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Forest Fragmentation and Cover Change (2000–2020) in Community-Owned Territories of Northwestern Mexico: An Analysis Using Landscape Metrics

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Abstract

Temperate forests play a key role in biodiversity conservation, climate regulation, and the provision of ecosystem services. However, land-use changes and urban expansion have intensified landscape fragmentation processes, reducing ecological connectivity and ecosystem functionality. Despite the importance of community-owned forests in northern Mexico, evaluations of landscape configuration within these territories remain limited. This study compared land-use and land-cover patterns and fragmentation metrics in four community-managed ejidos in Durango, Mexico, using Landsat imagery from 2000 and 2020. Land-cover maps were produced through supervised classification with a Random Forest algorithm and validated using standard accuracy metrics. Landscape composition, configuration and connectivity were assessed at class and landscape levels using a set of spatial metrics calculated with FRAGSTATS. The results reveal contrasts among ejidos. Ciénega de los Caballos and Navajas show greater representation of secondary vegetation accompanied by changes in patches and edge densities. San Isidro retains a more cohesive configuration with comparatively higher aggregation and connectivity, whereas El Tunal y Anexos exhibit stronger subdivision and lower connectivity. These outcomes emphasize the value of spatial metrics for identifying differences in landscape structure between observation years and for supporting comparative assessment in community-managed forest territories. The study provides spatially explicit information that may assist territorial planning and forest management at this scale.

Keywords: collective management; patches; ecological connectivity; forest ejidos; land-use change

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1. Introduction

Temperate forests are natural landscapes of high social, ecological, and economic relevance. They significantly contribute to biodiversity conservation, climate regulation, and the provision of essential ecosystem services [1,2], while also supporting regional economies through forestry and associated activities [3,4]. In Mexico, temperate forests are dominated by species of the genera *Pinus* and *Quercus*, hosting approximately 50% of

the world's pine diversity and 33% of oak species, which makes these ecosystems a key priority for conservation at the global scale [5,6]. In the state of Durango, temperate forests are primarily distributed along the Sierra Madre Occidental (SMO), a biologically diverse region that contains one of the largest forest reserves in the country and provides critical ecosystem services for northern and central Mexico [7,8].

However, various human activities, such as illegal logging and land-use change primarily for agricultural, livestock, and urban purposes, negatively impacted these landscapes, leading to deforestation and fragmentation [9–12]. Unlike deforestation, which involves the loss of forest cover, fragmentation refers to the process by which large, continuous areas are divided into smaller, more isolated patches, affecting ecological functions and species movement [13–19]. This process has been widely documented as one of the main factors affecting habitat quality and species persistence [20,21].

In northern Mexico, temperate forests have experienced a significant increase in both fragmentation and deforestation. Between 1990 and 2017 alone, primary forests lost 18.1% of their area [22]. In Durango, the conversion of forested areas to agricultural lands, mainly for livestock production and rainfed agriculture, timber extraction, and forest fires, has been a key driver of forest vegetation loss, which in many cases has been replaced by secondary vegetation such as shrublands and herbaceous communities [23]. Similar trends have been reported across the SMO, where moderate changes in total forest area coexist with increasing micro-fragmentation within forest stands, reflected in higher patch subdivision and edge density [24].

Several studies have shown that fragmentation not only reduces forest area but also deteriorates habitat quality, increases fragment isolation, and increases vulnerability to edge effects [20,21]. Fragmentation also has direct implications for ecological connectivity, which depends on fragment size, shape, isolation, and spatial arrangement, as well as on organisms' ability to move through the landscape. In the oak forests of central Mexico, large fragments concentrate the highest levels of connectivity, whereas small fragments play a key role as "stepping stones" for species movement [25]. Despite these advances, studies by Legarreta-Miranda et al. [22], Moreno-Sánchez et al. [26], and Márquez-Linares et al. [23] indicate that research addressing this problem in collectively managed territories, such as Mexican ejidos, remains scarce. Considering that these collective agrarian regimes occupy a significant portion of the national territory (close to 60% of total forest lands) and play a key role in forest conservation and sustainable management, it is a priority to understand how landscape fragmentation manifests and evolves in these areas.

In this context, the assessment of forest landscape structure and connectivity through spatial metrics has become a key approach for diagnosing fragmentation patterns and comparing landscape configurations across different land-use contexts [27–31]. The integration of these metrics with satellite imagery enables consistent comparison on landscape conditions observed at different moments in time, even where net changes in forest area are limited, providing valuable information for conservation planning and landscape management [32–34]. From a conceptual perspective, ecological connectivity can be approached through structural and functional frameworks. Structural connectivity focuses on the spatial configuration of habitat patches and can be evaluated using metrics derived from classified land-cover maps. In contrast, functional connectivity depends on species-specific movement and processes, which are often unavailable at regional scales. Consequently, landscape metrics derived from medium-resolution imagery offer a robust framework for comparative assessment of fragmentation and structural connectivity in heterogeneous forest territories [35–37].

The objective of this study is to compare landscape structure and fragmentation patterns between two observation years, 2000 and 2020, in four community-owned territories

(ejidos) located in the state of Durango, Mexico. We evaluated how spatial configurations and structural connectivity differ between these two temporal states under contrasting land-use contexts. Rather than reconstructing continuous dynamics of change, the analysis focuses on identifying differences in landscape conditions observed at the beginning and end of the study period. This approach provides a consistent basis for comparative assessment among ejidos and offers spatially explicit information useful for territorial planning and forest management.

2. Materials and Methods

2.1. Study Area

The four ejidos analyzed are in southwestern Durango, Mexico: El Tunal y Anexos, Navajas, Ciénega de los Caballos, and San Isidro, all of which belong to the municipality of Durango (Figure 1). Ejidos are legally recognized communal land tenure units in Mexico. They are characterized by collective ownership and local governance through ejido assemblies. These ejidos are situated within the SMO region, encompassing the Madrense and Madrense xerophytic subregions, which are characterized by temperate, sub-humid climates and the presence of pine, pine-oak, and oak-pine forests [8].

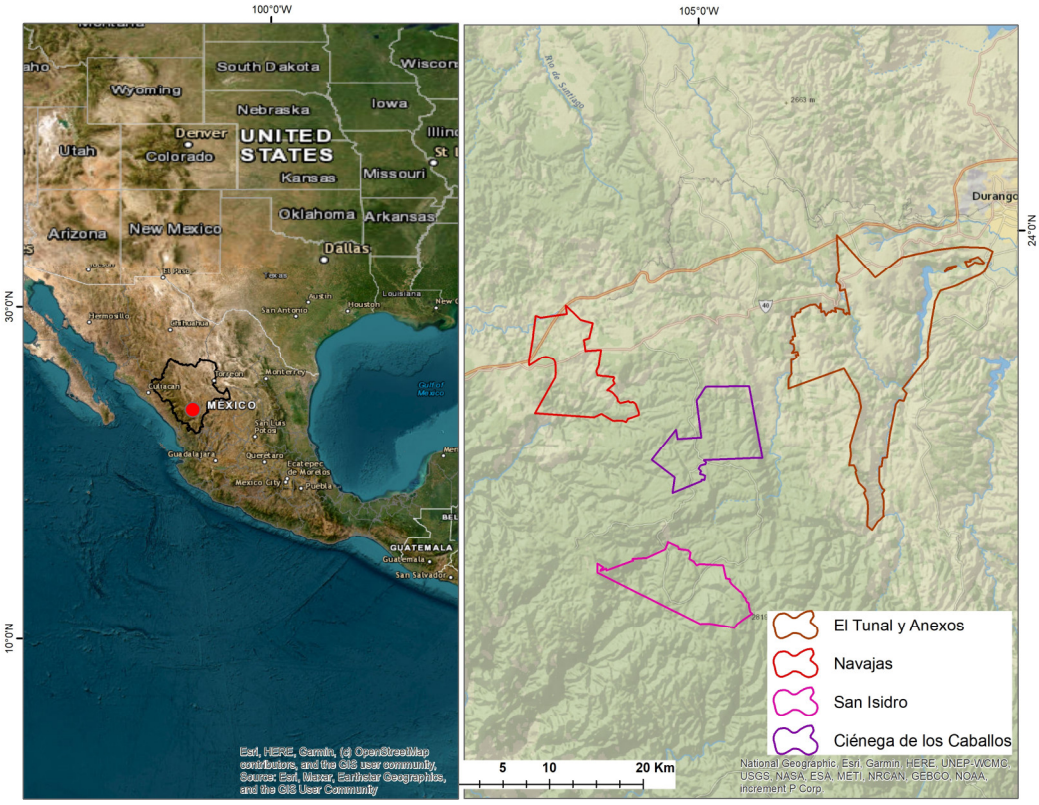


Figure 1. Study area, including the selected ejidos. Source: Authors' own elaboration.

The selection of the ejidos was based on their ecological representativeness within the Sierra Madre Occidental, covering temperature forest areas with different land-cover types and degrees of landscape transformation. In addition, their diversity, territorial dynamics, levels of anthropogenic pressure, and data availability were considered. Finally, accessibility and availability of geospatial and field data were prioritized, facilitating multitemporal analysis and validation of results.

The methodological framework of this study was structured into four main stages: Section 2.2: satellite image acquisition and preprocessing; Section 2.3: supervised classifi-

cation and validation; Section 2.4: multitemporal analysis; and Section 2.5: calculation of landscape fragmentation metrics (Figure 2).

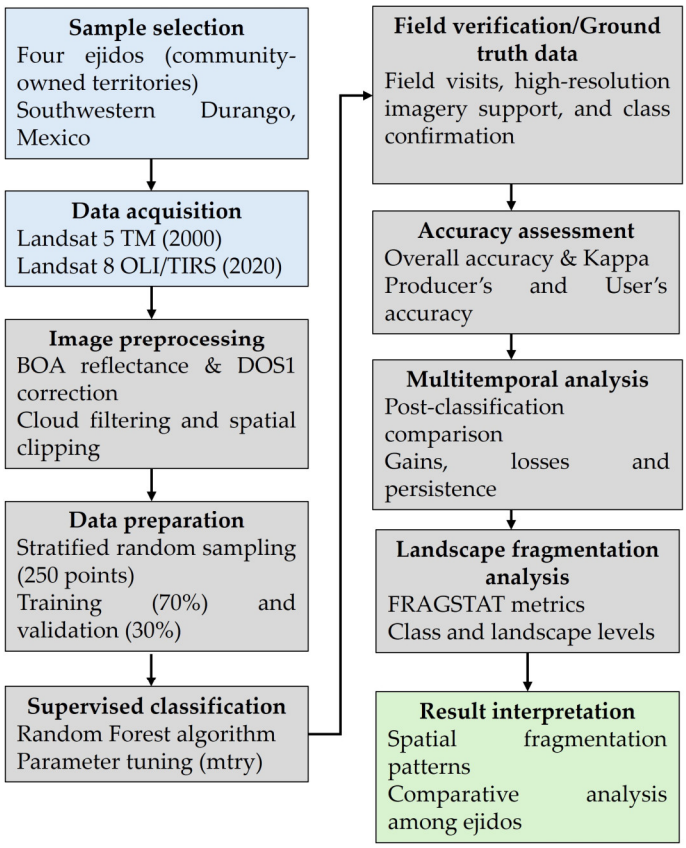


Figure 2. Methodological workflow for land-cover classification and landscape fragmentation analysis in the State of Durango, Mexico.

2.2. Satellite Image Acquisition and Preprocessing

Landsat 5 TM (year 2000) and Landsat 8 OLI/TIRS (year 2020) satellite images were used, with a spatial resolution of 30 m. The Bottom-of-Atmosphere (BOA) reflectance processing level was downloaded from the USGS Earth Explorer portal. This processing level ensured reflectance corrected for basic atmospheric effects and made it suitable for temporal comparisons [27,38–40].

For temporal selection and preprocessing, scenes corresponding from September to November with cloud cover below 5% were selected. Atmospheric correction was applied using the Dark Object Subtraction (DOS1) method [41], following Chávez, a procedure recommended for multitemporal analysis with Landsat sensors.

To facilitate visual interpretation of land-cover types, false-color composites were generated [40,42] and included Landsat 5 TM: B4-B3-B2 (near-infrared-red-green) and Landsat 8 OLI/TIRS: B5-B4-B3 (near-infrared-red-green). These composites allow the differentiation of forest, secondary vegetation, shrubland, agriculture, and bodies of water based on their spectral response.

Image processing, visualization, and spatial masking were performed using standard GIS procedures, including reprojection, clipping to ejido boundaries, and raster calculations, ensuring spatial consistency between the 2000 and 2020 datasets.

The temporal design adopted in this study is based on the comparison of two observation years rather than on continuous monitoring of intermediate conditions. Consequently, the analysis does not aim to reconstruct change trajectories or determine whether landscape transformations follow linear, exponential, or cyclical patterns. Instead, the purpose is

to evaluate differences in spatial configuration between two points in time, enabling a standardized and comparable assessment of fragmentation among ejidos. Under this framework, the twenty-year interval represents the elapsed time between landscape conditions, not a description of the pathway through which those conditions were reached.

2.3. Classification and Validation of Supervised Classification

After evaluating other machine learning models, land-use and land-cover classification were conducted using a supervised Random Forest (RF) algorithm. RF was selected for its robustness in handling complex, non-linear relationships, its ability to manage high-dimensional data, and its demonstrated performance across heterogeneous landscapes [43–45]. It provides high classification accuracy and reduces overfitting when applied to medium-resolution satellite imagery, such as Landsat data, particularly in environments with mixed land cover types and transitional classes [46–48]. Consequently, RF has been widely applied in land-cover mapping and landscape ecology studies addressing fragmentation and land-use change [21,22].

The classification was implemented in R 4.3.2 using the Caret package [49]. Model tuning focused on optimization of the number of variables randomly selected at each node (mtry), while the number of trees was set sufficiently high to ensure model stability. A repeated 10 × 10 cross-validation scheme was applied during model training to obtain robust performance estimates and reduce overfitting.

A total of 250 reference samples were selected using a stratified random sampling design with a spatial approach by class, ensuring balanced representation across forests, secondary vegetation, xerophytic shrubland, agriculture, urban areas, bodies of water, and roads/bare soil [46,50]. This approach follows the recommendation of Colganton and Green [51] and Olofsson et al. [52], who suggest that 50–100 samples per category are sufficient for regional-scale accuracy assessment.

Reference samples were spatially distributed across the study area to minimize clustering and reduce spatial dependence among samples. Training and validation subsets were generated from independent point sets, ensuring no spatial overlap. The stratified design resulted in a comparable number per class (approximately 35–40 samples per land-cover category).

The reference samples were partitioned into independent subsets: 70% for model training and 30% for validation. Classification accuracy was evaluated using overlay accuracy, confidence intervals, the Kappa coefficient, and class-level producers' and users' accuracies [53]. The classification served as a preparatory step to generate reliable spatial inputs for landscape fragmentation analysis, which constitutes the central focus of this study.

Uncertainty associated with land-cover classification was addressed through accuracy assessment metrics described above. Given the emphasis on comparative landscape patterns rather than absolute area estimation, no additional uncertainty propagation was applied to landscape metrics [54].

2.3.1. Class Adjustments

Spectral confusion between bare soil and roads was detected; therefore, both were merged into a single class, following the recommendation to minimize systematic errors when two classes exhibit similar spectral signatures [53]. In the study area, roads are primarily unpaved rural tracks whose spectral response is only marginally different from that of bare soil at Landsat's spatial resolution. For this reason, both features were merged into a single class denoting anthropogenically exposed surfaces, without implying specific assessment of road-driven fragmentation.

Additionally, areas initially classified as grassland were verified to correspond to forest clearings resulting from grazing or management activities rather than native grassland [24,55]. Due to their transitional nature and tendency to later integrate into agricultural land-use areas, these surfaces were reclassified within the agriculture category (Table 1).

Table 1. Description of land-use and land-cover classes.

Class	Code	Description
Forest	BQ	Pine forest, oak forest, mixed pine-oak forest, or oak-pine forest.
Secondary vegetation	VS	Secondary shrub vegetation is generally dominated by species such as manzanita (*Arctostaphylos pungens*) or charrasquillo (*Quercus depressipes*).
Xerophytic shrubland	MX	Vegetation is dominated by thorny shrubs and succulent plants.
Agriculture	AG	Areas devoted to agricultural activities, including both rainfed and irrigated crops.
Bodies of Water	CA	Rivers, streams, ponds, and reservoirs.
Roads and bare soil	CM	Surfaces are characterized by the absence of vegetation cover due to anthropogenic activities (deforestation, slope development, land clearing, fires, roads).
Urban area	ZU	Area with high building density and scarce or artificial vegetation, dominated by impermeable surface.

Source: Authors' own elaboration based on González-Elizondo et al. [56].

2.3.2. Sensitivity Analyses to Thematic Uncertainty

To assess the potential impact of thematic uncertainty, a sensitivity analysis was conducted targeting possible confusion between forest and secondary vegetation. Extreme scenarios were created by reallocating pixels between these classes and by merging them into a single woody vegetation category. Fragmentation metrics were recalculated under identical parameters to determine whether plausible misclassification could alter the comparative interpretation of spatial patterns among ejidos.

2.4. Multitemporal Analysis of Land-Cover Change

Forest cover change during the 2000–2020 period was evaluated using a post-classification comparison approach, which is considered the most accurate method for multiscale studies [57,58], based on the overlay of the classified maps from both years. From this comparison, losses, gains, and persistence of each land-cover class were quantified, and class-based transition matrices were constructed to describe the direction and magnitude of differences between the two observation years. In addition, annual rates of change were estimated using the standardized equation proposed by Puyravaud [59], which allowed a consistent assessment of the magnitude and direction of landscape transformations.

$$r = \frac{1}{t2 - t1} \ln\left(\frac{A2}{A1}\right)$$

where r = annual rate of change (%); $A1$ = area of the land-cover class at the beginning of the period (ha); $A2$ = area of the land-cover class at the end of the period (ha); $t1$ = initial year of the analyzed interval; and $t2$ = final year.

2.5. Calculation of Landscape Fragmentation Metrics

Fragmentation metrics were calculated using FRAGSTATS v4.2 [60] at both the class and landscape levels. This software is specifically designed for the quantitative analysis of landscape structure and allows evaluation of landscape configuration, composition, and special connectivity based on classified maps at 30 m spatial resolution.

Widely used metrics were selected to assess composition: PLAND, NP, LPI; configuration: PD, TE, ED, SHAPE_MN, PAFRACT, AI, CONNECT, IJI, DIVISION; and heterogeneity: CONTAG (Table S1, Supplementary Materials). These metrics were chosen for their ecological relevance and standardized use in fragmentation studies [33,61].

A comprehensive verification of current land-use and land-cover classifications was conducted using satellite imagery, forest management programs, and field surveys. The latter was conducted at previously selected sites, confirming the actual land use on the ground.

3. Results

3.1. Validation of the Classification Process for the 2000–2020 Period

The accuracy assessment of the Random Forest (RF) land-use and land-cover classification indicates overall satisfactory performance across ejidos in the two observation years (Table 2). Overall accuracy (OA) values range from moderate to high, with the lowest observed in 2000 for El Tunal y Anexos (OA = 62%; Kappa = 0.55) and the highest for Navajas and San Isidro (OA > 90%; Kappa > 0.85). Lower accuracy in El Tunal y Anexos for the year 2000 is mainly associated with higher thematic complexity and spectral similarity among land-cover classes, as well as with the use of the historical Landsat TM imagery. By contrast, higher accuracy values obtained in 2020 reflect improved sensor characteristics and data quality.

Table 2. Accuracy assessment of Random Forest (RF) land-use and land-cover classification used as input for landscape fragmentation analysis in the four ejidos (2000–2020).

Ejido	Year	Overall Accuracy (OA)	Kappa Index	95% CI
Ciénega de los Caballos	2000	0.83	0.77	(0.51, 0.97)
	2020	0.76	0.70	(0.46, 0.94)
Navajas	2000	0.94	0.91	(0.69, 0.99)
	2020	0.89	0.85	(0.65, 0.98)
San Isidro	2000	0.90	0.88	(0.58, 0.99)
	2020	0.94	0.91	(0.69, 0.99)
El Tunal y Anexos	2000	0.62	0.55	(0.40, 0.81)
	2020	0.87	0.85	(0.66, 0.97)

Source: Authors' own elaboration based on Landis & Koch [62].

Mean producers' (PA) and users' (UA) accuracies further support the reliability of the classifications, with most ejidos presenting mean PA and UA values above 0.85, particularly in 2020. Overall, the accuracy levels achieved are considered adequate for landscape-level fragmentation analysis, as the study focuses on relative spatial patterns rather than on precise land-cover area estimation. Detailed class-level accuracy and confusion matrices are provided in Table A1.

3.2. Spatial Land-Cover Change Between 2000 and 2020

The maps (Figures 3 and 4) show differences in land-cover distribution across the ejidos. Forest remains the dominant land-cover class; however, its spatial arrangement varies between the two observation years. In Ciénega de los Caballos and Navajas, a higher presence of secondary vegetation is visible in 2020, mainly in areas previously mapped as forest in 2000. San Isidro exhibits a relatively similar spatial configuration in both years, where differences are primarily associated with localized variations on roads or exposed soil. In Tunal y Anexos, forest patches appear more dispersed in 2020 compared with 2000, in areas that partially coincide with the urban interface.

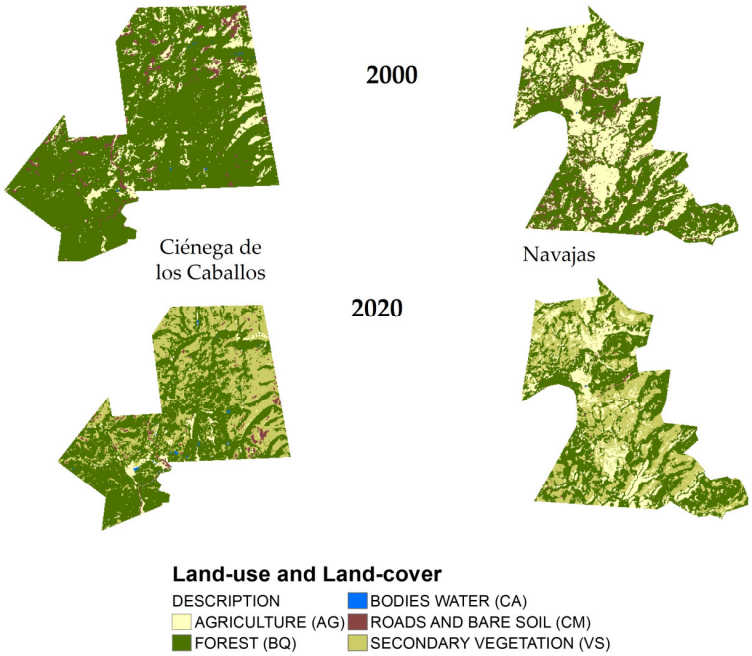


Figure 3. Land-use and vegetation-cover changes in the ejidos of Ciénega de los Caballos and Navajas for the years 2000 and 2020. Source: Author's own elaboration.

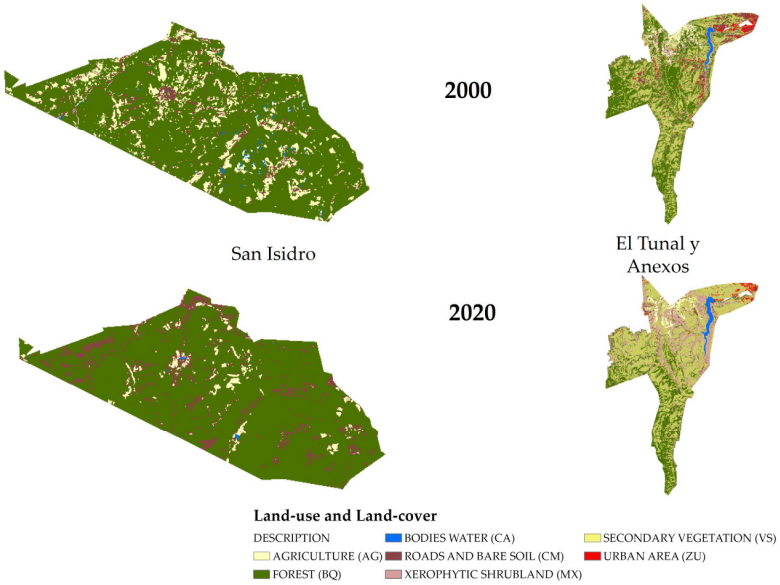


Figure 4. Land-use and vegetation-cover changes in the ejidos of San Isidro, El Tunal y Anexos for the years 2000 and 2020. Source: Author's own elaboration.

Sensitivity of Fragmentation Metrics

The sensitivity analysis indicates that extreme reallocations between forest and secondary vegetation lead to expected changes in class-level metric values. However, the broader landscape configuration and the relative contrasts among ejidos remain stable across scenarios. The ranking of territories in terms of fragmentation and connectivity is preserved, indicating that the main comparative conclusions are not artifacts of thematic confusion.

3.3. Percentage of Change by Land-Cover Class

Figure 5 presents the percentage change in land-cover classes between 2000 and 2020 for the four ejidos. The results show contrasting patterns among territories. An increase in

the relative proportion of secondary vegetation (VS) is observed in Ciénega de los Caballos, Navajas, and El Tunal y Anexos, whereas San Isidro does not exhibit an increase in this class and maintains a stable forest-dominated configuration. Overall, the observed patterns indicate differences in the proportional distribution of land-cover classes between the two observation years, including localized replacement of forest by secondary vegetation, rather than generalized forest loss.

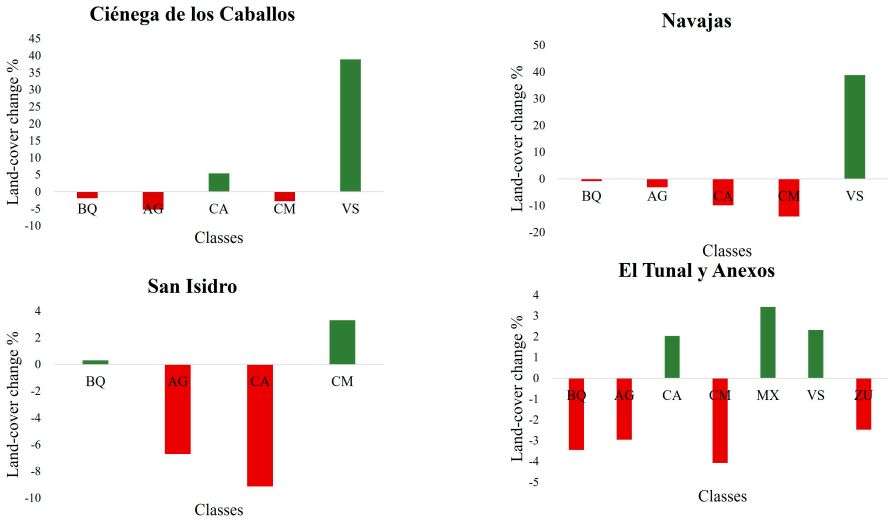


Figure 5. Percentage change in land-cover classes (2000–2020). AG (Agriculture); BQ (Forest); CA (Bodies of Water); CM (Roads and bare soil); MX (Xerophytic shrubland); VS (Secondary vegetation); ZU (Urban areas). Green bars indicate positive land-cover change, whereas red bars indicate negative change. Source: Author's own elaboration.

3.4. Class-Level Fragmentation Metrics

Figure 6 highlights the contrast in class-level metrics among ejidos and between 2000 and 2020. Ciénega de los Caballos and El Tunal y Anexos present higher PD values and greater variability among classes. San Isidro shows lower PD values in both years, whereas Navajas occupies an intermediate position in the metric distribution.

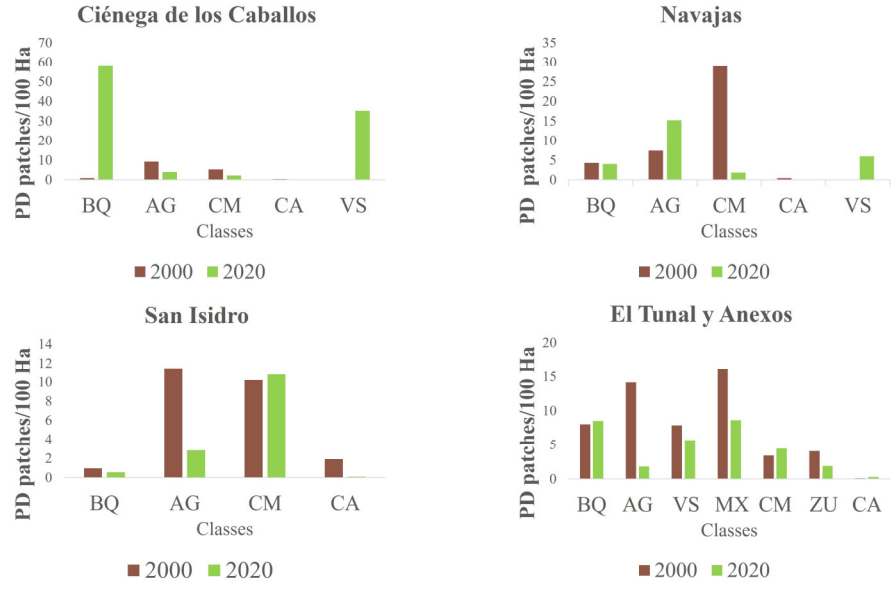


Figure 6. Patch density (PD) by land-cover class for the four ejidos in 2000 and 2020. AG (Agriculture); BQ (Forest); CA (Bodies of Water); CM (Roads and bare soil); VS (Secondary vegetation); MX (Xerophytic shrubland); ZU (Urban areas). Source: Author's own elaboration.

Edge density (ED) and aggregation index (AI) show pronounced variability among ejidos and land-cover classes (Table 3). Ciénega de los Caballos and El Tunal y Anexos exhibit higher ED values and wider class-level ranges, whereas San Isidro and Navajas present more stable patterns with consistently higher values. AI values in the forest, indicating greater spatial cohesion relative to the other ejidos.

Table 3. Class-level edge density (ED) and aggregation index (AI) values for the four ejidos in 2000–2020.

Ejido/Year	ED_AG	ED_BQ	ED_CA	ED_CM	ED_VS	ED_MX	ED_ZU	AI_AG	AI_BQ	AI_CA	AI_CM	AI_VS	AI_MX	AI_ZU
Ciénega de los Caballos 2000	50.34	51.17	0.75	21.08	0	0	0	64.49	94.77	39.82	58.73	0	0	0
2020	20.05	92.28	1.74	11.29	93.88	0	0	62.29	87.51	51.97	61.63	79.89	0	0
Navajas 2000	87.45	94.68	0.63	67.49	0	0	0	83.14	86.47	9.72	27.01	0	0	0
2020	81.46	91.11	0.05	3.83	91.54	0	0	70.76	84.87	78.81	32.82	85.71	0	0
San Isidro 2000	64.65	66.59	4.65	36.51	0	0	0	63.61	93.58	36.75	50.13	0	0	0
2020	15.19	5.23	0.39	54.43	0	0	0	67.77	95.42	75.2	61.52	0	0	0
El Tunal y Anexos 2000	37.62	130.68	1.15	20.21	94.98	59.08	14.07	52.63	77.12	93.75	73.72	78.4	47.5	52.33
2020	11.35	70.26	1.78	15.89	99.45	57.99	7.04	74.72	75.38	93.13	53.14	85.73	73.96	60.76

AG (Agriculture); BQ (Forest); CA (Bodies of Water); CM (Roads and bare soil); VS (Secondary vegetation); MX (Xerophytic shrubland); ZU (Urban areas). Source: Author's own elaboration.

Forest connectivity (CONNECT) shows contrasting levels among ejidos and shows similar magnitudes in the two observation years within each ejido (Figure 7). San Isidro exhibits the highest connectivity values in both years, while Ciénega de los Caballos, Navajas, and El Tunal y Anexos present lower and moderate connectivity levels.

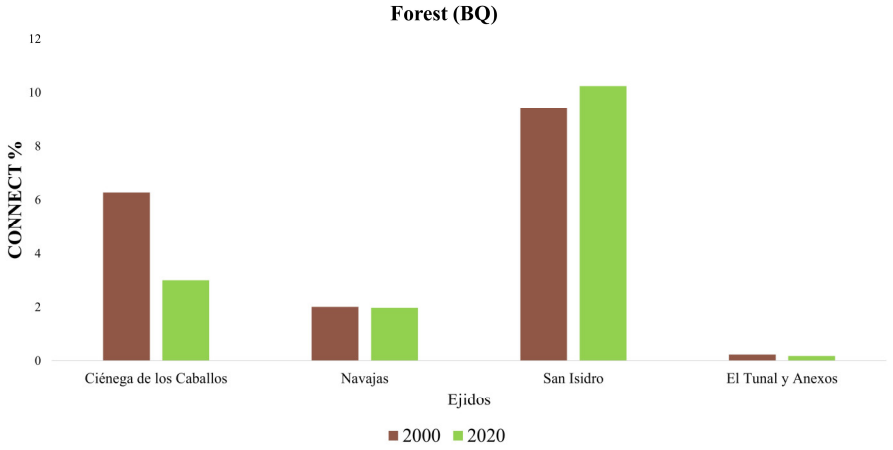


Figure 7. Forest connectivity (CONNECT) values for the forest class across the four ejidos in 2000 and 2020.

The landscape Division Index (DIVISION) and the interspersion and juxtaposition index (IJI) values reported in Table S2 (Supplementary Materials) show differences in spatial configuration among the analyzed ejidos. Ciénega de los Caballos, and El Tunal y Anexos present the highest DIVISION values and the lowest IJI values in both observation years. However, San Isidro presents lower DIVISION values and higher IJI values, while Navajas shows limited variation in both metrics in 2000 and 2020.

3.5. Landscape-Level Fragmentation Metrics

Figure 8 presents the landscape-level fragmentation metrics for the four analyzed ejidos. Cienega de los Caballos shows intermediate values of patch density (PD) and edge density (ED), together with comparatively higher values of the interspersion and juxtapo-

sition index (IJI). In both radar plots, each colors corresponds to specific ejido, while the radial distance from the center represents the relative magnitude of each landscape metric.

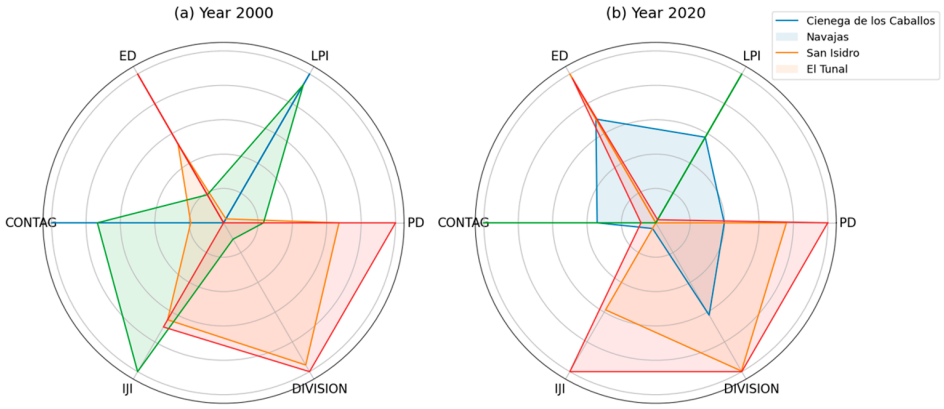


Figure 8. Radar chart of standardized landscape fragmentation metrics for the four ejidos: (**a**) Year 2000 and (**b**) Year 2020. Metrics were normalized using min-max scaling (0–1). ED (Edge density); LPI (Largest Patch Index); PD (patch density); DIVISION (Division index); IJI (Interspersion and juxtaposition index); CONTAG (Contagion index). Source: Author's own elaboration.

Navajas exhibits small differences between the two years in PD and ED values between 2000 and 2020, with moderate metric values at the landscape level. San Isidro presents the lowest PD and ED values and the highest contagion (CONTAG) values among the ejidos.

In contrast, El Tunal y Anexos shows the highest values of PD, ED, IJI, and DIVISION at the landscape level. Overall, the landscape metrics reveal differences in spatial configuration and subdivision among the four ejidos.

4. Discussion

The analysis of land-use and land-cover change revealed spatial patterns and variations in landscape structure across four ejidos for the years 2000 and 2020. The independent evaluation of classified maps for each date enabled comparison of landscape configuration over time, focusing on fragmentation, spatial arrangement, and connectivity metrics rather than precise quantification of land-cover transitions. This approach is appropriate when the objective is to characterize changes in landscape structure and configuration, particularly in heterogeneous forest environments, where reorganization may occur even without large net area changes [36,54,61,63].

Because only two observation dates were considered, the findings should be interpreted as a contrast between landscape conditions rather than a representation of temporal dynamics. The design allows identification of structural differences in spatial patterns but does not permit inference regarding the rate, direction, or functional form of change. Consequently, conclusions are restricted to comparative interpretation of landscape states.

Previous studies suggest that landscape metrics used for comparative purposes tend to be less sensitive to thematic uncertainty [35,64–66]. To further examine the influence of potential misclassification, extreme recollection scenarios between forest and secondary vegetation were implemented. While these adjustments modify class-level values, they do not substantially alter the overall landscape configuration or the relative differences among ejidos. Hence, the comparative interpretation of fragmentation patterns remains stable within plausible bounds of thematic uncertainty.

Clear differences in fragmentation patterns were observed among ejidos, expressed through variations in patch density, edge density, aggregation, and connectivity indices. These metrics describe contrasting spatial configurations rather than uniform trends across the study area [36,65]. Connectivity values between 5 and 10% indicate limited linkage

among forest patches and should be interpreted comparatively rather than as functional or species-specific thresholds [35,36,64–66].

Structural connectivity should not be equated with functional connectivity, which depends on species behavior, dispersal capacity, and matrix permeability. Nevertheless, structural indicators provide a widely accepted basis for comparative assessment, where biological or movement data are unavailable and where analyses rely on remotely sensed landscape configuration [35,37,67].

Because explanatory variables were not explicitly quantified and the number of spatial units is limited, fragmentation patterns are interpreted descriptively rather than through formal statistical testing. Previous research suggests that multiple interacting factors, including governance arrangements, accessibility, topography, and historical land-use, may influence landscape structure [35,61,68,69], and evaluating these mechanisms requires dedicated follow-up studies.

The lower classification accuracy observed for El Tunal y Anexos in 2000 is likely related to its greater thematic complexity and heterogeneous spatial configuration, conditions that increase spectral overlap and mixed pixels, particularly in landscapes combining urban areas, agriculture, and exposed soil. Additional uncertainty may also arise from the characteristics of early-generation Landsat TM imagery, as reported in comparable studies [35,44,45].

Navajas exhibited relatively limited variation in fragmentation metrics between 2000 and 2020, despite maintaining a historically fragmented configuration. This pattern suggests temporal persistence in landscape structure rather than recent reorganization. Similar stability has been documented in regions where long-standing fragmentation produces enduring yet heterogeneous spatial mosaics [35,61]. In contrast, Ciénega de los Caballos and El Tunal y Anexos display higher levels of subdivision and edge density.

The increase in areas classified as secondary vegetation in Ciénega de los Caballos and Navajas should be interpreted with caution. This category is derived from spectral and structural characteristics and therefore represents a land-cover condition rather than direct evidence of ecological succession. While similar spatial configurations have been reported in early or intermediate successional contexts in temperate forests of northern Mexico [7,9,22,23,56,70], confirming such trajectories would require field-based vegetation data, phenological information, or multi-temporal modeling, which are beyond the scope of this study. Consequently, the interpretation presented here is comparative and contextual, not demonstrative.

Changes observed in the roads and bare soil class reflect an increase in anthropogenically intervened areas. While road infrastructure has been widely associated with fragmentation and edge effects in other contexts [67,71,72], interpretations regarding the role of roads in this study should be considered indicative rather than causal.

Overall, the observed patterns emphasize the importance of evaluating landscape structure beyond net land-cover change. Spatial metrics reveal reorganization processes with implications for structural connectivity and landscape integrity that would remain undetected through area summaries alone [15,36,60]. Comparable approaches have been applied in restoration and conservation research to contrast alternative landscape conditions without assuming direct causal relationships [73]. These results underscore the value of spatially explicit assessment for understanding variation in forest landscapes of community-managed territories.

5. Conclusions

This study shows that community-owned forest landscapes in southwestern Durango display contrasting spatial configurations and fragmentation patterns between 2000 and 2020.

Rather than extensive forest cover loss, the main differences are expressed through variations in landscape structure, including patch subdivision, edge density, and connectivity.

The findings are consistent with the hypothesis that fragmentation levels differ among ejidos, with patch density, edge density, and connectivity emerging as particularly informative metrics for distinguishing landscape contexts. San Isidro retains the most cohesive and structurally complex configuration, Navajas shows relative stability despite its historically fragmented condition, and Ciénega de los Caballos and El Tunal y Anexos display more heterogeneous and subdivided landscapes. These patterns represent distinct spatial outcomes, although the specific drivers underlying them were not evaluated in this study.

From a methodological perspective, the integrated application of supervised land-use and land-cover classification and landscape metrics derived from FRAGSTATS proved effective for characterizing long-term fragmentation patterns using medium-resolution satellite imagery. This approach captures spatial reorganization processes that are not evident from land-cover area change analysis alone and provides a robust framework for comparative landscape assessment in other community-managed forest regions.

Although there may be causal relationship between fragmentation metrics and specific management or restoration measures, the results provide a spatial baseline that can inform territorial planning and forest management by identifying areas where maintaining or restoring structural connectivity may be prioritized. Future research integrating additional time periods, biophysical variables, and socio-economic information would allow a more comprehensive evaluation of the mechanisms driving fragmentation and their implications for ecosystem services and regional land-use police.

Because the study relies on two years, the results represent differences between landscape configurations observed at specific moments in time. Understanding the mechanism and potential pathways that produced these conditions will require future analyses incorporating denser temporal sampling and complementary explanatory variables.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/environments13020121/s1, Table S1: Description of fragmentation metrics; Table S2: Fragmentation metrics in the four ejidos during 2000 and 2020.

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Abbreviations

The following abbreviations are used in this manuscript:

SMO	Sierra Madre Occidental
BOA	Bottom-of-Atmospheric
DOS1	Dark Object Subtraction
RF	Random forest

BQ	Forest
VS	Secondary vegetation
MX	Xerophytic shrubland
AG	Agriculture
CA	Bodies of Water
CM	Roads and bare soil
ZU	Urban area
PD	Density patch
ED	Density edge
AI	Aggregation index
CONNECT	Connectance index
PA	Producer's accuracy
UA	User's accuracy

Appendix A

Table A1. Confusion matrices and producers' accuracy (PA) and users' accuracy (UA) by land-cover class for the years 2000 and 2020 in the four analyzed ejidos. Source: Authors' own elaboration based on Stehman [53].

2000								
Ciénega de los Caballos								
	AG	BQ	CA	CM	PA/PU			
AG	3	1	0	1	0.60/1			
BQ	0	3	0	0	1/0.75			
CA	0	0	2	0	1/1			
CM	0	0	0	2	1/0.67			
Navajas								
	AG	BQ	CA	CM	PA/PU			
AG	6	0	0	0	1/1			
BQ	0	5	0	1	0.83/1			
CA	0	0	2	0	1/1			
CM	0	0	0	2	1/0.67			
San Isidro								
	AG	BQ	CA	CM	PA/PU			
AG	3	0	0	0	1/1			
BQ	0	2	0	0	1/0.67			
CA	0	0	3	0	1/1			
CM	0	1	0	2	0.67/1			
El Tunal y Anexos								
	AG	BQ	CA	CM	MX	VS	ZU	PA/PU
AG	1	0	0	0	0	0	2	0.33/0.33
BQ	0	5	0	0	1	0	0	0.83/0.83
CA	0	0	3	0	2	0	0	0.60/1
CM	0	0	0	3	0	0	1	0.75/1
MX	1	0	0	0	0	0	0	0/0
VS	0	0	0	0	0	3	0	1/1
ZU	1	1	0	0	0	0	0	0/0

Table A1. *Cont.*

2020								
Ciénega de los Caballos								
	AG	BQ	CA	CM	VS	PA/PU		
AG	3	1	0	1	0.60/1	0.60/1		
BQ	0	3	0	0	1/0.75	1/0.75		
CA	0	0	2	0	1/1	1/1		
CM	0	0	0	2	1/0.67	1/0.67		
VS								
Navajas								
	AG	BQ	CA	CM	VS	PA/PU		
AG	6	0	0	0	1	0.86/1		
BQ	0	4	0	1	0	0.80/1		
CA	0	0	2	0	0	1/1		
CM	0	0	0	2	0	1/0.67		
VS	0	0	0	0	2	1/0.67		
San Isidro								
	AG	BQ	CA	CM	PA/PU			
AG	6	0	0	0	1/1			
BQ	0	5	0	1	0.83/1			
CA	0	0	2	0	1/1			
CM	0	0	0	2	1/0.67			
El Tunal y Anexos								
	AG	BQ	CA	CM	MX	VS	ZU	PA/PU
AG	2	0	0	0	0	0	0	1/0.67
BQ	0	5	0	0	0	0	0	1/1
CA	0	0	3	0	0	0	0	1/1
CM	0	0	0	3	0	2	0	0.60/1
MX	1	0	0	0	3	0	0	0.75/1
VS	0	0	0	0	0	1	0	1/0.33
ZU	0	0	0	0	0	0	3	1/1

Source: Author's own elaboration based on Congalton & Green [51]. AG (Agriculture); BQ (Forest); CA (Bodies of water); CM (Roads and bare soil); MX (Xerophytic shrubland); VS (Secondary vegetation); ZU (Urban area).

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