Changes in forest cover in Sierra Nevada, Mexico, 1994–2015

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ABSTRACT

Sierra Nevada, 153,437 ha, has the second and third highest mountains in Mexico and the most conserved coniferous forests of central Mexico. It comprises the Los Volcanes Biosphere Reserve, designated by UNESCO in 2010. A map was produced at 1:100,000 scale. Recent changes in forest cover were identified by visual interpretation of orthophotographs from 1994 and Spot 7 images from 2015. Changes were detected in forest cover density (closed, semi-closed, semi-open, open or deforested), together with a non-forest category that includes other land uses. Over the 21 years, 25% of the forest had undergone change: 14% recovery and 11% disturbance. Recovery outweighed disturbance in the Protected Areas, with possible factors being payment for environmental services, periodic reforestation and fire control. Outside this protected area, improvement outweighed degradation, mainly because of forestry programs. Overall in the Sierra Nevada, the trend appears to be forest recovery.

1. Introduction

The Sierra Nevada (153,437 ha) includes the Iztaccíhuatl (5280 m), Popocatépetl (5452 m), Tláloc (4151 m) and Telapón (4080 m) volcanoes. It lies east of Mexico City, and is an area of great scenic beauty, and enormous hydrological and biogeographical importance; it offers environmental services that benefit more than 18,000,000 inhabitants.

This region is part of the Trans-Mexican Volcanic Belt (TMVB) and has a broad altitudinal gradient (2200-5450 m), a wide range of temperatures, and high mountain ecosystems with a great wealth of species, some of which are endemic.

In November 1935, the Iztaccíhuatl and Popocatépetl peaks were jointly designated a National Park, with 3000 m a.s.l. as the lower limit (DOF, 1935). In March 1937, the Zoquiapan area was also designated a National Park, thus constituting the Iztaccíhuatl-Popocatépetl, Zoquiapan and Anexas National Park (DOF, 1937).

In February 1948 the lower limit was raised to 3600 m a.s.l., to establish on the lower slopes the Industrial Forestry Exploitation Unit that supplied raw material to the San Rafael paper mill; 54% of the National Park was thereby lost. In 1992 the Unit was closed down (DOF, 1992), but it was not specified whether the National Park should return to its original surface area.

In June 2010, UNESCO designated Sierra Nevada as ‘Los Volcanes Biosphere Reserve’ (UNESCO, 2010) and in 2013 the management program for the Iztaccíhuatl-Popocatépetl, Zoquiapan and Anexas National Park (IPZA-NP) was published.

Given its great biodiversity, Sierra Nevada was designated by the National Commission for the Knowledge and Use of Biodiversity (CONABIO) as a Priority Area for Land Conservation and Area of Importance for the Conservation of Birds (AICA C-72). Of the 471 registered species, 35 are in some risk category, including the 18 endemic species.

Within the Sierra Nevada, the IPZA-NP is under Federal control and there are also three State Protected Areas (SPAs): Atlautla-Ecatzingo Water and Forest Sanctuary, Manantiales Cascada Diamantes Water and Forest Sanctuary, and Tetzcotzingo Reserve System.

The IPZA-NP faces several threats, such as deforestation, habitat fragmentation, pollution, invasion by exotic species, forest fires, logging, and hunting (Ervin, 2003). The majority of forest fires are caused by unsustainable agricultural techniques carried out by farmers to renew the pasture, since extensive livestock farming is practised (SEMARNAT, 2013).

In spite of strong widespread forest closures with different periods of diverse duration at a national level between 1948 and 1992, Sierra Nevada has historically been exploited for wood extraction when the San Rafael Forest Exploitation Unit operated, leaving a fragmented landscape (Hernández-García & Granda-Sánchez, 2006; SEMARNAT, 2013). In the 1990s, forest use permits were granted to ‘ejidos’ and agrarian communities () without adequate forest management,
and this caused forest cover to decrease by 30% (SEMARNAT, 2013).

Ejidos and agrarian communities (social property) are the form of land tenure that covers most of the surface in the Mexican countryside. Constitutional Article 27 recognizes the legal personality of both the ejido and communal population centers, their right to land ownership for both human settlements and productive activities (Morett-Sánchez & Cosío-Ruiz, 2017).

In Mexico, the problem of land tenure within Natural Protected Areas (NPAs) is a common factor, and the most recent estimate indicates that of the land constituting the federal NPAs 60% is social property, at least 20% is public property and about 12% is privately owned (Bezaury-Creel & Gutiérrez-Carbonell, 2009).

This study examined the state of the forests under exploitation following suspension of the local paper industry in 1992. A comparison of the density of forest cover between 1994 and 2015 indicated the changes that had accompanied the forestry operations conducted by the ejidos and agrarian communities. The disturbance and recovery processes are analysed for areas with protection and for those without.

2. Study area

The mountain range comprising Sierra Nevada consists mainly of basalts and andesites, and extends into four states (México, Puebla, Tlaxcala and Morelos). With an altitudinal difference of 3250 m, it is part of a biogeographical region and is home to a diversity of coniferous and broad-leaved associations with notable species richness. The importance of its alpine vegetation lies in the abundance of endemic species, and because there are isolated associations of mesophilic mountain forest. In addition, this region is often visited by diverse species of migratory birds from the Gulf of Mexico and the Pacific Ocean.

Within this mountain range are the headwaters of a large catchment area that distributes water resources westwards to the Basin of Mexico, eastwards to the state of Puebla, and southwards to the valleys of Cuernavaca and Cuautla in the state of Morelos.

Sierra Nevada is the most important remnant of coniferous forests and high mountain prairies in the TMVB, where the Nearctic and Neotropical regions coincide. This mountainous area is of strategic importance because it preserves significant hydrological and forest resources, whose species include Abies religiosa, Pinus hartwegii, P. montezumae, P. ayacahuite, P. teocote, P. pseudostrobus, some associated species of the genera Quercus, Arbutus, Alnus, Salix, and Buddleja at the limits of arboreal vegetation, and Zacatonal ecoregion montane vegetation where Lupinus montanus, Agrostis, Festuca, and Muhlenbergia dominate (SEMARNAT, 2013).

The fauna includes endemic species such as the teporingo (Romerolagus diazi). The flora includes the protected species Juniperus montana, Cantharellus cibarius, Chroipterotriton chiroperus, Empidonax affinis, Vireo huttoni, and Myadestes townsendi, and the threatened species Boletus edulis, Amanita muscaria, and Agaricus augustus (SEMARNAT, 2013).

For this study the definition of terms follows FRA 2000: ‘forest’ has a tree canopy cover of >10%; ‘forest degradation’ and ‘forest improvement’ (decrease or increase in the density of trees) occur in forests with a cover that remains above 10%; ‘reforestation’ occurs within forests regrown after temporarily having had below 10% canopy cover, but having been considered as forests throughout that time; and ‘deforestation’ is the conversion of forest to another land use and ‘afforestation’ is the conversion from other land uses into forest. Finally, as a subdivision of the deforestation process, the term ‘loss to agriculture’ is used to designate the change of forest to agricultural activities.

Studies that evaluate the change in density of forest cover in NPAs are scarce, particularly at a scale of 1:5000 and using orthophotographs and Spot images through visual interpretation. For the Monarch Butterfly Biosphere Reserve, Mexico, photointerpretation has assessed disturbance and recovery for four periods between 1971 and 2013 (Manzo-Delgado, López-García, & Alcántara-Ayala, 2014) and has recorded separate processes of disturbance (López-García, 2011; López-García, Prado-Molina, Manzo-Delgado, & Peralta-Higuera, 2016; Vidal, López-García, & Rendón-Salinas, 2014).

Other studies have used satellite images and automated processing to determine changes in NPA cover (Miranda, Corral, Blackman, Asner, & Lima, 2014). Digital cartography has identified the processes of decrement and increment in the density of forest areas in the Nevado de Toluca National Park (Franco, Regil, González, & Nava, 2006). Using existing cartography, others analysed the disturbance-recovery dynamics in the State of Mexico on a small scale (Pineda, Bosque, Gómez, & Franco, 2010).

3. Methods

Twenty-four panchromatic orthophotographs (February–March 1994) from the archives of the National Institute of Statistics and Geography (INEGI) were used to obtain a mosaic, and two Spot-7 images (February 2015) were obtained from the Mexico Receiving Station – New Generation (ERMEX-NG). All the images were re-projected to UTM zone 14N, WGS84. The images were co-registered, using 10 control points taken from the orthorectified mosaic as reference. Then, a first-degree polynomial transformation was applied, resulting in a corrected image with a mean square error of 2.54 m.
The first step was to digitize the boundary of the continuous forest mass of Sierra Nevada from the orthophotographs from 1994 to provide a baseline; a 1 km² mesh was used to perform the digitization in an orderly fashion (right-left and top–bottom), to separate the cover density.

Through visual interpretation of all images, six categories were recognized: five by density of forest cover and one considered as non-forest (agriculture, pasture land, villages, and areas without apparent vegetation). This visual interpretation took into account the elements of photointerpretation and the characteristics of the image such as tone, texture, shape, design, and relationship with other objects (Horning, 2004). The density of forest cover was classified according to tree density: closed canopy (>75%), semi-closed (51–75%), open (10–25%), (López-García, 2009) and deforested (<10%) (FAO, 2010).

Once the cover density map of 1994 had been completed, the topology was verified and overlapping polygons or gaps in the map were corrected. This map was copied and renamed to provide the basis for the cover density map of 2015. The 2015 map was edited and overlaid on the Spot-7 image. A 1 km² mesh was used again, and the map was modified using the 2015 Spot-7 images to map the changes in the density of forest cover. Once finished, the topology was reviewed and errors were corrected.

A minimum mapping area of 5000 m² was used, based on the definition of forest for forest cover (FAO, 2010), and at least 625 m² for deforested or non-forest areas (López-García et al., 2016).

A map of changes was compiled using a comparison of the two maps. This map revealed positive and negative changes, as well as the permanence of the cover density. This procedure reduced potential errors because the areas of unchanged forest remained unmodified, and hence were not re-digitized; thus, only changes between 1994 and 2015 were digitized.

A circular sampling (1000 m²) of vegetation in the field allowed the validation of the different densities of the forest cover, type of vegetation, and the identification of the processes of change. The procedure was also supported by small unmanned aerial vehicle surveys (DJI Phantom 4 Pro), and mosaics were developed to corroborate the results of the sampling.

A confusion matrix classified the changes between the years 1994 and 2015. Processes of change were divided into gains and losses. The gains were forest recovery processes: ‘forest improvement’, forest density increase (from open to semi-open, from open to semi-closed, from open to closed, from semi-open to deforested, from semi-open to closed, or from semi-closed to closed), ‘reforestation’, restoration of vegetation (change from a deforested area to a forest with a cover density of >10%, with trees >5 m tall and with a diameter of >10 cm), and ‘afforestation’, with the return of agricultural land or pasture to forest. The losses were ‘forest degradation’ (decrease in the percentage of forest cover, which leads to a change in density category: from closed to semi-closed, from closed to deforested, from closed to open, from semi-closed to semi-open, from semi-closed to open, from semi-open to open).

The two processes compensate each other; forest degradation is compensated by forest improvement. The process of deforestation is compensated by reforestation, and loss to agriculture is compensated by afforestation, even if it occurs in a different place. In this way, it is possible to know the degree of conservation through the balance of forest disturbance and forest recovery.

4. Results

From 1994 to 2015, changes had occurred in 25.18% of the Sierra Nevada: 15.46% outside the IPZA-NP, 7.32% within the IPZA-NP, and 2.4% in the SPAs (Table 1 and Figure 1); 61.41% of the changes occurred in the non-protected area, 29.08% in the IPZA-NP and 9.51% in the SPAs (Table 1).

A confusion matrix allowed separation of the different change processes, with the most intense changes being forest improvement (11.58%) and forest degradation (7.64%). They dominated over the processes of deforestation and reforestation (2.55% and 2.23% respectively), as well as over those of loss to agriculture and afforestation (0.74% and 0.44% respectively) (Table 2 and Figure 1).

The recovery (14.24% of the forest) was higher than the disturbance (10.93%), with the closed and semi-closed categories being those that experienced the most changes, either positive or negative. Changes due to deforestation including loss to agriculture were minimal (Table 2).

There was more reforestation than deforestation outside the IPZA-NP. Also, more afforestation was observed outside the protected areas than in the

| Sierra Nevada                  | No change |         |         | Change |         |         | Total |         |
|-------------------------------|-----------|---------|---------|--------|---------|---------|-------|---------|
|                               | ha        | % Rel   | % Abs   | ha     | % Rel   | % Abs   | ha    | %      |
| Federal Natural Protected Area| 28,586.70 | 24.90   | 18.63   | 11,232.39 | 29.08   | 7.32    | 39,819.09 | 25.95   |
| State Protected Area          | 20,934.03 | 18.23   | 13.64   | 3,673.09 | 9.51    | 2.39    | 24,607.12 | 16.04   |
| No Protected Area             | 65,288.10 | 56.87   | 42.55   | 23,722.86 | 61.41   | 15.46   | 89,010.96 | 58.01   |
| Total                         | 1,14,808.82 | 100.00 | 74.82   | 38,628.35 | 100.00  | 25.18   | 1,53,437.17 | 100.00  |

Table 1. Comparison between 1994 and 2015 in forest cover in the Sierra Nevada, Mexico.
SPAs, and more loss to agriculture than afforestation in the federal NP (Table 3 and Figure 1).

The IPZA-NP had a recovery of 4.45% and a disturbance of 2.87%, while the SPAs had a recovery of 1.35% and a disturbance of 1.04%. In Sierra Nevada, 42% of the area has some protection status. However, there was more recovery, mainly forest improvement, outside the protected areas than in the IPZA-NP, but at the same time there was also more disturbance, mainly forest degradation, outside the protected areas than inside the IPZA-NP.

Recovery was greater in the IPZA-NP than in the unprotected zone (17.15% vs. 14.55% respectively), and there was also less disturbance inside the IPZA-NP than outside the protected areas (11.06% vs. 12.10% respectively) (Table 3 and Figure 1).

5. Discussion

Multitemporal analysis using orthophotographs and Spot-7 images allows a detailed comparative visual interpretation at a scale of 1:5000; this enables accurate determination of the processes of change in the forest cover in a NPA and its area of influence. This method is similar to those used in analyses performed in the Monarch Butterfly Biosphere Reserve, where only

Figure 1. Changes in forest cover in Sierra Nevada, Mexico, 1994–2015.
aerial photographs were used (López-García, 2011; López-García et al., 2016; Manzo-Delgado et al., 2014; Vidal et al., 2014). However, it has the advantage of combining two products of similar spatial resolution but of different origin and date, to achieve an adequate multi-temporal comparison with the support of geographic information systems.

The forest management outside the NPAs, carried out by the Industrial Forestry Exploitation Unit over a period of 44 years, left the region very much disturbed, and scarred with innumerable forest roads. Although there were later forest closures, forest exploitation permits were also granted to ejidos and communities after 1992, and this left an even more fragmented landscape (SEMARNAT, 2013).

The Sierra Nevada region, designated by UNESCO as ‘Los Volcanes Biosphere Reserve’ (UNESCO, 2010), faces a great problem, since it is in one of the most populated regions of the country with 18.67 million inhabitants in its surrounding areas (Censo de población y vivienda, 2010). In the period 1994–2015, Sierra Nevada has had more recovery (mainly forest improvement) than disturbance (forest degradation). Therefore, if the current dynamics are maintained, recovery of the forest can be expected along with a consequent improvement in the environmental services that these forests provide to the most populated region of the country. The importance of this region lies in the biodiversity of its forests (the most conserved forests in central Mexico), important water resources, and carbon sequestration (SEMARNAT, 2013).

The major changes in the landscape of Sierra Nevada between 1994 and 2015 occurred outside protected areas; but in relative terms there was more recovery in the protected areas than outside the protected areas. This suggests that the payment programs for environmental services, fire control and surveillance have contributed to the conservation and improvement of the Sierra Nevada forests.

With the designation of the IPZA-NP as a protected area, the lands were expropriated, but without compensation. This has created social conflict in the management of this NPA, since the ejido members and the agrarian communities demand their property rights; on the other hand, they have the right to payment for ecological services (PES), which in turn has led to the recovery and conservation of forests.

The IPZA-NP, as delimited above 3600 m a.s.l. (DOF, 1948), should be federal property, yet 27.15% of the land is socially owned and also has PES. All the lands outside the protected areas are social property, but only 39.09% have PES (CONAFOR, 2017). In comparison with the unprotected area, the IPZA-NP has been effective in preventing changes in forest cover. It is included in the 45% of National Parks

Table 2. Confusion matrix of density of forest cover between 1994 and 2015 in the Sierra Nevada, Mexico.

| Categories          | Closed | Semi-closed | Semi-open | Open  | Deforested | No forest | Total 1994 |
|---------------------|--------|-------------|-----------|-------|------------|-----------|------------|
| Closed              | 47.51  | 2.05        | 1.28      | 0.95  | 1.44       | 0.21      | 53.43      |
| Semi-closed         | 3.27   | 3.38        | 1.17      | 0.88  | 0.30       | 0.06      | 9.06       |
| Semi-open           | 2.12   | 2.39        | 2.52      | 1.31  | 0.26       | 0.13      | 8.76       |
| Open                | 1.35   | 1.28        | 1.16      | 4.14  | 0.53       | 0.13      | 8.59       |
| Deforested          | 1.07   | 0.19        | 0.29      | 0.08  | 2.82       | 0.21      | 5.26       |
| No forest           | 0.14   | 0.05        | 0.08      | 0.07  | 0.96       | 1.48      | 14.90      |
| Total 1995          | 55.45  | 9.35        | 6.48      | 8.02  | 5.49       | 15.20     | 100.00     |

Table 3. Disturbance and recovery in forests of the Sierra Nevada, Mexico, between 1994 and 2015.

| Change in forest cover Sierra Nevada | Federal Protected Area | State Protected Area | No Protected Area | Total |
|-------------------------------------|------------------------|----------------------|------------------|-------|
|                                     | he         | % abs rel | he         | % abs rel | he         | % abs rel | he         | % abs rel |
| Forest degradation                  | 3,914.93   | 2.55     | 9.83       | 1159.65   | 0.76     | 4.71       | 6640.89   | 4.33     |
|                                     | 6407.84    | 4.33     | 7.64       | 11715.67  | 7.64     |
| Deforestation                       | 365.39     | 0.26     | 0.97       | 339.47    | 0.22     | 1.38       | 3169.27   | 2.06     |
|                                     | 3169.27    | 2.06     | 2.55       | 3169.27   | 2.06     |
| Loss to agriculture                 | 102.55     | 0.07     | 0.26       | 97.81     | 0.06     | 0.60       | 142.54    | 0.09     |
|                                     | 142.54     | 0.09     | 0.74       | 142.54    | 0.09     |
| Subtotal                            | 4622.04    | 2.87     | 11.06      | 5497.13   | 3.04     | 6.69       | 10772.30  | 6.72     |
|                                     | 10772.30   | 6.72     | 10.93      | 10772.30  | 6.72     |
| Forest improvement                  | 6261.59    | 4.08     | 15.73      | 1652.97   | 1.01     | 6.31       | 9948.46   | 6.46     |
|                                     | 9948.46    | 6.46     | 11.58      | 9948.46   | 6.46     |
| Reforestation                       | 467.64     | 0.32     | 1.22       | 345.16    | 0.23     | 1.40       | 2696.66   | 1.69     |
|                                     | 2696.66    | 1.69     | 2.33       | 2696.66   | 1.69     |
| Afforestation                       | 91.20      | 0.06     | 0.20       | 77.63     | 0.12     | 0.72       | 47.64     | 0.27     |
|                                     | 47.64      | 0.27     | 0.44       | 47.64     | 0.27     |
| Subtotal                            | 6829.53    | 4.45     | 17.15      | 2075.96   | 1.36     | 8.44       | 21858.06  | 14.24    |
|                                     | 21858.06   | 14.24    | 18.58      | 21858.06  | 14.24    |
| Total                               | 11232.39   | 7.32     | 28.21      | 3673.09   | 2.40     | 14.93      | 23722.86  | 15.46    |
|                                     | 23722.86   | 15.46    | 25.18      | 23722.86  | 15.46    |
that have been effective in preventing such changes (Figueroa & Sánchez-Cordero, 2008). Sánchez-Azofeifa, Quezada-Mateo, González Quezada, Dayanan-dan, and Bawa (1999) observed less deforestation and habitat fragmentation within the NPAs of the Sarapiquí region of Costa Rica than in the unprotected area. This confirms the importance of NPAs in reducing the impact of changing forest cover, and thus in the conservation of biodiversity (Ervin, 2003; Sánchez-Cordero, Illoldi-Rangel, Linaje, Sarkar, & Peterson, 2005).

6. Conclusions

Between 1994 and 2015, the recovery of forests in Sierra Nevada has been greater than the general forest disturbance, with a tendency towards the improvement of the environmental services that these forests provide to the most populated region of the country.

The greatest change occurred in the area of influence of the PAs, and this was caused by the Industrial Forestry Exploitation Unit, and later, by the ejidos and agrarian communities. The significant conservation of the protected areas demonstrates the effectiveness of the current protection status, which is supported by the PES and several schemes developed in this region, such as ongoing reforestation, measures to reduce forest fires, and programs to reduce illegal logging.

The differences in the recovery processes outside and within the NPAs demonstrate the need for forest management for the recovery of forests.

Software

The photographs were enhanced with Adobe Photoshop v7.0. ESRI ArcGIS v10.2 was used for the digitization of the forest density polygons, the spatial comparisons and for the edition of the final map.

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