Geotechnology on the spatial analysis of land use and vegetation changes in natural protected areas of the State of Mexico (2011-2021)

Géotechnologie de l'analyse spatiale des changements d'utilisation des sols et de la végétation dans les zones naturelles protégées de l'État de Mexico (2011-2021)

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 Vol. 35.1 / 2025, 138-152

GEOREVIEW

Received:
22 January 2025

Accepted:
19 May 2025

Published online:
18 June 2025

How to cite this article:
Vilchis, I., Zepeda, M., Garatachia, J. (2025) Geotechnology of the spatial analysis of land use changes and vegetation in natural protected areas of the State of Mexico (2011-2021). Georeview, 35, 1, https://doi.org/10.4316/GEOREVIEW.2025.01.12

ABSTRACT: Land use and vegetation changes in the Natural Protected Areas (NPAs) of the State of Mexico are analyzed from 2011 to 2021, using geotechnical tools based on spatial modeling. The results show that human activities, deforestation, and conversion of primary vegetation to other uses are the main drivers of ecosystem transformation, impacting biodiversity and ecosystem services. Patterns of losses, gains, and systematic transitions between land use and land cover categories were identified and quantified. This analysis highlights the need for an ecosystem-based management approach that takes into account the interactions between biodiversity, ecological processes, and social factors. The study concludes that ecosystem conservation and restoration requires integrated planning to ensure resilience and sustainability for present and future generations.

KEYWORDS: Land use, Protected Natural Areas (NPAs), Vegetation changes, Ecological integrity.

RÉSUMÉ: Les changements d'utilisation des terres et de la végétation dans les zones naturelles protégées (PNA) de l'État du Mexique sont analysés de 2011 à 2021, à l'aide d'outils géotechniques basés sur la modélisation spatiale. Les résultats montrent que les activités humaines, la déforestation et la conversion de la végétation primaire à d'autres usages sont les principaux moteurs de la transformation des écosystèmes, avec un impact sur la biodiversité et les services écosystémiques. Des schémas de pertes, de gains et de transitions systématiques entre les catégories d'utilisation et de couverture des sols ont été identifiés et quantifiés. Cette analyse met en évidence la nécessité d'une approche de gestion basée sur les écosystèmes qui tienne compte des interactions entre la biodiversité, les processus écologiques et les facteurs sociaux. L'étude conclut que la conservation et la restauration des écosystèmes nécessitent une planification intégrée afin de garantir la résilience et la durabilité pour les générations actuelles et futures.

MOTS CLÉS : Utilisation des sols, zones naturelles protégées (PNA), Changements de végétation, Intégrité écologique.

1. Introduction

On a temporal scale, human activities that impact land use are the primary drivers of landscape changes. Some of these changes are triggered by specific management practices, while others result from social, political, and economic forces that govern land use (Medley *et al.,* 1995; Pan *et al.,* 1999). Human-induced temporal changes in landscapes affect both biotic and abiotic processes (Forman, 1995; Farina, 1998). By altering the environment to produce goods and services through land use—referred to as "uso del suelo" in Mexico—humans become the main cause of biodiversity loss and the disruption of ecological functions.

Research on land cover and land use change processes is a topic that bridges various dimensions of global environmental change (Manson, 2006). Consequently, its analysis tends to be interdisciplinary, integrating concepts, data, and methodologies from different fields of knowledge. However, quantitative analyses that highlight the significance of these factors in driving land cover and land use changes vary widely across regions, as their interactions differ in ways that stimulate change and influence interpretations. These analyses aim to identify the spatial distribution and quantify the magnitude of changes in land occupation.

The objective of this study is to identify the main processes of land use and vegetation change, as well as the set of forest formations, within the federally and state-protected natural areas (Áreas Naturales Protegidas, NPAs) of the State of Mexico during the period from 2011 to 2021. The study seeks to explore potential change trends and identify opportunities for more detailed studies of these processes, highlighting losses, gains, total changes, net changes, and exchanges between the evaluated categories. Furthermore, it analyzes the vulnerability of land occupations to being transformed into other categories by calculating persistence indices about gains, losses, and net changes in each category.

2. Study area

The State of Mexico is located at parallels 19°25'-20°20' north latitude and meridians 98°30'-100°30' west longitude, in the center-south of the United Mexican States, covering an area of 2235 1 km², and bordering to the north with the states of Queretaro and Hidalgo; east: Tlaxcal and Puebla; south: Mexico City, Guerrero and Morelos and west: Michoacan and Guerrero. The study area focuses on the federally and state-protected natural areas (Áreas Naturales Protegidas, ANP) of the State of Mexico (see Figure 1) during the period 2011–2021. These areas represent ecosystems of high ecological importance, where biodiversity and ecosystem services are fundamental for environmental stability and human well-being. The ANPs include forests, jungles, scrublands, and other vegetation formations that are essential for conserving biodiversity and regulating key ecological processes.

The study adopts a regional scale and utilizes tools such as Geographic Information Systems (GIS) and cartographic data from the National Institute of Statistics and Geography (INEGI) and the National Forestry Commission (CONAFOR). The methodology involves identifying spatial and temporal changes in land cover and vegetation through map overlays and analyses of transitions between land use categories.

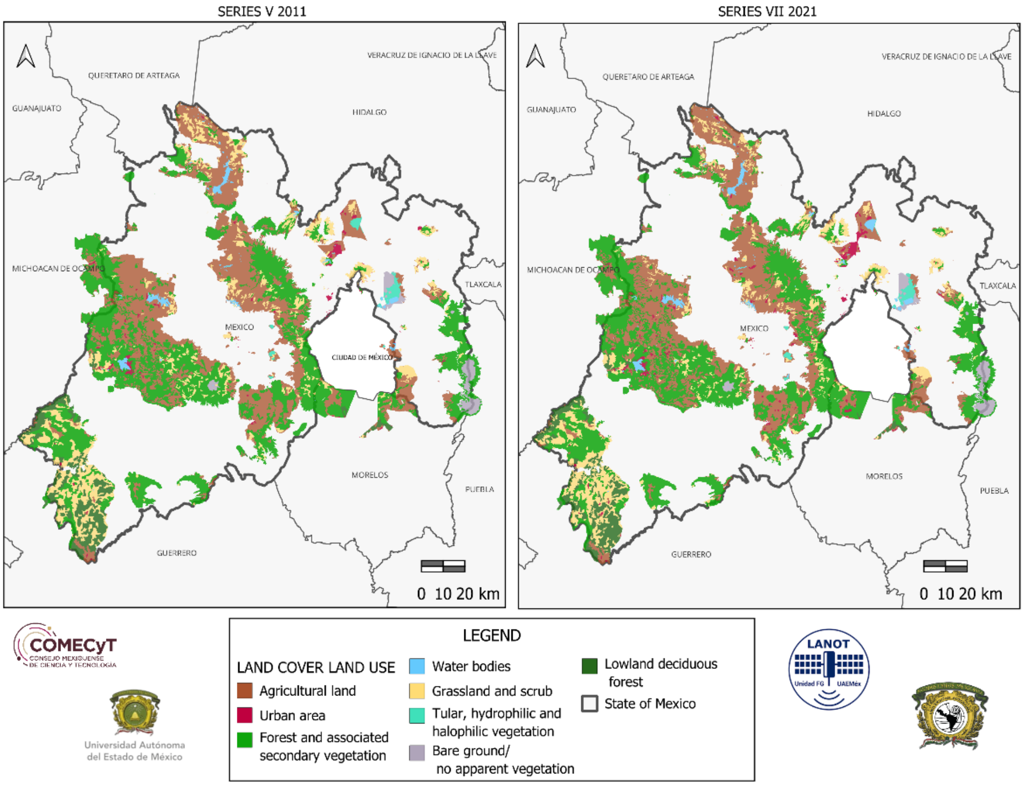

Figure 1 Source: Own elaboration based on INEGI cartographic data Land use and vegetation series V and VII.

Due to its geographical location, the State of Mexico hosts a wide diversity of ecosystems that are subject to anthropogenic pressures such as deforestation, urbanization, and agricultural practices. These activities cause significant changes in the NPAs, affecting their ecological integrity. This analysis aims to understand the dynamics of landscape transformation, identifying change trends and vulnerabilities to promote sustainable management strategies and environmental restoration efforts.

3. Methods

The methodology used consists of both conceptual and methodological components. In the conceptual part, according to Bocco *et al.* (2001), analyzing the process of land use and land cover change involves three main steps:

I. Detection and cartographic and digital interpretation of change,
II. Analysis of land cover and land use change patterns, and
III. Analysis of the causes of land use change.

The method used to determine the change in vegetation and land use involved spatial analysis, which allowed for the calculation of losses, gains, net changes, and exchanges between categories, as well as systematic and random transitions (Pontius *et al.,* 2004). These were based on identifying changes in spatial and thematic components and their relationship in representing space-time processes, carried out through the creation of a cartographic product expressing vegetation changes at time n (2011–2021). That is, the goal was "to express the differences between two temporal moments for the various observation units" (Gutiérrez and Gould, 2000).

The work was carried out at a geographic scale of 1:250,000, a regional level suitable for managing the entire state territory. Below are the methods and techniques used, along with the databases utilized for the work. INEGI's maps (Series V and VII), both in digital format, were used to define land use at the state level. The second product used in this work was the digital dataset of Forest Formations, according to the land use and vegetation classification of INEGI's Series VII, generated by the National Forestry Commission (CONAFOR) in synergy with INEGI. Other data used included the Continuum of Land Use and Vegetation of the State of Mexico, generated by CONAFOR, the state boundary map of the State of Mexico, based on the National Geo-statistical Framework 2023 by INEGI, and the boundaries of the State of Mexico's federally and state-protected Natural Areas (NPAs) (CONANP 2024, CEPANAF 2022).

The spatial analysis was carried out through the development of the following methodological processes, supported by ArcGIS, QGIS, and TerrSet software. Vector files were created (which would serve as base layers for subsequent procedures) corresponding to the geographic datasets of forest formation, land use, and vegetation for the State of Mexico. These files were extracted and homogenized, following the criteria listed below:

1. Boundary adjustment: Given that the input data had different reference systems, a clip operation and definition of the reference system were performed in the software to homogenize the matching boundaries within a single study unit.
2. Selection of aggregation level: The geographic entities of the vector inputs are accompanied by tables containing their corresponding attributes. These were grouped to represent the full range of features within the datasets.
3. Creation of vector files and corresponding maps for each year and series type (See the results section for the maps of 2011 and 2021).

Traditionally, the localization and quantification of land occupation changes are carried out through map overlays and cross-tabulation, generating maps and tables of change that help identify the magnitude and spatial distribution of the change dynamics (Velásquez *et al.,* 2002a; Reyes *et al.,* 2006; Dupuy *et al.,* 2007). Although this technique is widely used in this field of research, cross-tabulation is often not analyzed in depth, as it generally only provides transition matrices, annual change rates, and total surface areas occupied by different land categories at two different time points. To obtain the losses and gains for each category, a cross-tabulation matrix was first constructed with the map of time 1 and time 2 (Figure 2).

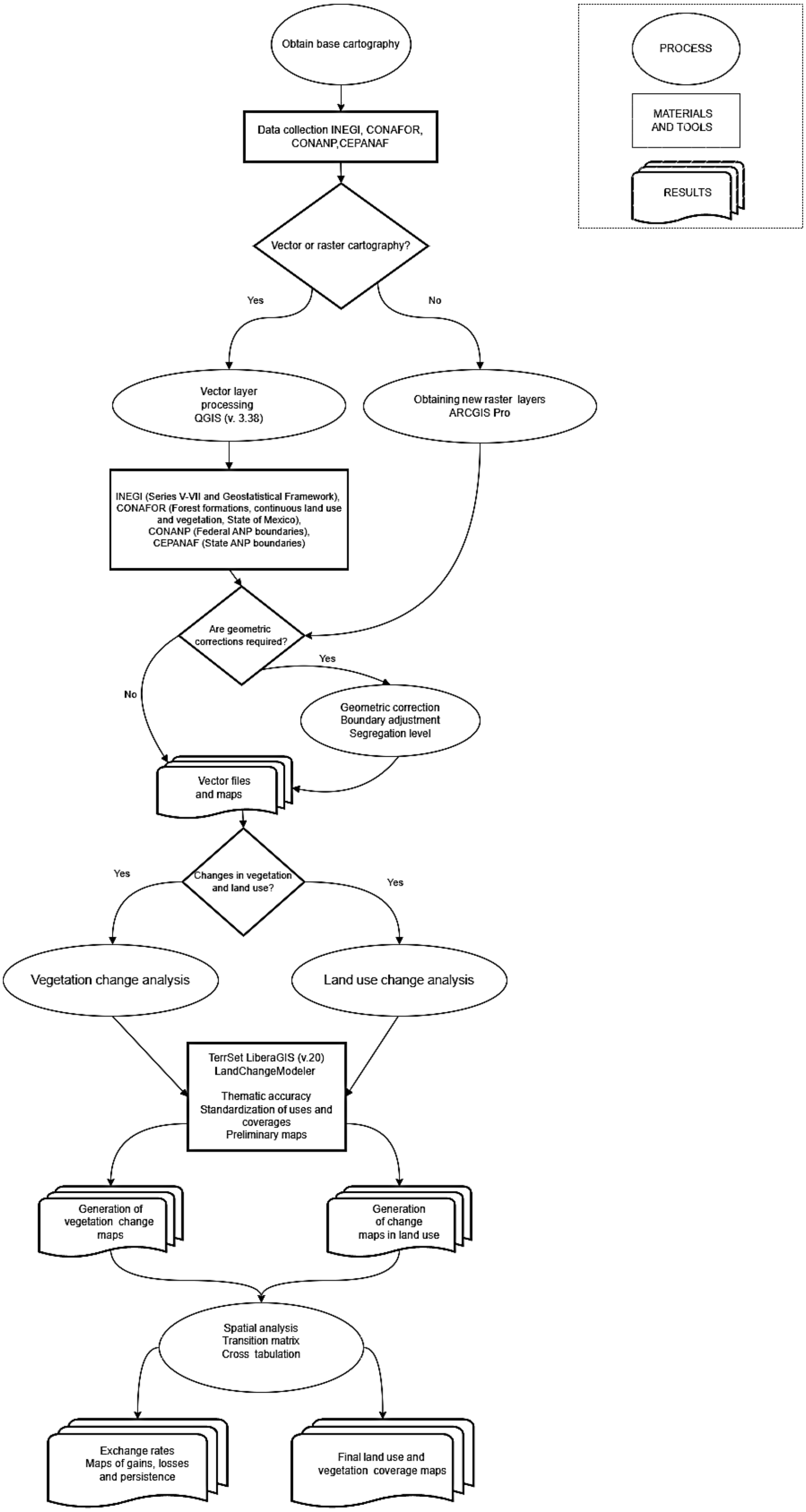

Figure 2 Methodological flow diagram. Source: Author.

Following the methodology of Pontius *et al.,* 2004 (see Figure 3), the total changes, net changes, gains, losses, and exchanges for each category were estimated.

Figure 3 Source: Author, adapted from Pontius *et al.* 2004.

		Tiempo 2 (j)					
		Categoría 1	Categoría 2	Categoría 3	Categoría n	Total T1	Pérdidas
Tiempo 1 (i)	Categoría 1	$P_{jj(11)}$	P_{i1j2}	P_{i1j3}	P_{i1jn}	P_{i1+}	$P_{i+1}-P_{jj(11)}$
	Categoría 2	P_{i2j1}	$P_{jj(22)}$	P_{i2j3}	P_{i2jn}	P_{i2+}	$P_{i+1}-P_{jj(22)}$
	Categoría 3	P_{i3j1}	P_{i3j2}	$P_{jj(33)}$	P_{i3jn}	P_{i3+}	$P_{i+1}-P_{jj(33)}$
	Categoría n	P_{inj1}	P_{inj2}	P_{inj3}	$P_{jj(nn)}$	P_{in+}	$P_{i+1}-P_{jj(nn)}$
	Total T2	P_{+j1}	P_{+j2}	P_{+j3}	P_{+jn}	1	
	Ganancias	$P_{+j1}-P_{jj(11)}$	$P_{+j1}-P_{jj(22)}$	$P_{+j1}-P_{jj(33)}$	$P_{+j1}-P_{jj(nn)}$		

The persistence indices proposed by Braimoh (2006) were used to evaluate the characteristics of stable areas about gains, losses, and net changes (see Table 1). The gain-to-persistence index is calculated as follows:

Table 1 Persistence index. Source: Author, adapted from Braimoh 2006.

	Description	Formula	Where
Gains	Are the differences between the total and persistence of the category described in each column	$Gij = P{+}j - Pjj$	Gij represents the values of the proportion of the landscape experiencing net gains in category j between (Q1) 2011 and (Q2) 2021.
Losses	Are the differences between the total and the persistence of the category described in each column	$Lij = Pj{+} - Pjj$	Lij represents the values of the proportion of the landscape experiencing net losses of categories i between (time one) '2011' and (time two) '2021'
Total change	These are all the changes that occurred in each category individually within the landscape	$Gij + Lij$	Equals the sum of the gains and losses of each category respectively

Inter-category transitions were calculated following the methodological steps proposed by Braimoh (2006), which somewhat systematized the approach suggested by Pontius *et al.,*2004. The diagram derived from systematic transitions is presented in the results section. Using the TERRSET liberaGIS software by Clark Labs, the vector files were rasterized, assigning each raster file its corresponding table with defined attributes using an identifier. For each series, a total of eight categories were counted, which are shown in Table 2, along with the total surface area in hectares for each category according to land use and land cover type. The procedure is illustrated with the following images.

Table 2 Area in hectares, number of categories and type of land use, and land cover of the *.rst files.

Category	Land cover/Land use	Surface (Ha)	
		2011	2021
0	Background	3,515,136	3,515,136
1	Agricultural land	352,542	340,985
2	Urban area	9,510	16,863
3	Forest and associated secondary vegetation	422,575	434,235
4	Water bodies	13,275	15,307
5	Grassland and scrub	137,262	128,845
6	Tular, hydrophilic and halophilic vegetation	8,333	6,777
7	Bare ground/ no apparent vegetation	19,138	19,139
8	Lowland deciduous forest	53,285	53,769

The model generation is based on importing vector elements into the software, utilizing the Land Change Modeler tool, which generates raster files and their corresponding attribute tables. This process aims to differentiate between the various types of maps produced, which will serve as the foundation for interpreting the changes.

The overlay of maps is commonly known as the "map overlay" process in Geographic Information Systems (GIS). In this study, this procedure is considered the most crucial, as it generated the cartographic product that enabled the spatial identification of vegetation and land use changes. This procedure involved manipulating the geographic entities of the land use and vegetation maps, resulting in a map that expressed the fusion of the geometry of both products, along with the new attributes used to identify changes in vegetation and land use.

Using the attributes of the resulting cover, a database was created for each type of Natural Protected Area (NPAs) (Federal-State), forest formation type, and land use. This frequency or combination table was used to identify the transition changes that occurred between periods and to total the surface area (in hectares) occupied by each category. This database was used to construct a transition matrix to analyze change patterns.

To analyze the main land use and vegetation changes at a regional level for the period 2011–2021, a random transition of land occupation categories was carried out. This examined whether categories gained area from other categories in proportion to the size of categories that had experienced losses, or whether the loss of a category was proportional to the size of categories that had gained area. It was observed that quotient values greater than 1 indicated a high tendency for a category to transition to another category rather than persist. However, any significant difference in these proportions represents a systematic landscape transition (Braimoh, 2006). According to Alo and Pontius (2008), a transition is considered systematic if the observed transition differs from the expected transition based on a random process. Therefore, the calculation of systematic transitions is made based on gains and losses separately.

Additionally, inter-category transitions were calculated following the methodological steps proposed by Braimoh (2006), which systematized the approach suggested by Pontius *et al.*, 2004. The systematic transitions were considered as change processes represented in a transition matrix for each type of vegetation during the analyzed period. As for net change, exchanges, and total change, the land occupation categories for time 1 and time 2 were analyzed, generating a tabulation of hectares and their percentages of losses, gains, total change, net change, and exchanges for these categories.

4. Results and discussion

In this analysis, eight land cover categories were evaluated for both periods 2011 (series V) and 2021 (series VII) (see Table 2), in all natural protected areas, changes within each category were described and quantified, showing a summary matrix of changes in hectares and percentages of loss, gain, net change, change, and total change.

The results show that of the 1,015,920 hectares of total decreed surface of the natural protected areas (see Table 3), speaking in terms of percentage, it is observed that the areas of forest and its associated secondary vegetation for both times are the most representative category, since for the year 2011 it represents 42% (422,575 Ha), while for the year 2021 this coverage represents 43% (434, 235 Ha), showing a slight increase in both percentage and surface area.

Agricultural land, on the other side, is the land use both in terms of surface area and percentage with the widest spatial coverage, for the year 2011 it represented an area of 352,542 hectares (35%), while for the year 2021, it shows a decrease with an area of 340,985 hectares, corresponding to 34% of the total surface area. The coverage corresponding to grassland and scrubland areas is the third category with the greatest change with an average percentage of 13%, equivalent to an average surface area of 133,054 Ha (Chart 1).

Table 3 Summary of the matrix of changes at the level of vegetation type (hectares and percentage).

Category	Total 2011	%	Total 2021	%	Gains	%	Losses	%	Total change	%
Agricultural land	352,542	35%	340,985	34%	12,163	18%	23,721	36%	35,884	27%
Urban area	9,510	1%	16,863	2%	7,836	12%	483	1%	8,319	6%
Forest and associated secondary vegetation	422,575	42%	434,235	43%	22,168	34%	10,509	16%	32,677	25%
Water bodies	13,275	1%	15,307	2%	2,261	3%	229	0%	2,490	2%
Grassland and scrub	137,262	14%	128,845	13%	14,573	22%	22,990	35%	37,563	28%
Tular, hydrophilic and halophilic vegetation	8,333	1%	6,777	1%	427	1%	1,983	3%	2,410	2%
Bare ground/ no apparent vegetation	19,138	2%	19,139	2%	733	1%	731	1%	1,464	1%
Lowland deciduous forest	53,285	5%	53,769	5%	5,898	9%	5,414	8%	11,312	9%
Totals	**1,015,920**	**100%**	**1,015,920**	**100%**	**66,059**	**100%**	**66,060**	**100%**	**132,119**	**100%**

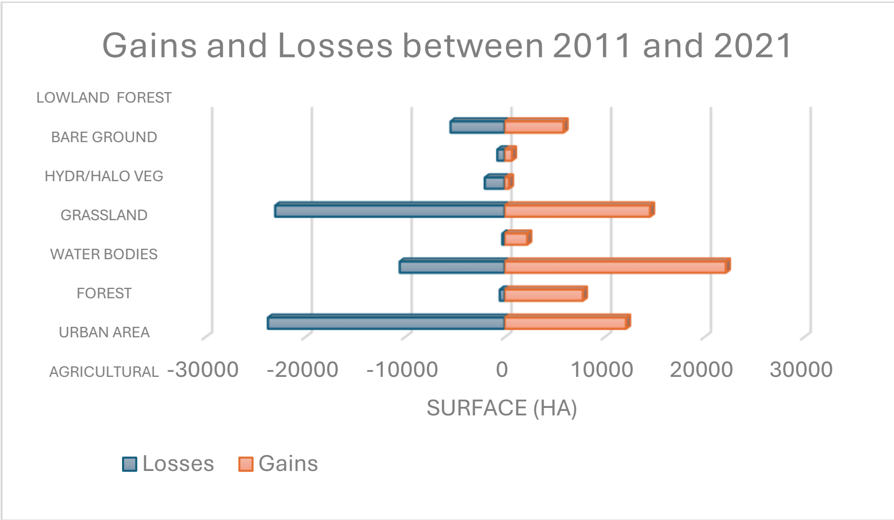

Chart 1 Gains and losses by data category of the area in hectares of the land use and land cover series V and VII.

The analysis of these categories establishes that the loss/gain (P/G) and gain/loss (G/L) ratios of these categories are greater or close to 1, respectively. The categories of forest and secondary vegetation are more vulnerable to change in their natural vocation due to an increase in the imbalance and alteration of the ecological succession process, which evokes them to lose more surface area, even though the cover of forest and associated secondary vegetation has been gaining more territory than the other categories, grassland/scrubland and agriculture are transitional covers that generate a process of change that in time can become irreversible or reversible depending on the natural vocation of the site and the anthropic or natural pressures that may arise in specific areas (Chart 2). These changes have been modeled and are shown in Figure 4, to understand and discern more clearly these gains, losses, and transitions.

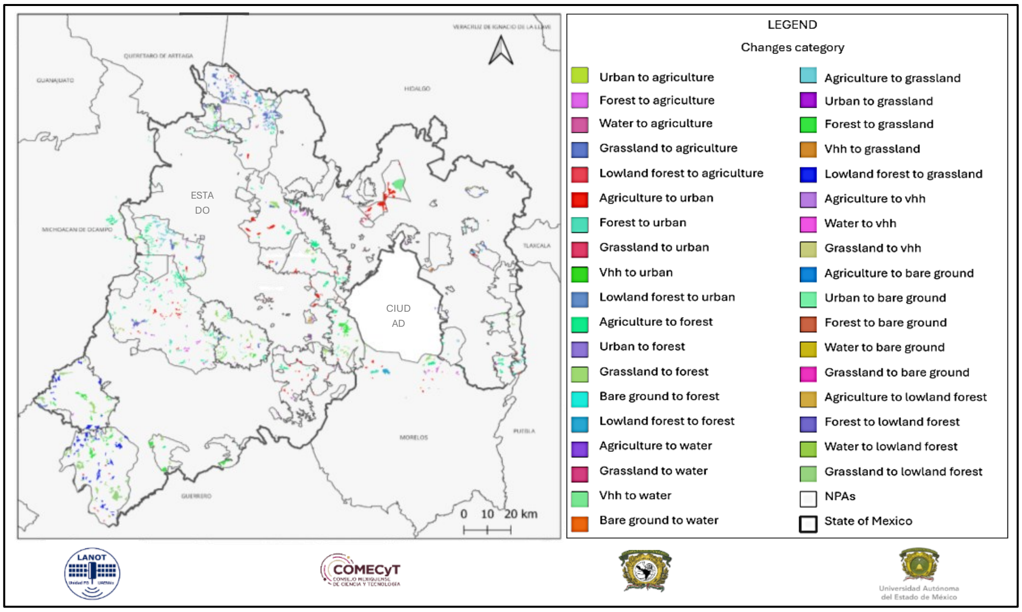

Figure 4 Map of land cover change, based on analysis of change between categories.

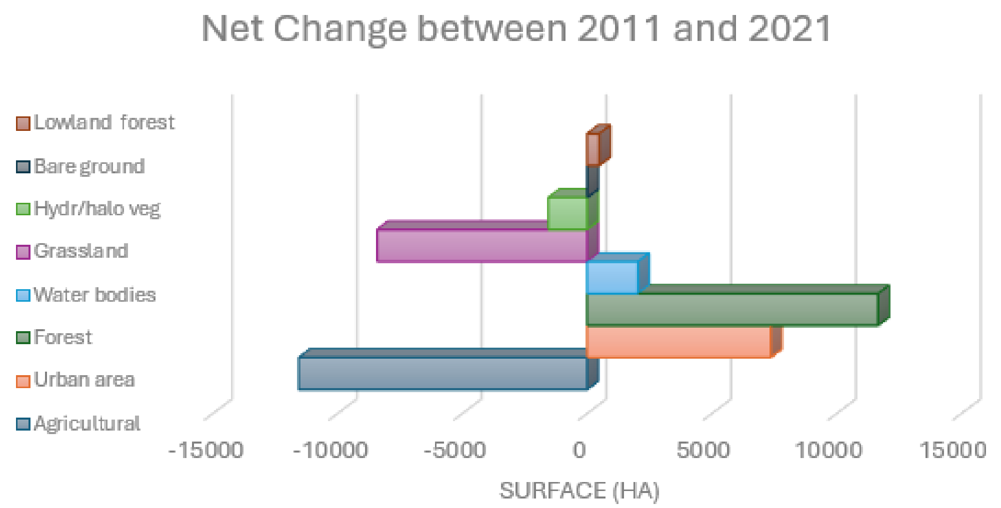

Chart 2 Net change by data category of the area in hectares of the land use and land cover series V and VII.

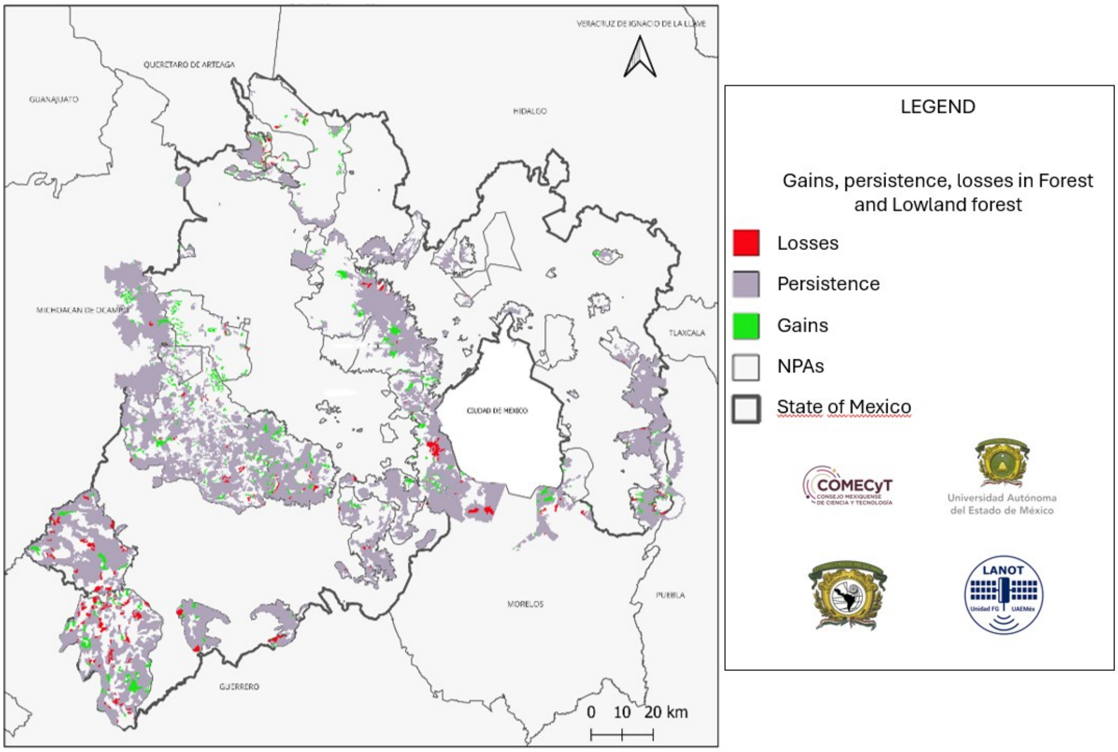

Figure 5 Map of gains, persistence, and losses in forest and lowland forest cover change, based on analysis of change between categories

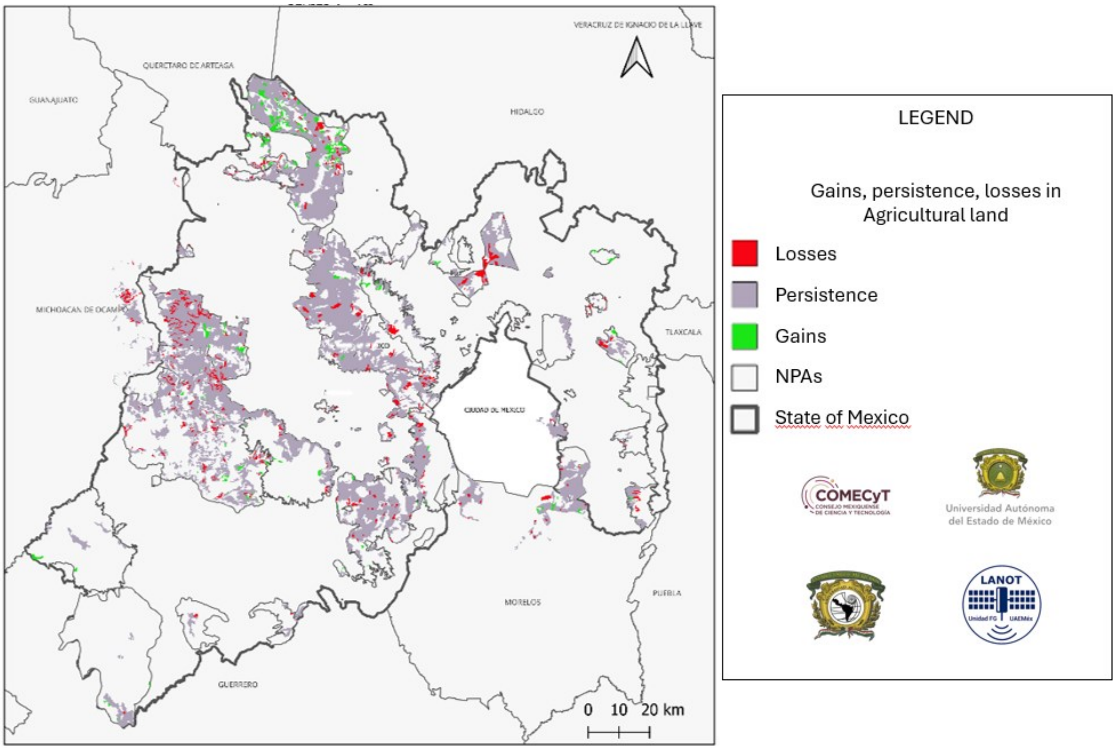

Figure 6 Map of gains, persistence, and losses in agricultural land cover change, based on analysis of change between categories.

Chart 3 and 4 Gains, losses, and persistence of the two most representative data categories, Forest and Lowland deciduous forest of the land use and land cover series V and VII.

The two most important areas derived from the previous analyses were analyzed and modeled, grouping the forest cover (with its respective associated secondary vegetation) with the low deciduous forest cover as a single forest entity; the second category that was considered by the area of land occupation was agricultural land use (Chart 3,4). This was done to be able to mathematically and cartographically detect the evaluation and determination of their values and thus detect employing maps and graphs the area and location of losses, persistence, and gains of both coverages. It was found that the forest areas present in the natural protected areas have increased over time, probably as a result of various recovery processes. The opposite is true of the agricultural areas, which, despite their size, have not been extensively occupied within the forest areas (Figure 5-6).

The analysis of land use change and vegetation allows us to evaluate the effects of ecosystem losses on the environment, which sometimes have a negative impact, sometimes, causing a decrease in their associated biodiversity, weakening ecosystems and reducing their ability to function; Air pollution hinders the absorption of carbon dioxide, contributing to climate change, while water and soil contamination has an impact on the loss of vegetation strata due to the lack of retention of elemental nutrients, causing a decrease in the infiltration capacity of the subsoil as well as a decrease in natural watercourses, These are often caused by industrial, agricultural and urban activities, with serious consequences for both human health and wildlife, reducing productivity and the ability of ecosystems to adapt to changes such as erosion, desertification, and soil degradation, preventing sustainable development, affecting their resilience and generating habitat loss.

It is not easy to have a clear understanding of what is happening in ecosystems. Traditionally, the concept of "deforestation" has been used to indicate the loss of forest ecosystems; however, this concept is limited to those ecosystems and only considers the loss of the dominant element: trees. Although the greatest threat to ecological integrity comes from human impacts, deforestation, fragmentation, and habitat loss are the main factors driving the loss of ecological integrity in a region. This leads to the disintegration of geographic patterns of large, continuous areas that are divided into smaller blocks due to the introduction of new elements or structures (such as the construction of roads, clearing for agriculture, or urbanization), which alter the prevailing functions in the natural habitat. This makes it difficult for species to survive and thrive as they are forced to adapt to certain remnant areas.

Protected natural areas represent a proportion of remaining natural surfaces that have not been transformed by human activity. These areas hold significant ecological value to the extent that they maintain the ability to self-organize, remain stable, and preserve their natural condition (Karen 1998, Riitters *et al.,* 2002, Hendriks *et al.,* 2009, Caniani *et al.,* 2016).

The extent of natural areas is measured by the coverage of natural vegetation (primary and secondary: forests, jungles, scrublands, grasslands, mangroves) and the available habitat, based on the land use and vegetation map of INEGI and the forest area estimates from "Global Forest Watch" (Hansen *et al.,* 2013). Thus, changes in the area occupied by each type of vegetation and land use can be grouped into two main categories: those caused by human activity and those that occur due to the natural dynamics of ecosystems.

5. Conclusion

This study has confirmed that the Natural Protected Areas (NPAs) of the State of Mexico are undergoing significant changes that directly impact land use covers in the period from 2011 to 2021. These types of loss and change trends are most evident in the natural areas located in the southwestern and central region of the State of Mexico.

It can be observed that the polygons of forested massifs exhibit a high level of ecological integrity, not only in terms of ecosystem services but also in the ability to assess ecological integration within the protected natural areas.

Since ecosystems are dynamic and their composition and structure change over time, disturbances such as fires, droughts, floods, and pest outbreaks periodically occur, substantially altering forest ecosystems and other communities. These disturbances generate disturbance regimes, which vary from region to region depending on climatic conditions.

The primary disturbance regime and its key processes of change are driven by anthropogenic activity, primarily the conversion of primary vegetation to secondary tree cover or shrubland. This is likely due to activities such as timber extraction from forests, grazing, and seasonal agriculture stemming from itinerant cropping systems, along with other activities that transform ecosystems into successional states.

Therefore, natural resource management must adopt an ecosystemic approach to maintain and improve the ecosystems that provide goods and services for both present and future generations. This should consider the interactions between various levels of biodiversity (genes, species, populations, ecosystems, landscapes), include an appropriate spatial scale that encompasses relevant ecological processes, define ecological boundaries rather than administrative ones, and involve societies as part of the ecosystem. This approach should also take into account an appropriate temporal scale that allows for the conservation and restoration of ecosystems and their synergies in planning and inter-institutional government coordination, alongside communication with society.

The current use of geotechnologies and the results derived from this series of derived from this series of land use change analyses, are being considered for implementation considered to be implemented within a geospatial platform for consultation, in order to to increase its access and dissemination.

Acknowledgments

To the Mexican Council of Science and Technology (COMECYT), for the scholarship awarded to MSc. Iris Sarai Vilchis Garcia within the framework of the “Researchers COMECYT 2024”. To the Universidad Autónoma del Estado de México, through the Secretary of Research and Advanced Studies.

To the National Laboratory of Earth Observation (LANOT). Faculty of Geography Unit, Autonomous University of the State of Mexico. For the technological support provided for the development of the research.

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