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Impact of timber harvesting on carbon storage in montane forests of central Mexico

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Abstract
Cut stumps are the legacy of forest harvesting and allow for the estimation of carbon loss from the ecosystem. The objective of this study was to estimate aboveground carbon storage and the impact of forest harvesting based on measurements of cut stumps in pine forests within the Área de Protección de Flora y Fauna Nevado de Toluca (APFFNT) in the state of México. A total of 1621 circular 0.1-ha sampling plots were established in a 12,924 ha pine forest (1.25% sampling intensity). Biomass was calculated using conventional volumetric equations incorporating species-specific wood densities. Aboveground carbon storage in the biomass was stratified by forest type including dense forest (≥ 336 trees), semi-dense forest (< 335 and > 150 trees), fragmented forest (< 150 and > 20 trees), and stands with isolated trees (< 20 trees). In the 12, 924 ha of forest dominated by *Pinus hartwegii*, 1,695,004 MgC was contained in aboveground biomass. Data on forest harvesting obtained by analysis of recent cut stumps allowed for the estimation of the removal of 42,701 MgC. In addition, we accounted for carbon in wind thrown trees of 14,904 MgC, some of which were removed over time in harvests. Total loss of carbon from the forest corresponded to 211,218 $MgCO_2$ per year. In the APFFNT, forests dominated by pine with high biomass (*P. hartwegii* and *P. montezumae*) are being replaced by those with lower biomass (*Alnus jorullensis*). Changes in these communities will result in lower carbon capture in the APFFNT.

Keywords Biomass · CO_2 emissions · Cut stumps · *Pinus hartwegii* · Wood volume

Introduction

The carbon (C) cycle comprises fluxes that depend on physiochemical and biogeochemical processes, such as photosynthesis, plant respiration and soil heterotrophic relationships (Cao and Woodward 1998). C sinks and natural sources regulate these fluxes. The oceans, the atmosphere, and forests are examples of C sinks; while plant respiration, decomposition of organic matter, and fires are examples of sources of C

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(Falkowski et al. 2000). The function of terrestrial ecosystems has been affected in the past 200 years by an imbalance in the C cycle, reflected by an increase in atmospheric CO_2 concentration from 280 to 400 ppm as of 2015 (Dlugokencky et al. 2016). The principle causes of this increase have been emissions of CO_2 from the use of fossil fuels and the impact of changes in land use (IPCC 2007). Furthermore, deforestation is the second largest source of anthropogenic greenhouse gas emissions (Gullison et al. 2007).

Vegetation acts as a C sink and mitigates increases in atmospheric CO_2 (Brown 2002), however the CO2 stored in vegetation can return to the atmosphere through the rate of respiration from plants, decomposition or occurrence of wildfire. Plant communities can be a source of C due to natural disturbances or human activities (Rojo et al. 2003). The loss of forest cover generates impacts at different scales. At landscape scale, it includes the degradation of soils, the loss of ability of biological systems to support human needs and the increased vulnerability of regions in situations of climatic disturbances (Lambin et al. 2003). At local level, it causes a decrease both in material goods and in the environmental services provided by the forest (MEA 2003), among them the C storage and capture (Lambin et al. 2003).

One of the strategies involved in decreasing the rate of loss in forest cover in Mexico is the establishment of Protected Natural Areas. The legal definition of these protected areas and their creation through presidential decree calls for special protection that promotes the storage of C in forests over the long term (Rojas-García 2008). The General Law of Ecological Equilibrium and Environmental Protection establish the activities permitted in such protected areas, between them protection, management, restoration, research, cultural and leisure. The National Commission of Protected Natural Areas administers 176 federal units representing 25.4 million ha. Protected areas in central México are present in mountainous areas where most previous studies have been on the response of forests to environmental changes and the growing areas of timber harvesting (Villers and Trejo 1998). One of the most utilized practices since the 1980s is the mitigation of environmental degradation through reforestation programs. These programs have mainly focused on conservation impacts than on forest harvesting processes, particularly, on the appropriate site selection for planted tree species (Rescala 2009).

The Forest Inventory of the State of Mexico indicates that 48% of the state is covered by forests, with 95% of these forests being temperate with different degrees of disturbance (PROBOSQUE 2010). Collado and Serrato (2009) estimated that, from 1900 to 2001, there was a 53% loss in forest cover in the state, which has caused temporary halts to logging because of deforestation and problems in the forest industry. The loss of temperate forests has had negative effects including soil degradation, reduction in watershed services, loss of diversity and increased pest outbreaks (GEM 1999).

The Intergovernmental Panel on Climate Change (IPCC) identified five C storage areas in plant communities: live aboveground biomass, live belowground biomass, dead aboveground biomass, leaf litter and soil. The storage of C in dead aboveground biomass includes a wide variety of stem types and diameter sizes that includes standing dead trees and fallen logs, stumps, fallen branches and roots (IPCC 2003).

Dead wood is a key component in the flow of energy and nutrients, it is fuel for potential wildfires and is one of the most important C storage components in natural forests (Baker et al. 2007; Chao et al. 2009). When a tree dies of natural causes or it is harvested for timber, its C enters one of the three reservoirs: woody debris, wood products, or the atmosphere (GOFC-GOLD 2010). The duration of C storage in dead wood in natural forests depends on the rates of mortality and decomposition (Palace et al. 2007).

Cut stumps are the evidence of forest harvesting, allowing for the estimation of C loss from the ecosystem. From them, it is possible to estimate volume, biomass, and amount of C removed from an ecosystem and allows for calculations of C emissions from timber harvesting. The Área de Protección de Flora y Fauna Nevado de Toluca (APFFNT), in the state of Mexico presented changes in land use that converted forested areas to agricultural land. This conversion occurred in spite of the fact that some areas were not suitable for agriculture. Furthermore, evidence of illegal harvesting was found, such practice can be responsible for the rise of wildfire probabilities, forest fragmentation and for the reduction of pest and disease outbreaks resistance (CONANP 2017). Due to the above, the objective of this study was to estimate aboveground C storage in forest trees and to assess the impact of forest harvesting based on measurements of cut stumps in pine forests inside the APFFNT.

Methods

Study area

The APFFNT is located in the state of Mexico, which includes the Nevado de Toluca volcano. The altitudinal range is 3000–4680 m asl. The protected area is located in the southern region of the state, comprising a surface of 53,590 ha. It was declared a national park in 1936 with the objective of safeguarding its scenic quality and hydrological importance (SEMARNAT 2013).

Andisols are the predominant soil type, covering 90% of the park, as well as feozem, regosol, cambisol, fluvisol and leptosol types, which are the products of extrusive igneous rocks of Tertiary and Quaternary origins (Sotelo et al. 2010). The instability of the soil structure, along with deforestation, overgrazing, steep slopes and torrential rain events, can generate intense soil erosions (Sánchez-Jasso et al. 2013).

The Nevado de Toluca volcano presents a vertical thermal gradient. Above the 3700 m altitude, the climate is cold with a summer rainfall regime (E(T)Hwig). Below this altitudinal elevation and up to 2800 m, the climate surrounding the volcano is subhumid, semi-cold with rainfall occurring in the summer (C(E)wig) (García 1981).

Sampling methods

The heterogeneity of the terrain and climate in the park were considered in developing a sampling protocol that included estimates of species diversity, tree sizes and tree conditions. Circular sampling plots of 0.1 ha (17.86 m in radius) were distributed systematically to each 200 m along transects, following the elevation contours separated by of 100 m, by above 3400 m. The distribution of plots allowing include changes in forest structure associated with climatic variation due to the elevation (Mayer and Ott 1991) (Fig. 1).

The 1621 sampling plots were established in 12,924 ha of pine forest occurring between August 2016 and August 2017. The sampling intensity recommended for the surface is 0.44% (Dauber 1995), in the present study a 1.25% was reached.

Plots were located using topographic maps and the center of UTM coordinates, and the altitude (m) was recorded with a GPS Rhino® 650 Garmin. For each sampling plot, we recorded the slope and aspect with a compass and clinometer (Tandem Suunto).

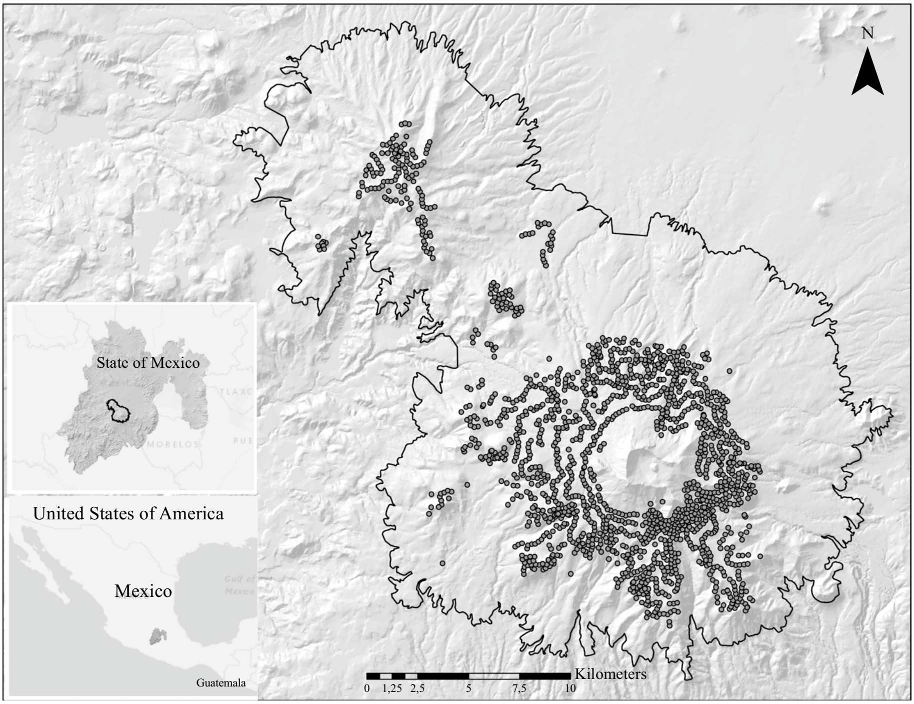

Fig. 1 Location of the study area and plots within the Área de Protección de Flora y Fauna Nevado de Toluca. Circles represent the sampling plots

The trees that had ≥ 7.5 cm diameter breast height (DBH, 1.30 m aboveground) were measured for DBH (cm), total height (m), and condition (e.g., presence of parasitic plants, disease). For standing dead trees or trees fallen in the past year, we observed the species, DBH (cm) and total height (m). The stumps that conserved their structural integrity, presence of resins and sawdust, lack of understory vegetation around or evidence of damage by felling of the surrounding trees, were measured. The diameter of the cutting surface (dt, 0.30 m above the ground) was recorded.

We additionally observed dominant tree species, percentage cover of herbaceous and shrub species, and any evidence of recent fire. The relative dominance of species in each plot by percent basal area was estimated (Kent and Coker 1992). The density of forests was defined by Endara et al. (2013), in dense forest (≥ 336 trees), semi-dense forest (150–335), fragmented forest (21–150), and isolated trees (≤ 20) (10% of the density over all plots).

Estimation of C storage in forest biomass

The stemwood volume in each measured individual tree was calculated using species-specific volumetric equations, developed by the National Forest and Soils Inventory (CONAFOR 2012):

$$V = (a0 + a1 * (DBH) + a2 * (HT)) \tag{1}$$

where V = volume (m^3); DBH = diameter at breast height (cm); HT = total height (m) and $a(n)$ = species-specific coefficients.

To convert volume to biomass, it is necessary to include basic wood density that allows for conversion of wet weight to dry weight (Brown et al. 1989). According to the recommendation of Brown and Lugo (1984) in the calculation of individual tree biomass, a multiplier of 1.3 for broad-leaved trees and 1.18 for conifers, the stem expansion factor (SEF), to include branch and foliar biomass is:

$$B = V * D * SEF \tag{2}$$

where B = biomass (kg), V = volume (m^3); D = wood density (kg/m^3), SEF = stem expansion factor (index). Table 1 shows the estimated wood density values for each species in mountain forests according to Markwar and Meck (Echenique and Díaz 1972).

The C content of individual trees based on biomass, which corresponds to 45–50% of dry weight, the most conservative value was used in this study (45%) (IPCC 2003).

Estimation of C loss due to timber harvesting

We used an equation developed in Mexico to estimate the DBH of pine trees based on measurements of the diameter of the stump (dt) (cm) (Corral et al. 2007):

$$DBH = 1.721 * (dt \wedge 0.8494) \tag{3}$$

Once the DBH was known (cm), the HT (m) was estimated by means of a correlation of the data of 30,599 individual trees measured ($R^2 = 0.849$):

$$HT = 0.3608 * (DBH \wedge 1.0374) \tag{4}$$

Table 1 Wood density values for high mountain forest trees

Species	Common name	Basic wood density (kg/m^3)	Classification of wood according to Markwar and Meck	
Abies religiosa (Kunth) Schltdl. and Cham.	oyamel	378.4	Moderately light	a
Alnus jorullensis Kunth	aile	289.8	Very light	a
Arbutus xalapensis Kunth	madroño	750.0	Excessively heavy	b
Buddleja cordata Kunth	tepozán	750.0	Excessively heavy	b
Cupressus lindleyi Klotzsch ex Endl.	cedro	381.0	Moderately light	c
Pinus ayacahuite C. Ehrenb. ex Schltdl.	ayacahuite	411.0	Moderately light	d
Pinus hartwegii Lindl.	pino de las alturas	496.5	Moderately heavy	e
Pinus montezumae Lamb.	pino real	511.5	Heavy	a
Pinus patula Schltdl. and Cham.	pino llorón	500.0	Moderately heavy	f
Pinus pseudostrobus Brongn.	pino blanco	540.0	Heavy	f
Quercus laurina Bonpl.	encino laurelillo	663.0	Very heavy	g
Salix cana M. Martens and Galeotti	sauce	560.0	Heavy	b

References: a = Rojas-García and Villers (2008); b = Aguilar et al. (2001); c = Rodríguez and Torres (1995); d = Honorato and Meraz (2002); e = Rojas-García and Villers (2005); f = Fuentes (1998); g = Bárcenas et al. (2007)

to determine the volume of the wood (m^3), and later the biomass, following the procedure of the live trees.

The values of the *V*, *B* and *C* content per sampling plot was obtained by adding the individual values of each individual tree in 0.1 ha. An average value of volume, biomass and C content of each of the sampling plots was obtained. Finally extrapolated per hectare into $m^3\ ha^{-1}$ for the volume, megagrams for biomass (Mg ha^{-1}) and megagramos of C (MgC ha^{-1}), considering the type of vegetation and the density of trees (Padmakumar et al. 2018). Subsequently, a conversion was made based on the molecular C equivalent (44/12), to estimate C emissions.

Results

Relative dominance and tree density

The relative density of natural pine forests within the 12,924 ha area included five monospecific communities of pine and 16 pine-dominated communities of the total 22 plant communities. Table 2 shows the basal area and density in plant communities representative of the four classes of forest density. In this study, we included areas with isolated trees that corresponded to 10% or less of the mean total density or basal area.

The evaluation of the inventory data allowed the identification of dendrometric characteristics of the forests that grow in the Nevado deToluca, which are described below. *P. hartwegii* forests occur on the slopes of the volcano from 3300 to 4375 m in altitude. The forests are monospecific from 3700 m up to the tree line. At lower elevations, forests are dominated by *A. jorullensis, A. religiosa* and *P. montezumae*. Individuals in this community have an average height of 18 m and an average DBH of 26 cm; however, DBH, height and the DBH to height ratio show a similar behavior along the altitudinal gradient (Fig. 2). An increase of these three characteristics is observed at 3000 m and at the elevation ranging from 3700 to 4100 m asl. Variation in tree size and allometry is attributable to environmental conditions such as temperature, precipitation, stone content in soil, and aspect. The shrub stratum has low density with a few individuals of *Penstemon gentianoides* (Kunth) Poir., *Eupatorium glabratum* Kunth and *Baccharis conferta* Kunth, *Cirsium nivale* (Kunth), *Robinsonecio gerberifolius* (Sch. Bip. ex Hemsl.) T.M.Barkley and Janovec Sch. Bip. The herbaceous plant stratum is represented by grass species, such as *Muhlenbergia quadridentata* (Kunth) *Trin., M. macroura* (Kunth) Hitchc. and *Festuca tolucensis* Kunth. Semi-woody shrubs, such as *Eryngium proteaeflorum* F. Delaroche and *Lupinus aschenbornii* S. Schauer in highly disturbed sites, are much less common.

A. jorullensis forests occur in stands frequently mixed with *A. religiosa* or *Pinus.* This community occurs between 3200 and 3500 m. Trees had an average diameter of 30 cm and varied in height from 5 to 30 m. *Roldana angulifolia* (DC.)H. Rob. and Brettell is dominant in the shrub stratum; and in the herbaceous stratum *Astragalus guatemalensis* Hemsl. and *Stellaria cuspidata* Willd. ex Schltdl are the most common species.

A. religiosa forests are distributed in pure stands or mixed stands with *Pinus* between 2800 and 3500 m asl and have a mean DBH of 30 cm and a height between 15 and 45 m. These forests occur on sites that are sometimes totally covered in moss and have a shrub stratum dominated by *Senecio cinerarioides* Kunth., *Baccharis conferta* Kunth, *Ageratina glabrata* (Kunth) R. M. King and H. Rob., *Asplenium monanthes* L. and *Fuchsia thymifolia* Kunth. In the herbaceous stratum, common species include *Festuca*

Table 2 Living trees density (ha^{-1}) and basal area ($m^2\ ha^{-1}$) of the trees of the APFFNT plant communities established above 3400 m

Dominance	Density				Basal Area			
	Isolated trees	Fragmented forest	Semi-dense forest	Dense forest	Isolated trees	Fragmented forest	Semi-dense forest	Dense forest
Abies religiosa–Pinus hartwegii	85 ± 25		147.5 ± 29.55	90 ± 20	3.31 ± 0.09		18.32 ± 1.53	40.89 ± 2.64
Alnus jorullensis	60 ± 23.8	90 ± 12.25			4.24 ± 1.44	11.96 ± 0.75		
Alnus jorullensis–Pinus hartwegii	85 ± 2.89	88.57 ± 19.93	178.33 ± 42.38	248.33 ± 50.16	6.19 ± 1.09	10.91 ± 0.64	16.9 ± 0.76	27.3 ± 2.15
Pinus hartwegii	110.63 ± 5.15	173.53 ± 6.63	245.85 ± 8.48	268.81 ± 7.48	5.24 ± 0.12	11.27 ± 0.09	17.57 ± 0.11	29.98 ± 0.4
Pinus hartwegii–Abies religiosa	172.5 ± 29.5	237.5 ± 84.4	212.5 ± 47.15	453.33 ± 153.01	5.51 ± 0.71	12.72 ± 0.14	17.03 ± 0.75	34.41 ± 6.1
Pinus hartwegii–Alnus jorullensis	101 ± 13.62	161.25 ± 22.3	205 ± 14.02	403.75 ± 60.35	5.62 ± 0.74	10.79 ± 0.4	17.78 ± 0.49	32.04 ± 3.52
Pinus montezumae	221.43 ± 83.25	223.33 ± 89.06	196 ± 91.9	136 ± 21.3	7.15 ± 0.45	11.41 ± 0.62	18.2 ± 1.3	34.36 ± 3.82

Values are the mean ± standard error

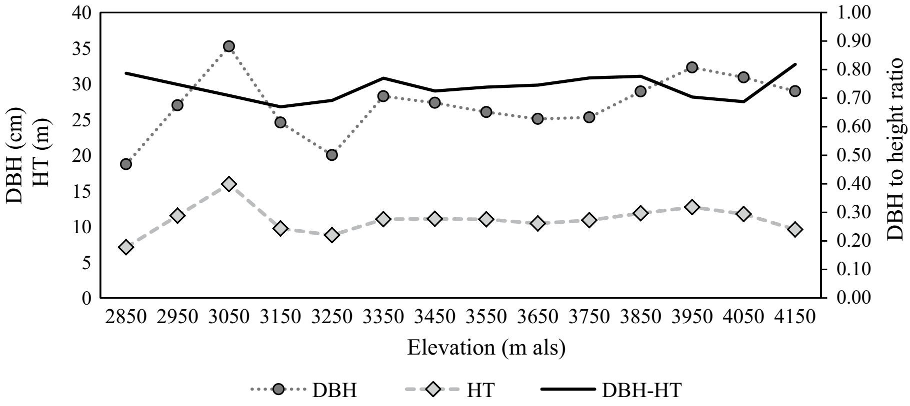

Fig. 2 Dendrometric characteristics of live trees of *Pinus hartwegii* in an altitudinal gradient. DBH (cm) represented with circular markers and the height of the trees (HT) (m) represented with rhomboid markers. The DBH to HT ratio represented with a continuous black line shows on the secondary axis

amplissima Rupr., *Castilleja arvensis* Schltdl. and Cham., *Salvia elegans* Vahl., *Senecio callosus* Sch. Bip. and *Vicia pulchella* Kunth. They occur in pure stands or in mixed stands with pine species or in association with pine and fir.

Pinus montezumae forests are distributed in isolated stands between 3000 and 3200 m in the center of the protected area. Trees in this forest are 15–30 m in height and have an average DBH of 30 cm. Inside these forests include species of *Pinus*, as well as *Q. laurina, A. religiosa, A. xalapensis, A. jorullensis, S. cana* and *B. cordata.* The shrub stratum is dominated by *Arctostaphylos pungens* Kunth, *Roldana barba-johannis* (DC.) H.Rob. and Brettell and *Pernettya prostrata* (Cav.) DC. In the herbaceolus stratum *Muhlenbergia macroura, Penstemon campanulatus* (Cav.) Willd., *Lupinus montanus* Kunth, *Castilleja tenuiflora* Benth., *Salvia laevis* Benth., *Cirsium subuliforme* Ownbey and *Senecio sinuatus* Gilib are common.

Wood volume and biomass

Table 3 describes wood volume and aboveground biomass in seven major plant communities and four density classes in the protected area. Wood volume and aboveground biomass presented a similar behavior along the altitudinal gradient. This behavior of the variables is more closely relate to the basal area than to the density of trees (Fig. 3).

Table 4 shows the number of stumps, the estimated volume and the aboveground biomass present in cut trees. Forests that were the most exploited were dominated by pine regardless of density class. Despite *P. montezumae* having the lowest density in forests of Nevado de Toluca, it is the most harvested specie, due to the stem size and wood density. In *P. hartwegii* stands, there was an average of 18.69 Mg of aboveground biomass harvested in all density categories. In *P. hartwegii–A. religiosa* and *A. jorullensis-P. hartwegii* forests, *P. hartwegii* stems were the most abundant, followed by those of *A. religiosa.* In general, *A. jorullensis* trees were not preferentially harvested due to the low density of the wood.

Table 3 Wood volume (m^3 ha^{-1}) and aboveground biomass (Mg ha^{-1}) in high mountain forests of the APFFNT

Dominance	Wood volume				Aboveground biomass			
	Isolated trees	Fragmented forest	Semi-dense forest	Dense forest	Isolated trees	Fragmented forest	Semi-dense forest	Dense forest
Abies religiosa–Pinus hartwegii	28.26 ± 6.69		228.53 ± 17.84	946.34 ± 148.2	14.95 ± 3.58		124.84 ± 10.83	511.66 ± 69.73
Alnus jorullensis	33.85 ± 8.27	105.15 ± 11.79			13.28 ± 3.36	43.52 ± 6.12		
Alnus jorullensis–Pinus hartwegii	54.93 ± 11.53	128.46 ± 8.27	175.28 ± 19.98	285.96 ± 16.59	26.05 ± 6.12	62.22 ± 3.56	84.25 ± 11.15	142.45 ± 10.05
Pinus hartwegii	52.67 ± 1.73	130.05 ± 2.25	211.58 ± 3	402 ± 7.62	33.95 ± 1.11	83.81 ± 1.46	136.19 ± 1.95	259.02 ± 4.93
Pinus hartwegii–Abies religiosa	44.39 ± 7.49	127.47 ± 22.81	241.77 ± 30.46	481.51 ± 124.52	25.44 ± 4.52	75.73 ± 12.22	140.25 ± 18.32	287.81 ± 78.59
Pinus hartwegii–Alnus jorullensis	51.93 ± 9.44	110.01 ± 6.86	183.09 ± 9.94	320.75 ± 42.44	28.79 ± 5.6	61.84 ± 4.03	101.46 ± 5.77	179.97 ± 23.47
Pinus montezumae	100.52 ± 25.93	148.81 ± 32.27	288.2 ± 30.8	559.46 ± 51.17	66.83 ± 17.25	98.87 ± 21.49	191.64 ± 20.48	372.02 ± 34.03

Values are the mean ± standard error

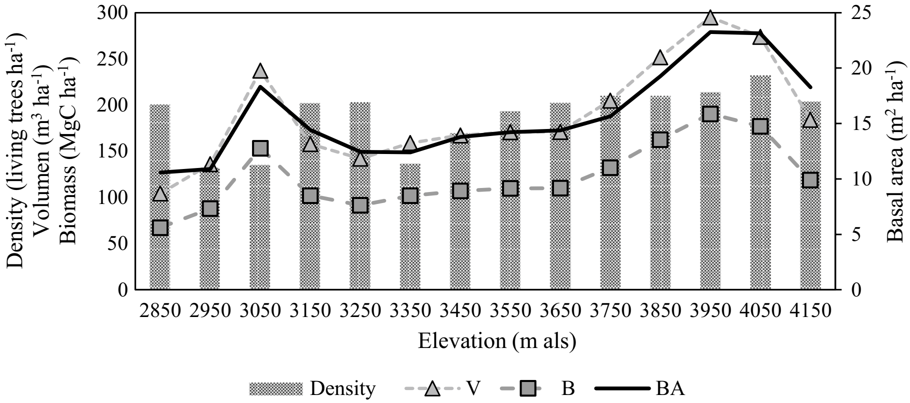

Fig. 3 Density, wood volume and aboveground biomass of live trees of *Pinus hartwegii* in an altitudinal gradient. Density represented with bars; wood volume (m^3 ha^{-1}) represented with triangular markers and aboveground biomass (Mg ha^{-1}) represented with quadrangular markers. Basal area (m^2 ha^{-2}) represented with a continuous black line shows on the secondary axis

Table 4 Wood volume (m^3 ha^{-1}) and aboveground biomass (Mg ha^{-1}) associated with forest extraction for 1 year of measurement in the protected area

Dominance	Stumps result of forest extraction 2016			
	Isolated trees	Fragmented forest	Semi-dense forest	Dense forest
Abies religiosa–Pinus hartwegii				
Stumps			20 ± 7.07	
Wood volume			24.73 ± 9.47	
Aboveground biomass			12.28 ± 4.7	
Pinus hartwegii				
Stumps	26.82 ± 1.06	27.23 ± 1.17	33.95 ± 2.18	28.48 ± 1.33
Wood volume	38.43 ± 2.05	37.07 ± 1.75	38.14 ± 2.3	36.98 ± 3.13
Aboveground biomass	19.08 ± 1.02	18.4 ± 0.87	18.94 ± 1.14	18.36 ± 1.55
Pinus hartwegii–Abies religiosa				
Stumps	35 ± 2.5			
Wood volume	81.88 ± 9.69			
Aboveground biomass	40.65 ± 4.81			
Pinus hartwegii–Alnus jorullensis				
Stumps	30 ± 4.47		20 ± 3.16	
Wood volume	20.27 ± 8.14		18.5 ± 4.83	
Aboveground biomass	10.06 ± 4.04		9.19 ± 2.4	
Pinus montezumae				
Stumps	22.5 ± 5.67	25 ± 2.89	13.33 ± 2.58	16.67 ± 1.83
Wood volume	72.47 ± 42.47	49.6 ± 3.61	17.41 ± 2.24	13.63 ± 0.82
Aboveground biomass	35.98 ± 21.09	24.63 ± 1.79	8.64 ± 1.11	6.77 ± 0.41

Stumps = number of stumps (ha^{-1})

Values are the mean ± standard error

Impact of harvesting on C storage

Table 5 shows the mean C storage in situ aboveground biomass and C removed due to harvesting in the seven communities and four density classes in high mountain forests.

Figure 4 shows the distribution of C in aboveground forest biomass in the protected area. A total of 1,695,004 MgC was stored in the 12,924 ha area (mean 131.1 MgC ha^{-1}). The harvesting data is in agreement with the survey of recently cut stumps, which allows for a defensible estimate in which 2.5% of C storage was removed from the protected area during the year of sampling (42,701 MgC). In addition, there was an estimated 14,903 MgC in fallen trees because of windthrow, although some of these trees had been removed during harvesting. Estimates are that 211,218 $MgCO_2$ were emitted during the year of the study.

Discussion

Storage of C in montane forests

Forest ecosystems are often seen as potentially large C sinks and plant biomass providers (Augusto et al. 2015). Improved knowledge of carbon stocks and fluxes is need in order to understand the current state of the C cycle and how it might evolve with changing land use and climatic conditions (Hollinger 2008).

Trees in temperate forests in México have a large economic importance and are the base of the forest industry in the country. However, the pursuit of suitable climates and fertile soils for agriculture are causing severe deforestation and degradation in this ecosystem (Challenger 1998).

Rzedowski (1978) calculated that between 50 and 67% of the original areas of these forests have been converted to other uses and now cover only 13% of the nation (Flores-Villela and Gerez 1994). These ecosystems are among the best represented within the national system of protected natural areas but, the majority of these areas are near large cities where they have been subjected to large human impacts, such as the case with the protected area of this study (Challenger 2003).

The Nevado de Toluca protected areas have been subjected to intensive human disturbances, such as potato farming and cattle ranching in recent years that have extended to elevations higher than 3700 m. The vegetation that develops in the APFFNT is the result of its geographic and altitudinal position conjugated with the characteristics of relief, geology, edaphic conditions and climate. Currently, it is possible to observe a mosaic of plant communities that vary with different tree densities within the protected area.

The high sampling intensity used in this study allowed the characterization of aboveground C storage in montane forests where composition, density, and dominance of species can change rapidly over small changes in altitude (Vázquez and Givnish 1998; Sánchez-González and López-Mata 2003). The inventory also permitted us to understand important aspects of forest communities, particularly, the distribution of resources among different species through indirect estimate of biomass, such as plant cover and basal area (Mueller-Dombois and Ellenberg 1974; Whittaker 1975). The density classes of the high mountain forests proposed in this study agree with the measurements made on tree densities reported in other studies in the Nevado de Toluca (Villers et al. 1998; Endara et al. 2013).

Table 5 C storage in high mountain forests and C removed by logging during 1 year of measurement (MgC ha^{-1})

Dominance	Storage of C				C removed after logging			
	Isolated trees	Fragmented forest	Semi-dense forest	Dense forest	Isolated trees	Fragmented forest	Semi-dense forest	Dense forest
Abies religiosa–Pinus hartwegii	7.48		62.42	255.83			6.14	
Alnus jorullensis	6.64	21.76						
Alnus jorullensis–Pinus hartwegii	13.03	31.11	42.12	71.22				
Pinus hartwegii	16.97	41.91	68.09	129.51	9.54	9.2	9.47	9.18
Pinus hartwegii–Abies religiosa	12.72	37.87	70.13	143.91	20.33			
Pinus hartwegii–Alnus jorullensis	14.4	30.92	50.73	89.98	5.03		4.59	
Pinus montezumae	33.42	49.43	95.82	186.01	17.99	12.31	4.32	3.38

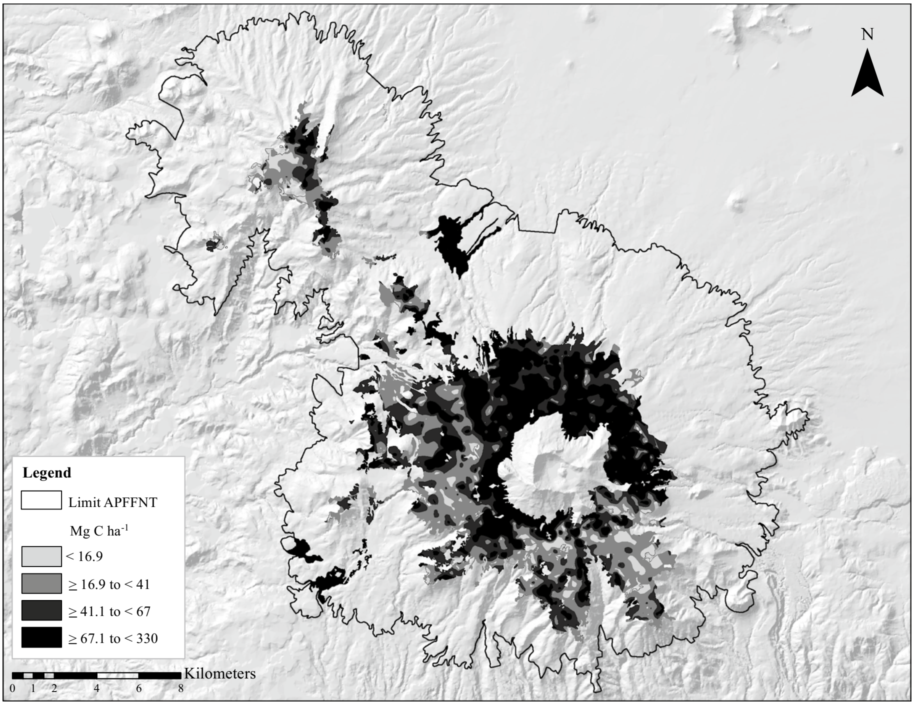

Fig. 4 Storage of C in the Área de Protección de Flora y Fauna Nevado de Toluca

The magnitude of C storage in the APFFNT is very important because it contains 1,695,004 MgC, although this storage had been diminished in recent years by 42,701 MgC due to forest harvesting. In multi-ages *P. hartwegii* forests, the application of thinning of an intensity not greater than 30% of the initial density (expressed in number of trees per hectare and the uniformly distributed cuttings by age classes) is recommended. In this way, a sustained yield of 4.74 m^3 ha^{-1} $year^{-1}$ would be guarantee (Sarukhán and Franco 1981).

It is important to establish strategies into management program of APFFNT that promotes the preservation, restoration and health of forest communities in the natural protected area (Rojas-García 2008). It was found in this work that the extraction of trees is the same in all the stand density categories (37.6 m^3 ha^{-1} $year^{-1}$). It is suggest that the thinning practices be carried out every 10 years, preferably in the dense and semi-dense stands of *P. hartwegii*. In this way, it is possible to achieve the highest annual yields in timber volume and thereby increase the C sequestration.

Further studies have measured the storage of C in the forests of *P. hartwegii* in different parts of mountainous Mexico, these data agree with the estimates made in this study, where on average in dense forests (268 individuals ha^{-1}) 129.51 MgC ha^{-1} has been stored. In the La Malinche National Park 111.35 MgC ha^{-1} were estimated in a dense forest (320 individuals ha^{-1}; Rojas-García 2008). For a similar type of dense forest at the Perote Natonal Park, Mendoza and Galicia (2010) reported an average C content of 146.3 MgC ha^{-1}.

Ecological impact of timber harvesting and implications for C storage

The estimation of aboveground biomass allows, first, to know the status of the forest at a given time to analyze how management can affect some aspect of the ecosystem, including the timber extraction (Vilanova et al. 2010). Second, if there is information collected in the long term, it is possible to evaluate changes and compare them in different periods (WWF 2004).

De Jong et al. (2010) noted that montane forests represent the large C storage area in Mexico. The wood volume contained in these forests is among the lowest in the country, but growth and regeneration is among the highest, although the continued development largely depends on management conditions (Beaman 1962; Anaya et al. 1980).

The extraction of timber, firewood and non-wood products in the foothills has occurred from the middle elevation foothills to the high elevation mountains with negative environmental impacts on the protected area. Along with this, weather variables (wind, frost, etc.), the impact of pests and diseases, and the occurrence of wildfires are factors that have been important in the modification and fragmentation of forest cover (SEMARNAT 2013). During March 2016, the eleventh winter storm and cold front number 45 from northern Mexico caused strong winds in central country, reaching 80 km/h. The strong winds brought down numerous trees in the *P. hartwegii* forest. These trees were measured and their aboveground biomass on the ground corresponds to14,903 MgC.

The politico-administrative condition of the Nevado de Toluca Protected Area and the lack of protection and control mechanisms lead to clandestine logging of trees for diverse products by unauthorized traders. Some of the common uses of these products are for furniture and construction wood, charcoal, and posts, the problem has extended to felling of large trees with diameters > 35 cm and heights of 20 m (Franco et al. 2006).

The loss of forest cover and tree density has not been homogeneous with the protected area. According to Endara (2010), the majority of trees harvested for all species are those less than 30 cm in diameter and used for firewood. *Pinus* forests are the most subjected to disturbance and have been the target of reforestation campaigns, often planted in mixtures with cedar (*Cupressus* spp.) (Endara 2007). The current major sources of damage and continuing threat to these forests is from pasture burning, conversion to agriculture, overgrazing, and overharvesting because of its important as a wood resource to the nation.

A. jorullensis is a successional plant community that often occurs in ecotonal boundaries mixed with pine and fir at elevations around 3500 m. *A. jorullensis* forests have few harvestable trees because of its value for artisanal wood. Species has a rapid growth rate and is increasing in abundance because of forest fragmentation and colonization of abandoned farmland (Endara 2010). It is possible that these forests have occupied area where *P. hartwegii* forests were harvested, burned areas or through long-term displacement at higher altitudes. The establishment of *A. jorullensis* is also associated with natural selection in montane forests because it is a nitrogen-fixing species (Tobita et al. 2016), that promotes regeneration of forests (Kumar and Ram 2005).

Species in montane ecosystems tolerate dramatic climate variation over short distances (Körner 2007) and displacement of species induced by climate change possible will cause changes in these communities with elevation (Hartl-Meier et al. 2014). Within the APFFNT, there has been a displacement of species with higher biomass (forests of *P. hartwegii* and *P. montezumae*) by those with lower biomass (*A. jorullensis*). This change could negatively affect CO_2 capture in this protected area.

Monitoring of logging is essential in all of the protected areas within the country, because extraction estimates are based on land use change determined through remote sensing (Rojas-García 2008). The inventory measurements carried out in the present work allowed us to estimate that 162,230 m^3 of wood volume were extracted in a year. Data on logging is necessary to calculate emissions of greenhouse gases attributed to land use change and forestry (De Jong et al. 2010).

Initiatives such as REDD + (Reducing Emissions from Deforestation and Forest Degradation and improving carbon stocks) are important efforts aimed at combating climate change. However, for the effective implementation of such mechanisms, accurate estimation and monitoring of aboveground biomass and associated C reserves in forests is first required (Salimon et al. 2011).

Reports on emissions of greenhouse gases, include C, are part of an international, state, and municipal agreement. It is imperative to carry out research directed to identify the factors that affect C storage and biodiversity both at the national and subnational levels (Armenteras et al. 2015), including protected natural areas as the Nevado de Toluca. During 2013, the Municipality of Toluca declared that it was not possible to evaluate the C emissions at the local level due to a lack of data of forest extraction and C storage (H Ayuntamiento de Toluca 2013). Therefore, the results of this work can contribute to the greenhouse gas inventories at the municipal, state and national scales.

Conclusions

Quantification of forest harvesting is necessary to calculate greenhouse gas emissions in the categories of Land Use Change and Silviculture at the local, state and national levels. It is estimated that 211,218 Mg CO_2 per year is emitted due to harvesting and natural treefalls in the Área de Protección de Flora y Fauna Nevado de Toluca, in the state of México.

C storage in dense forest (≥ 336 trees), semi-dense forest (150–335), fragmented forest (20–149), and stands with isolated trees (≤ 20), was estimated in 1621 circular plots of 1000 m^2 in pine forest. The large sampling effort allowed for an accurate estimation of C storage in montane ecosystems in Mexico. The montane forests of the APFFNT store 1,695,004 MgC in aboveground forests in the 12,924 ha.

Pinus trees are the primary one harvested in Mexico, followed by *A. religiosa*. Generally, *A. jorullensis* trees are not often harvested because their wood is not dense and is relatively weak. This harvesting creates a negative C balance in the ecosystem as a result of the unregulated extraction of 42,701 MgC during an year.

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Authors' contribution FRG contributed to conceive the study, data analysis, and discussion of results and wrote the manuscript, TSF contributed to discussion and writing, SVL contributed with the cartographic processing, AREA guided the development of the fieldwork and cabinet methodology and contributed to writing at discussion.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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