Article

Diagnosis of the use of soil and vegetation in the microbasin Tula, Mexico

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Abstract

Changes in land use and plant cover are the main component in global, regional and local deterioration, and have been documented as the second global environmental problem. In Mexico, there are few planning policies in the territorial development of the municipalities and a poor decision making in the management of natural resources, an example of which is the Tula microbasin. The objective of the research work was to diagnose the current situation and the changes in the coverage and land use of the Tula microbasin, through spatial analysis, to know its main processes of change, with the purpose of designing strategies that allow sustainable management of its natural resources. The spatial analysis was carried out, based on Landsat satellite images (1992, 2000 and 2017) using geographic information systems. To identify the changes, cross-tabulations were applied and exchange rates were estimated. In the analyzed period (25 years), the agricultural area increased 33% and a loss of forest area of 22%. Exchange rates and likelihood of permanence indicated that continuing with the current trend will continue to increase agricultural areas and bodies of water, as well as the abandonment of some areas due to their low productivity.

Keywords: geographic information systems, land use change, transition matrices, vegetation.

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Introduction

The change in land use and vegetation cover are the main component in the global, regional and local deterioration, and have been documented as the second global environmental problem (Xiao *et al*., 2006). For decades, human activities and the demand for goods and services have generated pressure on natural resources with large impacts, most of them negative, which are difficult to reverse (Rosete *et al*., 2008; Reynoso *et al*., 2015). Mexico is a country with high biological and cultural diversity, with high rates of deforestation and exploitation of natural resources (FAO, 2016; Sahagún-Sánchez and Reyes-Hernández, 2018). The loss and degradation of vegetation in a basin or microbasin, as well as the speed at which these changes occur alter the functions and the proper functioning of the exchange of matter and energy (Cuevas *et al*., 2011).

Consequently, it is necessary to analyze changes in plant cover to develop strategies that mitigate the negative impact on natural resources (Leija-Loredo *et al*., 2018). In the last decades, the fourteen municipalities that make up the Tula microbasin have had an annual average population growth of 2%, reaching a population of 288 196 in 2010 and an approximate density of 278 km^{-2} inhabitants (INEGI, 2013). The population density increased from 205 to 236 km^{-2} inhabitants in the period from 1990 to 2000 (INEGI, 1990; INEGI, 2000) and with it the demand for goods and services by society, as well as the problems associated with the change of use soil due to pressure on natural resources. The growth of urban stain in the municipality has been disorderly, expanding into areas of agricultural, forestry and grassland uses.

The extraction of construction materials (mining use) has increased in agricultural, forestry and areas near urban centers (INEGI, 2017a; INEGI, 2017b; INEGI, 2017c). The foregoing is the product of insufficient planning policies in the territorial development of municipalities, and of poor decision making in the management of natural resources. For all this, the need to analyze the changes that have taken place in the Tula microbasin, in addition, is a politically complex territory because it is made up of three states, which implies different state policies.

Therefore, this research work aims to diagnose the current situation of changes in the coverage and land use of the Tula microbasin, Mexico through spatial analysis, to know its main processes of change and thus contribute to the understanding of the system, with the purpose of designing strategies that allow a sustainable management of its natural resources.

Materials and methods

Study area

The Tula microbasin is framed within the geographical coordinates: 19° 55’ 31.05’’ and 19° 34’ 28.74’’ north latitude and 98° 39’ 59’’ and 98° 28’ 16.39’’ west latitude (Figure 1), has an area of 103 766 ha and covers the territory of the municipalities: Calpulalpan, Sanctorum de Lázaro Cárdenas, Benito Juárez, Almoloya, Apan, Emiliano Zapata, Singuilucan, Tepeapulco, Villa de Tezontepec, Tlanalapa and Zempoala of the state of Hidalgo, Axapusco and Nopaltepec of the State of Mexico and Temacalpa of the State of Tlaxcala. In addition, it is immersed in the Panuco river basin, within the physiographic province of the Neovolcanic axis. It has an altitude range of 2 333 to 3 223 meters above sea level, the average annual rainfall is 600 mm and the predominant soil types are Feozem, Cambisol, Litosol, Regosol and Vertisol (INEGI, 2017a; INEGI, 2017b; INEGI, 2017c), there are different types of vegetation, among which are the tascate forest, pine forest, oak forest, crasicaule thicket (INEGI, 2017d).

Figure 1. Location of the study area.

According to López *et al*. (2001), in order to analyze the process of change of land use and coverage, it is necessary to apply three stages: a) cartographic and digital change and interpretation of change; b) analysis of land cover change and land use patterns; and c) analysis of causes of change.

Generation of land use cartographic

The generation of cartography corresponds to the first stage to perform the change process analysis. According to Bautista *et al*. (2011) At this stage it is necessary to select and acquire the satellite images that will be worked on, then they must be performed a standard digital treatment (geometric, radiometric and atmospheric correction). Then the image transformation follows, where the image is classified, from the association of elements observed in the image to certain thematic categories, prior to classification, the classification system must be determined and the evaluation of the geographical digital bases must be carried out (Rosete *et al*., 2008; Bautista *et al*., 2011).

The generation of land cover and land use mapping in this study consisted of: a) selecting three satellite images: Landsat-5 TM (12/04/1992), Landsat-7 ETM + (02/12/2000) and Landsat -8 Oli Tirs (11/23/2017) with a resolution of 30 m and an L1TP processing level; and b) correct radiometrically and atmospheric these by means of the Atcor extension 2. Workstation of the Erdas Imagine program, to ensure a standardized comparison of data between them (Chander *et al*., 2009; Vargas-Sanabria and Campos-Vargas, 2018); c) determine the training areas where eight study categories corresponding to land cover were established: body of water, urban area, forest area, temporary agriculture, permanent agriculture, crasicaule scrubland, secondary vegetation and area without apparent vegetation (Velázquez *et al*., 2002); d) apply the Maximum Likelihood supervised classification algorithm to each image, in the ArcMap 10.5 software (Vargas-Sanabria and Campos-Vargas, 2018); and e) validate the classification of plant cover and land use for 1992 and 2000; through its comparison against the layers of land and vegetation use of the INEGI series II and III, respectively.

While to validate the coverage of 2017, this was done by establishing control points within the study area, using Google Earth® (Earth Google, 2018) and field trips to these points, with the purpose of corroborating the type of coverage corresponding to the training site (Torres *et al*., 2018). The pixel size of each of the land use maps was then homogenized at 30 m: 1992, 2000 and 2017 and reclassified based on the hierarchical system proposed by Velázquez *et al*. (2002) (Table 1) to achieve a hierarchical and homogeneous classification system.

Table 1. Hierarchical land use classification system.

Number	Class	Type of vegetation and land use
1	CA	Water body
2	ZU	Urban zone
3	AF	Forest area (low, medium and high density) and secondary vegetation
4	AA	Temporary and permanent agriculture
5	ASVA	Area without apparent vegetation (scrubland, mines, eroded areas)

CA= body of water; ZU= urban area; AF= forest area; AA= agricultural area; ASVA= area without apparent vegetation.

Transition matrix construction

For the stage of analysis of patterns of change of land cover and land use, matrices of transition matrices were constructed, which are described as tables with symmetrical arrangements that contain in the rows the types of vegetation and land uses in the first year or year base and in the columns these same types but of the second year. Each cell of the main diagonal of said matrix represents the area in hectares of each kind of vegetation cover and land use that remained in the same category during the period considered, while in the rest of the cells the surface area of a given coverage or type of land use that passed to another category (Dirzo and Masera, 1996 cited by López *et al*., 2001) which allows to understand the dynamics of change in land cover and land use at local and regional level.

From the shapefile maps obtained from the reclassification of vegetation cover and land use of 1992, 2000 and 2017, the transition matrices were constructed, performing the following steps: a) generate transition matrices between the different categories through a cross tabulation (Eastman, 2012), from the TerrSet Crosstab module, for the periods: 1992-2000 and 2000-2017; b) develop probability of belonging matrices for each class in each period with the transition matrices; these matrices are generated by dividing each of the cells of the transition matrix by the total surface area of the analyzed class (Vega *et al*., 2007); and c) estimate the probability of belonging (P_{ij}) of each class of the matrix, which is proportional to the remaining area of the same class between year 1 and year 2. Its mathematical expression (Sánchez *et al*., 2004) is:

$$Pij= \frac{S_{ij} \text{ (year 1)}}{S_j \text{ (years 2)}}$$

Where: S_{ij} = surface of element ij of the transition matrix of land cover and use in year 1; S_j = area of land use class j in year 2; and $\sum Pij = 1$ for each land use category j.

According to Sánchez *et al*. (2004), the probability of belonging is interpreted as follows: 0-33% (low), 34-66% (medium) and 67-100% (high).

Exchange rates

The processes of land use change are determined with the map resulting from the cross-tabulation and are classified: unchanged, conserved, urbanization, transition, anthropic use, deforested, degraded and by productive activity (Rosete *et al*., 2008; Cuevas *et al*., 2011). These were estimated using the equation proposed by (FAO, 1996):

$$\delta_n=\left(\frac{S_2}{S_1}\right)^{1/n} -1$$

Where: δ_n= average annual exchange rate for class i in the nth period evaluated (to express in (%) multiply by 100); S_1= total area of class i in period 1; S_2= total area of class i between period 2, and n = number of years between the two periods evaluated.

Results and discussion

Table 2 shows the results obtained from land use areas by category, for each of the years: 1992, 2000 and 2017. Of the 103 766.48 hectares that make up the total area under study, in 1992, the use of land was mainly dominated by the forest and agricultural area, with about 80%, while the remaining area was occupied by bodies of water, urban areas and areas without apparent vegetation, with about 20%. However, from the year 2000 with respect to the year 1992, the forest area significantly decreased its area, by about 55%, in contrast the agricultural area increased by approximately 84%.

The rest of the surface was reduced by 25%. Deforestation was mainly due to the absence of laws regulating forest use at any level of government and the lack of policies to reforest and restore degraded forest areas (PEF, 1989; PEF, 1995; Merino-Pérez and Segura-Wamholtz, 2002). Finally, the change in land use in 2017 with respect to 2000, the agricultural area increased the same as in the previous period, only now in 7%, this trend coincides with that set forth by Cuevas *et al*. (2011), who mention that agriculture is the activity that incorporates more hectares. Regarding the forest area, it presented an increase of 2%, but the area without apparent vegetation decreased 178%.

The forest increase is due to the fact that from the 2000-2006 six-year period, modifications were made, starting with the decentralization of the National Forestry Commission (CONAFOR) in 2001, which promoted reforestation programs; in addition, in 2003, the Law on Sustainable Forest Development (SEMARNAT, 2003; Del Angel-Mobarak, 2012) entered into application. Likewise, the largest increase in the reforested area occurred in the territory of the state of Hidalgo, due on the one hand, the implementation of state policies, among which the Law on Sustainable Forest Development for Hidalgo, which entered into application in 2006 and decree protected natural areas of state competition, such as the state reserve Cerros La Paila-El Xihuingo, in 2009, located within the Tula microbasin, on the other, the multiple annual reforestations carried out in this state (SADR, 2005; GEH, 2006) .

Additionally, in Table 2, it also shows the exchange rate both in hectares and in percentage by type of vegetation cover, for the period 1992-2017. In other words, the classes: forest area, urban area and area without vegetation decreased by 23 077.95, 334.14 and 11 300.64 hectares, equivalent to 22.2, 0.3 and 10.9%, respectively. Meanwhile, agricultural area and bodies of water increased by 34 639.14 and 68.88 hectares, equivalent to 33.4 and 0.1%, respectively.

Table 2. Land use surfaces by category for the years: 1992, 2000, 2017.

Class	1992		2000		2017		1992-2017	
	ha	(%)	ha	(%)	ha	(%)	ha	(%)
CA	652.48	0.6	472.95	0.5	722.36	0.7	+68.88	+0.1
ZU	6 244.63	6	6 638.49	6.4	5 911.49	5.7	-334.14	-0.3
AF	46 339.27	44.7	21 023.28	20.3	23 261.82	22.4	-23 077.95	-22.2
AA	35 793.97	34.5	66 102.39	63.7	70 433.61	67.9	+34 639.14	+33.4
ASVA	14 736.13	14.2	9 528.66	9.2	3 436.49	3.3	-11 300.64	-10.9
Total	103 766.48	100	103 766.77	100.1	103 766.77	100		

CA= body of water; ZU= urban area; AF= forest area; AA= agricultural area; ASVA= area without apparent vegetation.

Transitions of land use change

Table 3 and Figure 2 show the results obtained from the transition matrices and the probabilities of membership between categories, for the period from 1992 to 2000. The 54% $\left(\frac{416.57+2499.89+\cdots+3509.96}{103766.48}=53.47\%\right)$ of the vegetation cover of the Tula microbasin remained unchanged, while the remaining 46% presented some change (Table 3). According to Figure 3, of 100% of the agricultural area that was in 1992, 89% $\left(\frac{31781.21}{35793.97}=88.79\%\right)$ remained in 2000 being the only category with high probability of permanence and 11% changed to zone urban $\left(\frac{936.05}{35793.97}=2.62\%\right)$, forest area $\left(\frac{1213.07}{35793.97}=3.39\%\right)$, abandoned area or without vegetation $\left(\frac{1855.76}{35793.97}=5.18\%\right)$ and bodies of water $\left(\frac{7.88}{35793.97}=0.02\%\right)$.

Table 3. Transition matrix for the 1992-2000 period.

Surface (ha)	2000					
1992	CA	ZU	AF	AA	ASVA	Total
CA	416.57	37.49	36.77	124.61	37.04	652.48
ZU	9.86	2 499.89	386.33	2 361.74	986.81	6 244.63
AF	18.14	1 962.05	17 271.5	23 950.4	3 137.18	46 339.27
AA	7.88	936.05	1 213.07	31 781.21	1 855.76	35 793.97
ASVA	16.88	1 199.84	2 117.57	7 891.88	3 509.96	14 736.13
Total	469.33	6 635.32	21 025.24	66 109.84	9 526.75	103 766.48

CA= body of water; ZU= urban area; AF= forest area; AA= agricultural area; ASVA= area without apparent vegetation.

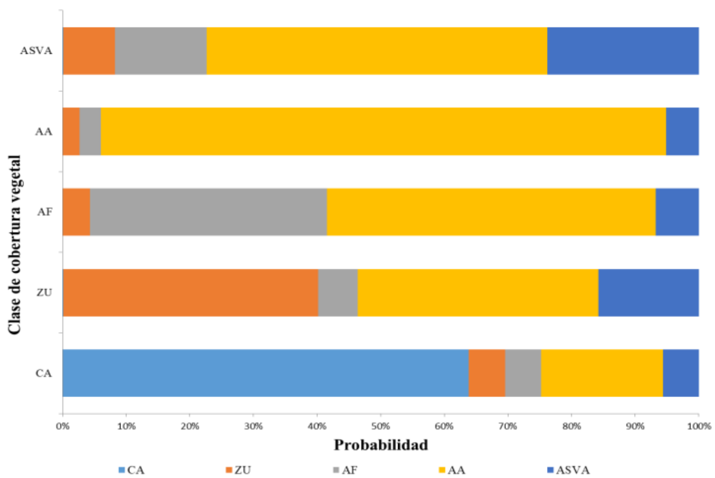

Figure 2. Probability of permanence of land use from 1992-2000.

In contrast, the forest area was the coverage that had the greatest change in surface area with 63% and only retained 37% of it. It should be noted that 52% $\left(\frac{23950.4}{46339.27}=51.68\%\right)$ of the forest area passed to agricultural area; which shows that agriculture is an activity that replaces other categories quickly (Sánchez *et al*., 2009; Cuevas *et al*., 2011), because the population demands goods and services, plays an important role in the change of use of soil, since with increasing population the pressure on natural resources also increases generating negative impacts such as deforestation (Rosete-Verges *et al*., 2014).

It is also important to mention that 4% of the forest area changed to urban area $\left(\frac{1962.05}{46339.27}=4.23\%\right)$, this is because the population went from 213 208 inhabitants in 1990 to 245 112 inhabitants by the year 2000 according to figures reported by (INEGI, 1990; INEGI, 2000). Regarding the urban area, 100% only remained 40% $\left(\frac{2499.89}{6244.63}=40.03\%\right)$, 60% change.

38% $\left(\frac{2361.74}{6244.63}=37.82\%\right)$ went to agricultural area and 16% $\left(\frac{986.81}{6244.63}=15.8\%\right)$ to area without vegetation or abandoned. This is due to the fact that the number of people increases and more goods are required to cover monetary needs, and in that decade according to Cruz (2018) there was an increase in return migration from the United States of America to the state of Hidalgo. On the other hand, areas without vegetation increase because they are abandoned due to the decline in agricultural production. During the period 2000 to 2017, 76% $\left(\frac{367.42+2739.10+\cdots+891.49}{103766.48}=75.67\%\right)$ of the total area of the basin remained unchanged, while the remaining 24% presented some change (Table 4).

Table 4. Transition matrix 2000-2017.

Surface (ha)	2017 layer					
2000	CA	ZU	AF	AA	ASVA	Total
CA	367.42	20.74	46.02	30.09	8.68	472.95
ZU	30.46	2 739.1	695.91	3 041.85	131.17	6 638.49
AF	24.16	292.36	16 253.85	3 660.42	792.49	21 023.28
AA	256.36	1 906.24	4057.5	58 269.63	1 612.66	66 102.39
ASVA	43.96	953.05	2 208.54	5431.62	891.49	9 528.66
Total	722.36	5 911.49	23 261.82	70 433.61	3 436.49	103 766.48

CA= body of water; ZU= urban area; AF= forest area; AA= agricultural area; ASVA= area without apparent vegetation.

According to the classification of Sánchez *et al*. (2003), the categories: body of water $\left(\frac{367.42}{472.95}=77.68\%\right)$, forest area $\left(\frac{16253.85}{21023.28}=77.31\%\right)$ and agricultural area $\left(\frac{58269.63}{66102.39}=88.15\%\right)$ are considered with high permanence probability; while the categories: urban area $\left(\frac{2739.10}{6638.49}=41.26\%\right)$ and areas without apparent vegetation $\left(\frac{891.49}{9528.66}=9.35\%\right)$ are considered with medium and low probability of permanence (Figure 3), respectively.

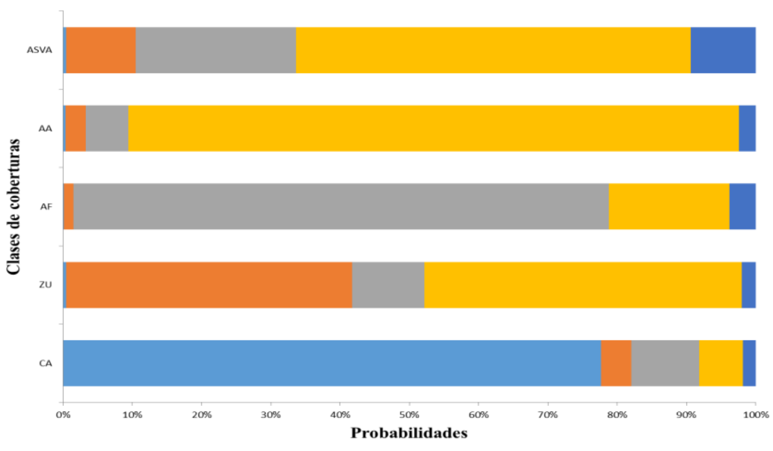

Figure 3. Probability of permanence of land use for the period 2000-2017.

It should be noted that the agricultural area increased 83% $\left(\frac{58269.63}{31781.21}\text{-}1=83.34\%\right)$; however, the forest area decreased 5.89% $\left(\frac{16253.85}{17271.5}\text{-}1=5.89\%\right)$, although at a lower rate compared to the 1992-2000 period. Something similar happens with the category without vegetation, it was reduced 75% $\left(\frac{891.49}{3509.96}\text{-}1=74.6\%\right)$, moving mainly to agricultural area and forest area.

As already mentioned, urban areas obtained an average probability of permanence, attributed primarily by the increase of the population in the microbasin, this being around 149% $\left(\frac{288196}{115547}-1=149.41\%\right)$, taking as the base year 1970 with a population of 115 547 inhabitants (INEGI, 1970) and as the final year 2010 with a population of 288 196 inhabitants (INEGI, 2013), the population had a growth rate of 2.3%, from 245 112 inhabitants in the year 2000 to 288 196 in the year 2010 (INEGI, 2000; INEGI, 2013).

The increase in the population results in a greater demand for land to meet the productive and consumption needs of the population (Cuevas *et al*., 2011; García *et al*., 2012; Torres *et al*., 2018).

Exchange rates

Table 5 indicates that the rates of land use change in the 1992-2000 period are higher than those recorded in the 2000-2017 period. In the case of the forestry area, it presents a negative rate for the period of 1992-2000 and positive for the period 2000-2017, which coincides with some studies carried out in Mexico, in similar periods (Velázquez *et al*., 2002; García-Barrios *et al*., 2009; CONAFOR-UACH, 2013). However, the result obtained by FAO (2010) is greater than 4%. Areas without apparent vegetation have a positive exchange rate that is maintained in both periods, indicating that the eroded areas used as a mine continue to exist.

Table 5. Land use change rate, 1992-2017.

Class	Change (ha)		Change (%)		Exchange rate	
	1992-2000	2000-2017	1992-2000	2000-2017	1992-2000	2000-2017
CA	-179.53	249.41	-0.17	0.24	0.04	-0.03
ZU	393.86	-727	0.38	-0.7	-0.01	0.01
AF	-25 315.99	2 238.54	-24.4	2.16	0.09	-0.01
AA	30 308.42	4 331.22	29.21	4.17	-0.08	0
ASVA	-5 207.47	-6 092.17	-5.02	-5.87	0.05	0.06

CA= body of water; ZU= urban area; AF= forest area; AA= agricultural area; ASVA= area without apparent vegetation.

The agricultural area in the first period had a positive exchange rate that goes hand in hand with the exchange rate of urban areas, this is because the population needs goods to meet their needs. During the second period, the area of bodies of water had an increase of 24%, which is related to the increase in the agricultural area, because it increases more water, which leads the population to build more jagüeyes to retain or capture rainwater.

With respect to the 1992-2000 period, shows the processes of change of the total area that occurred in the microbasin: 37% (38 667.76 ha) did not change, 28% was deforested mainly for agricultural use purposes, which coincides with exposed by SEMARNAT (2002) in the study carried out in the period 1993-2000 at national level (Rosete *et al*., 2008; FAO, 2010).

Conclusions

The Tula microbasin has presented significant changes in its land use, in the 1992-2000 period, the coverage with the greatest change was the forest area with 63%, 52% of the forest area passed to agricultural area, in addition the population increased 14%, which indicates that deforestation occurred mainly due to the need to produce goods to meet the needs of the population, and because there were no public policies to regulate the use of forest resources. During the 2000-2017 period, the forest area only decreased 6%, due to the implementation of federal public policies and the state policies of the state of Hidalgo, which contributed to counteract deforestation and recover abandoned areas. The trend of land use in the microbasin is that most of the area remains unchanged, existing agricultural areas are maintained and continue to increase until they are abandoned due to their decline in productivity and invaded by urban areas, which will increase due to population growth.

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