Deforestation and Trends of Change in Protected Areas of the Usumacinta River Basin (2000–2018), Mexico and Guatemala

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Abstract

Deforestation is one of the processes that most impact the functioning of terrestrial ecosystems. In Mexico and Guatemala, deforestation continues to increase at alarming rates, but there are still regions where extended areas of conserved vegetation persist, such as the Usumacinta river basin. Throughout history, various Protected Areas (PA) have been designated in this basin; however, anthropogenic activities put its natural heritage at risk. This research aimed to analyze the current status and process of forest cover loss in the region and compare it within and outside PA, as well as among different PA administrations. In 2000, 75 % of the basin's area was covered by some type of tree-dominated plant community. Over the following 18 years, this area was reduced by 27 %. Most of this forest loss occurred in Guatemalan territory. Although the net forest loss was higher in unprotected areas than in protected areas in Guatemala, the opposite pattern was observed in terms of the annual rate of forest loss. In the case of Mexico, forest loss was higher in unprotected areas in terms of both net forest loss and annual rates. Additionally, in both countries, PA under the administration of municipal authorities showed the lowest forest loss rates. This study showed that deforestation is an ongoing process in the Usumacinta basin with a heterogeneous spatial distribution, where PA have had different capabilities in helping conserve its forest cover. This information will be essential for binational conservation strategies aimed at preserving forest connectivity in the region.

Keywords

Mexico, Guatemala, loss of vegetation, tropical forest, evergreen tropical forest

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Introduction

Deforestation is one of the processes that most impacts the functioning of terrestrial ecosystems (Sugden 2018). This process substantially decreases primary production and interacts with other factors of global change, provoking the deterioration of social-ecological systems (Schoene et al. 2007). Among the most important effects of deforestation are biodiversity loss (Giam 2017), habitat fragmentation, modified water cycle (Patarkalashvili 2019), altered soil properties, decreased food security (Pimentel et al. 1997), altered ecosystem services, and changes in population dynamics (Rosa et al. 2016).

In Mexico and Guatemala, the two countries where the Usumacinta River basin is located, deforestation continues to advance at alarming rates. In the first 12 years of the 21st century, Mexico lost about 24 000 km^2 of forest cover, while Guatemala lost around 8 800 km^2 of forest cover (Hansen et al. 2013). This data ranks Mexico in the 15th position out of 180 countries with most net forest loss, while Guatemala ranks in the 34th place (Hansen et al. 2013). Although all terrestrial ecosystems in both countries are affected by deforestation, its distribution and its causal processes are very heterogeneous (Hodgdon et al. 2015; Secretaría del Medio Ambiente y Recursos Naturales [SEMARNAT] 2016). Indeed, two types of land areas can be differentiated according to their degree of transformation. The first and most common one consists of a land transformation that has led to the complete removal of forest cover, or it has been so severe that its original features have disappeared (Sánchez Colón et al. 2009). On the second type of transformation, vegetation has been slightly disturbed and thus, most of its original features are maintained. These areas should be included as conservation priorities for both countries (Arriaga-Cabrera et al. 2000). The Usumacinta river basin provides a clear example of such slight disturbed conditions. This drainage basin supports one of the continent’s best-preserved tropical rainforest massifs (≥ 3000 km^2), as well as one of Mesoamerica's main wetland areas (March-Misfut and Castro 2010; Carabias et al. 2015). Given its importance in terms of biodiversity and ecosystem services, various Protected Areas (PA) have been designated in this basin in order to preserve the region's biodiversity; most of them were declared between the 1950's and 1990's (Comisión Centroamericana de Ambiente y Desarrollo [CCAD] 2003; SEMARNAT and Comisión Nacional de Áreas Naturales Protegidas [CONANP] 2016).

PA are the central instrument for biodiversity conservation policies at both national and international level (Dudley 2008; Porter-Boland et al. 2012). The International Union for Conservation Nature [IUCN] defined PA as areas of land and/or sea especially dedicated to the protection and maintenance of biological diversity (IUCN 1994). In Mexico and Guatemala, the particular definition of PA and their different categories are set out in their corresponding environmental laws (see Methods section).

Around the world, particularly in the tropics, PA are under serious threat due to the pressures exerted by anthropogenic activities (Carey et al. 2000; Chape et al. 2005; Joppa et al. 2008; Cuevas et al. 2010). Thus, PA, as a conservation instrument, have been strongly criticized regarding their effectiveness in achieving the objectives stated in the underlying laws (Carey et al. 2000; Bray and Velazquez 2009; Gaveau et al. 2012). One of the most frequently cited arguments is that PA, which are conceived as "islands of untouched nature," are not immune to deterioration processes (e.g., deforestation, climate change, species extraction) that occur outside their boundaries (Hannah et al. 2002; Thomas et al. 2004; Naughton-Treves 2005; Toledo 2005). Some authors report that the effectiveness of a PA system relies heavily on the social matrix in which it occurs (e.g. Duran-Medina et al. 2005; Brechin 2003; Bray et al. 2008; Hodgdon et al. 2015), and call for a shift of paradigm that incorporates new ideas in the conceptualization, design and management of PA that consider emerging environmental concerns and different socioeconomic contexts (Phillips 2003; Lovejoy 2006; Miller et al. 2011).

In the center of the debate rests the need of measuring the conservation effectiveness of the existing network of PA (Chape et al. 2005; Locke and Dearden 2005; Figueroa et al. 2011). The analysis of the PA effectiveness based on systematic assessment frameworks that allow identifying strengths and weaknesses (Andam et al. 2008; Rodríguez et al. 2013) is crucial to make policy recommendations to strengthen the conservation scheme (Porter-Bolland et al. 2012; Schleicher et al. 2017; Burivalova et al. 2019). One assessment framework commonly employed is the analysis of ecological integrity, using indicators that quantify deforestation within and outside PA boundaries based on remote sensing techniques (González-Roglich et al. 2012). These methods allow to cover large areas of land, to study the spatial patterns of deforestation and to understand how the process has evolved over time. Quantifying deforestation provides a direct measurement of the capacity of PA to maintain the necessary conditions for the survival of the ecosystems they protect (Nagendra et al. 2013; Gillespie et al. 2015) and to assess the progress made towards reaching certain Sustainable Development Goals (UN General Assembly 2015).

In this respect, the purposes of this research were: 1) to analyze the current status and process of forest cover loss in the Usumacinta river basin, 2) to evaluate this loss within and outside the PA, as a mean to assess the PA conservation effectiveness and 3) to analyze forest cover loss between types of administration and categories of PA to detect differences among institutional contexts. It is important to note that this is the first effort to include all the PA under the jurisdiction of Mexico and Guatemala, and to analyze deforestation within and outside PA on an annual basis in a recent period (2000–2018).

Methods

Study area

The Usumacinta river basin is an area of geostrategic importance to both Mexico and Guatemala, as it supports the greatest biodiversity of the region and provides a wide range of environmental services. This basin is located in the central part of Mesoamerica and it covers an area of 77 435 km^2, of which 44 % (34 237 km^2) lies in Mexico, 56 % (43 167 km^2) in Guatemala, and the remaining 0.04 % (32 km^2) in Belize (Saavedra-Guerrero et al. 2015). The Mexican part of the basin covers 30 municipalities, in the states of Chiapas, Tabasco and Campeche (García and Kauffer 2011), while its Guatemalan equivalent lies in the departments of Huehuetenango, Quiché, Alta Verapaz and Petén (Cruz-Paz et al. 2018).

The flow of the Usumacinta river — after which the basin is named — is the highest in Mexico and Mesoamerica (Comisión Nacional del Agua [CONAGUA] 2014). Throughout the basin, rivers form a very dynamic and complex network that keeps ecological processes functioning and allows productive activities to take place (García and Kauffer 2011; Sánchez et al. 2015). The main plant communities found in the basin are: wetland vegetation (halophyte grassland and shrubland, seasonally flooded grassland and shrubland, flooded grassland, seasonally flooded forest, flooded forest), temperate forest (oak forest and coniferous forest), tropical forest (evergreen tropical forest, semi-evergreen tropical forest and deciduous tropical forest), as well as very diverse vegetation types created by human activities (induced pasture, agricultural fields, secondary vegetation; Fernández-Montes de Oca et al. 2015; Vaca et al. 2019).

The Usumacinta river basin has a long and complex history of human settlement (Toledo 2003; De Vos 2002; Trench 2014). Nowadays, the basin is characterized by a poor economy, a highly marginalized population (Vásquez-Sánchez et al. 1992; Rodríguez-Aldabe and Rodríguez-Aldabe 2015), and constantly invaded PA, which put the region's ecological and social equilibrium at risk.

Information sources

To analyze the spatio-temporal patterns of deforestation within and outside PA boundaries in the Usumacinta basin, two information sources were used: the officially established PA polygons and deforestation data from Hansen et al. (2013), which was updated for 2018.

Protected Areas in the Usumacinta river basin

In Mexico, the definition of PA and its corresponding categories, as well as their objectives and boundaries, are set out in the General Law of Ecological Equilibrium and Environmental Protection (Ley General del Equilibrio Ecológico y la Protección al Ambiente [LGEEPA], SEMARNAT 2003). The LGEEPA specifies the responsibilities for creating PA and ensuring their preservation in Mexico. These responsibilities may apply to public, communal as well as private land (SEMARNAT 2003). The Mexican federal law recognizes six categories of PA: Biosphere Reserves, National Parks, Natural Monuments, Natural Resource Protection Areas, Flora and Fauna Protection Areas, and Nature Sanctuaries. Three categories of PA are also recognized outside the federal sphere: Federated State Protected Areas, Municipal Ecological Conservation Areas, and Voluntary Conservation Areas at local scale (SEMARNAT 2003). The National Commission of Protected Areas (Comisión Nacional de Áreas Protegidas [CONANP]) administrates all federal PA in Mexico, while state and municipal governments manage those under their legal field of competence. Finally, Voluntary Conservation Areas are operated by individual or communitarian land owners. Therefore, three levels of government as well as local stakeholders are involved in the PA management.

In Guatemala, the operational principles and mechanisms for creating PA are set out in the Law on Protected Areas (Ley de Áreas Protegidas [Decree 4-89]; Congreso de la República de Guatemala 1989). This law establishes the following categories of PA: National Parks, Protected Biotopes, Biosphere Reserves, Multiple Use Reserves, Forest Reserves, Biological Reserves, Springs, Resource Reserves, Natural Monuments, Cultural Monuments, Scenic Paths and Roads, Marine Parks, Regional Parks, Historical Parks, Wildlife Refuges, Natural Recreation Areas, and Private Natural Reserves. Although all PA in Guatemala are registered into a single system called Guatemalan System of PA (Sistema Guatemalteco de Áreas Protegidas [SIGA]), each PA may be managed by either a government entity (national or municipal), an educational institution (the Universidad de San Carlos de Guatemala), an NGO ("Defensores de la Naturaleza"), or a landowner. Nevertheless, part of an increasing number of PA are managed by private owners out of SIGA and only integrated through the Private PA Association of Guatemala (Asociación de Reservas Naturales Privadas de Guatemala [ARPG]). The administration of the Guatemalan PA is conducted by eight different institutions or actors: National Council for Protected Areas (*Consejo Nacional de Áreas Protegidas*, [CONAP]), Institute of Anthropology and History (*Instituto de Antropología e Historia* [IDAEH]), National Forest Institute (*Instituto Nacional de Bosques* [INAB]), Ministry of Culture and Sports (*Ministerio de Cultura y Deportes* [MCD]), Municipality (M), University System of Protected Areas (*Sistema Universitario de Áreas Protegidas* [USPA]), "Defensores de la Naturaleza" [DN] and Private Natural Reserve (*Reserva Natural Privada* [RNP]).

Overall, Mexican and Guatemalan PA cover 34 % of the basin's total area (Fig. 1), with a larger proportion of Guatemala's territory being under some protection scheme compared with Mexico (38 % versus 30 %). In Belize, there are no PA within the basin's boundaries. In the Mexican side, 28 PA are wholly or partly contained within the Usumacinta river basin, corresponding to eight PA categories: Flora and Fauna Protection Areas, Biosphere Reserves, National Parks, Natural Monuments, Areas Subject to Ecological Conservation, Urban Parks, Natural and Typical Area and Voluntary Conservation Areas. In the Guatemalan side, 86 PA can be found within the basin limits, corresponding to eight different categories: Protected Biotopes, Cultural Monuments, National Parks, Municipal Regional Parks, Biological Reserves, Biosphere Reserves, Wildlife Refuges and Private Natural Reserves. The complete list of PA can be consulted in Tables 2 (Mexico) and 3 (Guatemala).

Data on deforestation in the Usumacinta river basin

The spatio-temporal patterns of deforestation in the Usumacinta basin were analyzed using the Global Forest Watch dataset (also referred to as Global Forest Change, Hansen et al. 2013). In this dataset, the annual loss of forest cover was calculated using a decision tree algorithm that compared data from bands in Landsat 5, 7 and 8 satellite images with calibrated data on worldwide forest cover from Quickbird and tree cover (%) layers from Landsat and Moderate Resolution Imaging Spectroradiometer (MODIS) sensors. Deforested sites were classified according to annual Normalized Difference Vegetation Index (NDVI) metrics, which included minimum, maximum, percentiles, bicentiles, and the slope of the temporal trend. This method solely focuses on detecting total replacement of forest cover (i.e., from an initial condition of > 10 % forest cover to ~ 0 % forest cover) in forests with a height greater than 5 m. The detailed procedure and data are available in Hansen et al. (2013). Previous studies have shown that this data source can be used to give a good approximation of national forest loss estimates (Blankespoor et al. 2017; Mildowski et al. 2017; Galiatsatos et al. 2020). In this study, the term deforestation was used as the loss of forest cover, whether it implied forested regrowth (secondary forest or plantations) or not.

Data analysis

In order to quantify deforested area during the 2000–2018 period, the information sources described above were spatially overlapped. In addition, the total forest change was quantified in the following 5 sets: 1) deforestation of unprotected area by country; 2) deforestation of protected area by country; 3) deforestation by PA administrative institution or actor; 4) category of PA in both Mexico and Guatemala and, 5) deforestation by PA. Finally, annual variation in forest loss was analyzed in protected versus unprotected areas both in Mexico and in Guatemala. Additionally, the annual rate of forest loss was calculated for all the previous sets as (Puyravaud 2002):

$$q = \left(\frac{A_2}{A_1}\right)^{1/(t_2-t_1)} - 1 \qquad (1)$$

Where A_2 corresponds to the forested area in time 2 (t_2) and A_1 to forested area in time 1 (t_1).

Results

In the year 2000, 75 % (5 776 038 ha) of the Usumacinta river basin's total area was covered by some type of tree-dominated plant community. Over the following 18 years, this area was reduced by 27 % (1 577 104 ha; q = -1.76 %). Forest loss followed a highly heterogeneous spatio-temporal pattern, reflecting political differences between Mexico and Guatemala, as well as different local conditions. These variations are described in the following paragraphs.

Total deforestation of unprotected area

In 2000, there were 3 736 682 ha of forest cover outside the PA boundaries in the Usumacinta river basin, of which 55 % lied in Guatemala and 45 % in Mexico. Over the following 18 years, total forest cover outside PA was reduced by 27% (996 821 ha; q = -1.71 %), leaving a total of 2 739 861 ha of forested cover. The proportion of forest lost was not the same in the two countries: Guatemala lost 29% (q = -1.88 %) of unprotected forest, while Mexico lost 24 % (q = -1.50 %, Table 1; Fig. 1).

Table 1. Area with forest cover in the year 2000, forest loss and annual rate of forest loss in both, protected and unprotected areas, in the Usumacinta River basin (2000–2018).

	Total Unprotected Area				Total Protected Area			
Country	Forest Cover 2000 (ha)	Forest loss (ha)	Forest loss (%)	Annual rate of forest loss (%)	Forest Cover 2000 (ha)	Forest loss (ha)	Forest loss (%)	Annual rate of forest loss (%)
Guatemala	2063212.7	597782.8	29.0	-1.88	1427749.8	533897.9	37.4	-2.57
Mexico	1670306.5	398882.1	23.9	-1.50	611605.7	46385.7	7.6	-0.44
Belize	3162.9	156	4.9	-0.28	0	0	0	0

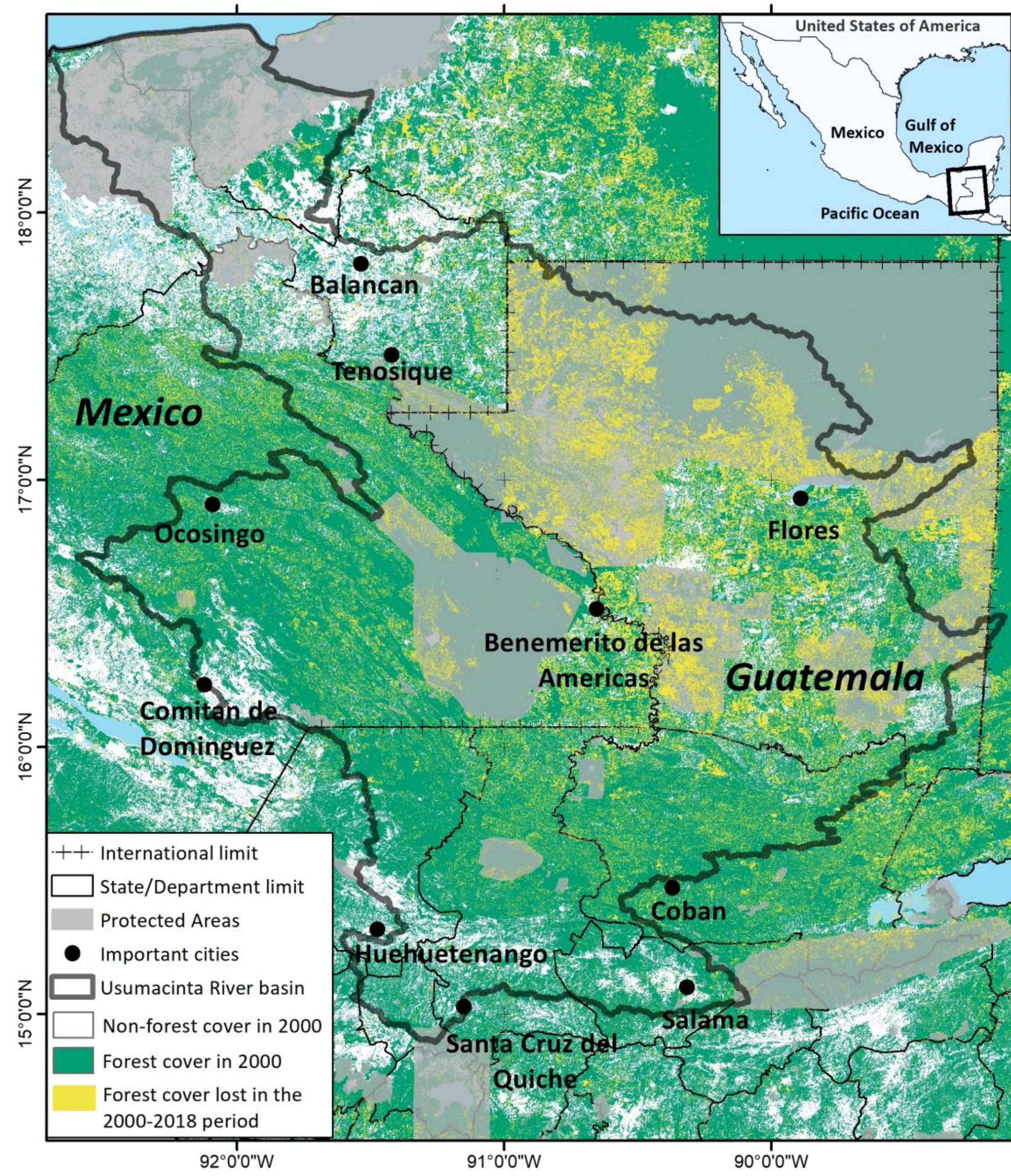

Fig. 1 Protected areas location and loss of forest cover in the Usumacinta river basin (2000–2018). Spatial resolution: 30 × 30 m/pixel. Geographic coordinate system: WGS 84. Source: Hansen et al. (2013), Mexico's Instituto Nacional de Estadística y Geografía (INEGI) and Guatemala's Instituto Geográfico Nacional (IGN).

Total deforestation of protected area

At the beginning of the analyzed period, the Usumacinta basin included 2 039 356 ha of forest cover within the PA boundaries. Most of these forests (70 %) were located in Guatemala, and the remaining 30 % in Mexico. Total forest area within PA was reduced by 28 % (q = -1.84; 580 284 ha) during the 2000–2018 period. In this case, the difference between the two countries was very large: while Guatemala lost 37 % (q = -2.57 %) of protected forest, Mexico lost 8 % (q = -0.44 %; Table 1).

Deforestation by type of Protected Areas administration

In Mexico, the PA with the largest area of forest cover were the federal ones, followed by the federated state, voluntary and municipal PA, respectively (Table 2). Of these PA categories, those with the largest percentage of forest loss were the federated state ones (21 %; q = -1.28 %), followed by the federal (7 %; q = -0.42 %), the voluntary (3 %; q = -0.17 %) and the municipal PA, which showed no forest loss (Table 2).

Table 2. Loss of forest cover and annual rate of forest loss in Mexican Protected Areas in the Usumacinta River basin (2000–2018). Forest Cover 2000: area covered by some type of forest in the year 2000. NM: Natural Monument. FFPA: Flora and Fauna Protection Area. BR: Biosphere Reserve. NP: National Park. ASEC: Area Subject to Ecological Conservation. ER: Ecological Reserve. NTA: Natural and Typical Area. UP: Urban Park. VCA: Voluntary Conservation Area. Administration: the level of government responsible for managing this Protected Natural Area in Mexico.

Protected Area	Category – Administration	Forest Cover 2000 (ha)	Forest loss (ha)	Forest loss (%)	Annual rate of forest loss (%)

Bonampak	NM – Federal	4360.52	0.90	0.02	0.00
Cañón del Usumacinta	FFPA – Federal	39423.56	8271.00	20.98	-1.30
Chan-Kin	FFPA – Federal	12178.59	455.10	3.74	-0.21
Lacantún	BR – Federal	61115.58	3188.35	5.22	-0.30
Laguna de Términos	FFPA – Federal	92962.59	3010.85	3.24	-0.18
Lagunas de Montebello	NP – Federal	5028.21	209.06	4.16	-0.24
Metzabok	FFPA – Federal	283.93	0.00	0.00	0.00
Montes Azules	BR – Federal	321105.18	27010.23	8.41	-0.49
Nahá	FFPA – Federal	380.05	26.04	6.85	-0.39
Palenque	NP – Federal	21.70	1.09	5.00	-0.28
Pantanos de Centla	BR – Federal	49323.10	648.61	1.32	-0.07
Yaxchilán	NM – Federal	2576.18	4.07	0.16	-0.01
Total Federal	**–**	***588759.21***	***42825.31***	***7.27***	**-0.42**
Bosques de Coníferas de Chanal	NTA – State	3855.32	1402.39	36.38	-2.48
Cascadas de Reforma	ER – State	3185.91	481.96	15.13	-0.91
Humedales La Libertad	ASEC – State	2481.15	434.76	17.52	-1.06
Sistema Lagunar Catazajá	ASEC – State	7068.09	1124.24	15.91	-0.96
Total State	**–**	***16590.47***	***3443.35***	***20.75***	**-1.28**
Carmen Yaxchuch	UP – Municipal	0.00	0.00	0.00	0.00
Lázaro Cárdenas	UP – Municipal	1.10	0.00	0.00	0.00
San Jerónimo Tulijá	UP – Municipal	0.90	0.00	0.00	0.00
Total Municipal	**–**	***2.00***	***0.00***	***0.00***	**0.00**
Unnamed	VCA	1572.93	54.80	3.48	-0.20
Unnamed	VCA	275.16	11.12	4.04	-0.23
Unnamed	VCA	88.89	3.16	3.56	-0.20
Unnamed	VCA	7.14	0.36	5.06	-0.29

Unnamed	VCA	66.64	0.00	0.00	0.00
Unnamed	VCA	1546.25	34.54	2.23	-0.13
Unnamed	VCA	207.70	12.30	5.92	-0.34
Unnamed	VCA	7.87	0.72	9.20	-0.53
Total VCA	**–**	***3772.58***	***117.01***	***3.10***	***-0.17***

In Guatemala, the PA managed by the CONAP had the largest area covered by forest in 2000 (1 116 073 ha), followed by those managed by the NGO “Defensores de la Naturaleza” (186 048 ha) and the USPA (74 700 ha). Of these PA categories, the greatest percentage of forest loss for the period analyzed occurred in those managed by the CONAP (41 % of forest area, q = -2.90 %), followed by those managed by the MCD (31 % of forest area, q = -2.05 %) and USPA (29 % of forest area, q = -1.91 %), respectively. It is important to highlight that the PA managed by the INAB and municipal governments registered the smallest forest loss (5 % and 4 % of forest area and q = -0.31 % and -0.23 % respectively; Table 3).

Table 3. Loss of forest cover and annual rate of forest loss in Guatemalan Protected Areas in the Usumacinta River basin (2000–2018). Forest Cover 2000: area covered by some type of forest in the year 2000. PB: Protected Biotope. CM: Cultural Monument. NP: National Park. MRP: Municipal Regional Park. WR: Wildlife Refuge. BiolR: Biological Reserve. BiosR: Biosphere Reserve. PNR: Private Natural Reserve. USPA: University System of Protected Areas. IDAEH: Institute of Anthropology and History. INAB: National Forest Institute. CONAP: National Council for Protected Areas. MCD: Ministry of Culture and Sports. DN: “Defensores de la Naturaleza”. M: Municipality. Administration: the individual or legal person responsible for managing this Protected Area in Guatemala.

Protected Area	Category – Administration	Forest Cover 2000 (ha)	Forest loss (ha)	Forest loss (%)	Annual rate of forest loss (%)
Cerro Cahuí	PB – USPA	721.90	2.20	0.30	-0.02
Laguna del Tigre–Río Escondido	PB – USPA	43708.20	20920.70	47.90	-3.55
Mario Dary Rivera	PB – USPA	151.00	1.20	0.80	-0.04
San Miguel la Palotada–El Zotz	PB – USPA	30119.20	980.10	3.30	-0.18
Total USPA	**–**	***74700.30***	***21904.20***	**29.30**	**-1.91**
Aguateca	CM – IDAEH	1591.40	1358.40	85.40	-10.13
Ceibal	CM – IDAEH	1417.70	92.70	6.50	-0.37
Dos Pilas	CM – IDAEH	2994.70	1912.00	63.80	-5.50
Tikal	NP – IDAEH	9564.10	7.80	0.10	0.00
Total IDAEH	**–**	***15567.90***	***3370.90***	**21.70**	**-1.35**
El Rosario	NP – INAB	1074.30	35.30	3.30	-0.19
Laguna Lachuá	NP – INAB	13833.30	766.60	5.50	-0.32
Total INAB	**–**	***14907.60***	***801.90***	**5.40**	**-0.31**
El Pucté	WR – CONAP	14800.70	3843.70	26.00	-1.66
Laguna del Tigre	NP – CONAP	246556.00	93857.80	38.10	-2.63
Machaquilá	WR – CONAP	13677.10	5559.90	40.70	-2.86
Machaquilá zone 2	WR – CONAP	56838.70	26416.70	46.50	-3.41
Maya (buffer zone)	BiosR – CONAP	287256.70	169716.40	59.10	-4.84
Maya (multiple-use zone)	BiosR – CONAP	271932.40	64895.90	23.90	-1.50
Montañas Mayas Chiquibul	BiosR – CONAP	15291.10	4986.70	32.60	-2.17
Montañas Mayas Chiquibul 2	BiosR – CONAP	24701.40	8343.10	33.80	-2.26
Riscos de Momostenango	NP – CONAP	137.10	2.40	1.70	-0.10
San Román	BiolR – CONAP	17856.60	13140.70	73.60	-7.13

San Román 1	BiolR – CONAP	107161.40	58191.00	54.30	-4.26
Visis Cabá	BiosR – CONAP	34350.90	3058.10	8.90	-0.52
Xutilhá	WR – CONAP	18269.90	6343.30	34.70	-2.34
Yaxhá–Nakum–Naranjo	NP – CONAP	7243.50	704.60	9.70	-0.57
Total CONAP	**–**	***1116073.50***	***459060.10***	**41.10**	**-2.90**
Sierra de las Minas	BiosR – DN	3217.10	251.40	7.80	-0.45
Sierra del Lacandón	NP – DN	182831.10	45493.30	24.90	-1.58
Total DN	**–**	***186048.20***	***45744.70***	**24.60**	**-1.56**
Petexbatún	WR – MCD	3209.40	1000.20	31.20	-2.05
Total MCD	**–**	***3209.40***	***1000.20***	**31.20**	**-2.05**
Chuna´a	MRP – M	47.70	1.40	3.00	-0.17
Cuchumatán	MRP – M	7.90	*0.00*	0.00	0.00
Cuevas de Actún Kan	MRP – M	71.50	34.00	47.60	-3.52
Cuevas El Tecolote	MRP – M	31.60	0.10	0.30	-0.02
Cumbre Laguna Seca	MRP – M	2.10	*0.00*	0.00	0.00
El Chicozapote	MRP – M	20.50	6.40	31.30	-2.07
El Copoito	MRP – M	67.50	0.00	0.00	0.00
El Esfuerzo	MRP – M	72.30	33.00	45.60	-3.33
El Mirador	MRP – M	11.30	2.50	22.40	-1.40
K'ojlab'l Tze´ te Tnom Todos Santos Cuchumatán	MRP – M	147.50	0.10	0.10	0.00
La Caridad	MRP – M	15.60	4.20	26.70	-1.71
La ENEA	MRP – M	62.90	7.30	11.60	-0.69
La Vega del Zope	MRP – M	31.00	0.10	0.30	-0.02
Los Altos de San Miguel Totonicapán	MRP – M	4747.40	128.50	2.70	-0.15
Los Cerritos–El Portezuelo	MRP – M	7.60	1.50	20.20	-1.25
Najochón	MRP – M	148.70	7.60	5.10	-0.29
Nueva Juventud	MRP – M	40.40	0.30	0.70	-0.04

Piedras de Kab'tzin. San Juan Ixcoy	MRP – M	191.40	5.10	2.60	-0.15
Sacbaquecán	MRP – M	43.10	0.70	1.70	-0.09
SacPetén	MRP – M	4.40	0.00	0.00	0.00
Santuario Botánico	MRP – M	8.00	0.40	4.50	-0.26
Txinivakán	MRP – M	5.30	1.30	23.90	-1.50
Venus Verdoso	MRP – M	5.00	0.10	1.80	-0.10
Total M	**–**	***5790.70***	***234.60***	**4.10**	**-0.23**
Cataljí o Sacataljí	PNR	180.20	32.80	18.20	-1.11
Ceibo Mocho Flor de la Pasión	PNR	388.10	122.20	31.50	-2.08
Cerro Verde	PNR	206.50	24.80	12.00	-0.71
Chajumpec	PNR	734.80	21.10	2.90	-0.16
Doña Chanita Flor de la Pasión	PNR	476.70	192.20	40.30	-2.83
El Aguacate	PNR	32.00	0.00	0.00	0.00
El Cibal	PNR	40.40	36.80	91.10	-12.57
El Manantial	PNR	456.90	69.40	15.20	-0.91
El Mangal	PNR	50.50	30.50	60.30	-5.01
El Naranjo	PNR	16.20	0.00	0.00	0.00
El Pollo	PNR	77.30	5.70	7.40	-0.42
El Recuerdo	PNR	23.40	0.80	3.50	-0.20
Entre Ríos	PNR	464.90	26.00	5.60	-0.32
Finca AA	PNR	452.10	13.50	3.00	-0.17
Finca Chacá	PNR	162.90	150.60	92.50	-13.39
Finca Los Tarros	PNR	556.70	330.40	59.40	-4.88
Finca Nitún	PNR	3.10	0.00	0.00	0.00
Finca Rincón Grande	PNR	869.20	69.50	8.00	-0.46
Finca Rústica Chimel	PNR	1987.40	12.70	0.60	-0.04
Finca San José	PNR	58.10	24.80	42.60	-3.04
Hacienda Pastores	PNR	32.10	7.50	23.40	-1.47
Häk Yahx Luúm	PNR	214.80	8.10	3.80	-0.21

Iglesia Católica Diócesis del Quiché	PNR	21.90	1.00	4.50	-0.26
Karnac	PNR	87.50	0.00	0.00	0.00
Katherine	PNR	46.70	5.70	12.20	-0.72
La Cumbre Flor de la Pasión	PNR	482.80	196.60	40.70	-2.86
La Democracia	PNR	135.50	61.70	45.50	-3.32
La Esperanza	PNR	58.90	6.20	10.60	-0.62
La Gloria	PNR	203.70	0.30	0.10	-0.01
La Ponderosa	PNR	154.90	62.20	40.20	-2.81
Laguna Perdida	PNR	44.00	15.30	34.70	-2.34
Los Lagartos	PNR	78.40	13.70	17.40	-1.06
Los Peñas	PNR	510.90	37.90	7.40	-0.43
Monte María	PNR	462.40	34.50	7.50	-0.43
Nitún I	PNR	4.00	0.00	0.00	0.00
Rincón del Zope	PNR	26.10	0.50	1.70	-0.10
Santa Rosa y Llano Largo	PNR	1372.90	42.70	3.10	-0.18
Santa Rosita	PNR	45.70	33.10	72.40	-6.91
Saq Ha	PNR	8.70	0.00	0.00	0.00
Tres Marías	PNR	40.00	13.10	32.80	-2.18
Yaxhá	PNR	181.90	77.80	42.80	-3.05
Total PNR	–	***11451.20***	***1781.40***	***15.60***	***-0.90***

Deforestation by category of Protected Areas

In Mexico, the largest protected area was found in Biosphere Reserves, followed by Flora and Fauna Protection Areas, Areas Subject to Ecological Conservation, Natural Monuments, National Parks, Natural and Typical Areas, Voluntary Conservation Areas, Ecological Reserves, and Urban Parks. Of these categories, those that showed the largest percentage of forest loss compared to their status in 2000 were: Natural and Typical Areas

(36 %; *q* = -2.48 %, 1402 ha), Areas Subject to Ecological Conservation (16 %; *q* = -0.98 %, 1559 ha), Ecological Reserves (15 %; *q* = -0.91 482 ha), Flora and Fauna Protection Areas (8 %, *q* = -0.47 %, 11 763 ha), Biosphere Reserves (7 %; *q* = -0.41 %, 30 847 ha), National Parks (4 %; *q* = -0.24 %, 210 ha), Voluntary Conservation Areas (3 %; *q* = -0.17 %, 117 ha) and Natural Monuments (0.1 %; *q* = -0.004 %, 5 ha). It is worth noting that in Urban Parks, 0 % of the forest was lost during the period analyzed (Table 2).

In the Guatemalan part of the basin, the largest protected area lied in Biosphere Reserves followed by National Parks, Biological Reserves, Wildlife Refuges, Protected Biotopes, Private Natural Reserves, Cultural Monuments, and Municipal Regional Parks. Of these PA categories, those with the largest percentage of forest loss compared to their status in 2000 were: Biological Reserves (57 %; *q* = -4.59 %; 71332 ha), followed by Cultural Monuments (56 %; *q* = -4.46 %; 3 363 ha), Wildlife Refuges (40 %; *q* = -2.84 %; 43 164 ha), Biosphere Reserves (39 %; *q* = -2.75 %; 251252 ha), National Parks (30 %; *q* = -2.00 %; 140 868 ha), Protected Biotopes (29 %; *q* = -1.91 %; 21 904 ha), Private Natural Reserves (16 %; *q* = -0.93 %; 1782 ha), and Municipal Regional Parks (4 %; *q* = -0.23 %; 235 ha; Table 3).

Deforestation by Protected Area

In Mexico, the three PA with the largest net forest loss were Montes Azules Biosphere Reserve (27 010 ha), Cañón del Usumacinta Flora and Fauna Protection Area (8 271 ha), and Lacantún Biosphere Reserve (3 188 ha). Compared to the total forest cover in 2000 in each PA, the forest lost between 2000 and 2018 represented 8 %, 21 %, and 5 % of forest lost, respectively. In turn, the annual forest loss rate corresponded to -0.49 %, -1.3 % and 0.3 %, respectively (Table 2; Fig. 1)

In the Guatemalan part of the basin, the three PA with the largest net forest loss were Maya Biosphere Reserve (sum of the buffer zone and the multiple-use zone: 234 612 ha), Laguna del Tigre National Park (93 858 ha) and San Román Biological Reserve (sum of the two officially established PA polygons: 71 332 ha; Table 3; Fig. 1). Compared to the total forest cover in 2000, it represented 42 %, 38 % and 57 % of forest cover lost, respectively. In turn, the annual forest loss rate was -3.0 %, -2.63 % and 4.6 %, respectively. It is worth noting that in Guatemala, 27 of the 86 PA lost over 30 % of forest cover during the period analyzed, and eight lost over 50 % of it (Table 3).

Annual variation in loss of forest cover

In Mexico, annual net forest loss within PA varied between 817 (in 2002) and 5 756 ha (in 2016) and showed a clear upward trend. Outside PA, annual net forest loss was an order of magnitude greater, with a minimum of 9 664 ha (in 2002) and a maximum of 47 262 ha (in 2016). Annual variation in net forest loss showed an oscillating pattern, with a clear peak in 2016 (Fig. 2).

Within Guatemalan PA, the lowest annual net forest loss occurred in 2011 (13 256 ha), and the highest, in 2007 (63 948 ha). Annual net forest loss generally followed an erratic pattern, but showed a clear downward trend between 2010 and 2015 (Fig. 2). Outside PA, the lowest annual net forest loss was 15 667 ha in 2011, and the highest value was 69 685 ha in 2016. Annual net forest loss in Guatemala also followed an erratic pattern, with no clear trend.

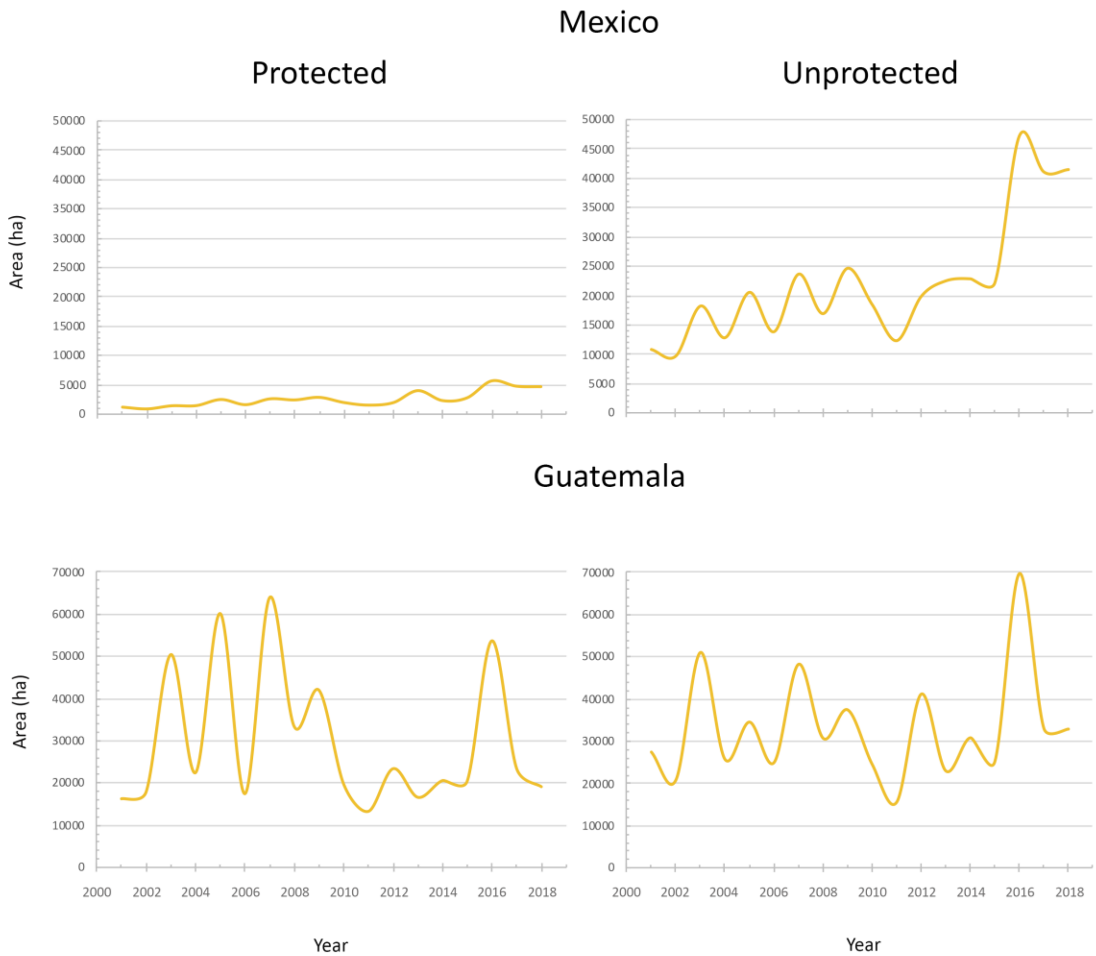

Fig. 2 Annual net forest loss in the Usumacinta river basin in Mexico and Guatemala for both protected and unprotected areas (2000–2018).

Discussion

The results of this study indicate that deforestation is an ongoing, widespread and growing problem in the Usumacinta river basin. In addition, deforestation shows a strong spatio-temporal variation, related to the sociopolitical contexts of Mexico and Guatemala. These variations can be explained by examining the results of the different analyses.

First, this study contributes to highlight the tremendous rate of forest loss inside the Usumacinta river basin, which was not reported as high in previous studies in the region

(Bray et al. 2008; Díaz-Gallegos et al. 2008), probably due to differences in methods used to identify deforestation. Nevertheless, more recent studies have reported forest loss rates in the region, similar to the ones we found (Hodgdon et al. 2013; Bullock et al. 2019). In terms of the percentage of forest cover lost, the Usumacinta river basin shows a value (27 %) five times higher than that observed in the Amazon river basin for the same period (6 %; Butler 2015). This situation poses a serious threat to biodiversity and jeopardizes the future of the Usumacinta river basin's largest remnants of rainforest and forested wetland.

Although this study does not systematically analyze the causes of deforestation, these can be deduced both from the literature and from our research team's knowledge and fieldwork in the region. Among the identified causes are farming (mainly the production of livestock and oil palm and rubber plantations, promoted by both private and government initiatives), agriculture expansion, illegal encroachments into PA, migration and lasting colonization waves, fires, oil activities, and the expansion of urban and communication infrastructures (López-Feldman 2012; 2014; Covaleda et al. 2014; Fernández-Montes de Oca et al. 2015; Ramos et al. 2017; Gollnow et al. 2018; Vaca et al. 2019). These activities derive from the political relations and land tenure patterns that determine access and control of the resources (Ramos et al. 2017; Burivalova et al. 2019; Vaca et al. 2019). These entangled sociopolitical events act as a driving force behind deforestation and forest conversion (Porter-Bolland et al. 2012). It is thus crucial to identify and understand the causes of deforestation and to adopt a holistic approach to effectively manage PA and its surrounding territory, in order to effectively achieve biodiversity conservation in the region (Díaz-Gallegos et al. 2008; Rueda 2010). In the following paragraphs, several possible causes are further discussed to explain the patterns observed in each analysis.

A second aspect revealed by our research is the deep difference between Mexico and Guatemala regarding the effectiveness of PA to conserve forest cover. While in Mexico, 8 % and 24 % of the forest cover was lost within and outside PA, respectively, in Guatemala the corresponding percentages (37 % and 29 %, respectively) indicate a very critical situation, regardless of whether or not PA are present in the region. Actually, the deforestation rates of unprotected areas in both Guatemala and Mexico (-1.88 % and -1.55 %, respectively) and PA in Guatemala (-2.57 %) are higher than the global rate, estimated in the same period (-0.12 %; Food and Agriculture Organization [FAO] 2020) and certainly higher than the deforestation rates of both countries (Guatemala, -0.94 % and Mexico, -0.20 %; FAO 2020). In fact, although the annual forest loss rate in PA in Mexico was the lowest (-0.44 %), it is still higher than the national rate (FAO 2020). Therefore, the Usumacinta river basin can be considered a deforestation hotspot.

In the Mexican part of the Usumacinta river basin, the PA network has certainly played a crucial role in controlling environmental deterioration, in spite of all the existing problems and conflicts. Previous studies have reported that certain PA in the region have been effective or weakly effective to help conserve its natural vegetation cover (Figueroa et al. 2011). With the aim of reaching the desirable conservation and sustainable development targets in the region, it will be necessary to strengthen PA and increase efforts for the conservation of surrounding areas. In contrast, the Guatemalan situation depicted here indicates that its PA system has a limited capacity to achieve its fundamental purpose: to conserve biodiversity and ecosystem services. Such a situation is common in various developing countries, where the state often plays only a small role in regulating land use within and outside PA (Quezada et al. 2014). This may be explained, among other reasons, by the short history of PA management, the limited importance given to natural heritage conservation, the prioritization of economic policies over environmental ones, the political and economic power of extractive companies, the local population's reliance on land resources, the cross-border condition of many of the PA, and the lack of funding and weak presence of the organizations responsible for PA management (Bruner et al. 2001; Brechin 2003; Medina-Sanson and Hernández 2018).

Thirdly, this study revealed marked differences in the observed forest cover loss between types of administration of PA (see also Schleicher et al. 2017). The case of Guatemala provides a clear example of this aspect. In this country, PA are managed by at least eight actors of very different natures, e.g., government, private, university, non-governmental ones and local stakeholders. Indeed, the analysis presented here clearly shows that the different types of administration and actors that manage PA, do not perform equally in conserving its forest cover. Although an initial glance at these results would suggest a better performance of INAB and municipal administrations, a more detailed assessment would be necessary to take into account the particularities of each PA and identify the factors responsible for this pattern.

In the case of Mexico, most of the PA are managed by the government (except VCA), but at different levels (i.e., federal, state and municipal). Among the PA that showed the lowest forest loss in both percentage and net values were municipal PA; however, these PA were also among the smallest ones. On the contrary, state-managed PA was the category where the highest annual forest loss rates were observable. These results seem to suggest that federal, municipal and VCA PA might be the areas with higher capabilities to promote its forest cover conservation. Again, individual assessments will help identify the particular contexts of each PA, which ultimately will explain the observed patterns.

Fourthly, the findings about the PA with the highest percentages of forest loss provide a deeper understanding of the transformation processes affecting the Usumacinta river basin. In Mexico, these were Montes Azules Biosphere Reserve, Cañón del Usumacinta Flora and Fauna Protection Area, and Lacantún Biosphere Reserve, three PA located in the region characterized by the largest proportion of biodiversity on the Mexican side of the border. In these PA, most of the deforestation begins at the edges and advances towards their centers, following the emergence of new land units used for food production (Fernández-Montes de Oca et al. 2015; Díaz et al. 2019). Inside PA, deforestation increases due to illegal settlements, through expansion of the areas used for housing and farming. This process is exacerbated by the particularities of the region where these PA are located, with one of the highest densities of indigenous inhabitants in the country, which are under different types of governance; frequent delays and omissions related to land tenure; and a lack of well-paid employment opportunities (Carabias et al. 2015).

In the Guatemalan part of the basin, the three PA with the greatest loss of forest cover were Maya Biosphere Reserve, Laguna del Tigre National Park and San Román Biological Reserve. All three are located in the Petén department, which is the largest in Guatemala. Several studies agree that the main causes of deforestation in this region are related to oil exploration and exploitation, road and highway construction, agricultural and livestock activities, establishment of oil palm plantations, illegal extraction of cultural assets, fires and the emergence of illegal settlements (De Jong et al. 2000; De Vos 2002; Bonham et al. 2008; Hodgdon et al. 2013; Instituto de Agricultura, Recursos Naturales y Ambiente de la Universidad Rafael Landívar [IARNA-URL] 2014; Furumo and Aide 2016; Hervas 2020). In the past few decades, due to the Guatemalan state's limitations and weaknesses to defend its territory and borders, to regulate land ownership, and to conserve biodiversity, large parts of Petén have been controlled by groups involved in the trafficking of drugs and guns, migrants and livestock (Consejo Nacional de Áreas Protegidas 2006; Bonham et al. 2008; Bullock et al. 2019). It is known that these groups launder their income through livestock activities in both countries, by promoting and financing actions consisting in setting up fires to increase deforested areas (Ramos et al. 2007).

Admittedly, we focused on evaluating the PA in a single aspect: forest cover loss. Cross-referencing this information with other socioeconomic databases will allow future studies to make assertions and predictions about the causes of deforestation in the Usumacinta river basin (see Quezada et al. 2014 for a thorough example; Vaca et al. 2019). One particularly important aspect in the region that weakens future conservation and land use planning is the large omissions and delays related to land tenure. In this regard, it has been shown that clarifying and strengthening land tenure can, by itself, significantly reduce deforestation and forest degradation (Bray et al. 2008; Hodgdon et al. 2015). This is due to the fact that insecurity in tenure often encourages unrestricted access to land without clear allocation, forest clearing and land grabbing (Angelsen et al. 2013). A comprehensive evaluation of the effectiveness of the PA in the region should consider such socioeconomic contexts, including suitability of lands for developing economic activities (Mas et al. 2003; Mas et al. 2005; Duran-Medina et al. 2001), land tenure and management practices (Hodgdon et al. 2015; Bullock et al. 2019; Vaca et al. 2019), historical processes and strength of institutional capabilities (Bruner et al. 2001; Brechin 2003).

Finally, evaluations such as the one presented here, which focuses on a complete transboundary basin, provides a better understanding of the forest loss and fragmentation at a regional scale. Thus, the research provides important forest loss information for binational conservation strategies that consider forest connectivity in the region, such as biological corridors. Based on the results of this research, different international coordinated strategies should be carried out in the region, in order to strengthen conservation and sustainable development actions, as well as to reinforce the governmental and non-governmental agencies, along with local stakeholders responsible for PA management in both countries.

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Table 1. Area with forest cover in the year 2000, forest loss and annual rate of forest loss in both, protected and unprotected areas, in the Usumacinta River basin (2000–2018).

Table 2. Loss of forest cover and annual rate of forest loss in Mexican Protected Areas in the Usumacinta River basin (2000–2018). Forest Cover 2000: area covered by some type of forest in the year 2000. NM: Natural Monument. FFPA: Flora and Fauna Protection Area. BR: Biosphere Reserve. NP: National Park. ASEC: Area Subject to Ecological Conservation. ER: Ecological Reserve. NTA: Natural and Typical Area. UP: Urban Park. VCA: Voluntary Conservation Area. Administration: the level of government responsible for managing this Protected Natural Area in Mexico.

Table 3. Loss of forest cover and annual rate of forest loss in Guatemalan Protected Areas in the Usumacinta River basin (2000–2018). Forest Cover 2000: area covered by some type of forest in the year 2000. PB: Protected Biotope. CM: Cultural Monument. NP: National Park. MRP: Municipal Regional Park. WR: Wildlife Refuge. BiolR: Biological Reserve. BiosR: Biosphere Reserve. PNR: Private Natural Reserve. USPA: University System of Protected Areas. IDAEH: Institute of Anthropology and History. INAB: National Forest Institute. CONAP: National Council for Protected Areas. MCD: Ministry of Culture and Sports. DN: “Defensores de la Naturaleza”. M: Municipality. Administration: the individual or legal person responsible for managing this Protected Area in Guatemala.

Figure captions

Figure 1. Protected areas location and loss of forest cover in the Usumacinta river basin (2000–2018). Spatial resolution: 30 × 30 m/pixel. Geographic coordinate system: WGS 84. Source: Hansen et al. (2013), Mexico’s Instituto Nacional de Estadística y Geografía (INEGI) and Guatemala’s Instituto Geográfico Nacional (IGN).

Figure 2. Annual net forest loss in the Usumacinta river basin in Mexico and Guatemala for both protected and unprotected areas (2000–2018).