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The northernmost tropical rain forest of the Americas: Endangered by agriculture expansion

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Abstract: This paper sets out to analyze the changes in vegetation cover and land use in the Huasteca region during the period 1990–2015, to find out its causes, and to create future land use scenarios based on historical trends. The last remnants of the most northerly tropical rain forest in the Americas are found in the region in Mexico known as the Huasteca. The main factors causing changes in land use that threaten biodiversity in the Huasteca are crop and livestock agriculture, making this region a conservation priority for the Mexican government. Historically, the region has long been subject to transformation by human activity, from Spanish colonization to development by the oil industry in the mid-twentieth century. Images from the SPOT and Landsat satellite, and the Dinamica EGO program were used. During the twenty-five–year period examined, 87,173 ha of tropical rain forest, 4709 ha of cloud forest and 388 hectares of Oak forest were lost. Projections for the years 2030, 2040 and 2050 show potential increases in agricultural land use at the expense of natural vegetation. By 2050, 155,856 ha of tropical rain forest and 7208 ha of cloud forest could be lost if current government agricultural policies and social trends continue. An analysis of changes in land use is fundamental for devising actions leading to the implementation of policies for both sustainable agricultural production and improving the living conditions of residents, as well as conservation of tropical rain forests in the Huasteca.

Keywords: Deforestation, Dinamica EGO, Drivers, Huasteca, Modeling Land use/cover change,

Introduction

The land area covered by tropical rain forest has shrunk dramatically in the last hundred years. Currently, disconnected fragments of tropical rain forest remain in areas that are often inaccessible to human activity. Most of these fragments are secondary tropical rain forest, surrounded by induced pasture and cropland. Estimates of the land area covered by tropical rain forest worldwide vary according to the satellite imagery and methods used, but average 1457.3 × 100 ha (Wright 2005). The Americas are the continental mass with the greatest proportion of the world's tropical rain forest with 58.1%. In general, however, this continent has also suffered the highest forest loss (FRA 2015). Tropical rain forest, in particular, has the highest deforestation rates, averaging 2.56% (Kim *et al.* 2015; Wright 2005).

Tropical rain forest deforestation processes have affected ecosystem services such as climate regulation, carbon storage and water availability (Foley *et al.* 2005; Reyes-Hernández *et al.* 2009; Stork *et al.* 2009). In addition, land use change is the main cause of local species extinctions (Foley *et al.* 2005; Sala *et al.* 2000). These processes have been driven by a combination of social, economic and political drivers (Bonilla-Moheno *et al.* 2012; Lambin *et al.* 2001, 2003). The expansion of the agricultural frontier (Lambin *et al.* 2001, 2003; Munsi *et al.* 2010; Ruiz *et al.* 2013) is the main cause of deforestation produced by increased pressure on the production of resources, markets,

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Table 1. Changes in vegetation cover and land use and deforestation rates in the Huasteca region. Negative values indicate loss of area for vegetation types and land use.

Vegetation cover	Area (ha)				Deforestation rate (%)		
	1990	2000	2015	Total	1990–2000	2000–2015	1990–2015
Tropical rain forest	374 181	322 546	286 007	–87 174	1.4	0.7	1.0
Cloud forest	17 031	14 382	12 322	–4 709	1.6	0.9	1.2
Pine-Quercus forest	2 943	2 743	3 560	117	0.7	1.5	0.7
Quercus forest	305	205	95	–288	3.8	4.4	4.5
Land use							
Grazing land	155 563	178 071	196 736	39 614	-	-	-
Agriculture fields	296 792	328 848	348 025	51 311	-	-	-
Human settlement	7 059	7 079	7 130	70.7	-	-	-
Water	2 416	2 416	2 416	0	-	-	-
Total -	856 291	856 291	856 291		-	-	-

globalization and the loss of local skills and attitudes (Lambin *et al.* 2003).

Except for Brazil, most of the tropical rain forest in Latin America is secondary, due to the history of deforestation dating back to pre-Hispanic times. In Mexico, there have been few studies of land use and land cover change in the tropical regions of the country. Tropical rain forest covers an estimated 2,939,031.7 ha, and the deforestation rate for the period 1993–2011 was 0.97% (FRA 2015). However, this average rate is well below that reported for some specific regions of Mexico. Deforestation rates of 2.4% have been recorded for the southeast coastal region of Oaxaca (Leija-Loredo *et al.* 2016), 4.5% for the Lacandona region of Chiapas, 2% for the Calakmul region of Campeche (Velazquez *et al.* 2002), and 4.3% for Los Tuxtlas in the state of Veracruz (Dirzo & Garcia 1991). One of the most important regions of the country is La Huasteca, which is located in the foothills of the Sierra Madre Oriental Mountains. This region holds fragments of the most northerly tropical rain forest in the Americas. It has a high level of cultural and biological diversity, but the region is economically marginalized, and the human development index is low (0.64) (PNUD 2012). The Huasteca is a region with priority for conservation because their biotic, and socio-cultural diversity (Boege 2008).

Estimating changes in land use, and locating areas threatened by deforestation and vegetation remnants are key elements for generating tropical rain forest conservation projects (Forester & Machlis 1996). These should be analyzed at different temporal and spatial scales to enable an overall understanding of the dynamics of vegetation cover (Geist & Lambin 2002). The main tools used for this are remote sensing and GIS, which enable spatially explicit models to be generated (Goodchild 1994; Weng 2010). Also, land use and deforestation trajectories have been projected using historical trends and futures scenarios of socio-economics drivers (Abuelaish & Camacho-Olmedo 2016; Stéphenne & Lambin 2001). In this paper, changes in vegetation cover and land use in the Huasteca region were analyzed for 1990, 2000 and 2015, using SPOT and Landsat satellite imagery. The data were then used to produce models of prospective land use change scenarios for 2030, 2040 and 2050. Social, economic and environmental drivers were also identified to explain the processes of land use change in the Huasteca region.

Materials and Methods

Study site

The Huasteca is a region where the transformation of the tropical rain forest unfolded as a long and difficult process, a result of native people excluded by the Spanish conquistadors (Santiago 2011). When the Spanish arrived, the Mesoamerican landscape was dominated by agriculture. Crops were grown on large tracts of flat land, hillsides, and ravines, under both settled and nomadic production systems (Guevara 2001). Although the aim of the Spaniards was to transform all the vegetation into pastures, they did not succeed in the Huasteca because of the war of independence and also because the indigenous population did not decline as it did in the Gulf of Mexico lowlands (Guevara & Lira-Noriega 2011).

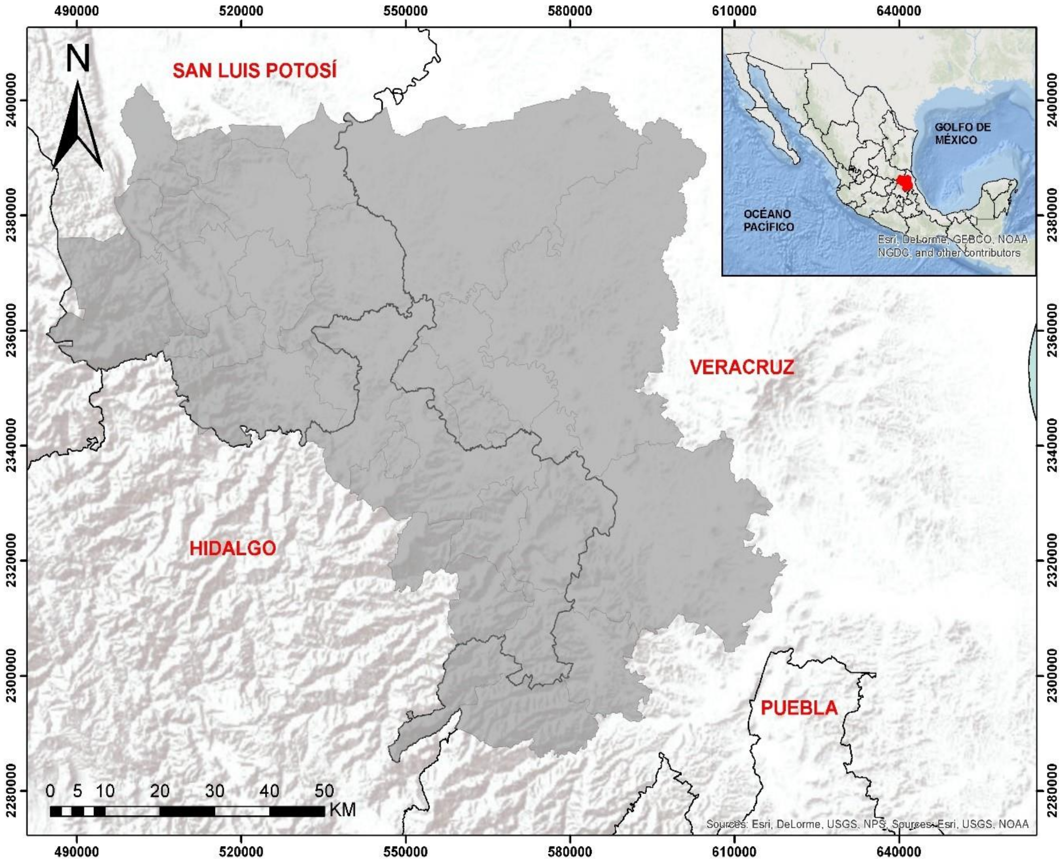

Fig. 1. Map of location of Huasteca region in the northeast of México. The study area in the Huasteca region converges three states of the country: Veracruz, Hidalgo and San Luis Potosí.

In 1876, "most of the land . . . is covered in impenetrable forests where trees, bushes, and plants intertwine their tightly woven branches and do not let the light in; that makes it so grasses are scarce in many places, making it inappropriate to raise cattle" (Santiago 2011).

Later though, the transformation of the tropical rain forest landscape increased at an accelerated rate, causing environmental problems such as soil erosion, flooding, loss of biodiversity, and crop loss, among others. Livestock farming is the main reason that natural ecosystems are transformed. It has been decisive in changing the original agricultural and natural landscape (Guevara 2001). Nevertheless, the expansion of pastured land over the past 60 years has been impressive, with high levels of deforestation and fragmentation of tropical rain forests. The Huasteca covers approximately 65,675.85 ha in a mosaic with three main types of cover; agricultural, induced pasture and secondary tropical rain forest.

The present study was carried out on a representative polygon of the Huasteca where three States of Mexico converge; Hidalgo, Veracruz and San Luis Potosí. It is located between 20°34' and 21°26'N, and between 99°14' and 97°2' W, and has an area of 8479 ha with elevations from 200 to 1000 masl (Fig. 1). Annual rainfall for the area ranges between 1000 and 3000 mm. Soils found in the region include lithosol, vertisol, rendzina, phaeozem, fluvisol, luvisol, and regosol (Puig 1991).

The tropical rain forest of the Huasteca is the most northerly tropical rain forest in the Americas. It is structurally simple, having one or two dominant tree species, unlike other forests more distant from the Tropic of Cancer (Rzedowski 1978). The dominant species are *Brosimum alicastrum, Dendropanax arboreus, Licaria capitata* and *Celtis monoica,* as well as other tree species that accompany them, including *Bursera simaruba, Ceiba pentandra, Dendropanax arboreus, Coccoloba barbadensis, Sideroxylon*

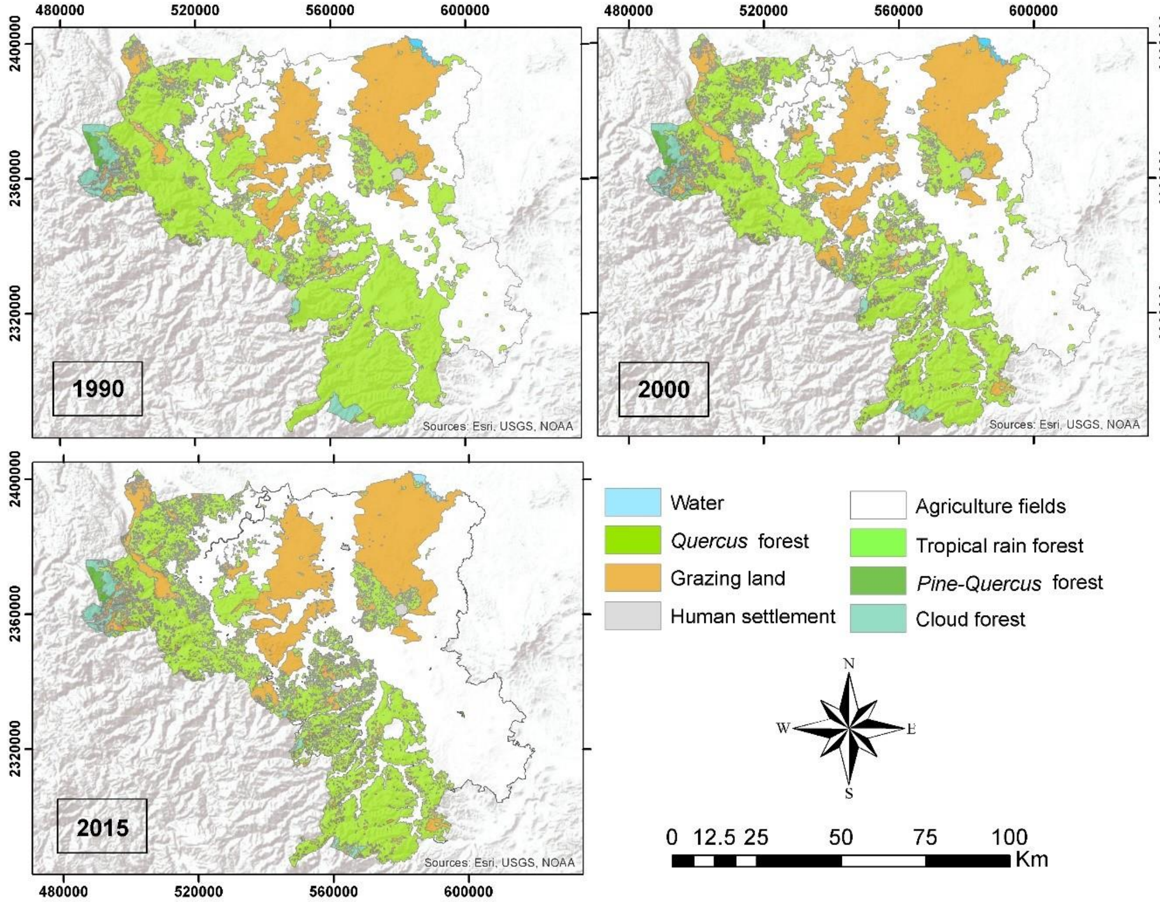

Fig. 2. Vegetation and current land use in the study area in the Huasteca region. Coordinates are in Universe Transversal of Mercator (UTM).

tepisque, Pithecellobium arboreum, Porteria hypoglauca, Capodiptera amelliae, Prutium copal and *Ficuss* spp. (Puig 1991; Rzedowski 1978). Other genera found in secondary forests include *Acacia, Adelia, Albizzia, Desmodium, Didymopanax, Inga, Mimosa, Piper,* and *Tabebuia,* among others (Rzedowski 1978).

Data Sources and Spatial Analysis

A 1:250,000 digital map of vegetation and land use for the region (series V) (INEGI 2013) was used as the basis for spatial identification of natural cover and land use. Eight SPOT 5 satellite images taken on January 5, 2015 (in a false-color combination with a 432 RGB band combination), and two Landsat 2000 and two Landsat 1990 images were used for visual interpretation of the coverage. The series V map was overlain on the SPOT satellite imagery to identify coverage patterns. Subsequently, to determine the dynamics of land use, the interpretation of the 2015 Landsat images was overlain on the 2000 and 1990 Landsat images (Mas 2005). Landscape elements and coverage were confirmed in the field. The images were analyzed using ArcGis 9.3.

Assessment of Accuracy

To evaluate the precision, eight categories of vegetation cover and land use were verified at 600 sampling points. The method consisted of verifying the sampling points, which had been classified by fieldwork and high-resolution satellite images (Mas *et al.* 2003). The degree of reliability is expressed as overall reliability; that is, the proportion of the map that has been correctly classified. This is calculated as the sum of user reliability (proportion of sites in a given category on the map that are correctly classified after been verified in the reference database) and producer reliability (proportion of sites in a given category of the satellite images which are correctly classified on the basis of contextual data) (Mas *et al.* 2009).

Deforested areas and areas whose land use had changed were identified and quantified using a cartographic overlay of maps for the intervals 2000–1990, 2015–2000 and 2015–1990. The deforestation rate and percentage change for each interval were calculated by the FAO formula (1996).

$C = [\{T_2/T_1\}^{1/n} - 1]*100$

Where C = rate of change, T_1 = cover area in the start year, T_2 = cover area in the current or most recent year, n = number of years between T_1 and T_2.

Finally, maps of deforested areas and areas with changes in land use were plotted, the areas were quantified, and the rates of change were calculated.

Spatial Modeling

The Dinamica EGO program (Soares-Filho *et al.* 2002) was used to generate future scenarios of natural vegetation cover and land use. This program enabled future scenarios to be modeled from previously observed trends by taking into account spatial and temporal patterns of the processes of change over time. The model is constructed using cellular automata and weights of evidence of the different biophysical and socioeconomic drivers identified as causal factors of transformation. Dinamica EGO has been used in numerous studies including the modeling of tropical deforestation processes (Mas & Flamenco-Sandoval 2011; Sahagún *et al.* 2011; Soares-Filho *et al.* 2002, 2004, 2006).

The model requires a multi-temporal cartographic raster database organized and structured with data on land use, and variables (biophysical/socio-economic) that could affect the transformation processes. The transition rates at different points in time are estimated from these data. The drivers were chosen according to other studies and on their availability in the raster format. The drivers used were the digital elevation model (DEM), economic marginalization, population density, vulnerability index, soil type, distance to rivers, distance to roads, slope, elevation, and social gap. These variables were standardized (georeference codes and pixel size) and exported to the model developed in DINAMICA EGO, where they were processed as a multi-layered file for convenient handling. Once the variables had been incorporated into the model, their influence on the changes and their representatively were analyzed. Spatial independence was evaluated by the Cramer statistic and/or the joint information uncertainty of Bonham-Carter (1994).

After this, a prospective change was modeled, simulating future changes in coverage and land use. This procedure follows a set of pre-established transition rules, in which the class assigned to each cell depends on the state of the neighboring cells (White & Engelen 2000). Maps of propensity to change produced from this stage are needed to construct the hypothetical scenarios of areas that might change in the future (Sahagún *et al.* 2011).

Simulation and Validation

Modeling the scenarios begins with the simulation, which consists of two essential functions: “patcher,” which estimates the formation of new patches or clearings in natural covers and “expander,” which adds new (adjacent) areas by expanding existing classes. To do this, the proportion of transitions for each function was calculated based on the mean and variance of the sizes of the patches/areas formed in previous periods (Godoy & Soares-Filho 2008). The result is a map of discrete time intervals, showing projections of the changes that follow from observed historical trends. The validation process considers only the spatial location of the changes. This was carried out by comparing the simulated map generated from these inputs with the 2015 map. This method of fuzzy comparison termed “reciprocal similarity,” which includes the respective metric (Kfuzzy) (Hagen 2003). This measure shows the extent, nature and spatial distribution of the similarity between two maps, where values close to 1 indicate greater similarity.

The final step was the validation of the model. In this case, the DINAMICA EGO program uses the result of the superimposition (real *vs* simulated coverage or vice versa) with the lowest percentage of agreement to avoid false changes or oversized results. Maps of vegetation cover and predicted land uses for 2030, 2040 and 2050 were constructed by the 2015 map.

Results

During 1990–2015 land use changed steadily in the Huasteca region, with the expansion of the areas used for crop and livestock agriculture. As a result, the tropical rain forest has been drastically transformed. In 25 years, 87,173 ha of tropical rain

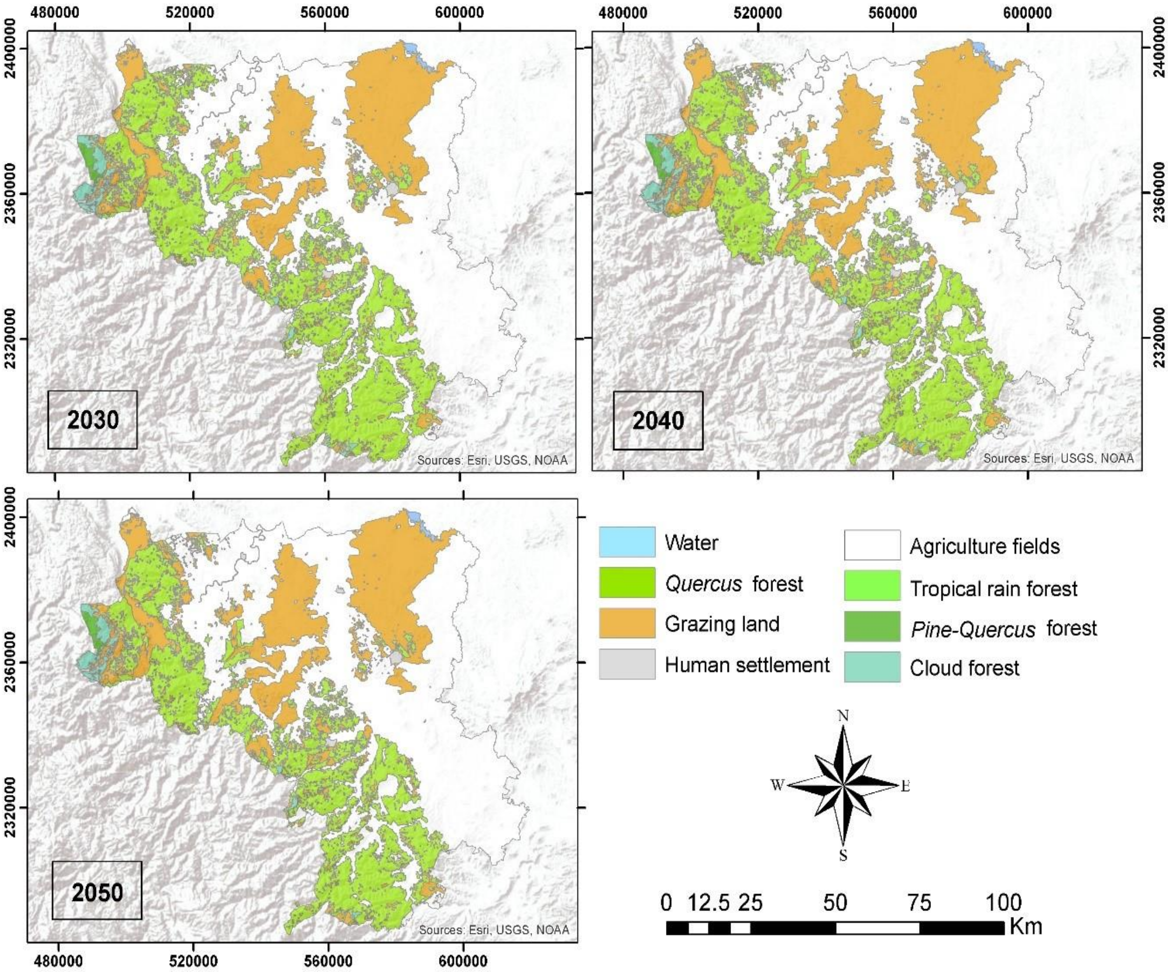

Fig. 3. DINAMICA EGO projections of vegetation and potential land use in the Huasteca region. Coordinates are in Universe Transversal of Mercator (UTM).

forest, 4,709 ha of cloud forest and 288 ha of Oak forest have been lost. In 1990, there was a total of 394,460 ha of natural vegetation cover recorded for the Huasteca region; 374,180 ha of tropical rain forest, 17,031 ha of cloud forest, 2,943 ha of Pine-Oak forest and 305 ha of Oak forest. Twenty-five years later, it was reduced to 301,984 ha (92,476 ha less). In proportional terms, Oak forest suffered the most drastic loss with 60% of its area, followed by cloud forest with 30% loss and tropical rain forest with 25% loss. Tropical rain forest step from 374,180 to 286,006 hectares during twenty-five years (Fig. 2, Table 1).

Deforestation rates calculated for natural vegetation coverage over the period 1990–2015 were 1.1% for the tropical rain forest, 1.2% for cloud forest, 0.7% for Pine-Oak forest, and 4.5% for Oak forest. Rates of deforestation diminish in all vegetation covers during 2000-2015 period, with exception to Pine-Oak forest (Table 1). The land use change found in this study took place in zones with higher elevations, slopes and foothills of the Sierra Madre Oriental, since zones with lower elevation had largely been transformed in prior periods and currently are used mainly for crops (Fig. 2). Total pasture area increased from 155,563 ha in 1990 to 196,763 ha in 2015. Croplands increased by 51,311 ha over 25 years.

A total of 290 weight functions with evidence of influence on land use change processes were obtained from the eight socio-economic drivers used in the prospective models. Drivers with the most weight on the transformation of natural cover were economic marginalization, slope, population density, distance to rivers and distance to roads.

The evaluation of reliability shows that the 2015 maps of land use and vegetation cover in the Huasteca region had an overall reliability of 73%.

Table 2. DINAMICA EGO projections of the nearest future under scenarios of changes in vegetation cover and land use in the Huasteca.

Vegetation cover	Area (ha)		
	2030	2040	2050
Tropical rain forest	258 086	237 074	218 814
Cloud forest	11 177	10 398	9 823
Pine-Quercus forest	2 945	2 949	2 948
Quercus forest	13	9	9
Land use			
Grazing land	202 262	210 972	218 814
Agriculture fields	371 171	384 209	395 623
Human settlement	7 180	7 193	7264
Water	2 403	2 403	2 403

This allows a high degree of confidence in the interpretation of maps of land use change. Also, they were successfully validated by stratified random sampling and sampling points in the field.

Trends in vegetation cover and land use changes show that by 2050, the Huasteca region would lose 155,856 ha of tropical rain forest, 7,208 ha of cloud forest and 295 ha of Oak forest (Fig. 3, Table 2). Major changes from natural vegetative cover to other uses are predicted for the mountainous area of the Sierra Madre Oriental, mainly in the municipalities of Tamazunchale, Xilitla, Matlapa, San Felipe Orizatlán, Huejutla, and Huautla. According to estimates, the Oak forest located in the municipality of Orizatlán and the cloud forest located in the municipality of Yahualica will disappear over the next 35 years. The tropical rain forest is the ecosystem that will lose the largest land area in absolute terms, where human settlements could increase near to 205 ha in 2050. Agriculture is a determining factor in the dynamics of land use change in the Huasteca region. By 2050 the land area covered by pasture is predicted to increase to 63,251 ha, while croplands will have gained the most area with 98,831 ha. The increase in agricultural land is expected to be at the cost of tropical rain forest (Fig. 3).

Discussion

Tropical rain forest is an ecosystem in danger of disappearing due to the expansion of agricultural activities. La Huasteca is a tropical region where the tropical rain forest has been undergoing transformation processes since the time of pre-Hispanic indigenous settlement (Tenek culture) and continues today. Tropical rain forest remnants have been preserved in high elevation areas with difficult access, where the process of land use transformation has been slow but continuous. One impact of colonization by the Spaniards was that extensive croplands and pastures were created in flat and low-lying areas, agriculture being a profitable economic activity (Guevara 2001; Toledo 1990). Ranching in Mexico was a livestock production mode that homogenized the landscape, converting it mainly into pasture. Crop farming was largely replaced by livestock raising as a powerful tool of European colonization (Guevara 2001). In the late nineteenth century and early twentieth-century African grasses were introduced and fields began to be fenced off with barbed wire, which radically transformed ecosystems in the Huasteca and other tropical regions (Aguilar-Robledo 1997).

The loss of more than 90,000 ha of natural ecosystems in the Huasteca between 1990 and 2015 has caused the landscapes in the region to become increasingly homogeneous. This is a process that causes loss of biodiversity (Carpenter *et al.* 2009). Selective logging and creation of areas for pastures are contributing factors to the fragmentation of the tropical rain forest, a process which alters the function, structure, and composition of ecosystems (Pompa 2008). Floristic studies of tropical rain forest relicts on the coastal plain of the Gulf of Mexico have documented that only 5% of tree species are the same as the species found five decades earlier for this type of vegetation (Reyes-Hernández *et al.* 2009). This tells of the high loss of biodiversity in Mexico through deforestation. On average 17.9 km^2 of tropical rain forest in Mexico is deforested, mainly for agricultural activities. Annual deforestation rates calculated for the Huasteca region range between 0.47 and 4.5%. These rates are higher than those reported for Mexico overall (1.1%) and other tropical regions (Dirzo & Garcia 1991; FRA 2015; Kim *et al.* 2015; Leija-Loredo *et al.* 2011, 2016; Rosete-Vergés *et al.* 2014; Velázquez *et al.* 2002; Wright 2005). Worldwide, tropical rain forest has the highest deforestation rates, averaging 2.56% (FRA 2015; Kim *et al.* 2015; Wright 2005). Deforestation of tropical rain forests in 34 countries was 62% in the period 1990–2000 (Kim *et al.* 2015). During the same period, 60 million hectares of tropical rain forest were lost in Latin America. Brazil lost the most tropical rain forest, at 33%. Asia has also suffered an increased net loss in forest area, decreasing from 350 million ha in 1990 to 318 million ha in 2000. This is a loss of more than 30 million hectares of its original area (Kim *et al.* 2015).

The change in land use has been the result of multifactorial processes that have influenced the loss of forest ecosystems through direct and indirect mechanisms (Lambin *et al.* 2001, 2003). Socioeconomic, political and environmental drivers have enabled an understanding of the processes and patterns of deforestation (Pijanowski *et al.* 2002). Many of the variables change over time but not necessarily in space (Irwin & Geoghegan 2001). In the Huasteca region, spatial variation regarding human population and poverty can be seen. Economic marginalization is a driver that contributes significantly to explaining deforestation rates. The population has increased in general, but there are places where the population has decreased locally due to migration. For the period 2000–2010, the population decrease was approximately 43% in poorer areas such as the municipalities of Chicontepec, Huautla, Chalma, Tamazunchale and Platón Sánchez.

Migration is common and frequent in the Huasteca because towns with greater urban and economic development exercise a strong attraction (CONAPO 2010). Vegetation recovery may be related to the abandonment of agricultural land due to migration (Velazquez *et al.* 2003). However, a positive correlation has also been reported between poverty and deforestation. An aggravating factor is that scarce economic resources contribute to the rapid degradation of newly cultivated land, leading to the continual clearing of new land for agriculture (Muñoz-Piña *et al.* 2003). This process occurs in numerous different regions of tropical countries (Pérez-Verdin *et al.* 2009; Watson *et al.* 2001).

Government policies in Mexico established to support the rural population and economy (PRONASOL, PROCAMPO, etc.) have played an important role in land use change processes in the Huasteca. These programs were oriented towards farmers with small holdings. Later, the programs broadened to finance pasture creation, equipment purchases, rural development, and agricultural mechanization, among others (Martinez & Sarmiento 1996; Reyes-Hernández *et al.* 2003). However, the subsidies granted by the government have had negative effects on vegetation by motivating large-scale deforestation through land clearing carried out to garner increased financial support. This has been reported for other regions of Mexico including the Sierra and coast of Oaxaca (Cortez 2000; Gaytan & González 1997). The rural public policy was not planned and designed with a focus on sustainable development and controlled production in small scale agriculture; rather it lacks vision concerning tropical rain forest conservation.

Forest cover conversion and overgrazing have also caused soil degradation, erosion and mass wasting (slope movement) (Grau *et al.* 2003; Lambin 1997). It has been documented that croplands and human settlements tend to be established in areas with shallow slopes and in the valleys and plains between mountains (Hall *et al.* 1995; Helmer 2003; Laurance 1999). This was not found to be the case throughout the area of the present study; it was confirmed that there were crops and pastures in some areas with slopes exceeding 40°, transforming the tropical rain forest in the region. This explains the occurrence of mass wasting generated by heavy rainfall on the windward side in the Huasteca.

The prospective scenarios predicted that conversion of tropical rain forest to other uses would persist, so the area of the forest will continue to shrink. It was estimated that by 2050 more than 160,000 ha of natural cover will have been lost. Agriculture is the main reason for new land to be cleared, mainly for cultivating corn (maize). Proximity to rivers is the main factor driving the selection of sites for crop agriculture. Expansion of human settlement also influences the creation of new clearings, as it leads to greater demand for natural resources to meet their needs. The dynamics of deforestation involve a relationship between social, economic, political and environmental drivers (Pijanowski *et al.* 2002). It is recommended that projections of land use changes be restricted to the near future. This is because the explanatory variables in the models also change in the short term, leading to modifications in the predictions (Mas *et al.* 2003). For example, a policy supporting rural agriculture that benefits expansion could accelerate forest loss in the medium term.

Conservation of the most northerly tropical rain forest in the Americas involves learning about the dynamic processes affecting vegetation cover and land use, which can be used to generate forecasts of deforestation and biodiversity loss (Guerra-Martínez & Ochoa-Gaona 2006;

Kaimowitz & Agelsen 1998; Priego *et al.* 2004; Velázquez *et al.* 2002). This is consistent with the provisions of the Millennium Ecosystem Assessment (MEA 2005). The present study found that clearing of land for agriculture is the factor causing the most forest loss, so it is necessary to create policies to reduce or avoid increasing cleared land. Action plans should be devised to recover the productive capacity of historical cleared fields and pastures on the plains and flatlands. This would reduce the pressure that leads to clearing new lands in the highland areas and help preserve the last remnants of tropical rain forest. The creation of conservation areas to conserve and protect flora and fauna of the Huasteca tropical rain forest should be considered.

Conclusions

Using SPOT 5 and Landsat satellite imagery from 1990, 2000 and 2015, land use change scenarios were modeled and future projections estimated for the Huasteca region in Mexico with the Dinamica EGO program. This region contains the remnants of the northernmost tropical rain forest in the Americas. During the period 1990–2015, 92,170 hectares of natural vegetation were lost due to the expansion of the agricultural frontier. Tropical rain forests made up 94.5% of this loss. Deforestation rates for tropical rain forest were high, at an average of 1.05%. pastureland increased by over 40 thousand ha and cropland by more than 50 thousand ha. The projection for 2050 predicts that the tropical rain forest would have an area of 155,856 ha, which is only 58.4% of its 1990 area. Other types of vegetation such as cloud forest area would have disappeared by 2050.

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References

Aguilar-Robledo, M. 1997. Indios, ganado, tenencia de la tierra, e impacto ambiental en la Huasteca Potosina, siglos XVI y XVI. Huaxteca. *El hombre y su pasado* **3**: 15–25.

Abuelaish, B. & M. T. Camacho-Olmedo. 2016. Scenario of land use and land cover change in the Gaza Strip using remote sensing and GIS models. *Arabic Journal Geoscience* **9**: 274, 1–14.

Bonham-Carter, G. F. 1994. *Geographic Information Systems for Geoscientists. Modeling with GIS*. Pergamon. Tarrytown, New York.

Boege, E. 2008. Construyendo las regiones bioculturales prioritarias para la conservación in situ y el desarrollo sostenible. pp. 136–157. *In*: *El Patrimonio Biocultural de los Pueblos Indígenas de México*. INAH, CDI. México.

Bonilla-Moheno, M., T. M. Aide & M. L. Clark. 2012. The influence of socioeconomic, environmental, and demographic factors on municipality-scale land-use/land-cover change in Mexico. *Regional Environmental Change* **12:** 543–557.

Cortez, R. C. 2000. Inseguridad alimentaria, pobreza y deterioro ambiental en el marco de la globalización. pp 39-59. *In*: E. Cortés (ed.) *Sector agropecuario y alternativas comunitarias de segundad alimentaria y nutrición en México*. Plaza y Valdez, México.

Carpenter S. R., H. A. Mooney, A. John, D. Capistrano, R. S. DeFries, S. Díaz, T. Dietz, A. K. Duraiappah, A. Oteng-Yeboah, H. M. Pereira, C. Perringsk, W. V. Reidl, J. Sarukhanm, R. J. Scholesn & A. Whyte. 2009. Science for managing ecosystem services: beyond the millennium ecosystem assessment. *Procedings of the National Academy of Sciences U.S.A.* 106**:** 1305–1312.

CONAPO. 2010. *Consejo Nacional de Población. Secretaria de Gobernación. México*. http://www.conapo.gob.mx/es/CONAPO/2010

Dirzo, R. & M. C. García. 1991. Rates of deforestation in Los Tuxtlas a neotropical area in southeast Mexico. *Conservation Biology* **6:** 84–90.

FAO. 1996. *Forest Resources Assessment 1990*: *Survey of Tropical Forest Cover and Study of Change Processes*. FAO Forestry Paper 140, FAO, Rome.

Forester, D. J. & G. E. Machilis. 1996. Modeling human factors that affect the loss of biodiversity. *Conservation Biology* **10:** 1253–1263.

Foley, J. A., R. DeFries, P. G. Asner, C. Barford, G. Bonan, S. R. Carpenter, F. S. Chapin, *et al.* 2005. Global consequences of land use. *Science* **309:** 570–574.

FRA. 2015. *Evaluación de los Recursos Forestales Mundiales*. Organización de las Naciones Unidas para la Alimentación y la Agricultura. Compendio de datos. Rome.

Goodchild, M. F. 1994. Integrating GIS and remote sensing for vegetation analysis and modeling:

methodological issues. *Journal of Vegetation Science* **5:** 615–626.

Gaytán, H. M. & R. R. González. 1997. La unión de comunidades Kyat-nuu y el problema del financiamiento. *Cuadernos Agrarios* **15:** 94–115.

Geist, H. J. & E. F. Lambin. 2002. Proximate causes and underlying driving forces of tropical deforestation. *Bioscience* **52:** 143–150.

Grau, H. R., T. A. Mitchell, J. K. Zimmerman, J. R. Thomlinson, E. Helmer & Z. Xioming. 2003. The ecological consequences of socioeconomic and land-use changes in post agriculture Puerto Rico. *Bioscience* **12:** 1159–1168.

Guerra-Martínez, V. & S. Ochoa-Gaona. 2006. Evaluación espacio-temporal de la vegetación y uso del suelo en la reserva de la biosfera Pantanos de Centla, Tabasco (1990–2000). *Investigaciones Geográficas* **59:** 7–25.

Godoy, M. M. G. & B. S. Soares-Filho. 2008. Modelling intra-urban dynamics in the Savassi Neighbourhood, Belo Horizonte city, Brazil. pp. 319–339. *In*: M. Paegelow & M. T. Camacho-Olmedo (eds.) *Prospective Modelling Environmental Dynamics*. Springer-Verlag, Berlin.

Guevara, S. 2001. Presentación. pp**.** 1–6. *In:* L. Hernández (ed.) *Historia Ambiental de la Ganadería en México***.** Instituto de Ecología, A.C. Xalapa, México.

Guevara, S. & A. Lira-Noriega. 2011. De los pastos de la selva a la selva de los pastos: la introducción de la ganadería en México. *Pastos* **34:** 109–150.

Hall, C. A. S., H. Tian, Y. Qi, G. Pontius & J. Cornell. 1995. Modelling spatial and temporal patterns of tropical land use change. *Journal* of *Biogeography* **22:** 753–757.

Hagen, A. 2003. Fuzzy set approach to assessing similarity of categorical maps. *Science* **17:** 235–249.

Helmer, E. H. 2003. Forest conservation and land development in Puerto Rico. *Landscape Ecology* **1:** 29–40.

Irwin, E. G. & J. Georghegan. 2001. Theory, data, methods: Developing spatially explicit economic models of land use change. *Agriculture*, *Ecosystem & Environment* **85:** 7–23.

INEGI. 2013. *Conjunto Nacional de uso de Suelo y Vegetación: Escala 1:250 000 (vectorial).* Serie V. DGG-INEGI. México.

Kaimowitz, D. & A. Angelsen. 1998. *Economic Models of Tropical Deforestation: A Review.* Center for International Forestry Research (CIFOR), Bogor, Indonesia.

Kim, D. H., J. O. Sexton & J. R. Townshend. 2015. Accelerated deforestation in the humid tropics from the 1990s to the 2000s. *Geophysical Research Letters* **42:** 3495–3501.

Lambin, E. F. 1997. Modelling and monitoring land-cover change processes in tropical regions. *Progress in Physical Geography* **3:** 375–393.

Laurance, E. F. 1999. Reflections on the tropical deforestation crisis. *Biological Conservation* **91:** 109–117.

Lambin, E. F., B. L. Turner, H. J. Geist, S. B. Agbola, A. Angelsen, J. W. Bruce, O. T. Coomes, *et al.* 2001. The causes of land-use and land-cover change: moving beyond the myths. *Global Environmental Change* **11:** 261–269.

Lambin, E. F., H. J. Geist & E. Lepers. 2003. Dynamics of land-use and land-cover change in tropical regions. *Annual Review of Environment & Resources* **28:** 205–241.

Leija-Loredo, E. G., H. Reyes-Hernández, J. Fortanelli & G. Palacio. 2011. Situación actual del bosque de niebla en el estado de San Luis Potosí. *Investigación y Ciencia* **53:** 3–11.

Leija-Loredo, E. G., H. Reyes-Hernández, O. Reyes-Pérez, J. L. Flores-Flores & F. J. S. Sahagún. 2016. Cambios en la cubierta vegetal, usos de la tierra y escenarios futuros en la región costera del estado de Oaxaca, México. *Madera y Bosques* **22:** 125–140.

Martínez, B. E. & S. S. Sarmiento. 1996. *Campesinos e Indígenas Ante Los Cambios de la Política Social, en las Políticas Sociales de México en los años Noventa.* Instituto Mora-UANAM-FLACSO, Plaza y Valdez, México.

Mas, J. F., J. Reyes & A. Pérez. 2003. Evaluación de la confiabilidad temática de mapas o de imágenes clasificadas: una revisión. *Boletín del Instituto de Geografía, UNAM* **51:** 53–72.

Muñoz-Piña, C., G. Alarcón, J. C. Fernández & L. Jaramillo. 2003. *Pixel Patterns of Deforestation in Mexico.* INE-SEMARNAT, México.

Mas, J. F. 2005. *Change Estimates by Map Comparison: a Method to Reduce Erroneous Changes due to Positional Error. Instituto de* Geografía, Unidad Foránea Morelia, UNAM, Mexico.

MEA. 2005. *Millennium Ecosystems Assessment. Ecosystems and Human Well-Being: Synthesis.* Island Press, Washington, DC.

Mas, J. F., A. Velázquez & S. Couturier. 2009. La evaluación de los cambios de cobertura/uso del suelo en la República Mexicana. *Investigación Ambiental* **1:** 23–39.

Munsi, M., S. Malaviya, G. Oinam & P. K. Joshi. 2010. A landscape approach for quantifying land-use and land-cover change (1976–2006) in middle Himalaya. *Regional Environmental Change* **10:** 145–155.

Mas, J. F. & A. Flamenco-Sandoval. 2011. Modelación de los cambios de coberturas/uso del suelo en una región tropical de México. *GeoTropico* **1:** 1–24.

Puig, H. 1991. *La Vegetación de la Huasteca México.* Instituto de Ecología A. C., Centre D´études mexicaines et centraméricaines (CEMCA). México, D. F.

Pijanowski, B. C., D. G. Brown, B. A. Shellito & G. A. Manik. 2002. Using neural networks and GIS to forecast land use changes: A Land Transformation Model. *Computers, Environment and Urban Systems* **26:** 553–576.

Priego-Santander, A. G., H. Morales-Iglesias & C. E. Guadarrama. 2004. Paisajes físico-geográficos de la cuenca Lerma Chapala, México. *Gaceta Ecológica* (Nueva época) **71:** 11–22.

Pompa, M. 2008. Análisis de la deforestación en ecosistemas montañosos del noroeste de México. *Avances en Investigación Agropecuaria* **2:** 35–43

Perez-Verdin, G., Y. S. Kim, D. Hospodarsky & A. Tecle. 2009. Factors driving deforestation in common pool resources in northern Mexico. *Journal of Environmental Management* **90:** 331–340.

PNUD. 2012. *Programa de las Naciones Unidas para el Desarrollo*. Informe Anual 2011/2012. El futuro sostenible que queremos.

Rzedowski, J. 1978. *Vegetación de México*. Limusa, México.

Reyes-Hernández, H., S. Cortina-Villar, R. H. Perales, M. E. Kauffer & F. J. M. Pat. 2003. Efecto de los subsidios agropecuarios y apoyos gubernamentales sobre la deforestación durante el periodo 1990–2000 en la región de Calakmul, Campeche, México. *Investigaciones Geográficas* **51:** 88–106.

Reyes-Hernández, H., L. Olvera-Vargas, F. J. Sahagún-Sánchez & J. F Mas. 2009. Transformation of the forest cover and future scenarios in the Sierra Madre Oriental, physiographic region, San Luis Potosí, México ISRSE 33. *33 International Symposium on Remote Sensing of Environment. Sustaining the Millennium Development Goals.* http://isrse-33.jrc.ec.europa.e.

Ruiz, V., R. Savé & A. Herrera. 2013. Análisis multitemporal del cambio de uso del suelo, en el paisaje terrestre protegido Miraflor Moropotente Nicaragua, 1993–2011. *Ecosistemas* **22:** 117–123.

Rosete-Vergés, F. A., J. L. Pérez-Damián, M. Villalobos-Delgado, E. N. Navarro-Salas, E. Salinas-Chávez & R. Remond-Noa. 2014. El avance de la deforestación en México 1976–2007. *Madera y Bosques* **20:** 21–35.

Sala, O. E., F. S. Chapin III, J. J. Armesto, E. Berlow, J. Bloomfield, R. Dirzo, E. Huber-Sanwald, *et al.* 2000. Global biodiversity scenarios for the year 2100. *Science* **287:** 1770–1774.

Soares-Filho, B. S., C. L. Pennachin & G. Cerqueira. 2002. DINAMICA a stochastic cellular automata model designed to simulate the landscape dynamics in an Amazonian colonization frontier. *Ecological Modelling* **154:** 217–235.

Soares-Filho, B. S., A. Alencar, D. Nepstad, G. Cerqueira, M. C. Vera-Díaz, S. Rivero, L. Solórzanos & E. Voll. 2004. Simulating the response of land cover changes to road paving and governance along a major Amazon highway. The Santarem-Cuiabá corridor. *Global Change Biology* **10:** 745–764.

Soares-Filho, B. S., D. Nepstad, L. M. Currant, G. C. Cerqueira, A. R. García, C. A. Ramos, E. Voll, *et al.* 2006. Modelling conservation in the Amazon basin. *Nature* **440:** 520–532.

Stork, N. E., J. A. Coddington, R. K. Colwell, R. L. Chazdon, C. W Dick, C. A. Peres, S. Sloan & K. Willis. 2009. Vulnerability and resilience of tropical forest species tool and use change. *Conservation Biology* **23:** 1438–1427.

Santiago, M. 2011. The Huasteca rain forest. *Lattin American Research Review* **46:** 32–54.

Sahagún, J., H. Reyes-Hernández, J. L. Flores & L. Chapa. 2011. Modelización de escenarios de cambio potencial en la vegetación y uso de suelo en la Sierra Madre Oriental de San Luis Potosí, México. *Journal of Latin American Geography* **2:** 65–86.

Stéphenne, N. & E. F. Lambin. 2001. A dynamic simulation model of land-use changes in Sudano-sahelian countries of Africa (SALU). *Agriculture, Ecosystems & Environment* **85:** 145–161.

Toledo, V. M. 1990. El proceso de ganaderización y la destrucción biológica y ecológica en México. pp. 191–227. *In*: E. Leff (ed.) *Medio ambiente y desarrollo en México*. Centro de Investigaciones Interdisciplinarias en Humanidades. Universidad Nacional Autónoma de México, México.

Velázquez, A., J. F Mas & J. L. Palacio-Prieto. 2002. *Análisis del cambio de uso del suelo, mapas del análisis del cambio de uso del suelo. Instituto de Geografía, UNAM.* Secretaría de Medio Ambiente y Recursos Naturales, Instituto Nacional de Ecología, Mexico.

Velázquez, A., E. Duran, I. Ramírez, J. F. Mas, G. Bocco, G. Ramírez & J. L. Palacio-Prieto. 2003. Land use-cover change processes in highly biodiverse areas: the case of Oaxaca, Mexico. *Global Environmental Change* **13:** 175–184.

White, R. & G. Engelen. 2000. High resolution integrated modelling of the spatial dynamics of urban and regional systems. C*omputer, Environment and Urban Systems* **24:** 383–400.

Watson, R. T. , I. R. Noble, B. Bolin, N. H. Ravindranath, D. J. Verardo & D. J. Dokken. 2001. *Land use, Land Use Change, and Forestry*. Cambridge University Press, UK.

Wright, J. S. 2005. Tropical forests in a changing environment. *Ecology and Evolution* **20:** 553–560.

Weng, Q. 2010. *Remote Sensing and GIS Integration: Theories, Methods, and Applications*. McGraw-Hill, New York.

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