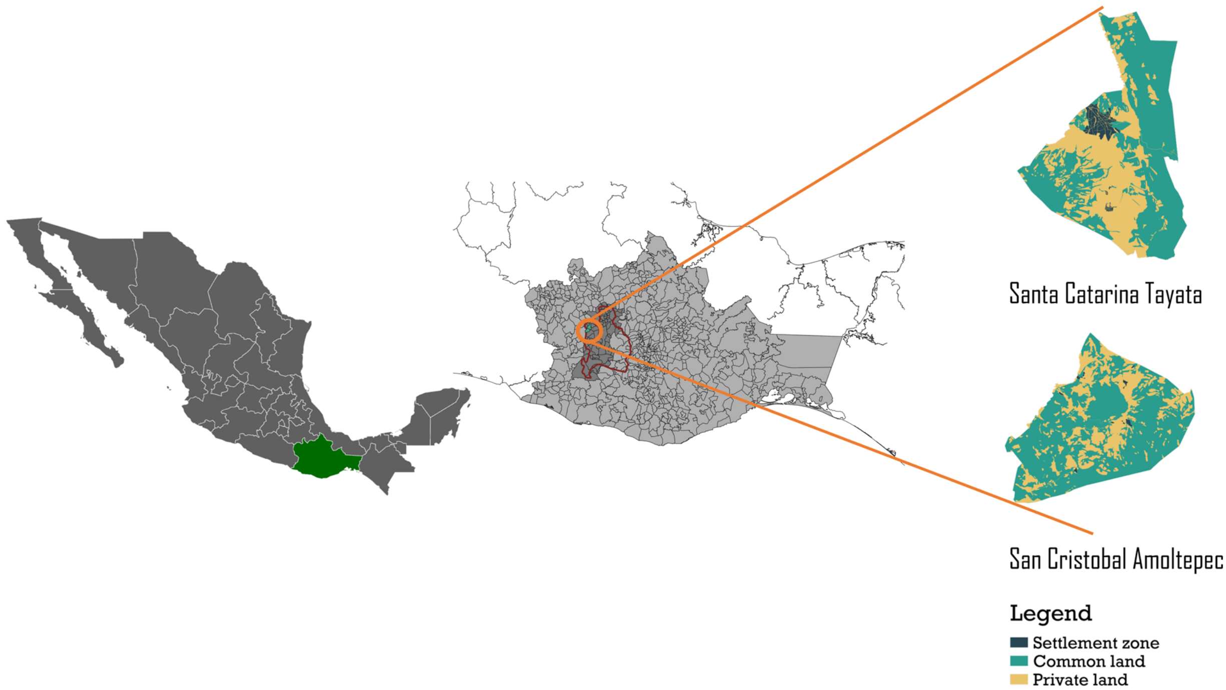

Fig. 1. The state of Oaxaca (in light gray) and the municipal boundaries, the Río-Sordo watershed (red border), the municipalities considered for the watershed analysis (in dark gray), and the two case study areas, Santa Catarina Tayata and San Cristóbal Amoltepec (in green). For each case study area land use is shown (data from Registro Agrario Nacional, 2018 -https://datos.gob.mx/busca/organization/ran). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

between 300 and 750 mm (Velasquez, 2002). The Mixteca Alta is known for its barren slopes, gully erosion, dry streams, and poor small villages (Mueller et al., 2012). Widespread erosion in the area is possibly related to over-exploration by farmers before the Hispanic era (Mueller et al., 2012). A large part of the Mixteca Alta is situated within the Río Atoyac-B watershed, within which we selected the watershed of Río Sordo for further study, which comprises around 7700 km^2 (Galindo et al., 2017). Two neighboring municipalities from this watershed, San Cristóbal Amoltepec (SCA) and Santa Catarina Tayata (SCT), were studied in depth.

San Cristóbal Amoltepec (SCA) (Fig. 1) covers 32 km2 and has a population density of 60 people/km2, calculated from 2010 census data (INEGI, 2010). Crop production in SCA is mostly for self-consumption and comprises predominantly maize (*Zea mays* L.) and bean (*Phaseolus vulgaris* L.). Sheep husbandry is the most important type of animal husbandry, although households usually have a few chickens and sometimes pigs in their yard.

Santa Catarina Tayata (SCT) stretches across 37 km^2 (Fig. 1). The population density in the municipality is 19 people/km^2 (INEGI, 2010), and has been strongly influenced by high emigration (Novotny et al., 2020). Since labor is scarce, households usually leave a portion of their land under fallow. Types of crops and animals in SCT are similar to SCA and are mainly used for self-consumption.

2.3. Land use change analysis for the Río-Sordo watershed

Landsat images were used to classify land use in the Río-Sordo watershed (Table 1). The images (with a 30 m resolution) were from 26 October 1989 and 22 November 2017. Since the whole watershed was covered by two distinct Landsat images taken months apart, the image comprising the larger part of the watershed was selected for the analysis (Fig. 1). The selected tile contained 63 municipalities. The analyzed images were taken at the end of the crop cycle, allowing a clear distinction between land uses. A 1984 image was available but not used for the watershed analysis because it was taken late in the season when most of the fields in the region had been harvested, resulting in misclassification of agricultural land as bare soil. An atmospheric correction was applied to the images to improve reflectance values (Ellis and Porter-Bolland, 2008). The land uses classified were forest, agricultural land (including cropland and grassland), shrubland (with grass between shrubs), and bare soil. Classification was performed using a semi-supervised classification method, where samples for each class were obtained by overlaying a high-resolution map from Google Earth (WorldView-2 with a resolution of 0.5 m) (Mekasha et al., 2014). A maximum-likelihood algorithm was applied to the training samples to obtain the final classification map (Ellis and Porter-Bolland, 2008; Tolessa et al., 2017). Land use areas for the 63 municipalities were calculated using the 1989 and the 2017 land use maps. Differences in land use area for each class and municipality between 2017 and 1989 were calculated to assess the change over the three decades.

A total of 29 explanatory variables (A.1), obtained for each of the 63 municipalities, were initially considered to explain changes in forest, shrubland, agriculture, and bare soil. These variables were categorized into socio-economic and biophysical. To reduce the dimensionality of the explanatory variables and increase the interpretation of land use change, a principal component analysis (PCA) was performed, and the municipalities with similar characteristics were grouped using a hierarchical cluster analysis (HCA). Four outlier municipalities were removed from the analysis, as they were not grouped with other municipalities. After reducing the dimensionality of variables in the PCA, a total of six socio-economic and five biophysical variables were kept for further analysis. The remainder socio-economic variables were marginalization index in 2015, migration in 1990, migration in 2015, population in 1990, population in 2015, and difference in population between 2015 and 1990. Marginalization index is defined by indicators of education, housing quality, population size and income (CONAPO, 2010). Marginalization index values can range between -1.9 and 3.8 for the state of Oaxaca. Municipalities with values greater than -0.7 are considered to be marginalized. The biophysical variables retained were slope, minimum elevation, maximum elevation, mean temperature and precipitation. Differences in the indicators among the groups of municipalities were tested using a non-parametrical Kruskal-Wallis test,

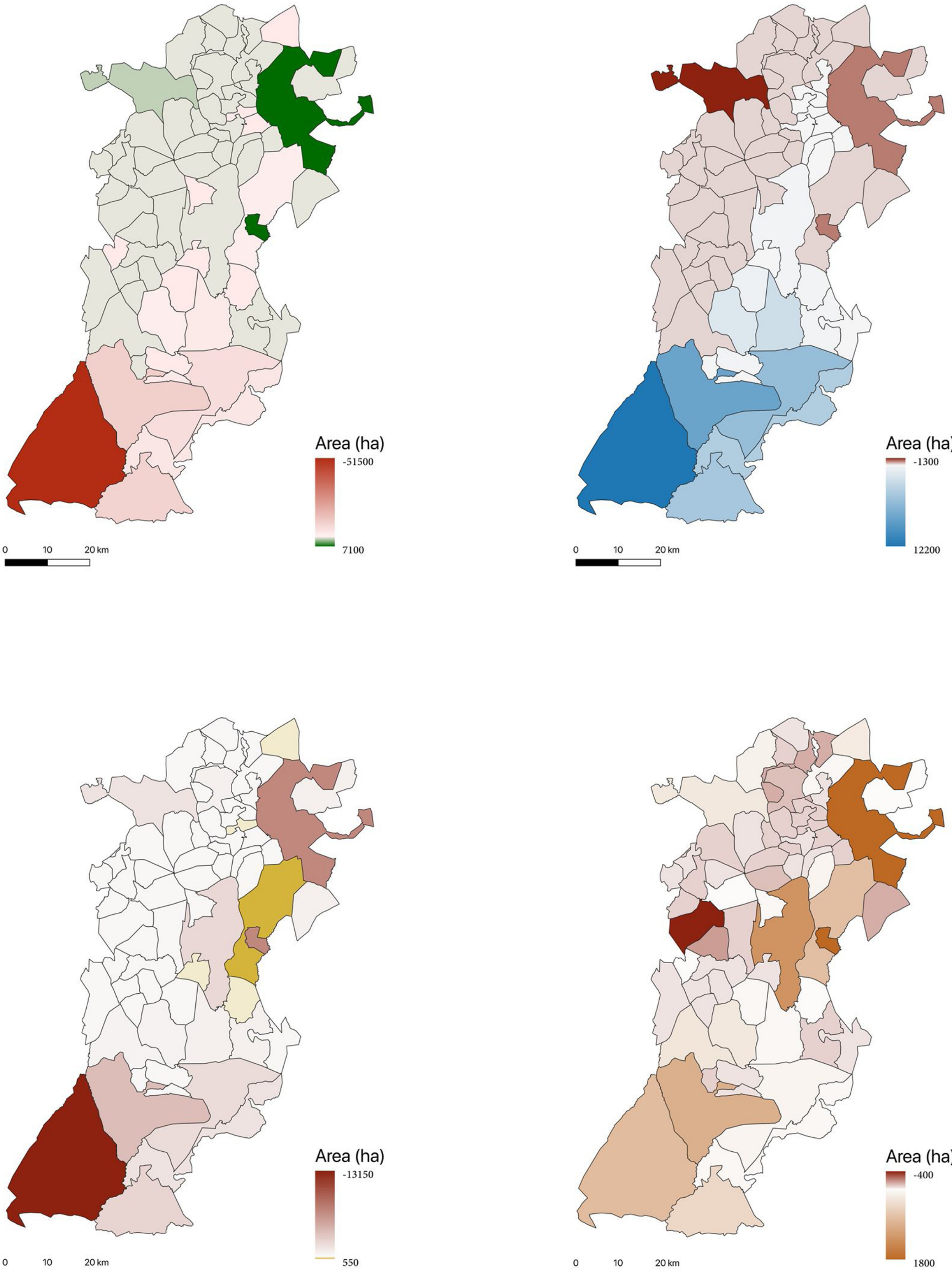

Fig. 2. Changes in areas of forest (top-left), shrubland (top-right), agriculture (bottom-left) and bare soil (bottom-right) per municipality within the Río Sordo watershed, Oaxaca, Mexico, over the period 1989-2017.

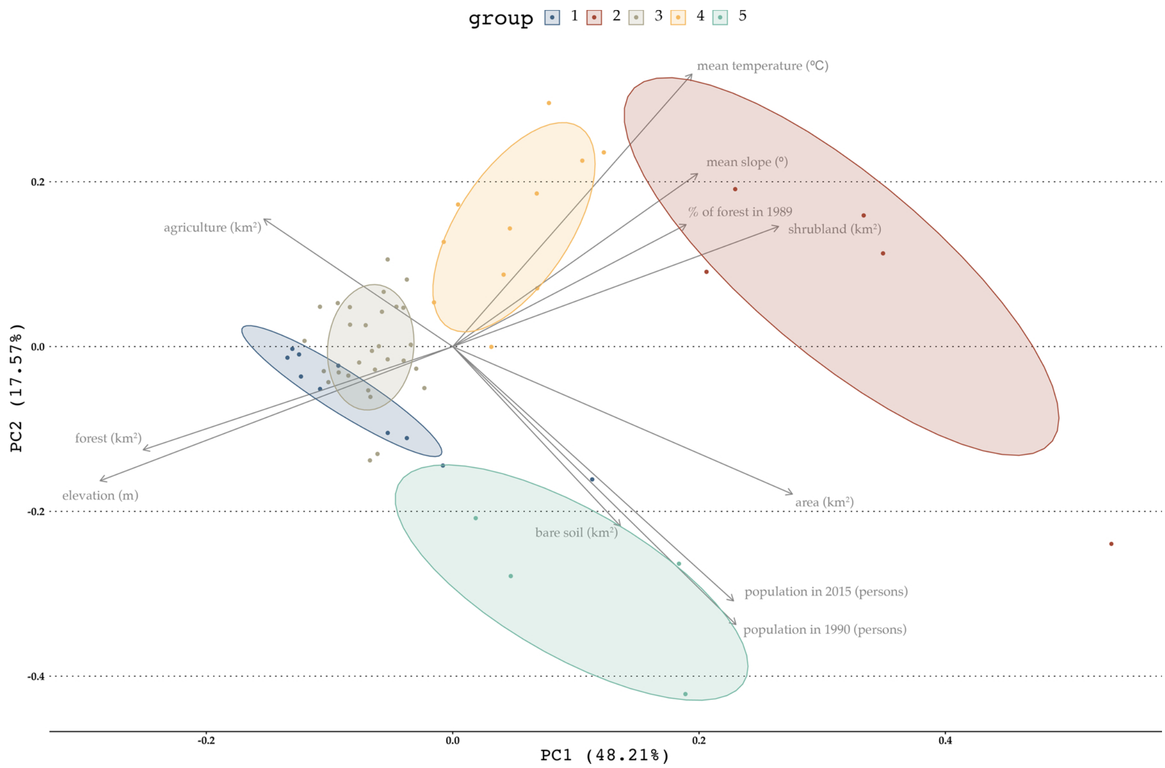

Fig. 3. Principal components 1 (x axis) and 2 (y axis). The 11 indicators are represented by arrows. Municipalities are represented as dots. Groups resulting from the hierarchical cluster analysis are displayed in different colors.

followed by a pair-wise comparison using the Dunn's test (Dinno, 2015). Statistical analyses were performed in R! v. 3.6.2. Packages used included the ade4 v. 1.7–15 (PCA), stats v. 3.6.2 (HCA and Kruskal-Wallis test), and FSA v. 0.8.30 (Dunn's test).

2.4. Land use change analysis for San Cristóbal Amoltepec and Santa Catarina Tayata

Land use change analysis was performed on 5 Landsat images taken in 1984, 1989, 1999, 2010, and 2017 (Table 2). The 1984 image was the oldest usable image that had a resolution of 30 m and no cloud cover. For the land use change analysis, we used the same workflow as described in the previous section. Land use was first classified as forest, cropland/grassland, or bare soil. Shrubland was not present in SCA and SCT, unlike in the regional analysis. Although cropland and grassland are distinct classes, the images' resolution in combination with the small plot sizes (less than one ha) did not allow for a direct separation during the image classification. A shapefile containing the delineation of private and common areas in both municipalities was used to separate cropland from grassland. Since common areas do not have crops, every pixel classified as cropland/grassland within common areas was considered to be grassland. Similarly, every pixel classified as cropland/grassland within private land was considered cropland. Applying the same method of separating cropland from grassland was not possible for the entire Río-Sordo watershed because of lack of spatial information. The generated land use maps were later used in workshops with local officials from SCA and SCT.

To analyze the causes of land use change, municipal officials that had been in the office around the time the land use images had been taken were approached. A total of 5 former elected presidents from the common goods commissariat for SCA and 6 for SCT were found willing to participate. Respondents for SCA had been in office in the following periods: 1979–1981, 1988–1990, 1996–1998, 2002–2004, 2011 – 2013. For SCT the periods included: 1969–1971, 1981–1983, 1987–1989, 1996–1998, 2002–2004, 2014 – 2016. In each municipality, a workshop was organized in September 2018 (A.2).

Each workshop consisted of two stages: 1) description of major changes in the municipality from the mid-60 s to 2018 and 2) evaluation of land use change using the classified maps. Participants were asked to first describe the major drivers of change around the time of their term in office. At the end of this stage, drivers considered relevant by the researchers that had not been discussed by the participants were brought forward and assessed. During the second stage of the workshop, the researchers explained the classified images to the participants and who were then asked to explain what they considered to be the drivers of change associated with the landscape change, using the list of drivers that had been established in the first stage. The workshops were recorded. Results were used to create a timeline per municipality describing drivers of change.

To complement the results from the workshops, data from the 1991 and 2007 agricultural censuses and the 1980, 1990, 1995, 2000, 2005, and 2010 population censuses were obtained (available on https://www.inegi.org.mx/datos/?ps = Programas). These censuses provided data on population size, income sources, crop, and animal production. Population size across the censused years was compared to identify population growth, stagnation, or decline. Furthermore, the population was arranged into five-year age categories to build age pyramids. Data on income sources showed the proportion of household heads relying

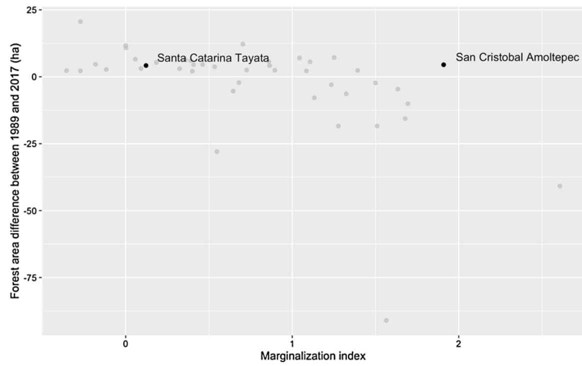

Fig. 4. Relation between marginalization index and forest area change between 1989 and 2017. Case study municipalities are highlighted in black.

on off-farm income. Crop production was expressed as average arable land per household, and animal production as an average number of sheep, goat, cattle, equine, and pig heads per household. We surveyed 31 households in SCA and 51 in SCT to obtain more recent data on crop and animal production. Crop and animal production and demographic change were used to assess the impact of these activities on land use change.

3. Results

3.1. Río Sordo watershed land use change

In 2017, forest covered the largest area in the Río Sordo watershed, occupying 66 % of the territory, followed by agriculture with 19.4 %, shrubland with 12.2 %, and bare soil with 2.4 % (Table 3). Overall, agriculture was the land use that changed most, with a net change of -6.5 % between 1989 and 2017. Over the same period, 8.8 % of the total territory was converted from agriculture to forest and 4.7 % from agriculture to shrubland. Forest area increased by 4.3 % between 1989 and 2017, mostly because of agriculture to forest conversion. Shrubland increased by 4.3 % due to conversion of agricultural land.

Among the 63 municipalities in the Río Sordo watershed, 18 decreased in forest area, 38 decreased in shrubland, 58 decreased in agriculture, and 23 decreased in bare soil (Fig. 2) The first three principal components in the PCA explained 77 % of the variability. The HCA revealed five groups of municipalities (Fig. 3 and Table 3). These groups shared some key socio-economic similarities. Migration was found in all groups and marginalization index ranged from -0.66 to 2.15 (Fig. 4). The marginalization index values indicate that all municipalities are considered marginalized. The distinctions between groups can be described as follows:

Group 1 comprised 10 municipalities with an average area of around 50 km^2. In terms of relative area, land use did not change over the last 30 years. The predominant land use in this group was

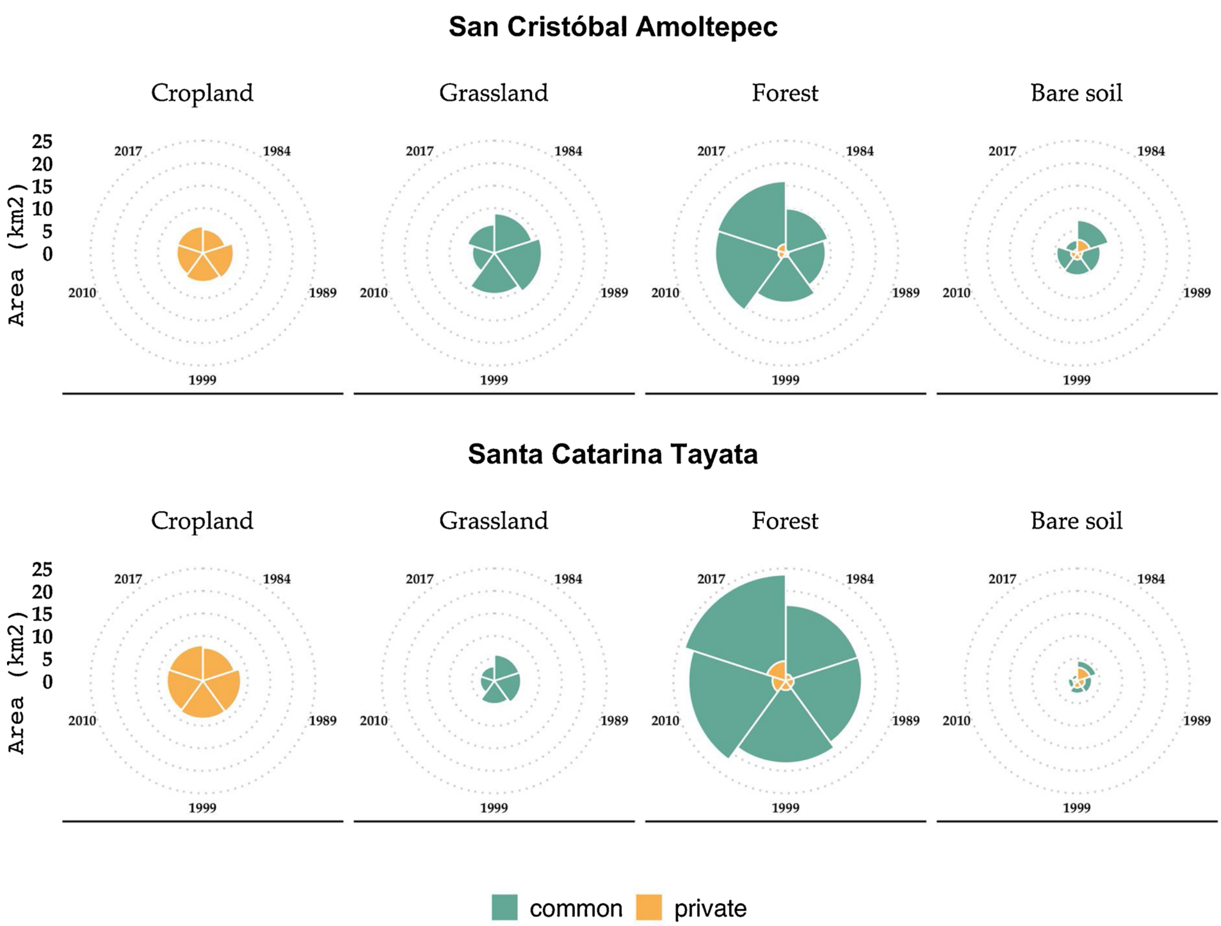

Fig. 5. Fraction land cover from 1984 to 2017 in the Mixteca Alta municipalities San Cristóbal Amoltepec and Santa Catarina Tayata in Mexico, based on analysis of Landsat images from 1984, 1989, 1999, 2010 and 2017.

agriculture, averaging 55 % of the territory. The marginalization index was lower than in other groups. Migration for this group increased between 1990 and 2015, resulting in an average net decrease in population of around 200 people. The average slope of around 8.5° was the lowest of all groups. Elevation ranged between 2000 and 2500 masl. The average temperature was around 16 °C.

Group 2 comprised 5 municipalities. These municipalities had a mean area of 215 km^2. Forest area decreased most, both in absolute (18 km^2) and relative terms (9 %). At the same time, shrubland increased in similar absolute and relative values. Despite the large deforestation, forest still occupied 74 % of the territory in 2017. Agriculture occupied around 15 % of the territory in 1989 and 2017. Marginalization index was 1. Migration increased between 1990 and 2015, but not enough to cause a demographic decline. The slope in the area was around 23° and elevation ranged between 779 and 2700 masl. The temperature was close to 19 °C.

Group 3 was the largest group with 29 municipalities. Average municipal area was 44 km^2. Forest area increased by 4 km^2 (9 %). The relative decrease in agriculture land was 7 %, although not statistically different from other groups. The marginalization index of 0.4 was similar to group 1. Together with group 5 migration for this group was the highest among the 5 groups. A slight demographic decline of 84 people occurred. Slope in the municipalities was around 15° and elevation ranged between 2000 and 2800 masl. The temperature was around 15 °C.

Group 4 comprised 11 municipalities with an average area of 60 km^2. Deforestation occurred in this group, although on a smaller absolute and relative scale compared to group 2. The average agriculture area in this group was similar to group 1. Marginalization index was 1.1. Despite showing migration patterns, the population size in these municipalities remained near constant between 1990 and 2015. The mean slope was the second highest, with 20° on average. Elevation ranged from 1300 to 2500 masl. The mean temperature was 18 °C.

Group 5 was the smallest group, comprising four municipalities with a mean area of 166 km^2. This group showed the same land use change patterns as group 1. On average, municipalities in group 5 differed from group 1 by their larger municipality area and larger population size.

3.2. Land use change in Santa Catarina Tayata and San Cristóbal Amoltepec

In 1984, cropland, grassland, forest, and bare soil occupied 17, 28, 32, and 23 % of the total territory of SCA, respectively (Fig. 5). By 2017, cropland area had not changed much. Grassland decreased from 28 to 20 %, forest increased from 32 to 51 %, and bare soil decreased from 23 to 9 % of the total area. These changes represent an average annual change in percentage points of 0.13 for cropland, -0.28 for grassland, 0.62 for forest, and -0.61 for bare soil.

In SCT, cropland, grassland, forest and bare soil occupied 21, 17, 13 and 49 % of the total area in 1984, respectively. Similar to SCA cropland barely changed between 1984 and 2017, grassland decreased from 17 to 9 %, forest increased from 49 to 65 %, and bare soil decreased from 13 to 4 %. The average annual growth in percentage points was 0.07 in cropland, -0.44 in grassland, 0.40 in forest, and -0.68 in bare soil.

Table 1
Acquisition date, type of mapper and analyzed area of the Landsat images used in this study.

Acquisition date	Type of Mapper	Analyzed area
22 November 2017	OLI/TIRS	Río-Sordo, SCA, and SCT
15 December 2010	ETM+	SCA and SCT
30 October 1999	TM	SCA and SCT
26 October 1989	TM	Río-Sordo, SCA, and SCT
23 December, 1984	TM	SCA and SCT

In SCA, forest expanded by 1 % annually between 1989 and 2010, but only by 0.15 % between 2010 and 2017. While in SCA forest growth seemed to have halted in recent years, forest expansion continued in SCT. Most of the increase in forest area occurred at the expense of grassland and, to some extent, cropland (Table 4). The expansion of forest to cropland in private areas is shown in yellow in Fig. 5.

Land use changes mostly concerned forest and grassland (Table 4). Forest loss was not common in SCA, with conversion to grassland limited to less than 5 % of the total territory. On the other hand, changes from grassland were mostly to forest, with 14 % of the total territory being converted between 1999 and 2010. We also observed some changes in bare soil, especially to grassland and cropland.

Similar to SCA, forest area in SCT increased. Grassland was mostly converted to forest, with a conversion peak of 7 % of the total territory between 1999 and 2010. A small amount (2–4 % per period) of cropland was converted to forest. Bare soil in SCT was mostly converted to cropland; the decadal conversion rate varied from 2 to 6 % of the total area. In both municipalities, forest increase mostly occurred around existing woody vegetation, rather than through newly established patches, suggesting natural reforestation (Fig. 6).

3.3. Local responses in SCA and SCT and impact on the land cover

In the workshops, participants identified the Common Goods Commissariat as the most important local institution for landscape change. The commissariat was established after a presidential resolution that converted SCA into an agrarian community in 1946, and SCT in 1962 (Fig. 7). SCA and SCT became agrarian communities to legally delineate their borders and reduce conflicts with neighboring communities regarding felling of trees on what they considered their territory. The populations of SCA and SCT voted in favor of a series of regulations in their local assemblies to address excessive logging and to rule out slash-and-burn. In SCA, the slash-and-burn restriction occurred around the same time as in SCT, but logging was restricted only in 1994, while in SCT logging was restricted in 1962. After the logging restriction, the Common Goods Commissariat was responsible for supervising logging activity. The commissariat was also responsible for granting logging rights to the community's dwellers, who could only log a restricted number of trees per year and only for household use (e.g. for firewood and construction materials).

Grazing, although not directly correlated with deforestation, was perceived by the local population as a damaging activity. The workshop participants stated that the local population deemed goats responsible for the degradation of common land. Therefore, a local regulation that would forbid goats to graze on common areas was approved in the local assembly in 2000 for SCA and in 1990 for SCT. This grazing regulation resulted in a decrease in the number of goats per household while increasing the number of sheep in both communities (Fig. 8). Despite the increase in sheep densities, forest areas replaced grassland in both municipalities over the past 20 years (Fig. 6). The workshop participants attributed this increase in forest and reduction in grassland to the fact that in contrast to goats, sheep allowed the growth of spontaneous tree saplings.

To restore degraded areas, both municipalities conducted a reforestation campaign targeting the eroded soils. These campaigns happened between 1990 and 2000 in SCA and between 2003 and 2015 in SCT. The workshop participants considered these campaigns only partially successful, as around 50 % of the sapling trees planted did not survive. They attributed this failure to the tree species chosen for the reforestation, *Pinus oaxacana*, which required deeper soils than prevalent in the area. The communities had no choice but to use this species, as this was the only option provided by the agency responsible for the forestry resources of Mexico (nowadays called CONAFOR). Planting was done by the locals through *tequio* - unpaid collective activity that the locals have to perform as part of the community duties.

Table 2
Land use in percentages of the total territory analyzed and their transition to other land uses between 1989 and 2017 for the Río-Sordo watershed, Oaxaca, Mexico.

	Land cover class	Year 2017 Bare soil (BS)	Agriculture (AG)	Forest (F)	Shrub and (SL)	% of the total territory in 1989[b]	Loss between 1989 and 2017[d] (*b-a*)
Year 1989	Bare Soil (BS)	1.2[a]	2.1	0.8	0.4	4.5	3.3
	Agriculture (AG)	0.9	11.5[a]	8.8	4.7	25.9	14.4
	Forest (F)	0.2	3.9	52.7[a]	4.9	61.7	19
	Shrubland (SL)	0.1	1.9	3.7	2.2[a]	7.9	5.7
	% of the total territory in 2017[c]	2.4	19.4	66	12.2	100	
	Gain between 1984 and 2017[e]	1.2	7.9	13.3	10		
	Net change between 1984 and 2017[f]	−2.1	−6.5	4.3	4.3		67.6[h]
	% Change[g]	−37.5	−33.5	6.5	35.2		

[a] Percentage of area that did not change land use class between 1989 and 2017.
[b] Sum of percentage in the row.
[c] Sum of percentage in the column.
[d] *b-a.*
[e] *c-a.*
[f] *e-d.*
[g] *(c-b)*100/c.*
[h] Percentage land cover that did not change land use class over time.

Census data from 1980 to 2010 showed that population size in SCA remained stable, with around 1200 inhabitants. Between 2010 and 2015 the population declined from 1271 to 1004. In SCT, on the other hand, population numbers declined from at least 1980. From 1980–2010, the population size dropped from 864 to 679 people. According to the workshop participants, out-migration has led to land abandonment and forest growth.

4. Discussion

The first research question was related to the socio-economic and biophysical attributes of the communities in the Río-Sordo watershed affecting land use change. Results showed that migration and marginalization were found across the municipalities in the Río-Sordo watershed. None of the groups showed expansion of agriculture. Despite these similarities, communities differed in their land use trajectory. A total of five groups were distinguished according to their socio-economic and biophysical attributes and land use changes. One group comprising 10 municipalities did not show any relevant change in their land use over the last 30 years. These communities were marked by a predominance of agriculture over other land uses, which occupied around 55 % of a municipality's territory, on average. This predominance of agriculture was likely related to lesser slopes compared to other groups. Two groups showed deforestation dynamics. These groups comprised communities with higher levels of marginalization and steeper slopes (20° on average). Agriculture in these groups occupied, on average, 15 % of the territory. The final two groups, containing more than half of the municipalities considered, were similar and showed reforestation dynamics. They differed in average area and population size per municipality. The second research question related to

Table 3
Land use change variables and their average values describing the 5 groups of municipalities in the Rio Sordo watershed analyzed. Different letters behind the values indicate significant differences between groups (Kruskal-Wallis test, $p < 0.05$).

Type	Indicator	Unit	Groups 1 (n = 10)	2 (n = 5)	3 (n = 29)	4 (n = 11)	5 (n = 4)
Land use	Area	km^2	50.5 a	214.8 b	44.5 a	60.6 ac	166 bc
	Absolute difference in forest (1989 – 2017)	km^2	−0.3 ab	−18.1 a	3.9 c	−0.6 ab	4.1 bc
	Absolute difference in shrubland (1989 – 2017)	km^2	0 ab	17.4 c	−1.1 a	1.6 bc	−2.3 ab
	Absolute difference in agriculture (1989 – 2017)	km^2	−0.9 a	−6.7 b	−2.8 c	−2.3 ac	−5.4 bc
	Absolute difference in bare soil (1989 – 2017)	km^2	1.1 ab	1.3 a	−0.3 b	0.3 ab	2.3 ab
	Relative difference in forest (1989 – 2017)	%	−0.7 a	−8.8 a	8.9 b	−2.7 a	2.6 ab
	Relative difference in shrubland (1989 – 2017)	%	0.8 ab	8.7 a	−2.3 c	3.5 ab	−1.6 bc
	Relative difference in agriculture (1989 – 2017)	%	−3.3 a	−3.3 a	−6.8 a	−3.4 a	−3.0 a
	Relative difference in bare soil (1989 – 2017)	%	1.3 a	0.7 a	−.5 a	.5 a	1.2 a
Socio-economic	Marginalization index 2015	–	0.2 a	1 ab	0.4 a	1.1 b	0.4 ab
	Migration (1990)	%	3.7 ab	0.9 a	4.2 b	1.6 a	3.4 ab
	Migration (2015)	%	6.8 ab	4.1 ab	8 a	4.7 b	8.8 ab
	Difference in population (1990 – 2015)	Number of persons	−188.6 a	293.8 b	−83.8 a	−11.8 ab	193 ab
	Population (1990)	Number of persons	1238.1 a	3158.2 b	845.9 a	904.6 a	4414.2 b
	Population (2015)	Number of persons	1049.5 a	3452 b	762.1 a	892.8 a	4607.2 b
Biophysical	Slope	°	8.5 a	22.9 b	15.3 c	19.9 bd	15 acd
	Minimum elevation	m	1963.3 a	770.8 b	2032.9 a	1310.5 b	1588.8 ab
	Maximum elevation	m	2476 a	2684.8 ab	2771.2 b	2481.6 a	3030.5 b
	Mean temperature	°C	15.7 a	18.9 b	15.1 a	18.4 b	15 a
	Precipitation	mm	760 ab	780 ab	784.5 a	977.3 a	449.8 b

Table 4
Percent of land cover change among land use classes from 1984 to 2017.

Changed from	Changed to	Percent change during			
		1984 – 1989	1989 – 1999	1999 – 2010	2010 – 2017
San Cristóbal Amoltepec					
Forest	Forest	27	27	34	46
	Cropland	1	1	1	1
	Grassland	5	1	0	4
	Bare soil	0	0	0	0
Grassland	Forest	1	2	3	2
	Cropland	14	18	15	15
	Grassland	0	0	0	0
	Bare soil	2	3	3	2
Cropland	Forest	1	7	14	4
	Cropland	0	0	0	0
	Grassland	21	23	12	12
	Bare soil	5	3	3	1
Bare soil	Forest	0	0	0	1
	Cropland	7	2	3	3
	Grassland	7	4	4	4
	Bare soil	10	10	9	7
Santa Catarina Tayata					
Forest	Forest	43	44	49	57
	Cropland	1	1	1	1
	Grassland	3	2	1	2
	Bare soil	0	0	0	0
Cropland	Forest	2	2	4	4
	Cropland	18	20	20	19
	Grassland	0	1	0	0
	Bare soil	3	2	2	1
Grassland	Forest	2	5	7	3
	Cropland	0	1	0	0
	Grassland	13	12	8	6
	Bare soil	2	1	0	0
Bare soil	Forest	0	0	0	0
	Cropland	6	3	4	2
	Grassland	2	1	1	1
	Bare soil	5	6	4	3

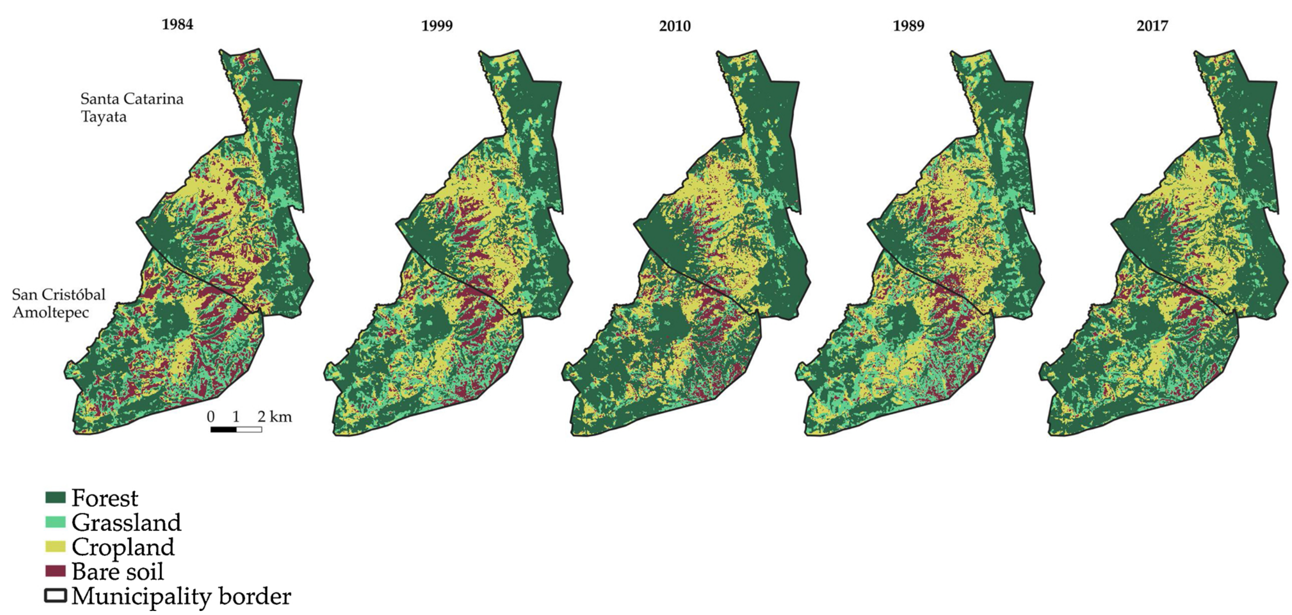

Fig. 6. Land cover in San Cristóbal Amoltepec and Santa Catarina Tayata in 1984, 1989, 1999, 2010 and 2017.

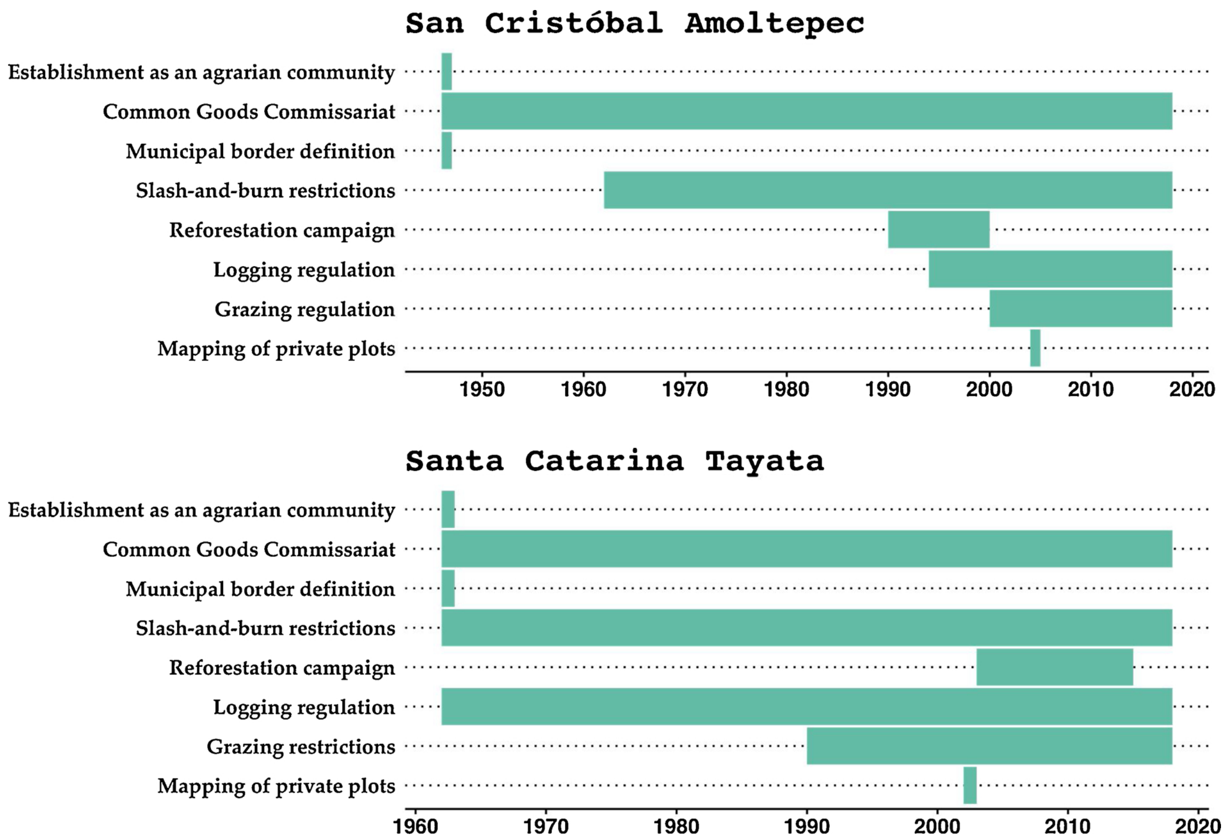

Fig. 7. Timeline of the major drivers of change in two municipalities in Oaxaca, Mexico, according to local officials.

how community decisions contributed to conserving natural resources. An in-depth analysis of two municipalities with reforestation patterns revealed how a series of community decisions affected landscape change. These decisions, in turn, were driven by how local citizens perceived landscape-level problems. Through communities' assemblies, the population voted in favor of forbidding slash-and-burn, controlling

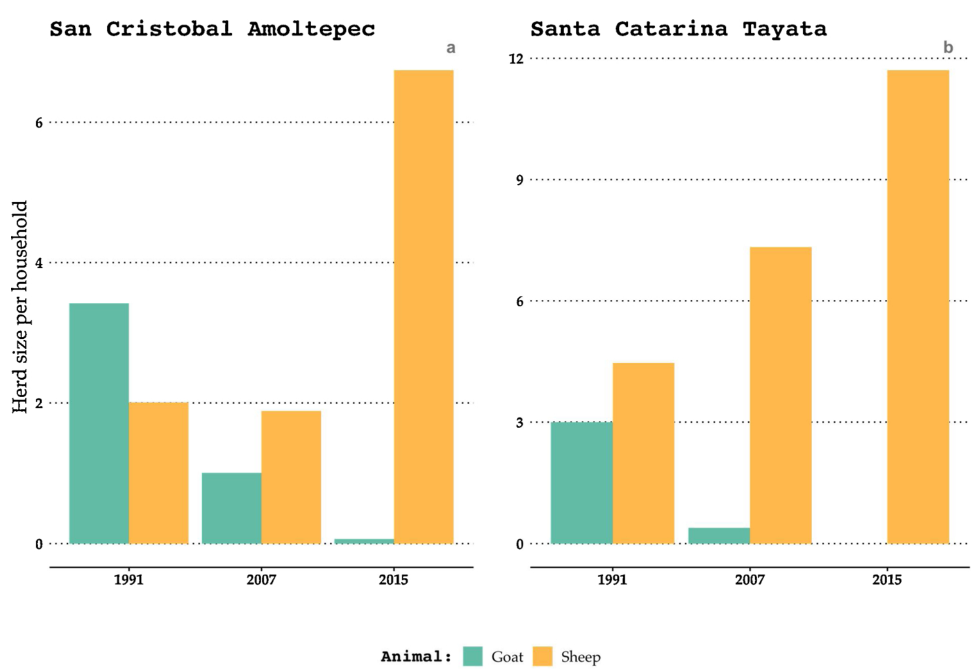

Fig. 8. Shifts in the average animal herd size per household in San Cristóbal Amoltepec and Santa Catarina Tayata.

logging, and forbidding goats to graze in common areas. These local decisions ultimately led to an increase in forest and a reduction in bare soil.

Often, studies on drivers of landscape change show contradictory results. For instance, Deininger and Minten (1999) concluded in a study for Mexico that poverty was associated with deforestation. Other studies around the world tried to link poverty to deforestation, with oftentimes contrasting results (Busch and Ferretti-Gallon, 2017; Gaveau et al., 2009; Khan and Khan, 2009). Mas and Cuevas (2015) showed that the relation between marginalization index and deforestation in Mexico could be positive or negative depending on the country's region. Such contradictory results led authors to agree that forest patterns in human-influenced landscapes are strongly affected by a combination of socio-economic and environmental factors that are site-specific (Angelsen, 1995; Bernard and Koninck, 1997; Geist and Lambin, 2002; Mather et al., 1998; Murali and Hedge, 1997; Rudel and Roper, 1996; Twongyirwe et al., 2018; Walker, 2010). This study shows that communities differed in socio-economic and biophysical attributes, and that the combination of these attributes led to different landscape changes. These attributes were migration, marginalization index and slope.

Since steep slopes are often associated with low crop production (Fombe and Tossa, 2015; Tuan et al., 2014; Wang et al., 2019), the flatter terrain found for group 1 explains why agriculture was the most common land use for that group. Municipalities in groups 2 and 4 were found to have steeper slopes and agriculture was less predominant. Furthermore, these two groups had the highest marginalization index values and deforestation levels. Marginalization and steep slopes are usually associated in th Mexican context (Gonzales et al., 1997). Group 2's deforestation trajectory was not related to agriculture expansion, but rather to forest to shrubland conversion. This suggests that logging could be steering deforestation. Municipalities in groups 3 and 5 showed reforestation dynamics. They also had greater migration rates than other groups, with municipalities in group 3 even showing a demographic decline. A positive relation between reforestation and migration has been discussed by other authors (Aide et al., 2000; Oldekop et al., 2018). The group description allows identifying, selecting, and studying communities with desirable landscape conservation patterns, such as reforestation, for scaling-out their characteristics to other communities.

The assessment of community attributes revealed associations with landscape changes. These structural attributes do not pay attention to the social role of communities as drivers of change. This is of particular importance in the case of Mexico, where an estimated 80 % of the forest area is under community care (Bray and Merino-Pérez, 2007). At the global level 65 % of the terrestrial area is under some sort of community control (Wily, 2010), and insights in the factors influencing natural resource conservation is both of local and global relevance. Several cases have documented the role of indigenous communities in reforestation processes worldwide (Herrmann, 2006; Ravindranath et al., 2008; Smith, 2001). Innah et al. (2013) described 4 types of collective indigenous action related to reforestation in Indonesia. These types were mostly defined by their leadership (e.g. formal authority and traditional leaders), motivation (e.g. innovation, rewards for reforestation, conservation of traditional customs and commercial), and regulatory structure (e.g. indigenous or formal regulations). Our results showed that SCA and SCT had a formal leadership sustained by the indigenous people who would vocalize their ideas and vote for approval of new local regulations through the local institution Bienes Comunales. The legal structures and the agency of the inhabitants thus cooperated in maintaining natural resource conservation strategies.

SCA and SCT were established as agrarian communities and formed their Bienes Comunales Commissariat to put an end to conflicts with neighboring communities. In the process, these communities demarcated and regulation of private and common land, which served to decrease land degradation and enhance forest development within the communities. This zoning process has also been identified by others as a measure that avoids deforestation (Bray, 2004; Dalle et al., 2006; Ellis and Porter-Bolland, 2008). In local assemblies, the population voted to forbid slash-and-burn practices to keep agriculture from expanding during a period of high pressure on land in the 1960s. Restricting grazing, especially by goats, affected land use in both communities. Goats are an exotic species to Mexico introduced during the Spanish colonization (Mindek 2003), and their feeding preferences impede the forest regeneration (Sierra et al., 1997). Perceiving the negative impacts caused by the goats on the environment, the local population through Bienes Comunales forbid goats to graze in common areas. The impact of the regulations on goat numbers was confirmed by comparing the 1991 and 2007 agricultural censuses and our 2015 survey data, from which we observed a reduction in average goat numbers per household (Fig. 8). By restricting goats, forest areas in both municipalities increased, while grassland and bare soil decreased (Table 4 and Fig. 6). Although we also observed a spike in sheep husbandry after 2007 in SCA and after 1991 in SCT, it was not associated with deforestation, as information from the local population revealed that sheep avoided feeding on sapling trees, thus allowing the forest regeneration process to continue.

García-Barrio and García-Barrios (1990) expressed concerns regarding how rural policies in the 1980s would induce migration and erode local institutions' capacity to mobilize collective labor.. According to these authors, these policies would undermine communities' ability to perceive and act against environmental degradation. Our study showed that the majority of municipalities were able to maintain their integrity and promote natural resource protection, despite their migration patterns. Nevertheless, municipalities in groups 2 and 4, comprising around 30 % of the municipalities assessed, showed deforestation dynamics, suggesting local differences in working towards resource conservation.

Land use planning is often driven by experts implementing topdown processes with limited inclusion of local communities, and sometimes even favoring particular interests of planners, policymakers, and others (Berkes, 2004; Glover et al., 2008; Hu et al., 2016). This study shows how communities that are engaged in land use planning using knowledge of their unique context and benefitting from national drivers took an active role in land use planning by developing and voting local rules and regulations for natural resource management. A limitation of this study is that only two municipalities out of the 63 in the watershed were evaluated in-depth. More studies linking local to regional and national developments may bring out patterns of local governance and their higher-level support for successful sustainable landscape change. Such studies require research engagement with each community to understand their historical context from often undocumented materials and are thus resource-intensive.

5. Conclusions

Grouping municipalities in a watershed based on structural and land use change attributes revealed five groups. Two of these groups showed deforestation trends, two reforestation and one group did not show much change in forest over the past 30 years. Agriculture expansion was not revealed for any of the groups. Deforestation was associated with more marginalized municipalities found on steep slopes. Municipalities showing reforestation dynamics had higher migration. Detailed analyses at the municipal level involving local officials and farmers showed how communities used local knowledge together with the opportunities afforded by national laws and regulations to counter landscape degradation. Although deforestation was associated with marginalization, even in situations of high marginalization reforestation was found to occur. Our results suggest that indigenous communities may provide learnings on resource aware communal decision making. These results are relevant, considering that 65 % of the world's land is managed by communities. To enhance community agency in natural resource conservation, community and governmental goals need to be carefully aligned to allow communities to effectively manage their natural resources.

CRediT authorship contribution statement

Ivan P. Novotny: Conceptualization, Methodology, Software, Formal analysis, Investigation, Resources, Data curation, Writing - original draft, Writing - review & editing. **Mariela H. Fuentes-Ponce:** Conceptualization, Writing - review & editing, Project administration. **Pablo Tittonell:** Writing - review & editing, Funding acquisition. **Santiago Lopez-Ridaura:** Writing - review & editing. **Walter A.H. Rossing:** Conceptualization, Writing - review & editing, Project administration.

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Appendix A

A.1 Variables used to explain land use in the Rio Sordo watershed based on random forest models and principal component analysis

Type	Indicators	Unit	Input for	Reference
Land use	Difference in forest (1989 – 2017)	Km^2	Random forest and PCA	Calculated from Land use classification
	Difference in shrubland (1989 – 2017)	Km^2	Random forest and PCA	Calculated from Land use classification
	Difference in agriculture (1989 – 2017)	Km^2	Random forest and PCA	Calculated from Land use classification
	Difference in bare soil (1989 – 2017)	Km^2	Random forest and PCA	Calculated from Land use classification
	Forest area in 1989	%	Random forest and PCA	Calculated from Land use classification
Socio-economic	Difference in marginalization index (1990 – 2015)	–	Random forest	CONAPO (2016)
	Marginalization index (1990)	–	Random forest	CONAPO (2016)
	Marginalization index (2015)	–	Random forest	CONAPO (2016)
	Difference in migration (1990 – 2010)	%	Random forest	INEGI (2015, 1990)
	Migration (1990)	%	Random forest	INEGI (1990)
	Migration (2010)	%	Random forest	INEGI (2015)
	Difference in population (1990 – 2015)	Number of people	Random forest	INEGI (2015, 1990)
	Population (1990)	Number of people	Random forest and PCA	INEGI (1990)
	Population (2015)	Number of people	Random forest and PCA	INEGI (2015)
	Difference in population density (1990 – 2015)	Number of people	Random forest	INEGI (2015, 1990)
	Population density (1990)	Number of people	Random forest	INEGI (1990)
	Population density (2015)	People/km	Random forest	INEGI (2015)
	Difference in population holding a job (1990 – 2015)	%	Random forest	INEGI (2015, 1990)
	Population holding a job (1990)	%	Random forest	INEGI (1990)
	Population holding a job (2015)	%	Random forest	INEGI (2015)
	Population with less than one minimum wage (2015)	%	Random forest	CONEVAL (2016)
	Population under poverty (2015)	%	Random forest	CONEVAL (2016)
	Population with no formal education (2015)	%	Random forest	CONEVAL, 2016)
	Socially vulnerable population (2015)	%	Random forest	CONEVAL (2016)
	Human development index (2015)	–	Random forest	CONEVAL (2016)
	Distance to the nearest city	Km	Random forest	CONEVAL (2016)
Biophysical	Drought risk index	–	Random forest	CENAPRED (2012
	Mean slope	°	Random forest and PCA	Derived from a 15 m DEM (INEGI, 2013)
	Mean temperature	°C	Random forest and PCA	Vidal-Zapeda (1990)
	Mean precipitation	mm	Random forest	Vidal-Zapeda (1990)
	Minimum elevation	m	Random forest and PCA	Derived from a 15 m DEM (INEGI, 2013)
	Maximum elevation	m	Random forest	Derived from a 15 m DEM INEGI (2013)
	Area	Km^2	Random forest and PCA	INEGI (2018)

A.2 Pictures from the workshop with former local officials in Santa Catarina Tayata

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