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Analysis Of Land Use Changes And Carbon Content In Forest Covers In The State Of Mexico With Spatial And Stochastic Methods

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Abstract

This paper presents the results of the application of a prospective model that combines the analysis of time series of land use in the State of Mexico, based on the land use information generated by the National Institute of Statistics and Geography (INEGI). We compare two sets of data to obtain a transition matrix that allows a future projection, using stochastic processes, Markov chains and cellular automata, and technical matrix spatiotemporal analysis environment incorporated in Geographic Information Systems (GIS). Thus an estimation of carbon content was obtained once applying allometric equations per categories and sampling points taking into account the National Forest Inventory and the development of vegetation, primary or secondary, and vegetative stages. As a result of this study the estimation of carbon reserves for 2010 in the State of Mexico summed up to 0.167556208 and 13,003 Gt in forest and tropical deciduous forests, respectively. We conclude that under the methodologies used, the possible variations of projected land establish a baseline to prospect on the efforts deployed in different evolving scenarios.

Keywords: Carbon, land use, stochastic models, spatial models, state of Mexico.

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1. Introduction

The changes in land use and the implication on the emission of greenhouse gases (GHG) into the atmosphere is related to the rate of conversion of the landcover; the effects on the fluxes depends of the direction of conversion of the coverture. The deforester process means the diminishment of live biomass, which delays the transition from secondary to primary vegetation depending also on the rate of increase and accumulation of biomass (Semarnat&INE, 2006).

The processes that influence directly over forest carbon reservoir are: a) the biomass production, that increases the carbon reservoir through its fixation during the photosynthesis process, and b) the gathering of industrial wood and timber that promotes carbon dioxide emissions to the atmosphere through combustion and plant biomass degradation. The balance of these processes establishes the net amount of gain and loss of carbon for forests due to their forestry management (Semarnat&INE, 2006).Forests in Mexico represent the mayor reservoir of carbon approximately ocho GtC (eight million tons of carbon) (Masera, Ordoñez &Dirzo, 1997), which is a similar amount than the yearly global emissions of the CO_2 inearth (Ordoñez & Masera, 2001). The storage capacity of the forest is decreasing rapidly because of deforestation and degradation of these wooden ecosystems (Ordoñez & Masera, 2001).

An alternative to reduce the amount of CO_2 emitted to the atmosphere is to absorb this gas, partially through the photosynthesis process, this means that the plants will behave as storage of C in terms of their plant biomass and afterwardsas organic matter (Avendaño, Acosta, Carrillo & Etchevers, 2009).The capture of atmospheric carbon through the forest management is based on the accumulation and storage of plant biomass. Any activity that leads to a positive effect over the capacity of a certain region to storage and capture carbon can be considered as a valid option to reduce the atmospheric CO_2(Pimienta, Domínguez, Aguirre, Hernández & Jiménez, 2007). On the other hand, the changes in land use are one of the most important factors that influence globally the emissions of CO_2. In Mexico this phenomenon is rather important since it is considered as one of the 20 countries with the higher emissions of GHG (Ordoñez y Masera, 2001).

For Mexico, the developed models on this subject have a national scale analysis, starting from the data given by the Intergovernmental Panel on Climate Change (IPCC), and for local scale studies, some monitoring has been done through destructive analysis that lead to an estimation of carbon content in trees (Masera *et al.* 1997, Avendaño *et al. 2009, Díaz, Acosta, Carrillo, Buendía, Flores, Etchevers,* 2007, Pimienta *et al.* 2007). The model proposed for this study is in an intermediate scale of description, applied to the State of Mexico.

Geographic Information Systems tools are used to develop the spatially-explicit models. In this model ArcGIS and Idrisi are used, mainly for the spatial-time description through transition matrixes obtained by the Cellular Automata Markov Chain and Stochastic Choice modules (Eastman, 2006).

2. Methods

2.1 Study area

The State of Mexico is located in the south of the meridional high plateau of the Mexican Republic, between north latitude 18°22' and 20°17' and west longitude 98°36' and 100°37'. It has an area of 22 333 km^2 which represents 1.1% of the national surface (Instituto Nacional de Estadística y Geografía, 2001 [INEGI]). It has important forest resources that consist mainly on coniferous forest, broadleaf forests, mixed forests and temperate mountain forest (Pineda *et al.* 2009). It is considered as the most populated state of the country with 15,175,862 habitants (INEGI, 2010b). In this state, the increase of population and the displacement of agriculture boundaries are two of the main factors that have impact in the land use change. Hence the need of precise knowledge of such changes to estimate the greenhouse gas fluxes.

2.2 Chart making spatial-temporal coverage of the State of Mexico

The analysis of changes in land use was obtained using land cover vectormaps from INEGI from Series I (1968-1986), Series II (1993-1996), Series III (2002) y Series IV (2007-2010) (INEGI 1993, 1997, 2003, 2010a). The State of Mexico is covered with six maps at a scale 1:250,000 that encloses a surface of 1° latitude and 2° longitude for each case.The classification of ecosystem for Series I was done using physiognomy, floristic, phonological and state of conservation criteria for the land uses. The FAO system was used to derive Series II and it includes 29 different types of vegetation. For Series III the classification system was organized hierarchically in four levels: phase, type, community and sub-community (INEGI, 2003). Finally, Series IV resulted from the same analysis as the one mentioned for Series III.

2.3 Combining the model and the input information

The six files for Series I to IV where merged in a vector value form, delimiting the political boundary to restrict the relevant information for the State. Afterwards, the resulting file was transformed to raster format, under a spatial resolution of 20 m leading to a 10,604 rows per 10,610 columns matrix; such matrix was reclassified under the field "tipo de vegetación", according to the Intergovernmental Panel Climate Change [IPCC] (2006).

For the case of forests, the areas where disassembled according to the different species, allometric equations where applied to calculate biomass and carbon for these species and afterwards the information was reassembled in accordance with IPCC criteria.In addition, the National Forest Inventory (Comisión Nacional Forestal, 2011 [CONAFOR]) was used to integrate a data base with 217 monitoring points that include: tree stems, cover, density, maximum height, average height, maximum diameter, average diameter and volume.

2.4 Spatial-temporal analysis for the land use

The model attempts to predict the changes in land use from *Markov chains* and *Stochastic* projections, therefore the procedures are temporally discrete. Using Paegelow, Camacho & Menor (2003) procedure we model long term land use change. The algorithms compare pairs of land use maps, for example Series II 1997 and Series III 2002 to obtain a probability transition matrix, matrix that gives us a set of maps that predicts land use behavior for future periods. For instance, 2010 is a prediction that can be validated with Series IV and its values represent the probability of being in a certain category (forest, tropical deciduous forest, scrubland, grassland, cropland, among others). The data was unified for the corresponding categories in order to apply the model as well as for comparison between the prediction and Series IV 2010. Using Idrisi, under the *CA_ Markov* module it analyses qualitatively land cover images for specific dates constructing different matrixes, a probability transition one, a surface transition one and a set of images for the conditional transition. This module requires: a) probability transition matrixes between categories; b) surface transition matrixes, which represent the number of pixels that can undergo a modification; c) a set of probability condition maps (0,1) for each categories at time t1 (Projection to 2010) obtained as the result of projecting t_0, i.e. Series III 2002;Notice should be made on the fact that the temporal units considered in the iterations between Series t_{-1} (Series II 1997) and t_0 (Series III 2002) and from this last date towards 2010 in a linear-like projection where eight iterations.

With the obtained probability transition maps per category, each pixel could be valued to identify its belonging to a certain land use, through *Stchoice* (Stocastic Projection) this turned into a unique map without incompatibilities for land use data. This tool creates an interpretation of land cover, upon evaluating the conditional probabilities for land use and a certain pixel vs. land use of a certain pixel with respect to a linear random probability distribution. It also depends on the probability to change towards a feasible category that overcomes a random distribution (one that changes for each iteration), giving to each pixel one of the most feasible category. The stochastic projection maps include markovian transition probabilities between land use categories for different times, hence being strictly probabilistic.

The *CA_Markov* from Idrisi, is a procedure that combines cellular automata and a Markov chain description to predict land use coverage together with the spatial contiguity and the knowledge of Markov probability transition analysis. This implement applies an algorithm of cellular automata (CA), with a medium Boolean filter 5x5.

2.5 Identifying the rate of change for land use

The dynamics of land use leads to the awareness of a yearly rate increment per characteristic specie for each of the botanic populations, hence the knowledge of the potential amount of CO_2 that can be captured per type (Palacio, Bocco, Velazquez, Mas, Takaki, Victoria, Luna, Gómez, López, Palma, Trejo, Peralta, Prado, Rodríguez, Mayorga& González, 2000).

To calculate the rate of exchange, the next expression was applied:

$$t = \left((S_2/S_1)^{1/n} - 1\right) \times 100 \qquad (1)$$

Here S_1 and S_2 are the surface covered at an initial and final time, respectively, and n is the size of the evaluated interval in year units (Palacio, Sánchez, Casado, Propin, Delgado, Velázquez, Chias, Ortiz, González, Negrete, Morales, Márquez, Nieda, Jiménez, Muñoz, Ocaña, Juárez, Anzaldo, Hernández, Valderrama, Rodríguez, Campos, Vera &Camacho, 2004).

2.6 Determining the biomass and carbon for forests andtropical deciduous forest

Allometric equations per species where used to estimate the content of biomass in forests. Using a correlation coefficient of 0.94 and higher, as the criteria to choose the favored equations such that they would ensure similarities with the forest characteristics of the State of Mexico.

The IPCC establishes that 50% of the above-ground biomass is carbon; this applies to national inventories, nevertheless when taking into account recent studies done in Mexico with certain details and using destructive monitoring by Acosta *et al*. (2009), Díaz*et al*. (2007) and Masera, De Jong & Ricalde, (2000), this obliged to apply discriminated conversion factors for conversions from biomass to carbon.

The contents of carbon was retrieved for each of the polygons in the map of land use from INEGI´s Series IV 2010. These points where regrouped by the type of woods:

Abies, oak, oak-pine tree, pine tree, pine tree-oak and medium dry deciduous forests (the other groups where considered dismissible, provided that the points had a very small contribution to the total grounds). For each point, the reordering considered the volume (m^3) and the aboveground (kg/tree), hence depending on the average mean distance between each group there was a cluster to apply over the points for three main categories.

Upon applying allometric equations and conversion factors given in *Table 2*, the estimation of content of carbon per sample point was obtained. Considering that the map of land use from INEGI makes a difference between forest in terms of their stages, from primary vegetative succession with timberline and secondary with shrub abundance, there was the need to identify the content of carbon from an average value for each class (1,2 or 3) consistently with its stage; for instance, the primary forest received the highest value for carbon, secondary forest with timberline class 2 value and finally class 3 value for secondary forest with shrub vegetation

For the case of mountain cloud forests the designated values where, for tascate the usual ones for pine tree –oak and for cedar lumbar the pine values. Finally, in the case of points for savannah, that consider a mixture of other types of vegetation the designated values where those of the most abundant specie, shrubs or arboreal species.

3. Results

We obtained nine types of land use for the State of Mexico, which are listed in *Table 1*.

Table 1: Reclassification of land use

IPCC	Reclassifying for late model	Vegetation types of land use series of INEGI	Value assigned to reclassification
Forest land	Forest	Forest farmed, cedar forests, oak forest, Oak-pine forest, oyamel forest, pine forest, pine-oak forest, temperate mountain forest	1
	Tropical deciduous forest	Tropical deciduous forest	5
Grassland	Scrubland	Crasicaule scrublands, rosette scrub, cactus scrub, Mezquital	2
	Grassland	Grassland cultivated, grassland halophilous, grassland induced, natural grassland, high-mountain prairies	3
Cropland	Cropland	Irrigation cropping, rainfed agriculture, cropland eventual irrigation water	4
Wetland	Wetland	Wetland	6
Settlements	Settlements	Settlements	8
Other Land	Other land	Swamp vegetation, halophytic vegetation	7
	Earth without vegetation	Earth without vegetation	9

Source: Prepared based on IPCC (2006) and the model´s objectives.

Once applying these data the *Stchoice* module generates a distribution map of the nine land use types see *Figure 1.*

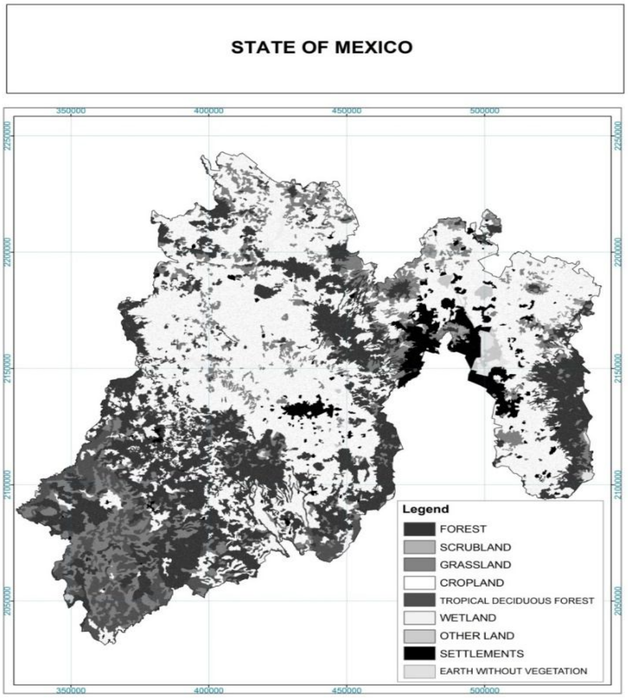

Figure 1: Stochastic approach map

Allometric equations and the factors used to calculate biomass in kilograms per tree and carbon percentage of each species are shown in *Table 2:*

Table 2: Allometric equations for biomass and factor in calculating carbon by specie

Biomass estimates (B) (kg / árbol)	Specie	coefficient of determination	Carbon conversion factor
$0.1033*DN^{2.39}$	*Quercus sp*	0,99	54.00 %
$0,0357 * DN^{2.6916}$	*Pinus patula*	0,98	50.31 %
$0.0754*DN^{2.513}$	*Abies religiosa:*	0,98	46.48 %
$10^{\{-0.535 + 0.966 \log 10 (BA)\}}$	*Dry climate zone (México)*	0,94	50.00 %

Source: Acosta *et al.* (2009); Díaz *et al*. (2007); Riofrío (2007), Masera *et al.* (2000) These equations were applied to each of the 217 sampling points shown in *Table 3,*using the National Forest Inventory (IFN) for the State of Mexico.

Table 3: Combined items by specie

Especie	Total de puntos
Abies forest	27
Oak forest	60
Oak-Pine forest	29
Pine forest	31
Pine-Oak forest	26
Tropical deciduous forest	22
Bosque bajo abierto	1
Crasicaule scrublands	1
Temperate mountain forest	2
Tascate forest	2
Savannah	16
Total de puntos	**217**

Source: Prepared according to the accorded array.

The cluster grouping type for *Abies* is shown in *Table 4*:

Table 4: Cluster of Abies forest

Average value cluster 1 90.36			Average value cluster 2 286.19			Average value cluster 3 504.28		
C Ton/ha								
Point number	ID NFI	Distance	Point number	ID NFI	Distance	Point number	ID NFI	Distance
1	61616	5	1	61856	69	1	59578	917
2	60320	61	2	59313	69	2	59814	2667
3	60589	443	3	62350	1337	3	59564	3585
4	62362	693	4	62849	1481			
5	61592	784	5	62848	1797			
6	60603	1035	6	62859	2059			
7	59828	1342	7	60605	2358			
8	59830	1964	8	62600	3010			
9	61855	2167	9	61095	3113			
10	60067	3077	10	60859	3254			
11	59312	3277	11	62872	3614			
12	62850	3359	12	62122	4000			

ID INF: Identifier of National Forest Inventory.
Source: Prepared to the accorded grouping.

Carbon content per growth phases, are shown in *Table 5*:

Table 5: Carbon content (ton / ha) assigned to land use by forestry specie

Forestry species	Development of vegetation		
	Secondary forest without shrub vegetation	Secondary forest vegetation	Primary forest vegetation
Abies	90.36	286.19	504.28
Quercus	51.49	163.77	294.99
Quercus -Pinus	72.33	178.55	318.10
Pinus	94.11	297.61	543.82
Pinus - Quercus	34.27	125.92	270.39
Tropical deciduous forest	00.03	000.16	000.44

Source: Based on the carbon content.

Modules *CA_Markov* and *Stchoice*are applied for comparison with current land use mapping (2010) and it is shown in *Table 6*:

Table 6: Comparison of results (surface in ha)

Clase	*Stchoice*	*CA_ Markov*	Land use 2010
Forest	636947.24	621294.76	625666.24
Scrubland	12938.52	16309.76	14689.56
Grassland	298795.36	316810.84	307351.92
Cropland	1013570.84	1030726.32	1029083.40
Tropical deciduous forest	119582.48	117338.84	118181.40
Wetland	19903.36	18364.68	18828.80
Other land	19945.36	10168.68	14144.76
Settlements	101121.76	92064.44	94992.20
Earth without vegetation	10436.28	10217.64	10303.04

Source: Prepared based on the results

The spatial results of applying the *CA_Markov* module are shown in *Figure 2*.

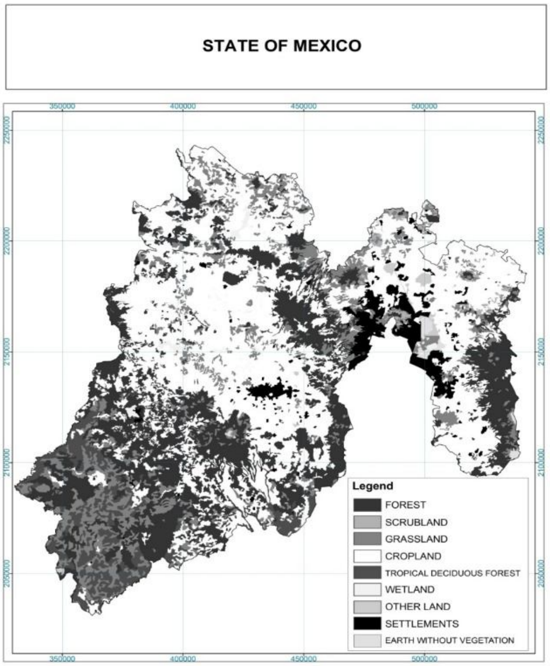

Figure 2. Markov chains and cellular automata approach map

The number of isolated cells presented in *Figure 1* where diminished considerably upon applying the cellular automata and Markov chain algorithm, this can be seen in *Figure 2.*To apply this procedure we use the same reference data, i.e. the transition matrixes comparing Series II 2002 and Series III 2002, once projected to 2010 the first one under a random distribution and the former one's projection includes correlation between first neighbor pixels.

Comparison between the land use surfaces per category for Series III 2002 and Series IV 2010 to obtain the rate of change is presented in *Table 7.*

Table 7: Rate of exchange of land use for series III and IV

Categories	Series III 2002 (Ha)	Series IV 2010 (Ha)	Rate of exchange Series III and IV
Forest	616933.76	625666.24	0.175
Scrubland	18106.88	14689.56	-2.580
Grassland	327544.28	307351.92	-0.792
Cropland	1033721.72	1029083.40	-0.056
Tropical deciduous forest	117392.32	118181.4	0.083
Wetland	17681.16	18828.80	0.789
Other land	4199.72	14144.76	16.391
Settlements	87576.44	94992.20	1.021
Earth without vegetation	10085.04	10303.04	0.267

Source: Prepared based on the results

Positive rate changes can be observed for wetlands, settlements, forests, tropical deciduous forests and other lands. On the other hand, land use presents negative rate changes for scrubland, grassland and cropland.When evaluating the errors, the addition of the stochastic linear model errors overcomes sum of the cellular automata and Markov chain procedure. The resulting errors also present a certain symmetry, when on model overrates the other underrates.The former data are the setup to calculate losses and gains of carbon from forest biomass, once applying the forest distribution to forests and tropical deciduous forests (*Figure 3*), both categories present the biggest carbon content.

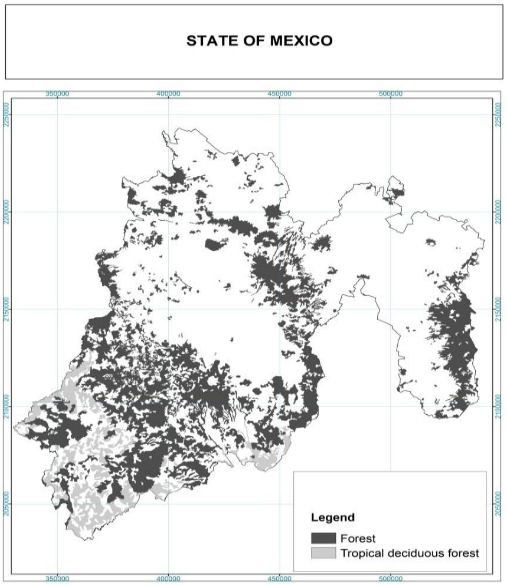

Figure 3: Location of forests and tropical deciduous forest

The content of carbon was calculated per specie, using the established values in *Table* 5results are shown in *Figure 4*.

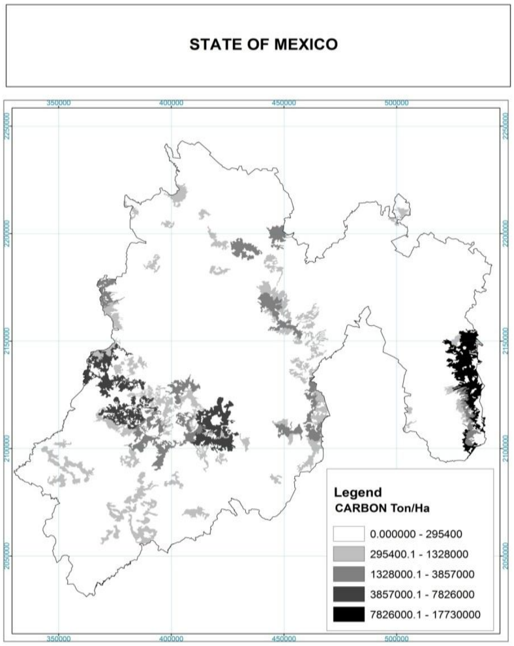

Figure 4: Carbon content per hectare

The National Park “Nevado de Toluca”, “Sierra de las Cruces” and “Sierra Nevada” are the zones that present the highest amount of carbon per hectare. While the lowest amount was shown in the tropical deciduous forests located at the south of the state of Mexico. Adding up the content of carbon in all the forest polygons for the state of Mexico shows that the carbon reservoirs for 2010 are 0.167556208 Gt in forests and 13,003 tons in tropical deciduous forests. The before mentioned amount represents 2% of the national reserves, value given be Masera *et al.* (1997).

4. Discussion

The Intergovermental Climate Change Panel (IPCC, 2006) proposes 6 general categories for Mexico, nevertheless this study for a state level, they where disassemble into 9 categories, differentiating between forests and tropical deciduous forests, between scrubland and grasslands, and finally between other lands and earth without vegetation.

Stchoice module results can be considered as intermediate probabilistic results since it evaluates the markovian transition probabilities between categories of land use in a certain time line. This turns up as a pixel map or isolated dispersed cells that diminish the precision that one would expect for the obtained results.In percentage values, *Stchoice* module presents higher values, for positive and negative rates, ensuing in a bigger land use change, for example the fraction change in forests is of -1.8, when for *CA_Markov* module the value would be 0.7; in tropical deciduous forests the values are -1.2 and 0.7 respectively. The average percentage for Stchoice is of -4.6 and 2.4% for *CA_Markov*, hence the average of the first model underrates and the second overrates.

From their strictly probabilistic function, the transition frequencies between categories, under stable conditions, and taking into account the land cover projections for 2010 lead to a scenario where the hectares of land occupied by forests, tropical deciduous forests, wetlands, other lands, settlements, scrubland, grassland and cropland are overrated and/or underrated.The first resulting scenario, from stochastic analysis draws attention to the recovery of forests and tropical deciduous forests and the second scenario from cellular automata and Markov chains shows the loss of forests and tropical deciduous forests in favor of grassland and cropland surface.

Even when the scenarios are useful to project ideal recovering and loss states, both models contribute to a general vision of the state of forest covering for certain times (discrete time series), nevertheless they do not bring enough information about land use changes for a continuum time line, this suggested to compare land use territories per category, from Series III and Series IV to estimate the rate of change in eight years.

The positive rate of changes presented by forests and tropical deciduous forests, lesser than 0.1% yearly are very small, this can confirm a minimum mending process from small areas of grassland and cropland, hence the vegetation recovery for the following first years and according to the growing stages will give a potential small carbon capture.

This scenario points out the discussion over the increase in a short term, of forest coverage, hence its potential capacity of capturing carbon. The scenario obtained through the applied allometric equations yields focalizing the most important elevations and ratifies the abundance of forest as a main reservoir of carbon in this territory. Its capacity diminishes as the trees aging increases, therefore the importance of taking into account the rate of growth and the intensity of the changes undergoing all year through tree cover in the forest and tropical deciduous forests. This implies a yearlong variation of size, but excludes facts about the delay in the transition from secondary to primary vegetation, knowledge that correlates to the accumulation of biomass.

The existing studies in Mexico about carbon capture are given in a national level or local, the former one by destructive sampling, the presented proposal provides a spatial image of the contents included in the State of Mexico, with and measurable intrinsic error depending on the chosen projection.Any activity that accrues forest coverage implies directly an increase of carbon capture capacity and this is considered as a potential way to mitigate the emissions of CO2 to the atmosphere.

5. Conclusions

In this study, stochastic analysis (Ross, 1996 and Van Kampen, 2003) through Markov chains and the cellular automata integrated spatial analysis and conditional probability description for a local environment, increasing significantly the validation of information from the National Forest Inventory and stochastic projection maps.The cellular automata procedure measured the local contiguity, increasing the possibility of being part of a certain category, integrating a spatial characteristic to the conditional probability, improving considerably the stochastic projection map.This type of model leads to a global and immediate vision for the potential carbon capture by forests, without making localized destructive sampling and avoiding higher investment of time and costs.

On the other hand, the knowledge of the spatial distribution of carbon content helps in evaluating decisions regarding mitigation measures at a municipal level.In this model the possible land use variations project and establish a baseline to outlook on the efforts deployed in various changing scenarios.

The offered model for land use changes is related to changes in carbon reservoirs, which decreases in the central region and remains high in the mountainous areas of the east and southeast of the State of Mexico. Whereas in the tropical deciduous forests, located in the south of the state, less amount of carbon stored.

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