Research Article

Fire Emissions and Carbon Uptake in Severely Burned Lenga Beech (*Nothofagus pumilio*) Forests of Patagonia, Argentina

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ABSTRACT

Forest wildfires are recognized as sources of CO_2 and other greenhouse gases (GHG) that, altering the dynamics between terrestrial and atmospheric carbon (C) exchange, influence global climate. In central Andean Patagonia, Argentina, severe wildfires affect temperate lenga beech (*Nothofagus pumilio* Poepp. & Endl. Krasser) forests, thereby increasing atmospheric CO_2 emissions and changing natural succession paths. In this study, we determined fire emissions and C uptake in three lenga beech forests stands burned in 1976 (Lago Guacho site), 1983 (La Torta site), and 2008 (La Colisión site). Forest structure and aboveground biomass and litter compartments in burned and adjacent unburned stands were quantified for each fire. Carbon stocks and GHG (CO_2, CO, CH_4, NO_2, NO_x and *Ce*) released by the fires, CO_2 removals, and mean annual C uptake were determined by following the International Panel of Climate Change guidelines. Total (aboveground plus root) C stock before fires was 301.8 Mg C ha^{-1} for La Colisión, 258.13 Mg C ha^{-1} for La Torta, and 270.7 Mg C ha^{-1} for Lago Guacho, while C losses

RESUMEN

Los incendios forestales son reconocidos como fuentes de emisión de CO_2 y otros gases de efecto invernadero (GHG) que, alterando la dinámica del intercambio entre el carbono (C) terrestre y el atmosférico, influencian el clima global. En la región central de la Patagonia Andina Argentina, incendios de características severas han afectado los bosques de lenga (*Nothofagus pumilio* Poepp. & Endl. Krasser), incrementando de esa manera las emisiones de CO_2 a la atmósfera y alterando asimismo sus patrones sucesionales. En este estudio, determinamos las emisiones y el secuestro de C en tres rodales, quemados en 1976 (Lago Guacho), 1983 (La Torta), y 2008 (la Colisión). La estructura forestal, y los compartimientos de biomasa aérea y broza fueron cuantificados en cada rodal quemado y en sus adyacentes sin quemar. El stock de C y de otros GHG (CO_2, CO, CH_4, NO_2, NO_x y *Ce*) emitidos por cada incendio, el CO_2 capturado y el C anual incorporado a la biomasa fueron determinados en base a las guías propuestas por el Panel Internacional para el Cambio Climático. El carbono total (biomasa aérea más radical) antes de los incendios fue de 301,8 Mg C ha^{-1} para La Colisión, 258,13 Mg C ha^{-1} para La Torta, y 270,7 Mg C ha^{-1} para Lago Guacho, mientras que las pérdidas de C debido a los incendios fueron de 104,6 Mg C ha^{-1}, 90,7 Mg C ha^{-1}, due to the fires were 104.6 Mg C ha^{-1}, 90.7 Mg C ha^{-1}, and 94.7 Mg C ha^{-1} for the three sites, respectively. Differences in pre-fire forest structures and biomass explained the values observed in CO_2 and other GHG emissions after the fires. Currently, the C balance is negative for the three sites. Without any active restoration and using actual growth rates for each site, the estimated C recovery time is 105.5 yr for La Colisión, 94.2 yr for La Torta, and 150.2 yr for Lago Guacho. By using variable rates of C uptake (which decrease as early succession proceeds), this recovery time will take 182 yr for La Colisión, 154 for La Torta, and 162 yr for Lago Guacho. Post-fire environmental and site conditions appeared to have a greater influence in forest recovery than primary fire effects. Active restoration activities may be necessary to increase C recovery rates and help to re-establish former lenga beech forest landscapes.

and 94,7 Mg C ha^{-1} para cada uno de los sitios, respectivamente. Diferencias en la estructura forestal y en la biomasa de cada sitio previo a los incendios explican los valores de emisión de CO_2 y otros GHG observados después de éstos. Al presente, el balance de C es negativo en los tres sitios. Sin ninguna acción de restauración activa y usando las tasas actuales de crecimiento para cada sitio, el tiempo estimado de recuperación del C perdido es de 105,5 años para La Colisión, 94,2 años para La Torta, y 150,2 años para Lago Guacho. Mediante el uso de tasas de captura de C variables (que decrecen a medida que la sucesión avanza), el tiempo de recuperación sería de 182 años para La Colisión, 154 años para La Torta, y 162 para Lago Guacho. El ambiente post-incendio y las condiciones de cada sitio parecen tener una mayor influencia en la recuperación de la vegetación que los efectos primarios del fuego. Tareas de restauración activas aparecen como necesarias para incrementar la tasa de recuperación del C post-fuego y ayudar a re-establecer el paisaje original en bosques de lenga.

Keywords: Argentina, carbon balance, fire, forest recovery, lenga beech, Patagonia

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INTRODUCTION

Fire is an evolutionary force that has shaped the structure and functioning of most terrestrial ecosystems since the origin of climate on earth (Wright and Bailey 1982, Crisp *et al.* 2011). From early human history to the present, fire also has had an important role in human evolution and development (Komarek 1965, Whitlock *et al.* 2010, Bowman *et al.* 2011). During the last century, however, humans have impacted terrestrial ecosystems in an unprecedented way (Morgan *et al.* 2003). These impacts are a result of both the direct manipulation of vegetation landscapes by clearing forests, suppressing fires, promoting grazing, dispersing plant propagules, and changing ignition patterns, and indirect actions, such as the increasing amounts of CO_2 and other greenhouse gases (GHG) that, released into the atmosphere, have altered the global carbon (C) cycle (Bowman *et al.* 2011, Defossé et al. 2011). This cycle involves CO_2 emissions and removals from the atmosphere, the oceans, and the terrestrial biosphere (Wayne 1993, Grace 2004, Nabuurs *et al.* 2007). Of all emissions, fossil fuel burning and wildland fires have been identified as the main sources of CO_2 and other GHG that alter the C cycle and influence global climate change (CC) (Battle *et al.* 2000, Bowman *et al.* 2011, Defossé *et al.* 2011, Sommers *et al.* 2014). Related to C removals, oceans and forest ecosystems are recognized as the main sinks of CO_2 in the biosphere. The total amount of C stored in forest ecosystems around the globe is around 650 Gt, more than the amount of C found in the entire atmosphere (FAO 2010). About 80% of the C exchange between the terrestrial biosphere and the atmosphere is mainly due to increases and decay of forest biomass (Böswald *et al.* 2002). Wildfires, however, could rapidly alter this exchange balance, transforming forest ecosystems from C sinks into C sources (Running 2008). Besides CO_2, wildfires may also emit other GHG and potentially harmful volatile organic compounds (Crutzen and Andreae 1990, Goode *et al.* 1999). In recent decades, an increase in wildfire activity in some regions of the globe has been associated with rises in global warming trends (Hennessy *et al.* 2006, Westerling *et al.* 2006, Flannigan *et al.* 2009, van Bellen *et al.* 2010). While this association is still debatable and controversial (Bowman *et al.* 2011, Stephens *et al.* 2013), changes in wildfire activity might have a significant influence in future levels of atmospheric CO_2.

Due to the long life span of trees and their capacity to sequester and store CO_2 (in the form of different C compounds), forests in general are considered excellent C reservoirs. For that reason, the role of forest ecosystems in C sequestration and storage has been internationally recognized by the United Nations Framework Convention on Climate Change (UNFCCC). This framework convention has proposed strategies on Reducing Emissions from Deforestation and Degradation (REDD+) (Daviet and Larsen 2012), which included forest activities to help mitigate the effects of increasing CO_2 in the atmosphere (IPCC 2006, Bowman *et al.* 2011, Daviet and Larsen 2012, Sommers *et al.* 2014).

Data from 2010 showed that, at a global level, forest ecosystems occupy slightly more than 4 billion ha, which represent 31% of the total land area (FAO 2010). These ecosystems, however, are unevenly distributed around the globe and comprise different forest types. The Northern Hemisphere contains all boreal and most of the temperate forests of the world, while in central South America (mainly in Brazil and Peru), and the equatorial regions of Africa and southeastern Asia, are located the most important tropical forests of the world. The southern parts of South America and Oceania only have a small part of the temperate forest ecosystems of the globe (FAO 2010).

In the southern tip of South America, the temperate forests of Patagonia cover a long (~2000 km) and narrow (~250 km) belt along both sides of the Andean Cordillera in Argentina and Chile, and are dominated by long-lived tree species of the genus *Nothofagus* (Dimitri 1972). On the eastern slopes of the Andes in Argentina, these forests occupy 4.1 million ha, of which 1.2 million ha are mainly composed of lenga beech (*Nothofagus pumilio* Poepp. & Endl. Krasser) forests (Bava 1998, SAyDS 2007; Figure 1). Similar to what occurred in other temperate forest biomes, it is probable that Patagonian forests have sequestered and stored significant amounts of C since their establishment at the end of the Last Glacial Maximum (LGM, 18 000 yr before present; Adams *et al.* 1990, Malhi *et al.* 1999), helping reduce the rise in CO_2 concentration since deglaciation (Markgraf *et al.* 1996). It could also be speculated that, during the first successional stages right after deglaciation, Patagonian forests may have had high C sequestration rates (Crowley 1995), followed by a climax period in which a dynamic equilibrium between C storage and emissions was reached. This dynamic equilibrium was disrupted when European settlement began in Andean Patagonia around 1850, although native people also used the fire as a mean to hunt after this date. From

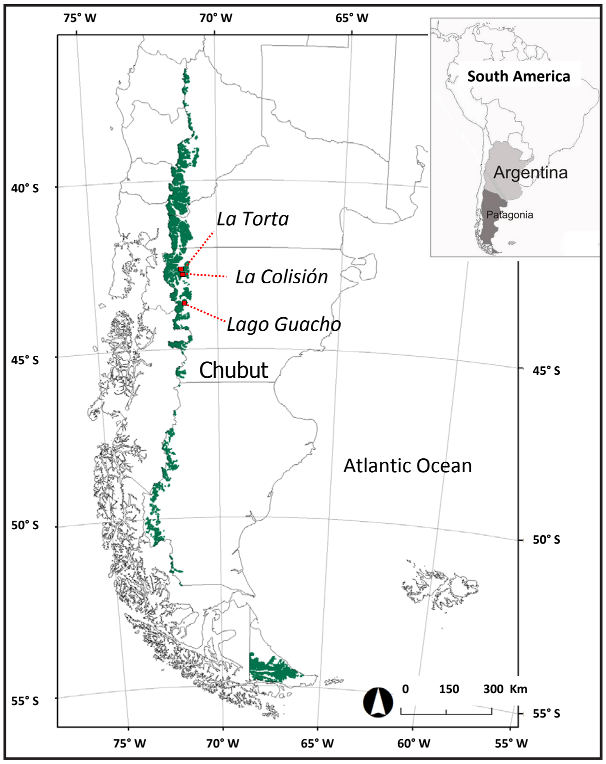

Figure 1. Distribution of lenga beech forests along the Andean Cordillera in Patagonia, Argentina (SAyDS 2007). Within it, the study sites are located in central Patagonia in Chubut Province.

then and until 1940, Patagonian forests were progressively cleared to open areas for grazing, hunting, or logging, and fire was used as the main tool to clear these forests (Markgraf and Anderson 1994, Goldammer *et al.* 1996, Veblen *et al.* 2011). The creation of the National Park Administration in Argentina in the mid 30s of the twentieth century brought about the enforcement of a fire suppression policy, and also restrictions in grazing and logging activities. In Patagonia, these policies and restrictions were strictly applied within national park boundaries, but were less enforced in other public or private forest lands. As a consequence, human-set wildfires continued to occur in these areas, and together with other disturbances such as grazing and logging, still persist. The combined effects of these disturbances on Patagonian forests are that they have produced a more fragmented, highly modified landscape, with likely less stored C as compared to the period between post-glaciation and the beginning of European settlement (Markgraf and Anderson 1994; Veblen *et al.* 1996, 1999). The response of forest vegetation to fire has been intensively investigated in Patagonia (Veblen *et al.* 1999, Urretavizcaya and Defossé 2004, Urretavizcaya *et al.* 2006, Urretavizcaya *et al.* 2013), yet emissions of CO_2 and other GHG from forest fires, especially in its central region, have not been previously studied.

The ratification of the Kyoto Protocol by most countries realized the possibility of celebrating a new international agreement in 2018 (UNFCCC 2008). Argentina, as a party of the UNFCCC, is committed to reporting GHG emissions from sources and removal by sinks to the United Nations' national inventories. Land use change and forest activities now require a GHG inventory, since article 3.3 of the Kyoto Protocol allows increases in C stocks due to afforestation and reforestation, to be used to offset inventory emissions. The term "inventory emissions" implies a detailed quantification and report, on a yearly basis, of GHG emitted by a country's different economic and productive activities (industry, agriculture, services, etc.), and also includes the emissions due to ecosystem degradation. Carbon reservoirs and CO_2 emissions by wildfires have been investigated by several authors in different countries (Crutzen and Andreae 1990, Fernandes 2005, Wiedinmyer and Neff 2007). In Patagonia, however, the only studies that dealt with C reservoirs of native forests were done in the southernmost region of Argentina and Chile in Tierra del Fuego (Ellyson 2007, Valdés Barrera 2012), and none were related to C emissions due to wildfires. In Argentina, the National Inventory of GHG (INVGEI), showed emissions of 238 700 Gg of carbon dioxide equivalent (CO_2e), of which 5.22% (12 460 Gg) corresponded to biomass burning from forests, grasslands, and shrublands (Fundación Bariloche 2007). Despite this report, there are no specific data of GHG emissions from fires and CO_2 uptake by forests of the central Patagonian Andean region of Argentina.

In this study, we quantified C stocks, C emissions, and post-fire rates of C recovery in three areas representative of lenga beech forests affected by wildfires at different times since fire (5 yr, 30 yr, and 37 yr) in the central region of Andean Patagonia. At a regional level and for Patagonian forests, the information generated casts light on how C stocks are affected by wildfires. Moreover, the study will determine probable rates of C recovery and the years needed to reach pre-fire C levels for each of the three sites studied without human interventions. Results will also be important to the proposal or exploration of alternative ways (i.e., active restoration practices) that could speed up the process of C recovery and help mitigate GHG emissions. Results from this study may also be important as an input for the Argentine national inventory of GHG stocks and emissions, and as a contribution of the role of Patagonian forests in CO_2 sequestration and storage at a global level.

METHODS

Study Area

Our region of interest corresponds to the Patagonian Andean forests located in the northwest of Chubut province, Argentina, between the 42° and 43° 40' S latitude, and the 71° 20' to 72° 08' W longitude. This area is dominated by lenga beech forests, and is considered representative of the north-central distribution of this species in Argentine Andean Patagonia (Dimitri 1972; Figures 1 and 2). Compared to other forest types (i.e., tropical rainforests), lenga beech forests are structurally very simple. Their stands are mainly composed of lenga beech trees as a dominant species, surrounded by typical lenga beech patch saplings (Bava 1998) and a sparse understory of other species that, in general, do not surpass 1 m in height. The exception is when the understory is covered by the bamboo-like caña colihue (*Chusquea culeou* Desv.), which may reach from 3 m to 4 m tall. Species richness comprises around 28 to 30 species. In the study area, three sites were selected to determine C stock before the fires, C emitted during the fires, and the rate of C uptake of each site from the fire events to the present. These fire sites are termed Lago Guacho, La Torta, and La Colisión, which burned in 1976, 1983, and 2008, respectively (Figure 1, Table 1).

Figure 2. Early autumn view of a typical mature lenga beech stand (~140 yr old, 40 cm to 60 cm at DBH), in central Patagonia. Photo by Miguel Davel.

Table 1. Description of the lenga beech forest study sites in Andean Patagonia, Argentina, including location, physiographic characteristics, area burned, and dates of fire occurrence.

Study site	Location	Elevation (masl)	Aspect	Slope (%)	Area burned (ha)	Fire date	Years since fire
La Colisión	42º 57' S, 71º 30' W	990	181º S	11	262.5	24 Feb 2008	5
La Torta	42º 51' S, 71º 33' W	1140	255º SW	10	400.0	12 Jan 1983	30
Lago Guacho	43º 48' S, 71º 27' W	1270	35º NE	12	41.0	1976	37

Theoretical Approach

Before a fire disturbance, a hypothetical forest ecosystem contains a determinate C reserve (stock A; Figure 3, left). This reserve is distributed into living aboveground and root biomass of different vegetation strata (herbs and grasses, shrubs, and trees), into dead biomass (litter, duff, and deadwood), and into different C compounds found in the soil (root biomass, soil organic matter, and microorganisms). When this hypothetical forest ecosystem is disturbed by a wildfire, the dynamics of its C cycle follows two major processes. The first occurs during fire, in which part of the C (stock A) is lost through combustion (*Cl*) and is released as smoke emissions into the atmosphere. These emissions do not only include different amounts of GHG (E_x), but also water vapor, particulate matter (PM), and black carbon (Figure 3, center). The amount of C lost during this process will vary according to fire intensity and severity, and the area burned. The second major process occurs after the fire and during the course of primary and secondary succession. As succession proceeds, C found in the atmosphere (in the form of CO_2), is sequestered by photosynthesis in tissues of recovering vegetation, and stored in different vegetation compartments (C_S). This sequestered C could be measured at different time scales, and termed as C stock B (forest recovery; Figure 3, right). When a fire occurs, C that is not lost directly by fire emissions (the remnant fire kill and charred remains) is transferred from the shallow soil and tree layer to an intermediate C layer that decomposes at the surface until burial by moss allows the materi-

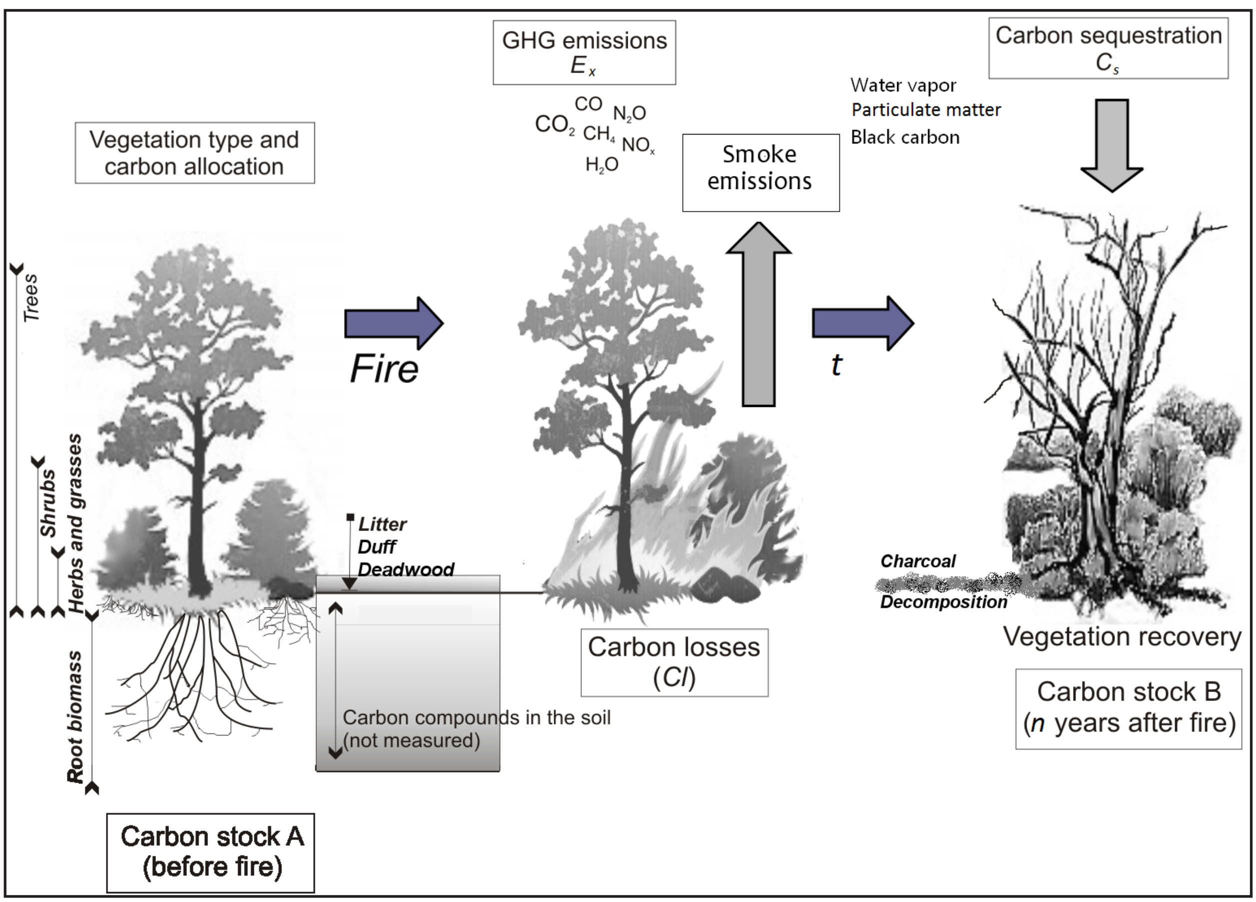

Figure 3. Parameters measured and estimated in this study showing the main processes involved in emissions and C exchange by forest fires. (Drawings modified from www.dreamstime.com).

al to decompose at slower rates at deeper layers (Harden *et al.* 2000). Both processes (C release and sequestration) have an important role in forest dynamics, and the changing rates of C uptake during succession will determine the time needed for the ecosystem to reach pre-fire levels of stored carbon. Important consideration should be given to the post-fire decay environment (i.e., litter and coarse woody debris) because decomposition processes (Maser and Trappe 1984) produce CO_2 (Wang *et al.* 2002).

Pre-Fire Carbon Stock A

Pre-fire C stock (in Mg ha^{-1}) of each burned site was estimated by sampling biomass of unburned lenga beech stands grown adjacent to each of the burned areas, following IPCC guidelines (2006). The area sampled within each site (ca 25 ha) was selected by analyzing aerial photographs or satellite images (or both) that were taken of the areas sampled before fire occurrence, and determining similarities to nearby unburned stands. Intensive samplings to determine pre-fire C stock were then carried out in these selected unburned stands. On each selected site, the sampling area comprised a 40 m × 1000 m rectangle (4 ha) in which the longest side (1000 m) was located perpendicular to the slope. The shape of the sampling area was chosen to capture as much stand heterogeneity as possible. Within this area, different-sized plots (according to ranges of vegetation height), were randomly placed along a 1000 m transect that divided the area in two rectangles of 2 ha each. Before sampling, vegetation was divided into three fuel compartments: 1) aboveground vegetation, 2) litter (including duff litter and fine deadwood, <10 cm in diameter), and 3) coarse deadwood (>10 cm in diameter). Living aboveground vegetation was also subdivided into three strata according to ranges of vegetation height: 1) from 0 m to 0.3 m (mainly herbs and grasses), 2) from 0.3 m to 2.0 m (shrubs), and 3) higher than 2.0 m tall (lenga beech saplings and trees).

To sample aboveground biomass of the first stratum (0 m to 0.3 m), we used 10 plots of 0.5 m^2, each randomly located along both sides of the transect. Aboveground biomass inside the selected plots was cut to ground level, collected, taken to the lab, oven-dried during 48 h at 100 °C to constant weight, and weighed. After that, litter was collected in each of these plots, put in plastic bags, and taken to the lab. The same drying and weighing procedure as mentioned for aboveground biomass of the first stratum was used to determine litter dry weight.

To sample the second stratum (0.3 m to 2 m), we used 10 circular plots of 5 m diameter each (19.6 m^2) randomly placed along the transect, in a similar way as mentioned for the first stratum. Within each plot, we determined cover (%) and height (m) of each shrub species. Biomass was estimated by using allometric equations developed by Loguercio *et al.* (2004) and Gyenge *et al.* (2009) for shrubs grown in the same Andean forests. When allometric equations for a particular shrub were unavailable, we determined its weight by using the destructive method (cut to ground level, collected, taken to the lab, oven dried to constant weight, and weighed). In these cases, we used 3 samples per species. Biomass was then estimated using density values according to the methodology proposed by Loguercio *et al.* (2004). Coarse deadwood was also sampled in the same plots by calculating their volume. These volumes were later transformed into biomass values by following the methodology proposed in Maser and Trappe (1984), adapted to coarse deadwood lenga beech forest floor by Loguercio *et al.* (2004).

Lenga beech saplings were sampled within 10 plots of 10 m diameter (78.5 m^2 each), also randomly placed along both sides of the transect. The sampling was done by measuring sapling trunk basal diameter (BD). Since no biomass equations have been developed for trees with less than 5 cm diameter at breast height (DBH), five samples of each category were cut at ground level, collected, oven dried, and weighed in the lab. To estimate sapling biomass, we divided them into two diameter categories: 1) from 0 cm to 3 cm BD, and 2) from 3 cm to 5 cm BD. Linear regressions were used to adjust the weight according to their respective BD for each class. For sampling aboveground biomass of lenga beech trees, we used 5 circular plots of 20 m diameter each (314.2 m^2). These plots were placed every 200 m along the transect. Inside the plots, we measured DBH of lenga beech trees, and biomass was estimated by using DBH and biomass functions for lenga beech trees proposed by Loguercio and Defossé (2001). All samples within each fuel biomass category were then averaged and SE calculated, and the C stock expressed in Mg C ha^{-1}. Root biomass was not measured. It was estimated, instead, as a fraction (termed *R*) of the total aboveground biomass. This fraction was assumed to be 0.24, and was based on estimations by Mokany *et al.* (2006) for temperate broadleaf forests in which shoot biomass was higher than 150 Mg C ha^{-1}. This value is slightly lower than the proposed for similar temperate forests (0.25) by IPCC (2006), and a little bit higher than the value determined for lenga beech forests grown in Tierra del Fuego (0.22) by Schmidt (2009). It should be noted that lenga beech forests in Tierra del Fuego grow under a climate characterized by cool summers with a very narrow annual temperature range and without water deficit throughout the year (Allué *et al.* 2010). In central-western Patagonia where this study was carried out, lenga beech stands grow under a mediterranean climate, with severe drought during late spring and summer. As it has been well established for different ecosystems, decreasing soil moisture produces higher root to shoot ratios (Nadelhoffer *et al.* 1985, Cairns *et al.* 1997). For that reason, we assumed that 0.24 was a good predictor of root to shoot ratio (*R*) for the lenga beech forests considered in our study.

Fire Emissions and Carbon Uptake

The surface area burned for each of the three fires were taken from data records provided by the Fire Program, Subsecretaría de Bosques de la Provincia de Chubut (2012) (see Table 1). These original data records were based on ground area measurements and references given by old aerial photographs taken after the fires. The burned surface areas of the three sites were later corroborated by digitalizing LANDSAT 5 TM satellite images. Biomass present in each of the burned sites was sampled in a similar way as that presented for pre-fire C stock.

In lenga beech forests that experience large fires (~10 ha or greater), the border that separates the burned and unburned stands is the area within which post-fire lenga beech trees first start to recover. This recovery is constrained, however, by topography (slope and aspect) of the burned site; the shape, size, and intensity of the fire; the presence or absence of non native species; wind intensity; and the availability of native seed sources needed for regeneration. According to the way regeneration starts to establish in these areas, we have defined them as the "regeneration border" for the La Torta and Lago Guacho fires. Due to its importance in the process of C uptake after the fire, we determined the mean extension and variability (in meters) of each regeneration border by measuring their respective widths. The procedure involved the establishment of five transects placed at regular intervals perpendicular to the line that separated the burned area from the unburned area. Transect widths were then averaged and their SE determined. We then measured the DBH or the BD of young regenerating trees (according to their sizes) in five 5 m diameter plots randomly located within these regeneration borders. We estimated the biomass of young trees using the procedure described by Loguercio and Defossé (2001), or calculated it according to the BD classes proposed in this study. In La Colisión, due to the relatively recent occurrence of the fire, this regeneration border had not yet established; for this reason, the sampling was done following the procedure mentioned for the unburned area.

To quantify the parameters explained in Figure 3, we followed the guidelines proposed by the International Panel of Climate Change (IPCC) for Land-Use, Land use Change and Forestry (LULUCF) (IPCC 2006). The amount of specific GHG (x) released from vegetation during fires (E_x) was calculated as follows:

$$E_x = A * B * (1 + R) * \varepsilon * \delta * 10^{-3} (\text{Mg GHG}_x) \quad (1)$$

where A is the total area of lenga beech forest burned (in ha) determined for each fire as mentioned above; B is the total aboveground biomass burned per unit area (Mg ha^{-1}) calculated as the sum of all aboveground biomass components as previously explained; R represents the ratio between roots and total aboveground biomass; ε is the combustion completeness (the fraction of the biomass consumed during the actual fire); and δ_x is the emission factor for the GHG_x, and is defined as the weight of the x gas released per kg of biomass (dry matter) burned.

As previously explained, the R parameter was assumed to be 0.24. According to the available information about the characteristics of each fire and based on empirical evidence and previous studies on lenga beech fires (Sagarzazu and Defossé 2009), the La Colisión and La Torta fires were defined as crown fires, with an ε index of 0.43 (IPCC 2006). Before the fires, these two sites presented abundant understory vegetation that favored fire crowning. This information was unavailable for Lago Guacho. For this reason, we conservatively assumed that the ε index for this site was 0.4, which corresponded to a natural burning according to IPCC (2006). However, due to post-fire observations of the biomass consumption and other fire effects observed on each site, we assumed that the three fire events were very severe and presented extreme behavior. In general, wildfires in lenga beech forests show low frequency intervals, but may present extreme behavior should they occur (Kitzberger *et al.* 2005, González *et al.* 2006, Sagarzazu and Defossé 2009; Figure 4). Values of δx for each GHG were based on Andreae and Merlet (2001) for extra-tropical forests.

Figure 4. Severely burned lenga beech stand located close to La Colisión study site. The photograph was taken one week after fire occurrence. At the time of the fire, the stand was about 110 yr old; mean tree DBH varied from 30 cm to 50 cm. Photo by Franco Todone.

Trace gases released by the three fires and considered in this study were CO_2, CH_4, CO, N_2O, and NO_x. Methane and nitrous oxide emissions were also expressed and calculated as C equivalent (*Ce*) according to their particular global warming potential (IPCC 2006). Although other C compounds are emitted during wildfires, such as alcohols, alkenes, and aromatic compounds (Kaiser *et al.* 2012), they were neither measured nor estimated in this study.

Carbon stock losses, as a fraction of the total organic C contained in the biomass and released by each fire (*Cl*), was calculated as follows:

$$Cl = A * B * (1 + R) * cf * \varepsilon * (\text{Mg C}) \quad (2)$$

The parameters *A, B, R*, and ε were the same as in equation (1); *cf* is the C fraction of the aboveground biomass, and it is assumed to be 0.48 for living biomass, 0.5 for organic dead matter and coarse deadwood, and 0.37 for litter (Lamlom and Sadvidge 2003, IPCC 2006).

Total C sequestered (C_S) by the new vegetation assemblage growing during the post-fire successional stages in the burned area was calculated as:

$$Cl = A * \beta * (1 + R) * cf \text{ (Mg C)} \qquad (3)$$

where *A, R,* and *cf* were the same as in equations (1) and (2), and β is the biomass of the aboveground vegetation grown after the fire event (in Mg C ha^{-1}). Assuming the present value of C sequestered by the new vegetation assemblage, we also calculated the rate of C uptake (C_u) for each burned site as:

$$C_u = \frac{C_S}{\theta_t} \qquad (4)$$

where θ_t is the time scale, in years, from the date of fire occurrence to the moment of sampling.

Carbon Balance in the Area Burned

In the process of photosynthesis, the CO_2 that is not lost by respiration is stored in the plant biomass and constitutes its C reserve. The C balance of forests is determined by the difference between the C assimilation and C losses of all its living plants, plus the C stored and lost in dead tissues and in the forest soil. Hence, the C balance in the whole burned area from the time of the fire until the present was estimated as the difference between the carbon dioxide and other C compounds lost due to the fire (as CO_2 and *Ce*), and the C sequestered and stored in the new vegetation assemblage. According to the CO_2 molecular relationship, C assimilation by photosynthesis was calculated as 44 ÷ 12 = 3.67 Mg of CO_2 per Mg of C content in the vegetation biomass.

Considering the rate of C uptake (C_u) and the C balance of the three burned sites, we estimated the time needed to reach pre-fire levels of accumulated C to compensate for GHG emissions from each fire. This was done by considering constant and variable C_u rates. The first approach to determine the time needed to reach pre-fire C levels used site-specific, constant C_u rates throughout the whole period, and considered the natural path of succession without any silvicultural intervention. The years needed to reach pre-fire levels for each site resulted then from dividing the C balance by the specific C_u rate. It should be noted, however, that these constant C_u rates represent the real C_u rates for each site from the time of the fire event up to the present, but it is uncertain that they will remain constant up to the time that the vegetation of each site has fully recovered the C lost. Recognizing this uncertainty, and since there are no growth curves for lenga beech forest development after a fire disturbance, we also explored the use of time-variable C_u rates. These variable C_u rates were based on empirical observations of lenga beech stand growth after fires and on the assumption that vegetation assemblages in these stands will grow at faster rates during the early successional stages right after the fire disturbance than in later stages. For that reason, we assumed that for the first 15 yr after the fire, these C_u rates will be somehow similar to those determined for La Colisión (1.1 Mg ha^{-1} yr^{-1}). The next 15 yr C_u rates will then be similar to those observed for La Torta (0.8 Mg ha^{-1} yr^{-1}), while after that time (from year 30 and after), C_u rates will be similar to those observed in Lago Guacho (0.5 Mg ha^{-1} yr^{-1}).

RESULTS

Pre-Fire Carbon Stock A

Before fire occurrence, total C (including root biomass estimates) were 301.8 Mg C ha^{-1}, 258.13 Mg C ha^{-1}, and 270.7 Mg C ha^{-1} for La

Colisión, La Torta, and Lago Guacho, respectively (Table 2). Total aboveground C stock (excluding roots) was 243.4 Mg C ha^{-1} in La Colisión, 218.3 Mg C ha^{-1} in La Torta, and 208.9 Mg C ha^{-1} in Lago Guacho. In these three sites, more than 90% of this aboveground C was stored in biomass of trunks and living parts of lenga beech trees, while the rest was stored in shrubs, herbs, litter, and coarse deadwood (Table 2). Excluding lenga beech saplings and mature trees, C stored aboveground in shrubs was relatively more important than that contained in herbs in La Colisión and La Torta, while the reverse was true for Lago Guacho. The relative magnitude of C content in litter was similar in all three sites, and varied from 3.5 Mg C ha^{-1} for La Colisión, 5.0 Mg C ha^{-1} for Lago Guacho, and 5.8 Mg C ha^{-1} for La Torta. Carbon stored in coarse deadwood, for instance, showed the highest amounts in Lago Guacho, followed by La Torta, while in La Colisión it was negligible and for that reason not determined (Table 2).

Fire Emissions and Carbon Uptake

Because of the characteristics of each site, trees consistently provided most of the *Cl* for the three study sites, while other fuels showed lower *Cl* values and presented high variability among sites (Table 3). Overall, total *Cl* per hectare was higher in La Colisión, followed by Lago Guacho, and then by La Torta. These differences likely occurred due to local scale variability and initial aboveground biomass stock (Bertolin *et al.* 2013). Also, the contribution to *Cl* by litter in La Torta was large relative to the other sites. The contribution from herbs and coarse deadwood to *Cl* was larger in Lago Guacho (the southern site), where herbs were present in higher amounts than shrubs.

La Colisión presented the highest total GHG emissions (E_x) values per hectare, fol-

Table 2. Carbon stock A before fire per fuel compartments (in Mg C ha^{-1}), determined for each of the three lenga beech forest sites studied in Andean Patagonia, Argentina. Biomass values are shown in parenthesis (mean ± one SE, expressed in Mg ha^{-1}). Root C stock and biomass values were estimated as a fraction (0.24) of the mean total aboveground biomass.

Study site	Trees	Shrubs	Herbs	Litter	Coarse deadwood	Total aboveground	Roots	Grand total
La Colisión	231.5 (482.4 ± 48.5)	6.8 (14.1 ± 2.2)	1.5 (3.1 ± 1.7)	3.5 (9.4 ± 0.7)		243.4 (509 ± 53.1)	58.42 (122.2)	301.8 (631.2)
La Torta	191.9 (399.7 ± 107.1)	6.4 (13.3 ± 1.8)	2.7 (5.5 ± 0.6)	5.8 (15.7 ± 1.0)	2.1 (4.2 ± 2.3)	208.9 (438.4 ± 112.8)	50.13 (105.2)	258.13 (543.6)
Lago Guacho	198.0 (412.5 ± 71.1)	0.8 (2.2 ± 0.4)	9.0 (16.8 ± 1.1)	5.0 (13.6 ± 1.8)	5.5 (11.1 ± 0.4)	218.3 (456.2 ± 74.8)	52.4 (109.5)	270.7 (565.7)

Table 3. Carbon losses (*Cl*) in Mg C per hectare and total for the fuel compartments in the three study sites analyzed in Patagonia, Argentina.

Study sites	Aboveground vegetation (Mg C)						Litter (Mg C)		Coarse deadwood (Mg C)		Total (Mg C)	
	Herbs		Shrubs		Trees							
	ha^{-1}	total	ha^{-1}	total	ha^{-1}	total	ha^{-1}	total	ha^{-1}	total	ha^{-1}	total
La Colisión	0.6	167.9	2.9	765.2	99.6	26 134.3	1.0	392.9			104.6	27 460.4
La Torta	2.0	810.5	2.7	1 095.4	82.5	33 002.4	2.5	997.9	0.9	361.2	90.7	36 267.5
Lago Guacho	4.6	187.8	0.5	18.9	85.1	3 490.8	2.2	88.9	2.4	97.7	94.7	3 884.2

lowed by La Torta and Lago Guacho (Table 4). In regard to the area burned (see Table 1), La Torta showed the highest total E_x values. Total CO_2 emissions (including *Ce*) for the three sites ranged from 12.11 Gg to 119.2 Gg. Carbon oxide emissions were about 7.2 % of the CO_2 emissions. Methane and non-methane hydrocarbon emissions were lower than carbon oxide emissions, and released only about 2 Mg ha^{-1}, across the three sites. The methane molar CO_2 equivalent (*Ce*) was 12.8 % of the CO_2 emissions (Table 4).

Carbon Balance in the Area Burned

Within the three burned sites, we observed the highest value of C_s in La Torta, followed by La Colisión, then Lago Guacho (Table 5). Although the regeneration border was wider and more variable in La Torta than in Lago Guacho (Table 5), the C content of trees inside the regeneration border was higher in Lago Guacho, with 19.64 Mg C ha^{-1} in contrast to 6.21 Mg C ha^{-1} registered in La Torta. On the other hand, the standard deviation of the regeneration border extension indicated differences in recovery. While La Torta presented a regeneration border showing an uneven-aged forest structure, in Lago Guacho it was even-aged. The C_u rates obtained for each site by applying equation 4 are shown in Table 5. These rates showed a declining trend, with the largest C_u value for the most recent fire (La Colisión, 1.1) and the lowest for the oldest fire (Lago Guacho, 0.5) (Table 5).

The C balance showed negative values for the three study sites (Table 6) with a maximum of −29.3 Gg CO_2 in La Torta, closely followed by La Colisión (−27.1 Gg CO_2), and then Lago Guacho with a modest −3.1 Gg CO_2. By applying the actual C_u rates for each of the three sites (derived from equation 4), the remaining time to reach prefire C levels (as CO_2 and *Ce* emissions) ranged from 94.2 yr in La Colisión, to 105 yr in La Torta, to 150.2 yr for Lago Guacho (Table 6). If we calculate the total time required, from time 0 (right after fire occurrence) up to when the C sequestered reach

Table 4. Emissions of the trace GHG during fires (E_x) in the three study sites analyzed in Patagonia. *Ce* = C equivalent.

Study site	Greenhouse gas emissions (E_x)													
	CO_2		CH_4		*Ce* (CH_4)		CO		N_2O		*Ce* (N_2O)		NO_x	
	Mg ha^{-1}	Gg	Mg ha^{-1}	Gg	Mg ha^{-1}	Gg	Mg ha^{-1}	Gg	Mg ha^{-1}	Gg	Mg ha^{-1}	Gg	Mg ha^{-1}	Gg
La Colisión	345.8	90.8	1.0	0.2	23.2	6.1	28.5	7.5	0.0	0.0	17.6	4.6	0.2	0.0
La Torta	297.9	119.2	0.7	0.3	19.5	7.8	24.5	9.8	0.0	0.0	15.2	6.0	0.1	0.0
Lago Guacho	295.5	12.11	0.8	0.0	18.9	0.7	23.8	0.9	0.0	0.0	14.8	0.6	0.1	0.0

Table 5. Carbon sequestered (C_s) and actual rate of C uptake (C_u) by the new vegetation assemblage in three lenga beech burned areas of Andean Patagonia. The width of the regeneration borders (*RB*) of two burned sites is also shown.

	C_s		C_u		*RB*
Study site	Gg C	Mg C ha^{-1}	Mg C yr^{-1}	Mg C ha yr^{-1}	m (mean ± 1 SE)
La Colisión	1.4	5.4	287.9	1.1	
La Torta	8.0	20.1	277.2	0.7	35.5 ± 19.9
Lago Guacho	0.8	18.4	20.9	0.5	32.6 ± 7.9

Table 6. Carbon balance (Gg CO_2) after the fire, and recovery years needed to mitigate C losses by fires. For recovery years, two C_u rates were considered. C_{u1} was based on present estimations derived from equation 4. C_{u2} was based on present estimations also derived from equation 4, but starting at year 0 (right after fire occurrence). C_{u3} was based on variable rates applied to different times at earlier stages of secondary succession after a wildfire, trying to mimic natural vegetation dynamics. *Cu* = carbon uptake.

	Carbon balance	Recovery years		
Study site	Gg CO_2	C_{u1}	C_{u2}	C_{u3}
La Colisión	–27.1	94.2	99	182
La Torta	–29.3	105.5	135	154
Lago Guacho	–3.1	150.2	187	162

pre-fire levels, these values are 99.2 yr for La Colisión, 135 yr for La Torta, and 186 yr for Lago Guacho. Considering variable C_u rates (1.1 for the first 15 yr, 0.8 for the next 15 yr, and 0.5 from year 30 and thereafter) and applying them to each of the three sites, the time required to reach pre-fire C levels will be 182 yr for La Colisión, 154 yr for La Torta, and 162 yr for Lago Guacho (Table 6).

DISCUSSION

Emissions from forest fires do not only affect the global C cycle (IPCC 2006, Bowman *et al.* 2011, Olah *et al.* 2011), but also contribute to increased atmospheric levels of other GHG (Goode *et al.* 1999). During the last two decades, many studies have focused on estimating C and other GHG released into the atmosphere by fires that occurred in different forest ecosystems around the world. In 1998, a particularly warm year, boreal forest fires emitted 290 Tg to 383 Tg of total C, 828 Tg to 1103 Tg of CO_2, 88 Tg to 128 Tg of CO, and 2.9 Tg to 4.7 Tg of CH_4 (Jabaud-Jan *et al.* 2004, Atkinson *et al.* 2006). These values represented about 9% of total C emitted, 13.8% of total CO emitted, and 12.4% of total CH_4 emitted globally for that particular year. Emission values may be highly variable from year to year. Global fire emissions quantified from 1997 to 2001 gave an average of 2000 Tg C per year, while for the period between 2002 and 2007 it was of 2100 Tg C per year (van der Werf *et al.* 2010). According to these authors, global forest fires contributed to about 16% of these estimates. Other C emissions came from fires in grasslands and savannas (44%), from tropical deforestation and degradation fires (20%), woodland fires (mostly confined to the tropics, 15%), agricultural waste burning (3%), and tropical peat fires (~2%) (van der Werf *et al.* 2010).

In South America, forest fires consumed about 1410 Tg of biomass per year, and CO_2 emissions were estimated at 1753 Tg yr^{-1} for the period 2005 to 2010 (Wiedinmyer *et al.* 2011). According to Kaiser *et al.* (2012), mean forest wildfire emissions in South America from 2003 to 2012 were 348.9 Tg C yr^{-1}, equivalent to 1162.5 Tg of CO_2. These figures demonstrate that wide variations may exist among different estimations, and that we should be cautious when dealing with emissions estimates.

In Argentina, a few GHG emission modelings and inventories have been done. They have mainly focused in the industrial, energy, burned urban residues, services, transportation, agriculture, and cattle sectors (Fundación Bariloche 2008, Consejo Empresario para el Desarrollo Sustentable 2012). None of them, however, have included emissions from forest fires. Data series of estimates of GHG emissions between 1990 and 2000 showed a substantial increase, ranging from 9.4 Gg CO_2 yr^{-1} to 14.0 Gg CO_2 yr^{-1}, agriculture and human residue sectors being the major contributors (Fundación Bariloche 2008). Furthermore, the Consejo Empresario para el Desarrollo Sustentable (2012) calculated an emissions value of 85 Gg of CO_2 for 2012, and included agriculture as the most important contributor. These values showed that, in Argentina between 1990 and 2000, GHG emission increased 6.7%, while between 2000 and 2012, these values increased about 60%. However, the first report did not include the transportation sector, and might certainly have underestimated emissions. Relative to the forest sector, large forest fires occurred in forests and rangelands of Patagonia between 1990 and 2012, probably increasing Argentina's total CO_2 emissions. Wildland fire statistics showed that, from 2003 to 2007, an annual average of 1.5 million ha burned in Argentina (SAyDS 2009). Of those, about 1.5% (roughly 23 000 ha) corresponded to different vegetation assemblages of the Patagonian Andean region, including ecotonal areas and conifer afforestations (SAyDS 2009, Defossé *et al.* 2011).

This study contributes to the knowledge of the C cycle and GHG emissions in lenga beech forests located in the central region of Argentine Patagonia. Overall, mean CO_2 emission for the three lenga beech study sites was 313.1 Mg ha^{-1}. By averaging all native forest lost annually by fires in the three provinces of central and southern Patagonia (Chubut, Santa Cruz, and Tierra del Fuego), we found that, between 1994 and 2013, an average of 395 ha yr^{-1} were burned in Tierra del Fuego (Pereslindo *et al.* 2013) and 1067 ha yr^{-1} in Santa Cruz (Díaz 2013). Data for Chubut during the period 1979 to 2003 showed an annual average of 378.4 ha burned (SBPCh 2012). According to these data, we estimated that 576.2 Gg of CO_2 is annually released to the atmosphere by native forest fires in central and southern Patagonia, excluding the provinces of Neuquén and Río Negro. Regarding the other trace gas emissions, we extrapolated the amounts of 71.7 Gg *Ce* (CH_4) yr^{-1}, 47.1 Gg CO yr^{-1}, and 12.5 Gg yr^{-1} for nitrogen compounds emitted to the atmosphere by these GHG gases. It is important to point out, however, that provincial fire statistics do not differentiate native forests by species composition. With this in mind, it is probable that the total area of lenga beech affected by fires has been slightly overestimated.

In this study, La Torta presented the highest values of total emissions and C lost, and La Colisión showed the highest values per area (see Table 2). The variability of emissions per area estimated for the three sites revealed differences among biomass amounts on each site. This variability is mainly explained by differences in each forest structure (i.e., the distribution of the living trees and the coarse deadwood at the time of the fires; Bertolin *et al.* 2013). Lago Guacho and La Colisión, for example, presented a typical irregular stand structure of an uneven-aged mature forest, with wide regeneration patches (Bava 1998). In La Torta, by contrast, the burned stands were less dense but their individual trees were bigger (mean DBH = 35.4 ± 23.61 cm) than those of Lago Guacho (mean DBH = 29.6 ± 20.1 cm), or La Colisión (mean DBH = 31.9 ± 16.4 cm) (Bertolin *et al.* 2013).

At both national and international levels, there is an increasing interest in the establishment of C and emissions inventories and in the development of monitoring programs. Fire, as a contributor to emissions, tends to be extremely variable and uncertain (van der Werf *et al.* 2006, Jain 2007, Wiedinmyer et al. 2011). In addition in Argentina, statistics of forest fires are rather territorially incomplete and often only recently compiled. This causes a gap in information that should be filled as soon as possible. This study is an attempt to provide valuable information about C emissions by lenga beech forests grown in central Patagonia. We are aware, however, that our data should be prudently utilized, since the use of fixed or variable C_u rates may produce different results.

After a fire event, the rate of growth of the new vegetation assemblage will determine the period needed to assimilate and recover the

CO_2 lost during the fire (Kashian *et al.* 2006). The success of lenga beech post-fire regeneration in its whole area of distribution has previously been reported as highly variable (Veblen *et al.* 1996, González *et al.* 2006, Valdés Barrera 2012). Some lenga beech stands affected by wildfires may show a very rapid recovery with massive seedling recruitment in a few years; others could take from 40 yr to 80 yr to recover (González 2002), while others do not recover (Rusch 1989, González *et al.* 2006). This variability in lenga beech forest recovery may not only be related to the severity and intensity of the actual fire, but also to the post-fire biotic, micro-environmental, and site conditions (González *et al.* 2006).

Based on this and according to the successional stages proposed by Rusch (1989) for lenga beech forests, the three burned sites analyzed in our study showed different regeneration paths and consequently different C recovery rates. The higher amounts of C sequestered in La Torta, as compared to the other sites, could be primarily explained by the rapid installation of a post-fire successional stage dominated by the bamboo-like caña colihue, which shows high productivity rates and may dominate the forest understory for a long time after a fire disturbance (Veblen 1982, Pearson *et al.* 1994). However, net annual C uptake was higher in La Colisión than in the other two sites. This may be due to the fact that at the moment of sampling, this site was in the earlier stages of succession (it burned in 2008), when colonizing grasses and shrubs showed their higher productivity rates. In contrast for Lago Guacho, and 37 yr after fire occurrence, the burned areas showed the lowest values of C uptake and C amounts. Despite closure to cattle grazing for the past 10 yr, forest recovery in the burned area was limited to the regeneration border mainly composed of young even-aged lenga beech saplings (mean DBH = 9.8 ± 6.7 cm) (Bertolin *et al.* 2013). It is interesting to note that lenga beech saplings were not observed outside this regeneration border. This situation could be mainly related to the extreme environmental conditions on the site (a NE slope highly exposed to direct sunlight and high winds) that generate unfavorable moisture conditions for lenga beech germination and establishment. Furthermore, the long history of cattle grazing may have produced changes in the understory vegetation, favoring the rapid establishment of non-native grasses and herbs that compete with lenga beech saplings (Quinteros *et al.* 2012). Although cattle grazing was excluded about 10 years ago, the area was not protected from browsing damage caused by the introduced European hare (*Lepus europaeus* Pallas). Hare-caused damage is observed not only on that site, but also on lenga beech seedlings in restoration trials carried out in different environments of Patagonian Andes (M.F. Urretavizcaya, Centro de Investigación y Extensión Forestal Andino Patagónico, Esquel, Argentina, unpublished report). We hypothesize then that the lenga beech saplings we see today in Lago Guacho are derived from a pulse of lenga beech germination following the exclusion of grazing when environmental conditions were favorable for lenga beech germination and early establishment. In La Colisión, however, this pulse of germination has not yet occurred due to the fire event occurring more recently.

In contrast, we found that, in La Torta, the regeneration border was more heterogeneous than in Lago Guacho, and showed the presence of saplings and young lenga beech trees of different ages. Although the site is still slightly grazed by cattle, it shows low presence of hares, and is less exposed to adverse environmental conditions (i.e., it contains small canyons protected from dominant winds, receiving lower direct sunlight, and having overall better moisture conditions than Lago Guacho). Furthermore, although the fire event in this site was considered a severe fire that reached the crowns of mature lenga beech trees, it left some small patches unburned in the canyons. This may have produced the heterogeneity in vegetation regeneration found in its regeneration border, making it different from that of Lago Guacho or La Colisión. The heterogeneity in lenga beech regeneration, then, may be related to the presence of some scattered mature lenga beech trees that survived the fire on this site. These mature trees may have provided, from time to time, the seed source needed for lenga beech germination and establishment. It should be remembered that mature lenga beech trees in this region produce fertile seeds once every 5 yr to 8 yr (Cuevas 2000), and this may explain the different cohorts of lenga beech saplings found in La Torta as compared to the single cohort found in Lago Guacho. As is true for plants of other mediterranean ecosystems (Moreno and Oechel 1994, Defossé and Robberecht 1996), our results suggest that post-fire environmental and site conditions may play a more important role in lenga beech forest regeneration than the fire event itself. For that reason, it is extremely difficult to propose and generalize hypothetical successional paths for burned lenga beech forests stands grown in central Patagonia in which a mediterranean type of climate prevails. These hypothetical paths may be even more complex and difficult to predict if grazing disturbance by big or small exotic grazers has been present right after or at any time following fire disturbance (M.F. Urretavizcaya, Centro de Investigación y Extensión Forestal Andino Patagónico, Esquel, Argentina, unpublished report; Quinteros *et al.* 2012).

The lack of specific literature on lenga beech growth rates made us consider the use of two C_u rates—one constant and the other variable. The constant C_u rate involved the biomass (or C) recovered on each site from the time of fire occurrence and up to the present, and that rate was applied to the rest of the time until the stand reaches pre-fire C levels. The use of variable C_u rates implied using different rates as the stand grows after the fire disturbance. While the real values could be in between these two values, it is clear that this range is greater as the time from the fire is shorter, and reveals that other biotic (presence or absence of non-native species, availability of native seed sources needed for regeneration) and environmental (slope and aspect, soil moisture and temperature, winds) factors, may also condition post-fire recovery rates. The C_u rates and recovery periods presented in this study are then approximations or rough estimations of the real C_u rates, and of the time needed to recover the C lost. These considerations should be taken into account when trying to apply these values to other lenga beech studies dealing with C estimates.

Future Perspectives

While either of these C recovery periods may be within the typical range for these long-lived forests, they may not be seen as "adequate" by many segments of our society that seek ways not only to speed up the recovery of C lost but also to rapidly recuperate former forest landscapes. Furthermore, governments are not only required by law to reduce emissions and increase the sources of C sinks, but are also committed to preserve and restore forest ecosystem diversity and connectivity affected by different disturbances. In this way, the slow regeneration rates shown by lenga beech stands affected by fire may be changed by implementing active restoration management plans that have demonstrated potential for lenga beech forest recovery (M.F. Urretavizcaya, unpublished report).

In terms of maintaining or extending the capabilities of C sequestration by forest ecosystems via restoration activities or other managements practices, we should focus our future works on: 1) assuring that forest systems that are currently capturing C will continue to do so in the future, 2) reducing C losses from disturbances, 3) manage old growth forests to allow them to continue storing and capturing C, and 4) conserve the diversity and connectivity of the forest systems that are vulnerable to modern climate change.

This study provides specific data of GHG emissions and CO_2 uptake from three fires that occurred at different times in lenga beech forests grown in the central Patagonian Andean region of Argentina. These data would be important not only as an input for future emissions inventory in Argentina, but also as a reference for other studies at global levels.

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