Changes in the constituents of the “Bosque de Agua” of the Sierra Cruces-Ajusco-Chichinautzín, Mexico, an area with payment for environmental services

José López-García¹ · Rafael María Navarro-Cerrillo²

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Abstract

The “Bosque de Agua”, to the west and south of Mexico City, which is the fifth largest city in the world, has historically suffered disturbances in forest cover, with a consequent reduction in the environmental services provided. Changes in the state of the forests between 1994 and 2017 are here analyzed in terms of the annual net change in area of the different cover densities and the different change processes. In general, the net change was favorable in all cases: forest improvement vs. forest degradation, reforestation vs. deforestation, and afforestation vs. land use change. There were changes in 16.03% of the *Bosque de Agua*: recovery in 11.09% and disturbance in 4.94%. This marked recovery is the result of the protected status of two-thirds of the forest, the payment for hydrological environmental services in 29.33% of the forest, as of 2003, and the continuous programs of reforestation, fire control and surveillance by the local communities, circumstances that have allowed the recovery to exceed the disturbance in most of the *Bosque de Agua*. One-third of the forest disturbance is concentrated in six of the 35 municipalities in the southern region, caused by clandestine logging by organized gangs, due to the state of ungovernability that reigns in these municipalities.

Keywords *Bosque de Agua* · Forest area net change · Recovery disturbance · Protected natural areas · Payment for hydrological environmental services · Reforestation

Introduction

Climate change will affect the availability, quality and quantity of water, hindering the sustainable management of water resources, which is already under pressure in many parts of the world; global water use has increased sixfold in the past 100 years (UNESCO, ONU-Agua 2020). Therefore, water shortages are expected. The degradation of ecosystems produces a loss of biodiversity and affects the availability of ecosystem services, which depend on water. At

the global level, efforts to curb deforestation have decreased it from 16 million ha/year during 1990–2000 to 15 million ha/year during 2000–2010 and 11 million ha/year during 2010–2020 (FAO 2020). As a result, annual forest area net change decreased globally from 7.8 million ha/year during 1990–2000 to 5.2 million ha/year during 2000–2010 and 4.7 million ha/year during 2010–2020 (FAO 2020).

Water scarcity and deforestation are two of the most important environmental challenges in Mexico (Muñoz-Piña et al. 2007). In the first case, two-thirds of the 188 most important aquifers in Mexico are overexploited (DOF 2003). In the second, the annual deforestation rate was 0.21% between 1990 and 2015 (FAO 2015), with the main causes of deforestation being as follows: changes in land use due to population growth, urban expansion and public policies that promote agriculture; illegal logging of the forest and overexploitation of forest resources; pests and diseases of the vegetation; and forest fires (Perevochtchikova and Vázquez 2010).

On a national scale, several studies have estimated the deforestation rate within Mexico (Mas et al. 2002, 2004,

✉ José López-García
jlopez@unam.mx

Rafael María Navarro-Cerrillo
rmnavarro@uco.es

¹ Instituto de Geografía, Universidad Nacional Autónoma de México, Ciudad Universitaria, C.P. 04510 Coyoacán, DF, Mexico

² Departamento de Ingeniería Forestal, Universidad de Córdoba, Campus de Rabanales, Carretera 7 Nacional IV km 396, 14014 Córdoba, Spain

2009; Palacio-Prieto et al. 2000; Rosete-Vergés 2014). However, the annual net change in forest area determined by disturbance and recovery is unknown; that analysis would allow evaluation of the efficiency of public policies in mitigating water scarcity and reducing deforestation. To address this, several federal initiatives of Environmental Public Policy have been implemented. The most notable is the Payment for Hydrological Environmental Services (PHES) program, created in 2003 and operated by the National Forestry Commission (CONAFOR); its objective is to contribute to the preservation of forest resources, as well as to reduce the marginalization of the population that lives on forest lands and owns forests (CONAFOR 2007). At local government level, the PHES program of the Protectora de Bosques del Estado de México (PROBOSQUE) has operated since 2007, with the objective of maintaining the recharge of aquifers (CONAFOR 2007); it is funded by the fees charged to water users, of which about US\$18 million is allocated for the payment of environmental services (Muñoz-Piña et al. 2007).

To reduce deforestation, the Mexican government has adopted a strategy of prohibiting the change of land use, and it promotes sustainable activities such as the declaration of Protected Natural Areas (Muñoz-Piña et al. 2007). Although Mexico dedicates 9.54% of forests to biodiversity and conservation (FAO 2016), the decline in annual deforestation rate achieved was merely from 0.27% for 1990–2000 to 0.2% for 2000–2010 and 0.13% for 2010–2015 (FAO 2015), a rate that is still alarming. Whereas the PHES program involved 15 protected natural areas (PNAs) in 2003, there were 50 in 2008 (CONANP 2010). In 2016, the PNAs amounted to 31,248 million hectares legally established by various environmental policy instruments, whereby 15.91% of Mexico is subject to conservation (CONANP 2016). Payment for Environmental Services (PES) programs have helped reduce deforestation and illegal logging of areas mistakenly perceived as unproductive (Alix-García et al. 2012). PESs are generally accepted by individuals and communities, but the effectiveness of these programs, especially in the long term, is debatable (Costedoat et al. 2015; Martin et al. 2014; Alix-García et al. 2012). In the case of the PNAs in central Mexico, in eminently mountainous terrain, policies concerning the use of forest resources must take into account agricultural activities that promote community development, social well-being, and the conservation of biodiversity (Arteaga et al. 2017).

The high rate of loss of forest ecosystems due to deforestation in the Trans-Mexican Volcanic Belt is one of the main ecological problems in central Mexico, even in PNAs (Díaz de la Vega-Pérez et al. 2019). These ecosystems have been transformed into agrosystems and human settlements (Sánchez-Cordero et al. 2005). In addition, the average annual water availability per capita in central Mexico is lower than in the rest of the country, so Mexico City and its

metropolitan area, with 28 million inhabitants, face serious problems in meeting the high demand for water (CONAGUA-SEMARNAT 2018). An alternative way to improve the water resources of this area has been to conserve the forests of the mountainous regions that surround Mexico City (Sierras de Las Cruces-Ajusco-Chichinautzín), to improve the ecosystem services associated with the capture of rainfall, river infiltration and aquifer recharge.

This region in recent years has received attention thanks to the Water Forest Initiative (Iniciativa Bosque de Agua), which is directed technically by the Anáhuac A.C. Biosphere Foundation and administratively by Pronatura México A.C., mainly with funding from the Gonzalo Río Arronte Foundation, A.C. and CONANP, whose objective is to conserve forests and improve the practices of exploitation of natural resources. In this context, Bosque de Agua is the name given to the area under the aegis of these bodies, as described herein in “Study area”; although it translates as Water Forest, this is an administrative term, rather than an ecological description, and not all of the vegetation is water forest. Its biogeographic history has led to one of the richest biological profiles in the country, and various parts of its water forest have been recognized as a priority terrestrial region for conservation (CONABIO 2000), as a priority hydrological region at the national level (CONABIO 2002) and as an area of importance for the conservation of birds (Arizmendi and Márquez-Valdelamar 2000). In addition, it is part of one of the most biologically important regions of Mexico, according to the Biological Importance Index (BII) based on 47 variables, including the cover of primary vegetation, number of vegetation types, number of endemic species of vertebrates, and species of plants and vertebrates included in NOM-059-SEMARNAT-2001 (CONABIO et al. 2007).

The purpose of this study was to analyze the dynamics of the *Bosque de Agua*, in the period 1994–2017, considering the processes of change of the forest cover to determine the net change of the forest area and evaluate the effect of environmental public policy programs that address water scarcity and reduce deforestation.

Data and methods

Study area

The region known as Bosque de Agua covers 241,893 ha in the States of México and Morelos and the Federal District in central Mexico (18° 53' to 19° 49'N and 98° 53' to 99° 40'W) (Fig. 1).

The climate is temperate sub-humid with summer rains. The altitude ranges from 1800 m at the southern end to 3900 m at the Ajusco volcano. It lies on the Trans-Mexico Volcanic Belt, made up of Tertiary Andesite rocks

Fig. 1 Location of the region designated Bosque de Agua

and Plio-quaternary basalts, partially or totally covered by pyroclastic products, which have given rise to volcanic soils dominated by andosols, with high moisture retention capacity. It represents a transition between the Nearctic and Neotropical zones.

Comprising one of the most extensive and important continuous forest areas in the central region of Mexico, Bosque de Agua covers the “Las Cruces-Ajusco-Chichinautzín mountains, west and south of Mexico City (ECOA 2012). It includes three hydrographic basins and is the recharge zone for 41 aquifers, 29 in the valleys of Toluca, México and Cuernavaca and 12 within the *Bosque de Agua* (DOF 2003) (Fig. S1c Supplementary Material). These aquifers provide 70% of the water to the metropolitan areas of Mexico City, Toluca and Cuernavaca, with > 28 million inhabitants (López-Morales 2012; CONAGUA 2020). Finally, it includes 24 PNAs with coniferous and broadleaf vegetation (Figure S1b Supplementary Material).

Mexico City is one of the five most populated cities in the world (Koop 2021). It is within an endorheic basin, with

coniferous forests in its mountainous areas. It has historically suffered clandestine logging and the granting of forestry concessions to paper manufacturers that have impeded conservation (Vitz 2012); this has led to a reduction in the recharge of aquifers. Currently, 75% of the *Bosque de Agua* has some protection status, namely the 75% with forest cover at > 10%, of which only one-third has received PHES.

Different altitudinal zones determine specific types of vegetation: on the lowest areas, at 2400 m, are broadleaf forests dominated by oaks (*Quercus leiophylla* A.DC, *Q. laurina* Humb. et Bonpl., *Q. obtusata* Bonpl., *Q. mexicana* Humb. et Bonpl. and *Q. rugosa* Née); at 2400–2900 m are pine forests (*Pinus pseudostrobus* Lindl., *P. montezumae* Lamb., *P. oocarpa* Shiede, *P. leiophylla* Schl. et Cham., *P. teocote* Schl. et Cham. and *P. michoacana* Mart.); at > 2900 m are fir forests (*Abies religiosa* Kunth Schldl. et Cham.); and finally, above 3500 m, are scattered pine forests (*P. hartwegii* Lindl. and *P. rudis* Endl.).

Throughout Bosque de Agua, local communities exploit or adapt the natural resources. In Mexico, land tenure is

mostly social (collective), composed of ejidos and agrarian communities (Merino and Martínez 2014), with an ejido being an area of land farmed under a communal land tenancy agreement recognized by the National Agrarian Registry.

Data

The images used were 29 panchromatic orthophotographs at 2 m per pixel (February–March 1994) from the archives of the National Institute of Geography, Statistics and Informatics (INEGI), and five Spot-7 images at 1.5 m per pixel (January 2017) from the Mexico-New Generation receiving station (ERMEX-NG). Orthophotographs were re-projected from ITRF92 to WGS84 to create a mosaic, and Spot images were re-projected to the Universal Transverse Mercator (UTM) 14 N zone, WGS84 to create another mosaic. Both mosaics were recorded using 45 control points taken in the field with a differential GPS; a digital terrain model with contour lines every 20 m was used. Next, application of a first-degree polynomial transformation resulted in mosaics corrected with a mean square error of 2.54 m for the orthophotomosaic and 2.35 m for the mosaic of the Spot images.

Sources of cartographic information (Figure S1a, b Supplementary Material) and databases were platforms of institutions of the Mexican government (INEGI, CONABIO, CONAFOR, SEMARNAT and PROBOSQUE). Information on payment for hydrological environmental services, reforestation and forest fires was obtained by the data transparency law of the Government of Mexico (Figure S1d Supplementary Material).

Records of the number of inhabitants per municipality (INEGI 1990, 2000, 2010) allowed the annual projection of the population between 1994 and 2017. The absolute marginalization index was also used at the municipal level 1990–2015 (CONAPO 2016a, b). The marginalization index is an indicator of the deficiencies suffered by the population as a result of the lack of access to education, residence in inadequate housing, and a perception of insufficient monetary income (CONAPO 2016a).

Delimitation by density of forest cover

To define the study area, the continuous mass of forest in the orthophotographs of 1994 provided the baseline. The forest cover density was digitized by visual interpretation of the orthophotomosaic at a 1:5000 scale on a PC screen, using ArcGis 10.2.2, for which the photointerpretation elements of the image were taken into account, such as tone, texture, shape, design and the relationship with other objects. Six categories of forest cover were recognized, five by density of forest cover, according to tree density: closed canopy (> 75%), semi-closed (51–75%), semi-open (26–50%), open (10–25%) (López-García et al. 2016) and deforested (< 10%)

(FRA 2000); the sixth category, non-forest, was represented by agriculture, pastures, and human settlements. A minimum mapping area of 5000 m² was used for forest cover, based on the definition of forest (FRA 2000), and at least 625 m² for deforested or non-forested areas (López-García et al. 2016).

Once the 1994 cover density map had been completed, the topology was verified and overlapping or hollow polygons were corrected on the map. Using interdependent classification (FAO 1996), the 1994 forest cover density map was copied and renamed to provide the basis for the 2017 cover density map, to modify only the polygons that changed. The 2017 map was edited and superimposed on the Spot-7 image mosaic to edit changes in forest cover density, the topology was reviewed and errors were corrected.

Field verification

Density of trees per hectare was measured through 84 circular field samplings of 1000 m² between November 2017 and March 2018; this allowed validation of the densities of the forest cover, the type of vegetation and the identification of change processes. The procedure was also supported by small surveys by unmanned aerial vehicles (DJI Phantom 4 Pro), and mosaics were developed to corroborate the sampling results.

Identification of forest dynamics processes

The data for cover density of 1994 and 2017 were organized in a matrix of changes: those associated with the disturbance processes: forest degradation, deforestation and change in land use (Table 1 and Figure S2 Supplementary Material), were located above the diagonal; those associated with the recovery processes: forest improvement, reforestation and afforestation (Table 1 and Figure S2 Supplementary Material), were located below the diagonal. Deforestation and afforestation represent transfers between forests and other types of land use.

Determination of annual net change in forest area

In accordance with the criteria established by FAO (2020), forest area net change is the sum of all forest recoveries minus the sum of all disturbances of forest areas registered in the period studied (1994–2017). Positive results represent gains and negative results are losses. The parallels between the recovery and forest disturbance processes were also used to trace the effects of environmental services. Disturbance favors the loss of environmental services. Equity between disturbance and recovery suggests that environmental services are in balance. Recovery suggests the optimization of environmental services. Net change also indicates the degree of conservation of the forest. If forest degradation due to

Table 1 Change processes in forest; terminology

Change processes		Definition (FRA 2000)	Change type
Recovery	Forest improvement	Increase in forest density, whether natural or with the help of man (densification)	Cover change from open to semi-open, from open to semi-closed, from open to closed, from semi-open to semi-closed, from semi-open to closed, semi-closed to closed, or semi-closed closed
	Reforestation	Deforested land that is reforested and passes into a forest with a cover density of > 10%, with trees > 5 m high and with a diameter of > 10 cm) or in a natural way (regeneration)	Change of deforested land to closed, semi-closed, semi-open or open cover
	Afforestation	Transition through reforestation of agricultural land or grassland to forests, or naturally (expansion)	Change of agricultural or pasture land to closed, semi-closed, semi-open or open cover
Disturbance	Forest degradation	Decrease in forest cover density to < 10%, leading to a change in the density category	Cover change from closed to semi-closed, from closed to semi-open, closed to open, semi-closed to semi-open, semi-closed to open, semi-open to open
	Deforestation	Forest temporarily reduced to < 10% of its forest cover density	Change in cover density of closed, semi-closed, semi-open or open to deforested
	Land use change	Transition from forest land to non-forest use	Change in density of closed, semi-closed, semi-open or open cover to agricultural use, pasture or human settlements

logging dominates, the forest cover density decreases, or if there is deforestation or land use change conservation is not being achieved. If recovery dominates, the cover density increases through natural regeneration or reforestation with human intervention; the ensuing recovery and conservation of the forest favors the uptake and recharge of aquifers.

A net change in forest area can indicate the degree of conservation in the recovery-disturbance balance. If forest degradation dominates within the protected area, the cause is selective logging (“ant logging”), whereas if it happens outside the PNA it may be due to forest use with a concomitant decrease in forest density. If, on the other hand, forest improvement dominates it is due to the natural regeneration of the forest or to reforestation with human intervention, with a concomitant increase in forest density. If deforestation dominates it is due to intensive clandestine logging, with the consequent loss of forest environmental services. If reforestation dominates, then there is a recovery of environmental services, but with lower forest quality. Lastly, if a change of forest to other land uses dominates, there is a decrease in carbon sequestration, loss of biodiversity and a decrease in aquifer recharge, but if the forest cover is recovered by afforestation, then there is recovery of environmental services.

Results

Annual net change in forest area

Annual net change of forest area was 0.36% and the annual deforestation rate was 0.14%. In terms of individual change processes, the net annual change was positive in each case:

forest improvement vs. forest degradation 0.17%; reforestation vs. deforestation 0.08%; afforestation vs. land use change 0.10%. In forest covers of > 50%, cover increased during 1994–2017 at a rate of 409 ha/year, while covers of 10–50% decreased by 70 ha/year; deforested and non-forest areas decreased by 339 ha/year.

In the period 1994–2017, 16.03% had a change in cover, consisting of 11.09% recovery and 4.94% disturbance; among these changes, 68.74% occurred in closed cover, where in 52.14% of the closed cover it was recovery (Table 2).

Between 1994 and 2017, 16.03% (38,782 ha) changed in cover; of these changes, 69.16% were recovery and 30.84% disturbance. The recovery of forest cover due to reforestation and afforestation was greater than the disturbance due to deforestation and change of land use, with a net gain of 20.08%. Changes in forest density were the dominant processes, where forest improvement exceeded forest degradation, with a net gain of 18.25% (Table 2; Fig. 2). The majority of changes occurred in the closed cover, with 52.14% of the recovery and 16.60% of the disturbance. Overall, the forests had a net gain of 18.25% due to forest improvement, 8.85% to afforestation and 11.23% to reforestation. Recovery exceeded disturbance in each of the three States and in each of the three hydrographic basins, although this was marginal in the Rio Grande de Amacuzac watershed (Table 3, Figs. 2 and S1c Supplementary Material).

In 2017, reforestations covered only 4.73% of the forest, with the State of México having carried out the most reforestations, mainly with pines; this is reflected in the recovery of large homogeneous forested areas of different ages, as a result of continuous reforestation and afforestation of

Table 2 Matrix of changes in the cover between 1994 and 2017 (1% = 2418.93 ha)

Changes 1994–2017 (%)	Closed	Semi-closed	Semi-open	Open	Deforested	Non-forest	Total 1994
Closed	45.89	0.97	0.35	0.13	0.58	0.63	48.55
Semi-closed	2.89	10.04	0.39	0.16	0.81	0.14	14.44
Semi-open	0.86	0.24	0.37	0.06	0.21	0.07	1.8
Open	0.59	0.24	0.17	0.55	0.26	0.18	1.99
Deforested	2.2	0.67	0.21	0.2	5.96		9.24
Non-forest	1.82	0.45	0.3	0.25		21.16	23.98
Total 2017	54.25	12.62	1.77	1.36	8.37	21.63	100
Recovery processes	%	%	Disturbance processes		No change 83.97%		
Forest improvement	4.99	2.06	Forest degradation				
Reforestation	3.28	1.86	Deforestation				
Afforestation	2.82	1.02	Land use change				
Total	11.09	4.94	Total

Fig. 2 Change processes in the Bosque de Agua 1994–2017

Table 3 Changes in the “Bosque de Agua”, 1994–2017, according to region and administration (1% = 2418.93 ha)

Change processes %	States		Watershed				Protected area				Not protected	
	Federal District	México State	Morelos	Grande de Amacuzac			Lerma-Toluca	Moctezuma	State	Federal	Community	Total protected
Forest improvement	1.53	3.15	0.31	0.70	1.63	2.66	1.63	2.66	2.54	0.38	1.61	4.53
Reforestation	0.81	2.34	0.13	0.50	0.62	2.16	0.62	2.16	1.73	0.22	0.73	2.68
Afforestation	0.60	2.18	0.04	0.09	1.07	1.66	1.07	1.66	1.65	0.13	0.53	2.31
Recovery	2.94	7.67	0.48	1.29	3.32	6.48	3.32	6.48	5.93	0.73	2.86	9.52
Forest degradation	0.77	1.23	0.07	0.31	0.62	1.14	0.62	1.14	0.92	0.14	0.69	1.74
Deforestation	0.79	0.86	0.21	0.93	0.19	0.74	0.19	0.74	0.59	0.31	0.73	1.63
Land use change	0.18	0.81	0.03	0.04	0.47	0.51	0.47	0.51	0.61	0.05	0.14	0.81
Disturbance	1.74	2.90	0.30	1.27	1.28	2.39	1.28	2.39	2.12	0.49	1.56	4.18
No change	16.42	53.29	14.25	29.01	15.15	39.81	15.15	39.81	32.30	16.39	14.32	63.02
Total	21.11	63.86	15.03	31.58	19.74	48.68	19.74	48.68	40.35	17.61	18.75	76.72

agricultural land. Reforestation programs have recovered 2.88% of the *Bosque de Agua*, including 1.02% for afforestation of agricultural land.

Among the disturbances, forest fires between 1995 and 2017 occurred in 8.44% of the forest; of this area, 10.40% recovered after the fires, 12.63% failed to recover and 76.96% showed no changes in this period. The Federal District had 17.24% of its forests affected, the State of Morelos 10.7% and the State of México 5.24%.

Change in forest cover inside and outside protected areas

Most PNAs are administered at State level with 2.79 times more recovery than disturbance; those with federal status had 1.48 times more recovery than disturbance, and those with community status 1.83 times (Table 3). Of the *Bosque de Agua*, 76.72% has some degree of protection: federal (40.48%), State (17.49%) and community (18.75%). The changes in 16.03% were mainly in the PNAs (13.70%: 9.52% recovery and 4.18% disturbance) rather than outside the PNAs (2.34%: 1.57% recovery and 0.77% disturbance). Seven of the 24 PNAs are concentrated in 60% of the *Bosque de Agua*. In those PNAs, 87.21% of the changes exceeded 1400 ha.

Lastly, closed cover increased by 8.93% at the expense of the other categories, with the deforested and non-forest categories decreasing by 1.87% and 2.02%, respectively. 83.96% of the *Bosque de Agua* maintained its forest cover: 63% in protected areas and 20.96% in unprotected forest. The recovery processes in the PNAs varied between 0.19% and 27.88%, and the disturbance processes from 0.6 to 14% (Figure S1a Supplementary Material).

Payment for hydrological environmental services (PHES)

PHES is granted to forests with a cover of > 50%; between 2003 and 2017, 22.1% of the *Bosque de Agua* had PHES and 20.23% within PNAs (Table 4). Closed and semi-closed forest increased by 2.19% in this period. In total there were changes in 16.03%, with area of recovery being twice the area of disturbance; 13.70% occurred in PNAs (9.52% recovery) and 2.34% occurred outside the PNAs (1.57% recovery). 4.10% of the changes occurred in parts covered by PHES (3.02% recovery) and 11.94% in parts outside the PHES program (8.07% recovery). In areas without PHES there was more forest disturbance (3.87%), than where payment operated (1.08%). In addition, there were changes in 4% of areas that received PHES within PNAs (2.95% recovery) (Table 4). For 2017, 95.10% retained the PHES program; 1.92% had been deforested by clandestine logging and forest fires, and 2.98% had forest degradation by small-scale

Table 4 Matrix of changes in forests with or without Payment for Hydrological Environmental Services (PHES), whether inside or outside Protected Natural Areas (PNAs), 1994–2017

%	PNA			Outside PNA			Total		
With PHES	1.05			0.03			1.08		
	0.64	<i>1.1</i>	<u>0.04</u>	0.31	<i>0.31</i>	<u>0.21</u>	0.95	<i>1.41</i>	<u>0.25</u>
	2.95			0.07			3.02		
	1.69	<i>0.85</i>	<u>0.41</u>	0.44	<i>0.56</i>	<u>0.5</u>	2.12	<i>1.41</i>	<u>0.91</u>
Without PHES	3.13			0.74			3.87		
	1.1	<i>0.64</i>	<u>0.77</u>	0.01	<i>0.01</i>	<u>0</u>	1.11	<i>0.66</i>	<u>0.77</u>
	6.57			1.5			8.07		
	2.85	<i>1.83</i>	<u>1.89</u>	0.02	<i>0.04</i>	<u>0.01</u>	2.87	<i>1.87</i>	<u>1.91</u>
Total	4.18			0.77			4.94		
	1.74	<i>1.95</i>	<u>0.81</u>	0.32	<i>0.87</i>	<u>0.21</u>	2.06	<i>2.06</i>	<u>1.02</u>
	9.52			1.57			11.09		
	4.53	<i>2.68</i>	<u>2.31</u>	0.46	<i>0.59</i>	<u>0.51</u>	4.99	<i>3.28</i>	<u>1.73</u>
							16.03		
							7.05	<i>5.34</i>	<u>2.75</u>

Above the dotted line, the numbers in bold indicate forest disturbance processes (normal numbers indicate processes of forest degradation; numbers in italics indicate deforestation; and underlined numbers indicate land use change. Below the dotted line, the numbers in bold indicate forest recovery processes (normal numbers indicate forest improvement processes; numbers in italics indicate reforestation, and underlined numbers indicate afforestation).

logging, which may reflect problems between social groups due to boundary disputes between agrarian communities and ejidos.

Of the loss of forest cover due to deforestation and change in land use, 79.72% (> 200 ha) occurred in 10 of the 35 municipalities; these municipalities receive 49.56% of the PHES granted to these forests. Reforestation of > 200 ha occurred in 21 municipalities (Fig. 2); four of these municipalities have the largest area receiving PHES and 94% of their area within PNAs, but they also have the greatest deforestation and forest degradation; they are in the south of the Bosque de Agua, at the junction of the three states and the three watersheds (Fig. 3).

The map of estimated forest cover density in 2017 had an overall accuracy of 97.70% and a kappa coefficient of 96.83%. Omission errors occurred for semi-closed cover (4%) and open cover (6.25%), and commission errors occurred for semi-open cover (14.29%). In the closed and deforested categories there were no errors of omission or commission.

Discussion

Annual rate of deforestation in the Bosque de Agua was 0.14% from 1994 to 2017, lower than the nationally reported 0.2% annual deforestation between 1990 and 2020 (FAO 2015). The annual net gain in forest area, 0.36%, contrasted

markedly with the loss of 0.24% at national level between 1990 and 2020 (FAO 2020); this positive recovery would not be expected in a forest region subject to strong anthropic pressures (Alatorre et al. 1997; Bojórquez-Luque 2011; Sejati et al. 2018; Ruiz et al. 2019; Cruz 2019). This illustrates the positive effect of the PHES in this region, coupled with the public environmental policies in place, the protection status of most of these forests, and the support and awareness of the agrarian communities.

In a survey of temperate forest inventories in Mexico that encompassed a wider scale of work than the present study, the deforestation rate was 0.25% for 1976–2000 (Mas et al. 2004). From the forest inventories of Mexico and the vegetation maps at the national level, some authors have produced maps of changes (Mas et al. 2002, 2004, 2009; Palacio-Prieto et al. 2000; Rosete-Vergés et al. 2014) and others have evaluated the quality of the original reference material (Mas et al. 2009) produced at a scale of 1:250,000; however, with small working scales and with materials so diverse the results are not always comparable. Most of the published studies are on land use change, on the basis of the automated scanning of satellite images (Mas et al. 2004; Frolking et al. 2009; Arunarwati et al. 2012; Kerebeh and Shiferaw 2018). In contrast, the present study, based on visual interpretation of orthophotographs and Spot images with a spatial resolution of 2 m/pixel and 1.5 m/pixel, respectively, has allowed an evaluation of forest degradation, forest improvement, deforestation that

Fig. 3 Area with the greatest changes in forest cover; in addition, three municipalities where disturbance exceeded recovery (Milpa Alta, Ocuilán and Huitzilac)

occurs in a scattered manner on a small scale (Muñoz-Piña et al. 2007), and small-scale logging, not detectable with satellite images (Vidal, et al. 2014); evaluation of this type at the spatial resolutions used in the present study would

be difficult to achieve with satellite images at this resolution and over this time frame.

Evaluation of forest cover density from Landsat images has generally achieved an overall precision of < 90% (Panta

et al. 2008; Pujiono et al. 2019; Farooq and Humayun 2010; Azizi et al. 2008). In contrast, detailed studies by visual interpretation of orthophotographs and Spot panchromatic images, at a 1:5000 working scale, have allowed the detection of fine changes and an overall precision of 95.29% (López-García et al. 2016) and 95.65% (López-García and Navarro-Cerrillo 2019); such precision is surpassed by the 97.70% estimated in the present work.

Mexico is subject to the main environmental problems of deforestation and water scarcity (Alatorre-Troncoso and Knight 2014), and the federal government has responded with compensation mechanisms to stop deforestation and forest degradation, such as the program of PHES, established in 2003 (CONAFOR 2007). In the case of the *Bosque de Agua*, a marked decrease in disturbance in this period was due to the following: the PHES, reflecting the greater recovery than disturbance between 1994 and 2017; continuous and highly successful reforestation programs covering 6.31% of the terrain (DOF 2016), with acceptance and surveillance by the ejidos and communities; and fire control, which, through prompt attention to losses and to lesser damage, has restricted the lasting impact on trees to only 12.63% of the burnt area (DOF 2016). Despite the lower forest disturbance in the areas with PHES, recovery was proportionally greater in the forests without PHES than with PHES; this may be attributable to the desire of the owners of these forests, especially those within the PNAs, to be included in this program particularly in the State of México where this would entail a double payment; this would necessitate similar programs in the other States, to maintain equity and to ensure the greatest conservation of the forests. In the areas with PHES, there is less recovery because in general they are forests with densities of > 50% and they only need to preserve their cover to receive the PHES.

At the international level, the efficiency of PNAs depends on the land ownership regime (Melo 2002; Velázquez 2007). In Mexico this is a challenge, since 59% of the forested area is communally owned by ejidos and agrarian communities (Merino and Martínez 2014). The center of Mexico is the part with the most extensive communal tenure (Morett-Sánchez and Cosío-Ruiz 2017). This hinders forest management plans and the implementation of environmental public policy programs. The situation has been exacerbated by the declaration of PNAs that were expropriated without compensation (ECOPA 2012), and in which the owners claim usufruct of their forests. When property rights are weak, implementation of PES programs can be a challenge (Clements et al. 2010). In Mexico, direct payment to ejidos or communities has been an effective way to support conservation, despite the challenges inherent in governance (Dietz et al. 2003; Muñoz-Piña et al. 2007). Part of the innovative approach is the funding of a PHES through an allocated portion of the tariff imposed on water users, thereby creating

a link between those who benefit from environmental services and those who provide them (Muñoz-Piña et al. 2007). Most negative changes in the forests with PHES were linked to extreme meteorological events with strong winds that caused tree fall, or were the result of fires that were generally anthropic; lesser causative factors were agricultural practices or clandestine logging.

For some of the southern municipalities of the *Bosque de Agua*, their position near the State boundaries and at the confluence of the three basins impedes governance; a background of management difficulties is compounded by mismanagement, scarcity of resources and the minimum of personnel in protected areas (Melo 2002). This has impeded forest conservation and recovery; although there are community brigades for environmental surveillance, and there has been investment in social programs, there are still irregular settlements. Illegal logging and the invasion of PNAs have increased during the covid-19 pandemic. There is a dispute over land boundaries and there are constant complaints from ejido shareholders regarding tree felling and the lack of vigilance by the authorities in various municipalities. The concentration of one-third of the forest disturbance in six municipalities in the southern region, and 54.66% of the deforestation in five municipalities with governance problems, has led to clandestine logging by organized gangs, mainly in Ocuilán, State of México (Ramos 2019), Huitzilac, Morelos (Flores 2020), and Milpa Alta (González 2019) and Tlalpan (González and Bravo 2020), Federal District. The legislation is lax, since illegal logging is considered a non-serious crime. The problem is not the law, but its application.

Despite the historical difficulties experienced in conservation of this area, the present data reveal that recovery processes have outweighed the disturbance processes in the *Bosque de Agua* during 1994–2017, under the combination of various environmental policies. The generally better recovery in areas without PHES than in those with PHES may have been because the PHES requires only conservation rather than active recuperation. This is a new program as of 2003, with a supplement in the State of México from 2007 onward; it is to be expected that the communities and ejidos would support future PHES programs, especially within PNAs where these are not available. Outside the PNAs, the tendency may be to increase the PHES programs in the future, but this will not be easy because if a program were not maintained there would be a resurgence of clandestine logging.

The constant increase in areas dedicated to conservation through the creation of PNAs has allowed 15.91% of México to have some protection status, but their mere creation is insufficient; they must fulfill the function for which they were created. In the *Bosque de Agua*, the annual net increase in forested area within the PNAs was double that outside the PNAs, which demonstrates the

effectiveness of the conservation measures (Figueroa et al. 2011). The remarkable recovery has also been driven by continuous reforestation, mainly in the State of México by PROBOSQUE, which has favored the recovery of forests and afforestation of agricultural areas; thus, counteracting deforestation and land use change in other areas.

The most important socioeconomic parameter used as input for forest deforestation models is the distance from communities stratified by level of marginalization (Lubowski et al. 2014). In *Bosque de Agua* municipalities, there is no clear influence of marginalization on disturbance, so marginalization is not the main driver of deforestation there; rather, it is due to the ungovernability that reigns in some municipalities with regard to decisions on environmental aspects (Wigle 2010) and laxity in crime prevention.

Migration occurs from the poorest communities and ejidos, where the decrease in the extraction of wood from the forest has affected their livelihood; 27.9% are losing young people to the United States of America (Morett-Sánchez and Cosío-Ruiz 2017). The theory of forest transition suggests that the decrease in logging and abandonment of agricultural land is due to migration, which ultimately leads to the recovery of forests, since agriculture in Mexico accounts for only 5% of the Gross Domestic Product, employs only 20% of the workforce and has a net migration rate of 2.77 per 1000 (Klooster 2003). Family farming in Mexico represents 81.3% of rural economic units (SAGARPA 2012). These factors may be the causes of the evident afforestation of these agricultural lands, together with the reforestation of deforested areas, and this would account for the dominance of forest recovery in the *Bosque de Agua*.

The increase in the forested area with the increase in the reforested and forested areas and the improvement by forest densification will be reflected in the recharge of the aquifers. Up to 2.3 times the volume of surface and underground renewable flow is used annually in central Mexico (CNA 2011). *Bosque de Agua* aquifers provide 70% of the water to the metropolitan areas of Mexico City, Toluca and Cuernavaca, where more than 28 million people reside (López-Morales 2012). This must have been increased by the greater forest recovery in this period, far exceeding the disturbance. The overexploitation of the aquifers that threatens the present and future groundwater is compounded by the growth of the metropolitan area in its recharge zones, especially in the region called *Bosque de Agua* (López-Morales 2012). The 3.90% increase in the net forest cover during 1994–2017 implies an increase in the infiltration capacity and in the recharge of aquifers; this is beneficial, since a little more than 28 million people live in municipalities that draw water from aquifers that are recharged in the *Bosque de Agua* (López-Morales 2012).

Conclusions

Visual interpretation of orthophotographs and Spot images in terms of five classes of forest cover density has allowed analysis of the dynamics of the *Bosque de Agua* in the period 1994–2017; this has yielded information regarding the processes of change in forest cover, the annual net change in forest area, and the efficacy of public environmental policy programs in confronting water scarcity and reducing deforestation.

In a developing country such as Mexico, where social ownership of land predominates, with high rates of deforestation and with an annual net decrease in forest area, it is a challenge to reduce the disturbance. However, this study has shown that, in this *Bosque de Agua* near one of the largest cities in the world, implementation of public environmental policy programs by the federal government, such as the PHES, reforestation, fire control, surveillance by ejidos and agrarian communities, and the declaration of PNAs, have reduced the annual net loss of forest area during 1994–2017; since recovery exceeds disturbance, a greater recharge of aquifers is to be expected. These results establish solid bases to motivate sustainable management policies to reduce overexploitation and promote the conservation of aquifer recharge zones. Such policies may also be relevant in other countries where cities are exerting strong pressure on their forests.

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Declarations

Conflict of interest We declare that we do not have any financial, personal or organizational relationship that may influence our work

in any inappropriate way, nor are there professional interests that can be interpreted as influencing the revision of the manuscript entitled "Changes in the constituents of the "Bosque de Agua" of the Sierra Cruces-Ajusco-Chichinautzín, Mexico, an area with Payment for Environmental Services".

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