Forest Ecology and Management 261 (2011) 2243–2254

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Potential CO_2 emissions mitigation through forest prescribed burning: A case study in Patagonia, Argentina

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ARTICLE INFO

Article history:
Received 29 July 2010
Received in revised form 21 November 2010
Accepted 24 November 2010
Available online 18 December 2010

Keywords:
CO_2 emissions
Prescribed burning
Kyoto protocol
Emissions mitigation
Biomass growth

ABSTRACT

Wildland fire is a natural force that has shaped most vegetation types of the world. However, its inappropriate management during the last century has led to more frequent and catastrophic fires. Wildland fires are also recognized as one of the sources of CO_2 and other greenhouse gases (GHG) that influence global climate change. As one of the techniques used to reduce the risk of destructive wildfires, prescribed burning has the potential of mitigating carbon emissions, and effectively contributes to the efforts proposed as part of the Clean Development Mechanism within the Kyoto protocol. In order to apply this concept to a real case, a simulation study was conducted in pine afforestation in the Andean region of Patagonia, Argentina, with the objective of evaluating the potential of prescribed burning for reducing GHG emissions. The scenario was established for a ten year period, in which simulated prescribed burning was compared to the traditional management scheme, which included the probability of annual average of wildfire occurrence based on available wildfire statistics. The two contrasting scenarios were: (1) managed afforestation, affected by the annual average rate of wildfires occurred in the same type of afforestation in the region, without prescribed burning, and (2) same as (1) but with the application of simulated prescribed burning. In order to estimate carbon stocks, and CO_2 removals and emissions, we followed the guidelines given for GHG inventories on the Agriculture, Forestry and Other Land Uses (AFOLU) sector of the International Panel on Climate Change (IPCC), while the terminology used was the established by IPCC (2003). Data of afforested area, thinnings, and biomass growth were taken from previous surveys in the study area. Downed dead wood and litter (forest fuel load, FFL) was estimated adjusting equations fitted to those fuels, based on field data. Results show that comparing the two scenarios, prescribed burning reduced CO_2 emissions by 44% compared to the situation without prescribed burning. The prescribed burning scenario represented about 12% of the total emissions (prescribed burning plus wildfires). Furthermore, avoided wildfires by simulated prescribed burning allowed an additional 78% GHG emissions mitigation due to extra biomass growth. Simulated prescribed burning in commercial afforestation of Patagonia appears to be an effective management practice not only to prevent wildfires, but also an efficient tool to mitigate GHG emissions. However, more studies in different scenarios would be needed to generalize these benefits to other ecosystems.

1. Introduction

1.1. Wildfire and climate change

Fire is a natural force that has shaped most vegetation types of the world, helping to maintain the function of ecological processes in many ecosystems (Komarek, 1965; FAO, 2006a). Historically, humans have learned to use fire, and its management as an agricultural tool is deeply rooted in culture, society and traditions of many countries (FAO, 2001). In agriculture, fire has been used to prepare lands for crops or grazing, and to open impenetrable lands for new agricultural uses (FAO, 2001). More recently, fire has also been recognized as an important tool, not only for achieving land management goals (such as prescribed fire), but also for fire-fighting activities (suppression fire, Narayan et al., 2007). This evidence, however, does not obscure the fact that unwanted or unmanaged wildfires annually consume millions of hectares of forests throughout the world, affecting biodiversity, and threatening property as

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doi:10.1016/j.foreco.2010.11.021

well as human lives and wildlife. Besides the economic impact caused by the destruction of forest resources and other environmental, recreational and amenity values, wildfires contribute to global emissions, and are increasingly costly in terms of firefighting and suppression activities (FAO, 2005; Bowman et al., 2009).

The fire exclusion and suppression policy implemented in several countries about a century ago has failed in achieving the overall goal of reducing wildfire risks and impacts (Wuerthner, 2006). In fact, changes in land use and the effectiveness achieved in suppressing wildfires immediately after ignition has produced a general increase in biomass buildup in many ecosystems (Kitzberger and Veblen, 1999; Morgan et al., 2003). This unprecedented fuel accumulation has led to catastrophic events if a fire (either started by humans or by lightning) occurred under a set of extreme environmental conditions such as very high winds, hot and dry air masses, presence of a cold front, etc. (Brown et al., 1994; Dentoni et al., 2001; Defossé and Urretavizcaya, 2003; Fernandes and Botelho, 2003; Graham, 2003; Graham et al., 2004, 2009; Omi and Martinson, 2004; Vaillant et al., 2009).

One of the most important consequences of forest wildfires is their contribution to CO_2 concentration in the atmosphere through the alteration of the spatial and temporal dynamics of carbon storage between the atmosphere and the biosphere (Narayan et al., 2007; Balshi et al., 2009). The amount of biomass burning has significantly increased during the last decades, and is recognized as a significant source of atmospheric emissions at a global scale (UNEP, 1999). The global value of emissions for Agriculture, Forestry and Other Land Uses (AFOLU) reported for year 2000 was 7.6 Gt CO_2 e, 10% higher than the estimates for 1990 (WRI, 2005). Biomass burning increases greenhouse gas emissions (GHG's), such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). In the global context, these emissions should be added to those already produced by fossil fuels and their derivates (UNEP, 1999).

Forest biomass burning has been pointed out as the main source of atmosphere contamination in South America (Mielnicki et al., 2005). About 27% of CO_2 emissions are due to land use changes (basically by deforestation activities) which have occurred in this subcontinent (WRI, 2005). In Argentina, the National Inventory of GHG's (INVGEI), published in 2000, showed a level of emissions of 238,700 Gg of carbon dioxide equivalent (CO_2 e), of which 12,480 Gg of CO_2 e corresponded to biomass burning from forests, grasslands and shrublands (Fundación Bariloche, 2007). The AFOLU sector showed net removals of 43,280 Gg of CO_2 e. Wildland fire emissions accounted for about 30% of the gross removals of that sector (Fundación Bariloche, 2007). In correspondence with these numbers, from 2003 to 2007 an annual average of 1.5 million ha was affected by wildfires in Argentina, including 23 thousand ha in the Patagonian Andean region. About 2–3% of the vegetation affected by wildfires in Patagonia corresponded to conifer plantations (SAyDS, 2009). As is occurring in many countries around the world, in Argentina, and especially in the Andean Patagonian region, more people are moving to establish their dwells in forest wildland urban interfaces (WUI). This fact also increases the risk of fire occurrence in those areas (FAO, 2006b).

1.2. Afforestation projects in Patagonia and the CDM of Kyoto protocol

The Argentinean Patagonian region has approximately 2 million ha of potential land for afforestation (Ferrer et al., 1990; Irisarri and Mendía, 1991; Irisarri et al., 1995; Loguercio et al., 2004). Environmental and economic constraints, however, may reduce this figure to about 800,000 ha (Loguercio and Dececchis, 2006a,b). In spite of these constraints, and if compared to other areas of the world, Andean Patagonia presents good competitive and comparative advantages to develop afforestation within the Clean Development Mechanism (CDM) of the Kyoto protocol (Loguercio et al., 2004). These advantages can be summarized by mentioning that this region comprises vast overgrazed rangelands with low above ground biomass vegetation, and rich subsoil of volcanic ashes to which roots of native vegetation generally do not reach (Colmet Daage et al., 1995). Pine afforestation in these zones of Patagonia have shown good growth rates, and the low amount of carbon found in native vegetation (the base line) enhances their potential for carbon sequestration within CDM (Loguercio et al., 2004).

By 2005, conifer afforestation in the Patagonian provinces Neuquén, Rio Negro and Chubut, covered 76,000 ha. These afforestation were planted with the objective of diversifying production, and, at the same time, satisfying the demands of an incipient forest industry (Loguercio et al., 2004, 2005; Gonda, 2005). The main species used is ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.), which comprises about 75% of all plantations (Gonda, 2005; Loguercio et al., 2005). The afforestation productivity and growth rates are greater than the sites of origin in northwestern United States (Urzúa, 1991; Gonda and Lomagno, 1995; Gonda, 1998).

In the development of any economic activity, it is necessary to minimize risks in order to preserve the productive assets from unwanted events. Related to conifer afforestation in Patagonia, wildfires constitute a high risk. In this region, human set fires are recognized as the primary source of ignition, accounting for about 80% of all wildfires affecting afforestation. About 9% are produced by lightning while the rest are due to unknown causes (Servicio Provincial de Lucha contra Incendios Forestales, Río Negro Province; Servicio Provincial de Manejo del Fuego, Chubut Province, and General Direction Forests of Neuquen province, unpublished data). Fire suppression capacity is constituted by a national firefighters brigade based in Río Negro Province, and several brigades belonging to provincial services. Afforestation owners are starting to create first attack private consortiums with the economic support of the national government. As a result of these facts, however, fire protection of these plantations at present only imply firefighting activities, and fuel management (i.e. prescribed burning) is rare or uncommon (Kunst et al., 2002). It is probable that the fire exclusion policy, strongly advocated and supported for many years by National Parks Administration, and later adopted by the Provincial forest resources management agencies, has influenced afforestation management practices carried out by many producers. Another detail that may explain this factor is the lack of interest, or reluctance, of some forest producers to use prescribed fires as a management tool, because the afforestation stands are still young (about 20–25 years) and the need for fuel management is not yet appreciated. It should be remembered, though, that ponderosa pine is a fire prone species (Wright and Bailey, 1982), and sooner or later it would need prescribed burnings to develop viable plantations and reduce the risk of unwanted wildfires (Weaver, 1957).

1.3. Prescribed fire to reduce wildfire emissions

The effectiveness of prescribed burning to reduce wildfire intensity and severity has been well established in international literature (Weaver, 1957; Fernandes and Botelho, 2003, 2004; Finney, 2001, 2003, 2007; Ager et al., 2006; Finney et al., 2005, 2007; Vaillant et al., 2009). There is also much information on the usefulness of this practice, either alone or combined with other silvicultural treatments, to reduce fuel buildup and continuity (Graham, 2003; Graham et al., 2004, 2009; Hurteau and North, 2009; Omi and Martinson, 2004; Pollet and Omi, 2002). However, literature as well as data and information about the effectiveness of prescribed burning in reducing GHG's emissions as compared to the emissions produced by wildfires, is rather scarce (Fernandes, 2005; Narayan et al., 2007; Wiedinmyer and Hurteau, 2010).

One of the few studies developed in this area was carried out by Fernandes (2005), who concluded that in the long term, prescribed burning emissions would be lower than emissions from wildfires, if wildfire return intervals are less than forty years. The release of CO_2 and other compounds from prescribed burning under average conditions resulted 62% below the emissions due to a more severe wildfire (Fernandes, 2005). Other studies also agreed that prescribed burnings could be effective in reducing wildfire risk of a given area for up to about 10 years after their application (Van Wagtendonk, 1995; Fernandes et al., 2004; Finney et al., 2005; Finney, 2007). It should be considered, though, that fuel hazard minimization through the application of prescribed burning in cycles of less than 5–6 years could be detrimental for the site, and may result in biodiversity losses and reduction of productivity (Fernandes et al., 2000).

The effectiveness in fuel load reduction through prescribed burning is highly variable, mainly due to the natural conditions of the fuels and their dependence on weather conditions. Some researchers suggest that, in conifer plantations, fine and medium fuels could be reduced up to about 90%, and large fuels to about 50% of their total load, and a value of around 7 t/ha of unburned fuels left on the ground would be the desirable goal to reach after a prescribed burning (Molina, 2000). By applying an experimental prescribed burning to a ponderosa pine plantation in Patagonia, Kunst et al. (2002) got an average fine and medium fuel reduction of 57% (from 20 to 8.6 t/ha), with burning conditions which included low intensity fires with low flame length (Byram, 1959).

Within this context, and considering the global interest to promote afforestation in Patagonia under CDM and its probable contribution to mitigate CO_2 emissions, this study was aimed at addressing some of the following uncertainties. (1) Will prescribed burning practices be useful in reducing fire risk in Patagonian Afforestation?. (2) What are the current wildfire emissions and potential GHG emissions reductions of an alternative prescribed burning scenario in ponderosa pine plantations in Patagonia, Argentina?. (3) Will it be possible to quantify the amount of GHG mitigated by applying this practice?. (4) Will the overall balance (in terms of emissions reduction) be positive, as to suggest this practice in afforestation carried out in other countries/ecosystems?. Our work was not only focused in finding answers to these specific questions, but also provide science evidence for resolving the fire paradox in conifer afforestation management practices.

2. Materials and methodology

2.1. Study area, afforestation structures and scenarios used

The study area was located in northwestern Patagonia, Argentina, in the Andean region of Neuquén, Rio Negro, and Chubut provinces. The climate of the area is cold temperate, dry in the steppe zone and more humid towards the Andean cordillera (Veblen and Lorenz, 1987; IPCC, 2006). Both zones present a Mediterranean type of climate, with precipitation concentrated during winter and early spring in the form of either rain or snow (Barros et al., 1983). There is, however, a huge variation in total precipitation, the steppe showing values of around 300–500 mm/year, while in the ecotone with the Andean forests, precipitation could reach 1200 mm/year (Veblen and Lorenz, 1987). Soils are predominantly Andosols, while the sub-soil, originated from volcanic ashes, is rich in nutrients, and has a very high water retention capacity (Colmet Daage et al., 1995). These characteristics make them very suitable for dry-land afforestation, since water retained in the ashes during winter is released during the summer drought, allowing obtaining very high rates of tree growth and development (Colmet Daage et al., 1995; Gonda, 1998). The afforestable region of Patagonia outside native forests covers about 2 million ha, of which 800 thousand ha are of very good quality. Today, there are about 76 thousand ha planted in a very disperse way within this region (Fig. 1).

Table 1
Ponderosa pine afforestations in Patagonia considered in this study, stratified according to age-classes and management status.

Structures	Age-classes and management status
C1 unthinned	0–9 year – unthinned
C2 unthinned	10–21 year – unthinned
C2 thinned	10–21 year – thinned
C3 unthinned	22–30 year – unthinned
C3 thinned	22–30 year – thinned
C4 unthinned	>30 year – unthinned
C4 thinned	>30 year – thinned

The area covered by afforestation was taken from a previous study carried out by Loguercio et al. (2008), who used information derived from different sources, such as the forest plantation inventory from Neuquén province (CFI-FUDFAEP, 2007), plant cover of afforestation in Chubut province (DGByP-CIEFAP, unpublished), and other secondary sources of available information (Todone and Gonda, 2005; Bava et al., 2006). Afforestation was stratified according to age-classes and management status (thinned or not thinned) as shown in Table 1.

Carbon stocks of different compartments or pools were determined, and their changes predicted for a period of ten years, considering the effects of wildfires and prescribed burnings. In these determinations, we analyzed the changes occurring through time, following the guidelines for GHG given by the IPCC, according to the "gain and loss" method (IPCC, 2003, 2006). In doing so, we considered the three most significant compartments, or carbon pools, as follows:

- biomass (above and belowground);
- downed dead wood;
- litter.

The "gains" corresponded to aerial and belowground growth and the "losses" to disturbances such as timber thinning, wildfires, and prescribed burnings. Carbon dioxide removals are transfers from the atmosphere to a pool, whereas CO_2 emissions are transfers from a pool to the atmosphere. Not all transfers involve emissions or removals, since any transfer from one pool to another is a loss from the donor pool, but is a gain of equal amount to the receiving pool. For example, a transfer from the above-ground biomass pool to the dead wood pool is a loss from the above-ground biomass pool and a gain of equal size for the dead wood pool, which does not necessarily result in immediate CO_2 emission to the atmosphere (IPCC, 2006). Biomass extracted as a consequence of thinning is considered as immediate emissions, since it "disappears" from the system. Dead roots remaining after wildfire occurrence, and also wood affected but not consumed by wildfires, are fluxes to other pools, but they are not considered emissions.

In order to evaluate the potential for GHG's emissions reduction through the application of simulated prescribed burnings during a period of ten years, we estimated the projection of carbon stocks under two different scenarios:

1. Managed afforestation, affected by the annual average rate of wildfires occurring in the same type of afforestation in the region, without prescribed burning.
2. Managed afforestation, affected by the annual average rate of wildfires occurred in the same type of afforestation in the region, with prescribed burning.

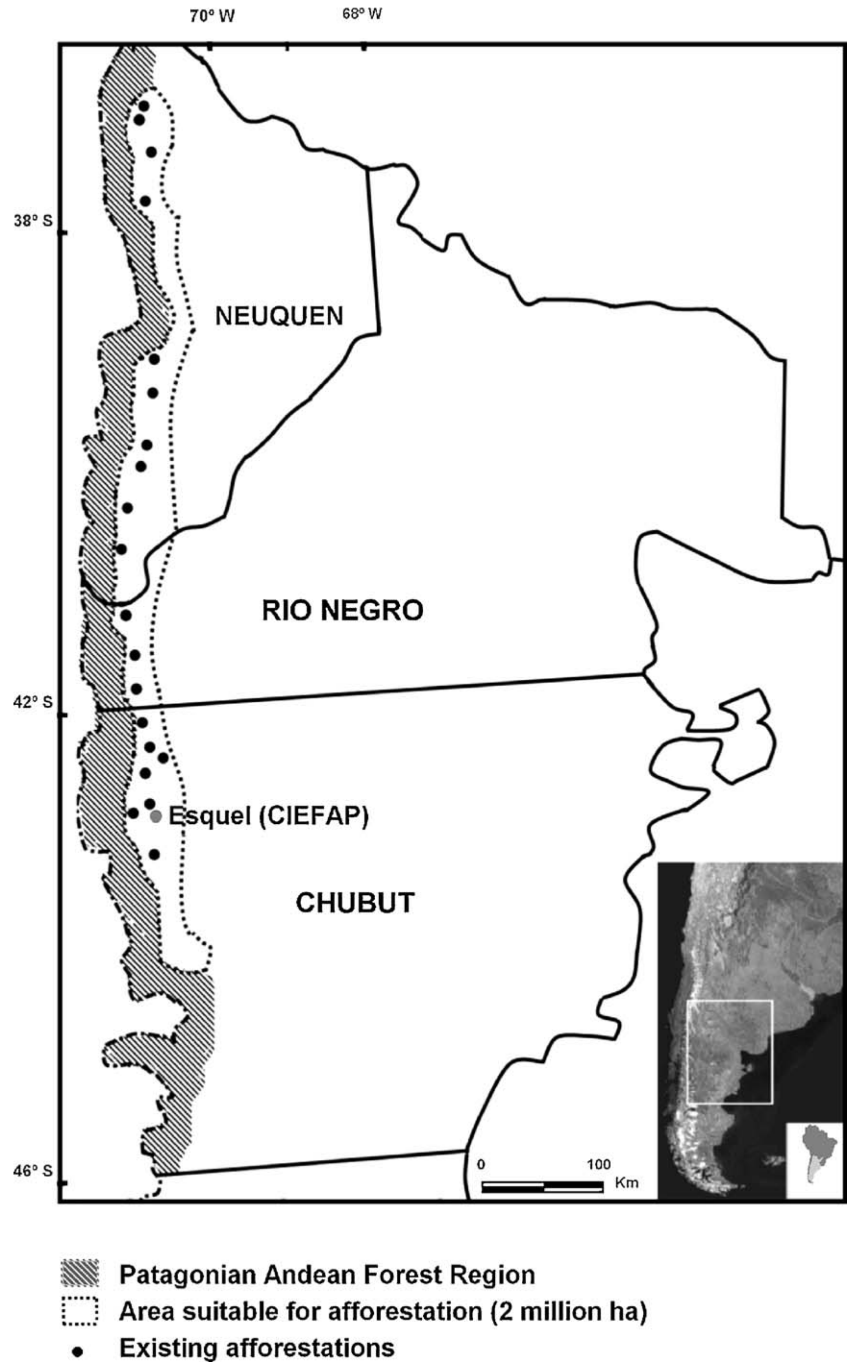

Fig. 1. The Patagonian region in Argentina, showing the area suitable for afforestations in the piedmont of the Andean Forests. Existing ponderosa pine afforestations are rather dispersed in the region, covering an area that goes from the 37°05′ to the 43°30′S parallels and from the 70°30′ to 71°W meridians.

2.2. Carbon stock by structural type

Carbon stocks in the biomass for each structure (age-class and management status) was estimated using the guidelines for the AFOLU sector given by the IPCC (2006), as shown in Eqs. (1) and (2). To determine initial values of biomass stock and forest fuel load (FFL) for each age-class and management status, we used dasometric variables which characterize each structure (number of trees/ha (TPH), quadratic mean diameter (QMD), age (E), and mean height (MH) of each structure). This initial variables were taken from the forest inventory. Biomass stock was determined based on biomass functions developed for ponderosa pine. These functions included biomass in the trunk, branches, pine needles, and roots (Loguercio et al., 2004). Carbon present in downed dead wood and litter (forest fuel load, FFL) (2) was determined by the adjusted equation given in Appendix I.

$$C_{stock} = C_{biomass\ stock} + C_{FFL} \quad (1)$$

$$C_{FFL} = C_{dead\ wood\ stock} + C_{litter\ stock} \quad (2)$$

where

C_{Stock} = amount of C (t/ha CO_2 e);
$C_{biomass\ stock}$ = amount of C in biomass (above and belowground) (t/ha CO_2 e);
C_{FFL} = forest fuel load (t/ha CO_2 e);

$C_{\text{dead wood stock}}$ = amount of C in dead wood compartment (t/ha CO_2 e);
$C_{\text{litter stock}}$ = amount of C in litter compartment (t/ha CO_2 e).

Every year, each forest structure presented changes in carbon stocks, which could have been either positive due to current growth, or negative due to thinning. These changes were accounted for by using a stand growth model for ponderosa pine developed by Andematten and Letourneau (2003), by projecting the mean dasometric variables which characterize each structure. Based on these projections, we estimated the expected values of extracted biomass due to thinnings and the annual growth of each structure. Changes in FFL were determined based on the biomass that remains on the site as thinning residues. For every other year of the analyzed period, carbon stock was obtained according to Eq. (3):

$$C_{\text{stock year } i} = C_{\text{stock year } i\text{-}1} + \Delta C_{\text{biomass stock } i} + \Delta C_{\text{FFL}i} \quad (3)$$

where

$C_{\text{stock year } i}$ = total amount of carbon in year i of that period (t CO_2 e);
$C_{\text{stock year } i-1}$ = total amount of carbon in the year previous to year i (t CO_2 e);
$\Delta C_{\text{biomass stock } i}$ = changes in the amount of C in biomass (due to gains and losses) in year i of the period (t CO_2 e);
$\Delta C_{\text{FFL } i}$ = changes in FFL (due to gains and losses) in the year i of the period (t CO_2 e).

The total amount for each structure was obtained by multiplying mean values per ha times their respective areas.

Downed dead woody material and litter made up the forest fuel load (FFL), and comprised of all dead fuels available for combustion. In order to establish C stock in the FFL, a regression function was developed. These initial variables consider the stand management status and its dasometric parameters. In doing this, a sample was performed of different ponderosa pine stands, to cover a wide range of age-classes and management status. Twenty-seven stands were surveyed, totalling 80 sampling units (3 per stand). The sampling units were rectangular plots covering 300 m^2 (15 m × 20 m each), to best represent the structural characteristics of the selected stand. In each plot we measured forest fuel load according to the method proposed by Brown (1974), and the methods by Sánchez and Zerecero (1983) (see Appendix I). In each plot we made additional measurements of diameter at breast height (DBH) and age of each tree (E), from which we derived number of trees/ha (TPH), quadratic mean diameter (QMD), basal area (BA), and Reineke's density index (RDI, Reineke, 1933). Finally, stands were classified according to their forest management (FM) receiving values of 0 (no management), 1 (stands which have been thinned once), and 2 (stands which have received 2 or more thinnings). This classification allowed for the possibility of including an ordinal variable to the model.

2.3. Regression analyses

In order to analyze and adjust the proposed model, we used the Statgraphics Plus 5.1 statistical software (Statgraphics Plus 5.1, 1994–2001). Linear multiple regression was used, including as candidate independent variables, DBH, E, TPH, QMD, BA, RDI, and FM. In order to analyze relationships among variables, a correlation matrix was built, the significant level for t at 95%. To adjust the model, we evaluated R^2 and F (95%). Also, evaluation of residuals to determine dispersal and homogeneity of variances was done.

2.4. Wildfire and prescribed fire emissions modeling

In order to predict the area likely to be affected by future wildfires, we based our estimates from provincial fire records of annual average of the area covered by ponderosa pine afforestation burned by wildfires during the last 10 years (from Neuquén province, SPLIF, and SPMF, unpublished data). We then assumed that the area to be affected by wildfires would remain fairly constant for the next 10 years. In the scenario with prescribed burnings, it is expected a diminution of the area affected by wildfires, which in turn has a direct effect in reducing the amount of GHG emissions. To estimate C emissions in CO_2 equivalent units, we used emission factor (c) as well as global warming potential (WPG, Gohar, 2007). The c (Emission factor) was obtained by multiplying C content by a factor. For ponderosa pine this factor is assumed as 0.5 (IPCC, 1997), as well as the molecular weight relationship between carbon and CO_2 (44/12). For CH_4 and N_2O, we used the mean values published by IPCC (2006) for non-tropical forests, while for non-CO_2 GHGs, WPG values proposed by IPCC (1997) were used.

In order to quantify the effects of prescribed burnings in GHS emission reduction, we based our study on the following assumptions:

1. Finney (2001, 2003) and Narayan et al. (2007), noted that if a strategically located area, equivalent to 20% of the area really affected by wildfires every year is treated annually with prescribed burnings, the probability of occurrence of future wildfires of the same magnitude is reduced by about 50%. It is important to note that these authors consider this value as a very conservative, since it only considers the effect of reducing fuel load on fire behavior, and not the positive effects of suppressing wildfires.
2. The application of prescribed burning, will reduce fuel load in the forest to an optimal value (OV), thus assuring fire risk reduction, facilitating its control in case it may occur, while the site still maintains its ecological and productive properties. The amount of fuel load that should remain after application of prescribed burnings in pine plantations has been proposed to be from 7 to 10 t/ha (De Ronde et al., 1990). For other vegetation types, Fernandes (*per. comm.*) recommend values ranging from 6 to 10 t/ha. In our study, and based on these figures, we adopted 8 t/ha as the target value to be achieved in one or several burns.

CO_2 and non-CO_2 gases emissions for both scenarios were determined by the following Eq. (4):

$$CO_2 \text{ and non-}CO_2 \text{ WF}_i \text{ emissions} = A_{\text{WF}_i} \times M_{\text{B}} \times \text{fc} \times c \times \text{GWP} \quad (4)$$

where

CO_2 and non-CO_2 WF_i emissions. = CO_2 and non-CO_2 emissions by wildfires in the year i of the period (t CO_2 e);
$A_{\text{WF}i}$ = area of afforestation that will be burned by wildfires in year i of that period (ha);
M_{B} = fuel load available to be burned by a wildfire (t/ha);
fc = mean fraction of the available fuel burned during the fire. We used the 0.45 value proposed by the IPCC for non tropical forests
c = emission factor or weight of gas released per weight of dry matter burned per gas type (CO_2, CH_4 and N_2O in this case);
GWP = global warming potential. Conversion factor of each gas type to CO_2 e values.

Prescribed burning emissions are due to reduction in fuel load up to an optimal value (8 t/ha).

Forest fuel load (FFL) reduction is given by the following equation:

$$\textit{Forest Fuel Load Reduction} = (FFL_i - OV) \times \textit{Area PBi} \quad (5)$$

where

forest fuel load I reduction = reduction in C of FFL for the scenario with prescribed burning in the year *i*, considering the annual burned area (*t*);
FFL *i* = forest fuel load to year *i* of period (t/ha);
OV = optimum fuel load (t/ha);
Area PB *i* = prescribed burning area to year *i* of the period (ha).

Forest fuel load reduction due to prescribed burning was then converted into CO_2 e, by multiplying the amount of emissions by the emission factors and by the warming potential values of each gas.

$$CO_2 \text{ and non-}CO_2 \text{ PB}_i \text{ emissions} = \text{forest fuel load reduction}_i \times c \times \text{GPW} \quad (6)$$

where CO_2 and non-CO_2 PBi emissions = CO_2 and non-CO_2 emissions by prescribed burning (t CO_2 e).

2.5. Carbon balance (removals/emissions) between the two scenarios

The reduction potential of total emissions was estimated according to Eqs. (7–9).

$$CO_2 \text{ reduction pot.} = CO_{2\,10}\text{rem.}_{(\text{with PB})} - CO_{2\,10}\text{rem.}_{(\text{without PB})} \quad (7)$$

$$\text{Non-}CO_2 \text{ reduction pot.} = \text{non-}CO_{2\,e}\text{emis.}_{(\text{without PB})} - \text{non-}CO_2\text{emis.}_{(\text{with PB})} \quad (8)$$

$$CO_{2\,10}\text{rem.} = C_{\text{stock}\,i+10} - C_{\text{stock}\,i} \quad (9)$$

where

CO_2 reduction pot. = potential reduction of atmospheric CO_2 (t CO_2 e);
$CO_{2\,10}$ rem.$_{(\text{with PB})}$ = CO_2 removals during the 10-year period considered by applying prescribed burning (Gg CO_2 e);
$CO_{2\,10}$ rem.$_{(\text{without PB})}$ = CO_2 removals during the 10-year period considered, without applying prescribed burning (Gg CO_2 e);
Non-CO_2 reduction pot. = non-CO_2 gases (t CO_2 e) potential reduction. This is equal to the difference of Non-CO_2 gases emissions between the scenarios with and without prescribed burnings (Gg CO_2 e);
Non-CO_2 emis.$_{(\text{without PB})}$ = Non-CO_2 emissions in the scenario without prescribed burning (Gg CO_2 e);
Non-CO_2 emis.$_{(\text{with PB})}$ = Non-CO_2 emissions in the scenario with prescribed burning (Gg CO_2 e).

The potential reduction of emissions due to the application of prescribed burning is then the result of the addition of Eqs. (7) and (8), and is presented as Eq. (10).

$$\text{GHG reduction pot.} = CO_2 \text{ reduction pot.} + \text{non-}CO_2 \text{ reduction pot.} \quad (10)$$

Table 2
Correlation matrix for the candidate variable diameter at breast height (DBH), age of each tree (E), number of trees/ha (TPH), quadratic mean diameter (QMD), basal area (BA), Reineke's density index (RDI)[a] and forest management (FM).

Variables	Cte	BA	TPH	QMD	E	RDI	FM	FFL
Cte	1							
BA	0.066	1						
TPH	−0.907	0.100	1					
QMD	−0.701	−0.204	0.681	1				
E	0.131	0.338	−0.144	−0.609	1			
RDI	0.220	−0.910	−0.411	−0.116	−0.289	1		
FM	−0.422	−0.182	0.380	0.137	−0.344	0.124	1	
FFL	0.202	0.437	−0.331	0.694	0.684	0.444	0.534	1

[a] Reineke (1933).

Table 3
Multiple regression analysis adjusted for the selected independent variables (number of trees/ha, TPH; quadratic mean diameter, QMD; and previous forest management, FM), used to determine forest fuel load (FFL).

Parameter	Estimation	Standard error	*T*	*p* value
Cte	−8.338210	7.601200	−1.096960	0.2840
TPH	0.010871	0.005432	2.000980	0.0573
QMD	0.561596	0.152610	3.679930	0.0012
FM	8.968710	2.889020	3.104410	0.0050

3. Results and discussion

3.1. Multiple regression analysis for forest fuel load model

The result of correlation analysis between dasometric variables and forest fuel load is presented in the matrix of Table 2.

This table indicates that the variables quadratic mean diameter (QMD), number of trees per hectare (TPH), and previous forest management (FM), were the main determinants of this correlation. Considering these as independent variables, we adjusted a multiple regression model (Table 3), and ANOVA (Table 4) which gave a satisfactory result ($R^2 = 0.654$, $F = 14.52$). The expression and statistics of the model are the following:

$$\text{FFL} = -8.338210 + 0.561596 \times \text{QMD} + 0.010876 \times \text{TPH} + 8.96871 \times \text{FM} \quad (11)$$

where

FFL = forest fuel load (t/ha);
QMD = quadratic mean diameter (cm);
TPH = number of trees per hectare;
FM = management (0 = unmanaged, 1 = one thinning, 2 = two or more thinnings).

The residual analysis showed a homogeneous distribution, with a slight overestimation when there is little FFL in the stand (Fig. 2).

The equation uses simple independent variables easily gathered from forest inventories. Although some equations have been adjusted for higher levels of accuracy, they require further field measurements related to litter, or using more specific simulation models (Fernandes and Botelho, 2003). The adequate estimation

Table 4
Analysis of variance based on the independent variables (number of trees/ha, TPH; quadratic mean diameter, QMD; and previous forest management, FM) used to determine forest fuel load (FFL).

Source	SS	df	Average square	*F*	*p* value
Model	3295.68	3	1098.5600	14.52	0.0000
Residual	1740.64	23	75.6799		
Total	5036.32	26			

$R^2 = 0.654$; R^2 error = 0.610.

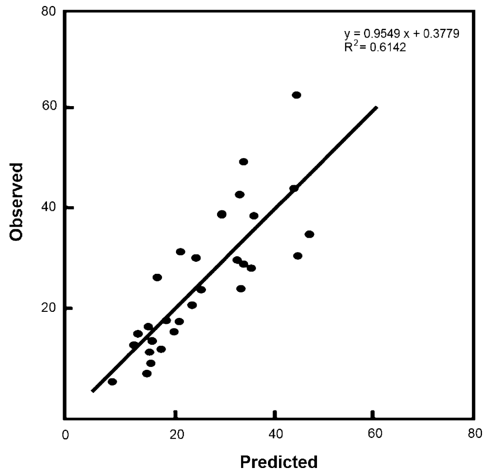

Fig. 2. Residual analysis of FFL relating observed versus predicted values. The model slightly overestimates its predictions when there is a little amount of FFL in the stand.

of the FFL is one of the main points that should be considered when planning a prescribed burning treatment set for avoiding, or reducing, the effects of wildfires. This measure, together with shape, size, and spatial arrangement of the fuels in the area to be treated, strongly affects the efficacy of the prescribed burning treatment (Agee et al., 2000; Ager et al., 2006; Fernandes and Botelho, 2003; Fernandes and Rigolot, 2007). In planted pine forests such as the afforestation that we dealt with in Patagonia, fuel arrangement could be strategically located within the landscape after thinning and pruning. This artificially created regular landscape fuel treatment pattern (*sensu* Finney, 2001) would be much more efficient in protecting the landscape from wildfires as compared to fuels accommodated in random patterns (Finney, 2003).

3.2. *Current stock and its distribution according to age-classes*

In Andean Patagonia, the total area covered by established forest plantations was 76,408 ha. The temporal increase in the afforestation rate can be seen in the largest areas of lower-age classes. Thus, an age-class less than 10 years occupies 46% of the area, though they only concentrate 2.5% of the fuel that could be affected by wildfires (aboveground biomass plus forest fuel load, Table 5), while both intermediate age-classes (C2 and C3), concentrate 92% of the fuel. The previous analyses are important when priorities are set to choose the most convenient area to be protected from the point of view of CO_2 emission reduction, and when considering where and which area is to be treated to attain this.

3.3. *Recent wildfires*

According to provincial statistics on wildfires in afforestation over the last 10 years, the annual mean area affected in each province is about 170 ha. However, there were some years when greater wildfires occurred, such as in Río Negro Province in 1999 and 2009, similar to what happened in Chubut Province in 2002, 2007 and 2008 (Table 6). The exception was a 1800 ha wildfire which occurred in 2005 affecting a young plantation (2 year old) belonging to one company in Neuquén Province. The average area of wildfires affecting afforestation at a regional level is 509 ± 182 ha/year. If applying the assumptions described in the methodology, prescribed burnings would be carried out in 20% of this area, which is 102 ha/year. It should be remembered that in the calculations, it was assumed that either the areas affected by wildfires or those treated with prescribed burning practices would only affect afforestation older than 10 year.

Table 6
Area of afforestations affected by wildfires in Neuquén, Río Negro and Chubut provinces during the last decade.

Year	Area affected by wildfires (ha)			
	Chubut	Río Negro	Neuquén	Total
1999	88	989	29	1106
2000	16	1	0	17
2001	4	0	0	4
2002	304	7	1	312
2003	14	54	8	76
2004	78	43	30	151
2005	202	12	1806[a]	2020
2006	17	77	212	306
2007	299	11	24	334
2008	463	1	32	496
2009	29	739	9	777
Average ± 1 SE	138 ± 47	176 ± 104	195 ± 162	509 ± 182

(Sources: Neuquen province; Servicio Provincial de Lucha contra Incendios Forestales (S.P.L.I.F), Río Negro; Servicio Provincial de Manejo del Fuego (SPMF, Chubut), unpublished data).

[a] This number corresponds to a single wildfire which affected a 2 year old plantation.

3.4. *Removals and C emissions evolution in scenarios with and without simulated prescribed burnings*

Between 2009 and 2018, in the scenario where no simulated prescribed burnings will be carried out, wildfires will produce increasing C emissions to the atmosphere between 43 and 61 Gg CO_2 e per year, respectively, and a total for the period of 519 Gg CO_2 e (Fig. 3).

In the scenario where simulated prescribed burning has been carried out, C emissions for the same period will range between 24 and 34 Gg CO_2 per year, and a total of 292 Gg CO_2 e. In the analyzed 10 year-period, prescribed burning will have avoided a total of C emissions of about 227 Gg CO_2 e. At the same time, the reduction of the area affected by wildfires in the scenario with prescribed burnings will allow for a portion of the forest to continue growing and accumulating additional biomass. In the 255 ha per year where no

Table 5
Afforested areas and current biomass and forest fuel load stock per hectare and totals (Mt dm) for each age-class.

Structure	Afforested area (ha)	Aboveground biomass		Belowground biomass		Forest fuel load		Total (Mt dm)
		t/ha	Total (Mt dm)	t/ha	Total (Mt dm)	t/ha	Total (Mt dm)	
C1 unthinned	34,834	3.0	0.11	2.6	0.09	0.0	0.00	0.20
C2 unthinned	20,417	64.9	1.33	31.0	0.63	22.9	0.47	2.43
C2 thinned	7643	61.5	0.47	31.2	0.24	28.05	0.22	0.93
C3 unthinned	3892	144.7	0.56	63.9	0.25	26.2	0.10	0.91
C3 thinned	8279	97.4	0.81	46.6	0.39	31.1	0.26	1.45
C4 unthinned	368	228.6	0.08	92.1	0.03	28.4	0.01	0.13
C4 thinned	975	137.4	0.13	56.7	0.06	32.7	0.03	0.22
Total	76,408		3.49		1.68		1.09	6.26

Mt dm = mega tons of dry matter.

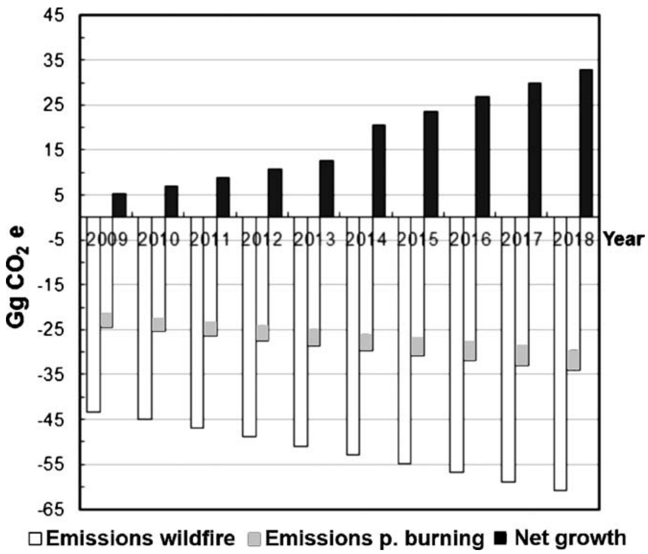

Fig. 3. Annual emissions and C net growth projection. White bars with negative values correspond to emissions due to wildfires in the scenario without prescribed burning. White/grey bars with negative values correspond to wildfires plus prescribed burnings in the scenario with prescribed burning, while the positive values (black bars) correspond to net growth in the areas where wildfires were avoided.

wildfires will occur, additional C removals will take place, increasing in this 10 year period from 5 to 33 Gg CO_2 e, due to stand growth (Fig. 3), totalizing 178 Gg CO_2 e for the period. These removals, which we call "net growth" include extractions due to thinnings (Fig. 3).

Net removals, that is the difference between with and without simulated prescribed burnings scenarios, will be 405 Gg CO_2 e (Fig. 4). Of this value, about 44% is due to net growth, while the remaining 56% is due to emissions mitigation through the application of simulated prescribed burning. The emissions per unit area in simulated prescribed burning represent in average 35% of those produced by wildfires. This value is slightly lower than the 38% informed by Fernandes (2005), and assumed by Narayan (2006). The emissions in the scenario with simulated prescribed burning are 44% below the ones corresponding to the scenario without prescribed burnings (Fig. 4).

The emissions due to simulated prescribed burning represent about 12% of the total emissions (prescribed burning plus wildfires) within their scenario. The complete balance between scenarios with and without simulated prescribed burning, in terms of afforested area, stock and gains and losses estimations in both large pools considered, above and belowground biomass, and FFL (downed dead wood and litter) is presented in Table 7 (a and b).

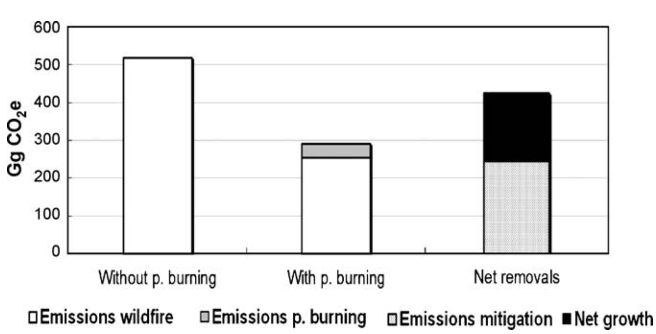

Fig. 4. CO_2 emissions generated by wildfires and prescribed burnings for scenarios with and without prescribed burnings (left and center), and net removals (emissions mitigation and net growth) in the 10 years covered by this analysis (right).

A summary including removals, non-CO_2 emissions and GHG's balance between scenarios during the ten-year projection period between both scenarios is presented in Table 8. The final result of GHG's emission mitigation through the application of prescribed burnings in the evaluated 10 years reached 426 Gg CO_2 e.

It is worth noting that afforestation in Patagonia are carried out over vast overgrazed rangeland areas outside native forests. These overgrazed areas, occupied by native shrubs and grasses, contain very low amounts of carbon (the base line) in their aboveground organs. This aspect makes them very attractive within CDM for help mitigating climate change through carbon sequestration by afforestation (Loguercio et al., 2004). This attractiveness is enhanced when comparing carbon balance with projects developed for other ecosystems, since in our case, even small increases in biomass growth above the low base line (taking into account the emissions incurred during plantation) would be considered as a positive measure of carbon sequestration for climate change mitigation. However and as in any other temperate forest ecosystem, these afforestation would not be free of risks during their life span, and these beneficial effects could be rapidly reversed by natural or human disturbances (Galik and Jackson, 2009; Hurteau et al., 2009, 2010). Some natural disturbances affecting forests (earthquakes, avalanches, wind storms) are well beyond human manipulation. Others, such as wildfires, could be either suppressed by all available means, or avoided or mitigated by manipulating forest structure and fuels (by thinning, pruning, and/or applying prescribed burning). While there is a general consensus that the application of prescribed burning could be effective in fire hazard reduction (Sackett, 1981; Agee et al., 2000; Finney, 2001, 2002, 2003; Liu, 2004; Fernandes and Botelho, 2003; Agee and Skinner, 2005; Baeza et al., 2002; Ager et al., 2010, and references therein), its effects as means to reduce carbon emissions is still at least controversial (Ferguson et al., 1998; Fernandes, 2005; Narayan, 2006; Narayan et al., 2007; Wiedinmyer and Hurteau, 2010; Meigs and Campbell, 2010; Hurteau and Wiedinmyer, 2010; Hurteau et al., 2010). In our simulation study and comparing two possible scenarios in Patagonia, we showed that prescribed burning, applied to either 10% of the maximum area affected annually by wildfires during the analyzed period, or to 20% of the average area affected annually by wildfires, produced net removals of CO_2 and other GHG from the atmosphere (426 Gg CO_2 e in 10 year). These results are promising and allowed us to suggest that more studies such as this should be carried out in other ecosystems, before generalizing or promoting this practice as a proved means for help mitigating carbon emission. Nevertheless and for afforestation carried out in Mediterranean type of climates such as this of Patagonia (similar to temperate forest ecosystems), our results support the statements made by Hurteau and Wiedinmyer (2010) that "*prescribed burning could reduce CO_2 and other emissions from forest fires*", and that "*prescribed burning is a potential way to manage CO_2 fluxes*". One detail that may weaken these statements is that at present, almost all studies dealing with the effects of prescribed burning in reducing CO_2 emissions are based on simulations studies. Perhaps the best way to cast light on these assertions would be if convincing simulation studies were compared with field data, such the one presented by Fernandes (2005) in maritime pine stands of Portugal.

Summarizing, prescribed burnings in planted forests en Patagonia could be a forest management practice which not only will prevent fires in order to achieve productive objectives (soil protection or others), but also could contribute to effectively mitigate GHG emissions. The Kyoto protocol, as an international ruling reference to combat climatic change, states that countries having no commitment for GHG emission reductions, such as Argentina, can only participate of the Clean Development Mechanism (UNFCCC, 1998). According to the Marrakech Agreements (UNFCCC, 2001), the forestry activities that can be chosen for such

Table 7
Afforested area, stock and gain and losse estimation in both large pools considered. Biomass (above and belowground) and FFL (downed dead wood and litter) for each year in the scenario without prescribed burning (A) and with simulated prescribed burning (B).

Year	Afforested area (ha)	Stock (Mt CO_2 e)				Gain (Gg CO_2 e)	Loss (Gg CO_2 e)			$\Delta^e = a - b - c - d$
		Biomass		Forest fuel load	Total	Biomass growth[a]	Thinning		Wildfire emission[d]	
		Aboveground	Belowground				Aboveground[b]	Belowground[c]		
(A)										
2008	76,408	6.39	3.09	1.64	11.13					
2009	75,900	6.62	3.25	1.82	11.70	1050.9	242.9	192.7	43.2	572.0
2010	75,391	6.84	3.42	2.00	12.27	1043.5	239.9	190.6	45.1	567.9
2011	74,882	7.07	3.58	2.18	12.83	1035.8	237.0	188.4	47.0	563.4
2012	74,373	7.29	3.75	2.35	13.39	1028.0	234.0	186.2	48.9	558.8
2013	73,864	7.51	3.91	2.52	13.94	1020.1	231.0	184.1	50.9	554.2
2014	73,355	7.72	4.08	2.69	14.48	1004.1	228.1	181.9	52.8	541.3
2015	72,846	7.93	4.24	2.85	15.02	994.7	225.1	179.7	54.8	535.1
2016	72,337	8.13	4.40	3.02	15.55	985.4	222.1	177.6	56.8	528.9
2017	71,828	8.34	4.56	3.17	16.07	976.0	219.1	175.4	58.8	522.7
2018	71,319	8.54	4.72	3.33	16.59	966.6	216.2	173.3	60.8	516.4
Totals						10,105.1	2295.4	1829.9	519.2	5460.7

Year	Afforested area (ha)	Stock (Mt CO_2 e)				Gain (Gg CO_2 e)	Loss (Gg CO_2 e)				$\Delta^f = a - b - c - d - e$
		Biomass		Forest fuel load	Total	Biomass growth[a]	Thinning		Wildfire emission[d]	P. burning emission[e]	
		Aboveground	Belowground				Aboveground[b]	Belowground[c]			
(B)											
2008	76,408	6.39	3.09	1.64	11.13						
2009	76,154	6.64	3.25	1.83	11.72	1057.7	242.9	194.3	21.6	2.8	596.1
2010	75,900	6.89	3.42	2.01	12.32	1055.7	242.1	193.7	22.5	3.0	594.4
2011	75,645	7.14	3.59	2.19	12.91	1053.6	241.3	193.1	23.3	3.2	592.7
2012	75,391	7.38	3.75	2.37	13.50	1051.5	240.5	192.5	24.2	3.4	590.9
2013	75,136	7.63	3.92	2.55	14.09	1049.3	239.7	191.9	25.1	3.6	589.1
2014	74,882	7.87	4.08	2.72	14.67	1045.0	238.9	191.3	26.0	3.7	585.0
2015	74,627	8.11	4.25	2.90	15.26	1042.4	238.1	190.8	26.9	3.9	582.8
2016	74,373	8.35	4.41	3.07	15.84	1039.9	237.3	190.2	27.8	4.1	580.5
2017	74,118	8.59	4.58	3.25	16.42	1037.3	236.4	189.6	28.7	4.3	578.3
2018	73,864	8.83	4.74	3.42	16.99	1034.8	235.6	189.0	29.6	4.5	576.0
Totals						10,467.2	2392.8	1916.4	255.7	36.5	5865.8

[a] Aboveground and belowground biomass.
[b] Aerial thinned biomass, corresponds to wood products emissions.
[c] Belowground biomass emissions corresponding to thinnings.
[d] Emissions due to wildfires.
[e] Changes, gain-loss difference.
[f] Changes, gain-loss difference.

Table 8
Removals, non-CO_2 emissions and GHG's balance between scenarios during the ten-year projection period.

Scenarios	CO_2 removal during 10 years (Gg CO_2 e)	Non-CO_2 emissions during 10 years (CO_2 e)	GHG's balance (Gg CO_2 e)
Without p. burning	5461	48	5413
With p. burning	5866	27	5839
Difference	405	21	426

projects are Afforestation and Reforestation, not including conservation and forest management. As a consequence of these decisions, prescribed burning practices are not eligible activities for CDM projects, although it has been proved they can theoretically contribute to GHG emissions mitigation. Wildfires that may occur in implanted forests created within the frame of CDM projects will reduce the potential number of Emission Reduction Credits. In this sense, prescribed burnings could be included in the design of Afforestation projects as CDM, as another forestry management practice, like pruning, thinning, etc., in order to reduce wildfire risk. This is the way prescribed burnings could contribute to the CDM of Kyoto protocol.

At present, a discussion is taking place on the possibility of celebrating a new international agreement in 2018 (post Kyoto), which might include activities for Emission Reduction through avoiding Deforestation and Degradation (REDD) (UNFCCC, 2008a,b,c). This generates expectations on the possibility that, in the future, activities such as prescribed burnings can be considered for GHG emission reduction. The results of this research provides useful information on this issue, and could be used as an example for proposing and defining new policies to be considered not only at European level but also within the frame of the UNFCCC negotiations.

Acknowledgements

The authors would like to acknowledge the European Commission for providing the funds to carry out the FP6 Project "Fire Paradox"; most of the activities reported in this study were done within the frame of that Project. Authors would also like to acknowledge Patricia González for her help during many stages of manuscript writing and the work done by three anonymous reviewers who helped improve earlier versions of this paper.

Appendix I. Methodology and field sampling carried out for FFL estimation

For each stand, forest fuel load (FFL) was estimated. This FFL results of the addition of downed dead wood and litter. For the first one, planar intersection method (Brown, 1974) was used, which consisted of two semi-diagonal transects (Fig. A.1), upon which the times each evaluated material is intersected is quantified. Downed dead wood was classified into the following size categories (Table A.1) according to the physical dimensions and time-lags defined by the NFDRS (Anderson, 1982).

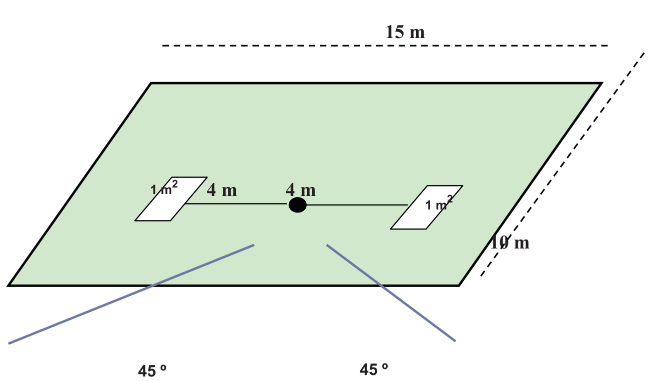

Fig. A.1. Design of the sampling unit.

Table A.1
Different size classes, diameter and defined timelags.

Size class name	Size diameter		Timelag[a]
	Inch	cm	
Fine	<¼	0.6 cm	1
Medium	¼ to 1	0.6–2.5 cm	10
Regular	1–3	2.5–7.5 cm	100
Large	>3	>7.5 cm	1000

[a] Timelag is the time necessary for a fuel size class to change 63% in weight due to loses in moisture content (Anderson, 1982).

Along each transect, fine fuels were quantified in the first 2 m, mediums in the first 4 m, regulars in the first 8 m, while large fuels were quantified along the whole transect (15 m). In this class, fuels were also classified as healthy or rotten. Litter was measured by recollection and was weighed on terrain in two 1 m^2 plots, located at 4 m from the center of the stand, in opposite directions. Dry weight was determined in the laboratory, after drying the material in a stove at 103 °C to constant weight. Fig. A.1 shows the design of the sampling plot.

A.1. Field data processing

Fuel load calculus (t/ha) considering the number of times that material from each class crossed over the transect, was carried out by using Eq. (12) (for fine, medium and regular material), and Eq. (13) (for thick, healthy as well as rotten material) (Brown, 1974, modified by Sánchez and Zerecero, 1983).

$$W_y = \frac{w \times n \times p}{N \times L} \tag{12}$$

$$W_y = \frac{w \times \sum D^2 \times p}{N \times L} \tag{13}$$

where

W_y = fuels dry weight (fine–medium–regular–large healthy or rotten (in t/ha));
n = frequency or number of intersections;
p = correction factor per slope $\sqrt{1 + (i^2/100)}$ where i = slope (%);
$\sum D^2$ = Sum of square diameters of each piece or branch >7.5 cm
N = number of transects;
L = measurement Length of each material size within the transect, in feet (1 m = 3.28 feet);
w = coefficient dependant on fuel size.

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