Forest Fires in Mediterranean Countries: CO$_2$ Emissions and Mitigation Possibilities Through Prescribed Burning

Terhi Vilén · Paulo M. Fernandes

Abstract Forest fires are an integral part of the ecology of the Mediterranean Basin; however, fire incidence has increased dramatically during the past decades and fire is expected to become more prevalent in the future due to climate change. Fuel modification by prescribed burning reduces the spread and intensity potential of subsequent wildfires. We used the most recently published data to calculate the average annual wildfire CO$_2$ emissions in France, Greece, Italy, Portugal and Spain following the IPCC guidelines. The effect of prescribed burning on emissions was calculated for four scenarios of prescribed burning effectiveness based on data from Portugal. Results show that prescribed burning could have a considerable effect on the carbon balance of the land use, land-use change and forestry (LULUCF) sector in Mediterranean countries. However, uncertainty in emission estimates remains large, and more accurate data is needed, especially regarding fuel load and fuel consumption in different vegetation types and fuel layers and the total area protected from wildfire per unit area treated by prescribed burning, i.e. the leverage of prescribed burning.

Keywords Forest fires · Prescribed burning · CO$_2$ emissions · Kyoto Protocol

T. Vilén (✉)
European Forest Institute, Torikatu 34, 80100 Joensuu, Finland
e-mail: terhi.vilen@efi.int

P. M. Fernandes
Centro de Investigação e de Tecnologias Agro-Ambientais e Biológicas (CITAB) and Departamento de Ciências Florestais e Arquitectura Paisagista (CIFAP), Universidade de Trás-os-Montes e Alto Douro, Quinta de Prados, 5001-801 Vila Real, Portugal
e-mail: pfern@utad.pt

Introduction

Fire is a fundamental disturbance in the Mediterranean region. Paleoecological studies show that fires were common during the late Quarternary and many species are adapted to frequent fire events (Carrión and others 2003; Pausas and others 2008). Although fire is intrinsic to Mediterranean ecosystems, the number of fires has increased dramatically during the recent decades, mostly due to changes in land use (Pausas 2004; Pausas and others 2008). From 1996 to 2005 the annual average number of fires in Southern Europe exceeded 61,000, which is 34% more than recorded during 1986–1995 (Miranda and others 2009), and currently 0.5 million hectares are burned every year in the five southern EU member states (Portugal, Spain, Greece, Italy, France) (EC 2009). As a result of more frequent and more severe fires, Mediterranean ecosystems can experience loss of biodiversity, soil erosion and desertification (Pausas and others 2008). Fires also cause large economic losses and threaten human lives. In addition, forest fires are a remarkable source of greenhouse gases (GHG). In Portugal the exceptionally large forest area burned in 2003 turned the land use, land-use change and forestry (LULUCF) sector from a net sink into a carbon source of 7,076 Gg CO$_2$ (FCCC 2006).

Climate and weather are major factors influencing fire incidence. Summer drought and area burned are strongly linked (Camia and Amatulli 2009; Carvalho and others 2010; Flannigan and Harrington 1988; Pausas 2004; Pinol and others 1998). Over the next 100 years, climate change is expected to result in summer temperature increases of 4–5°C throughout Southern Europe and up to 50% decreases in rainfall during summer, which means more extended hot periods and droughts and hence increased fire risk (Lindner and others 2010). In Portugal, dramatic

increases in fire occurrence and area burned of respectively 279 and 478% are predicted for 2071–2100 in comparison with the 1980–1990 period (Carvalho and others 2010).

Prescribed burning can be used to manage forest fuels to reduce fire risk (e.g., Fernandes and Botelho 2004; Fernandes and others 2004). Prescribed burning decreases the intensity of wildfires by decreasing fuel loads and by disrupting the horizontal and vertical continuity of the fuel complex (Fernandes and Botelho 2003). Prescribed burning has been shown to substantially decrease potential or actual fire intensity in western USA forests (Arno and Brown 1989; Ager and others 2010; Finney and others 2005; Stephens and Moghaddas 2005) and in European pine stands (Fernandes and Botelho 2004; Fernandes and others 2004; Fernandes 2009). The objective of prescribed burning is not to exclude unplanned fires from the landscape, but to decrease their intensity and damage caused thus preventing large and catastrophic fires (Fernandes and Botelho 2003; Loehle 2004). However, fire management in Europe relies heavily on fire suppression and disregards fuel treatments (e.g., Fernandes 2008), and prescribed burning is either not used or remains underdeveloped (Lázaro 2010).

As a by-product, prescribed burning could also result in a net reduction of CO_2 emissions from forest fires. Fire emissions have been thoroughly studied in different parts of the world, but few studies have considered prescribed burning in the context of carbon emissions mitigation. Wiedinmyer and Hurteau (2010) found that wide-scale prescribed fire application in the western USA could reduce CO_2 emissions from forest fires by 18–25% and as much as by 60% in specific forest systems. Narayan and others (2007) studied the effects of prescribed burning on GHG emissions for 33 European countries. Their results indicated that the potential of prescribed burning as an emission mitigation technique is rather low for most European countries, albeit prescribed burning could be used to mitigate emissions in Southern Europe where wildfire incidence is high. Defossé and others (2011) evaluated the potential of prescribed burning for reducing greenhouse gas emissions in pine afforestations in the Andean region of Patagonia, Argentina. Their results suggest that prescribed burning would reduce CO_2 emissions by 44% compared to the situation without prescribed fire and the avoided wildfires would allow an additional 78% GHG emission mitigation due to extra biomass growth. Using prescribed burning and other fuel treatments to increase the resistance of fire-prone forests to wildfire should improve their long-term carbon storage (North and others 2009; Stephens and others 2009), although the conclusion is affected by the carbon accounting system used (Sorensen and others 2011). Whether or not prescribed burning can contribute to carbon sequestration depends on how it changes the fire regime, especially in respect to the overall area burned and fire intensity (Bradstock and Williams 2009).

Our aim is to calculate average CO_2 emissions from wildfires in the Mediterranean countries and then estimate the potential of prescribed burning to mitigate emissions, by following the IPCC guidelines and using the most recent data available. We also assess the effectiveness of prescribed burning in the Kyoto Protocol context.

Data and Methods

Approach

The total amount of burned biomass was calculated as per Seiler and Crutzen (1980):

$$M = A \times B \times \mathrm{CF} \ [\text{g dry matter per year (g dm/year)}],$$

where A is the total land area burned annually (m^2/year), B is the average organic matter per unit area (g dm/m^2), and CF is the biomass burning efficiency. Burned biomass was then converted into CO_2 emissions, E_c, using the equation:

$$E_c = M \times E_{fc}$$

where E_{fc} is the emission factor, as the weight of released CO_2 per weight of dry matter burned.

We followed the IPCC guidelines (IPCC 2006) and differentiated three fuel components: aboveground tree biomass (further separated into foliage and branches), deadwood, and litter.

Area Burned and Biomass

Because the aim was to calculate average annual emissions, the long-term (1980–2008) annual average burned area (European Commission 2009) was used in the calculations (Table 1). To estimate biomass in the burned area, first the mean biomass stock (t/ha) for each fuel compartment (aboveground biomass, deadwood and litter) was calculated using data from the Global Forest Resources Assessment (FAO 2005). Since the burned area includes both forest and other wooded land, we used average values of forest and other wooded land. Biomass allocation (Vilén and others 2005) was then used to calculate the share of foliage and branches biomass from the total aboveground biomass. Deadwood data were available for France and Italy only, and litter data was available just for Italy. Therefore, we calculated the share of deadwood and litter from aboveground biomass based on the data for Italy and France and used these proportions to estimate the carbon stock of these compartments for the other countries (Table 1). The Global Forest Resources Assessment data

Table 1 Forest area, average burned area and mean biomass stocks in different compartments

Country	Forest area, 1,000 ha[a]		Burned area (ha/year) Average 1980–2008[b]	Mean stock (t dm/ha)[a]					
				Forest			Other wooded land		
	Forest	Other wooded land		Aboveground biomass	Deadwood	Litter	Aboveground biomass	Deadwood	Litter
France	15,554	1,708	28,460	118.94	*17.36*	21.72	50.94	*6.95*	*12.52*
Greece	3,752	2,780	49,044	26.12	*4.01*	*4.78*	1.80	*0.25*	*0.44*
Italy	9,979	1,047	118,022	104.52	16.03	18.15	84.05	11.46	20.65
Portugal	3,783	84	109,327	38.59	*5.93*	*7.06*	95.24	*12.99*	*23.40*
Spain	17,915	10,299	179,043	36.9	*5.09*	*6.07*	0.10	*0.01*	*0.02*

Values in italics are estimated based on data from other Mediterranean countries

[a] FAO (2005)

[b] European Commission (2009)

(FAO 2005) for deadwood and litter are given as carbon stocks only, and the values were converted back to dry mass by assuming factors of 0.5 carbon units per fuel weight unit for deadwood (IPCC 2006) and 0.37 for litter (Smith and Heath 2002). The total biomass in the burned area was then calculated by multiplying burned area and the calculated mean biomass stocks of different biomass compartments (foliage, branches, deadwood and litter).

Combustion Factors (CF)

Usually only a fraction of the aboveground biomass burns, and most standing biomass remains in the stand as living trees, dead organic matter or charcoal. The combustion factor (CF) is the fraction of biomass exposed to fire that is actually consumed (Ito and Penner 2004). In Mediterranean conditions, the mean combustion factor of aboveground tree biomass was assumed to be 1 for foliage and 0.1 for branches in a crown fire (Reinhard and others 1997). These factors were adjusted by 0.75 assuming that 75% of the burned area is the resultant of a crown fire. Belowground biomass was assumed to be left unburned. A combustion factor of 0.9 was used for both litter and deadwood, which corresponds to the customary near-complete removal by fire under the Mediterranean dry summer conditions (e.g., Fernandes and others 2004).

Emission Factors (E_{fc})

The emission factor is defined as the amount of a released compound per amount of dry fuel consumed, expressed in units of g/kg (Andreae and Merlet 2001). The emission factors from Carvalho and others (2007) for Mediterranean conditions were used. Since CO_2 emission factors are given separately for coniferous and broadleaved trees with 1,627 and 1,393 g/kg, respectively, we divided the burned forest

area into predominantly conifers, predominantly broad-leaved and mixed forests on the basis of forest data from MCPFE (2007). An emission factor was not available for mixed forests, which were attributed with the average value of coniferous and broadleaved fuels, i.e., 1,510 g/kg. The mixed forest value was also used for deadwood and litter in the absence of more adequate data.

Effect of Prescribed Burning

Prescribed burning will not benefit the carbon balance unless it succeeds in decreasing the area burned by wildfire. This effect is directly quantifiable by determining the leverage (Loehle 2004) or return for effort (Price and Bradstock 2011) of prescribed burning, i.e., the area protected (saved) from wildfire per unit area treated by prescribed fire. In Europe, this analysis is precluded by the absence of long-term prescribed burning programs. However, analysis of past wildfire data can be used to uncover the general effect of fuel reduction (as opposed to weather) on future area burned. We determined burning leverage using data from Portugal, which is characterized by wide regional variation in fire incidence and variety in land use and land cover (Nunes and others 2005).

We divided Portugal ($\approx 89 \times 10^3$ km^2) into its 12 ecoregions (Albuquerque 1961). For each ecoregion and year (1998–2010) we used official Forest Service data to determine: (i) wildfire incidence as the percentage area of forest and shrubland burned; (ii) cumulative wildfire incidence in the preceding two to eight years; and (iii) the 50th, 90th and 95th percentiles of the Canadian Fire Weather Index (FWI) (Van Wagner 1987), used in Portugal for fire danger rating.

The variables within groups (ii) and (iii) were assessed for their ability to explain variation in fire incidence. The selected variables and ecoregion were used as independent

variables to model wildfire incidence; we used linear mixed modelling (with year as the random variable) to account for the lack of independence between cumulative fire incidences within each ecoregion. Burn leverage should vary with fire incidence. To identify extremes in burn leverage that could be used in emissions scenarios, we distinguished between ecoregions displaying low (mean annual burned area <2%) and high (mean annual burned area ≥5%) incidence of fire, and fitted separate models to the respective sub-sets of data. Burn leverage was interpreted as the slope of the equation relating wildfire incidence and past fire incidence, multiplied by the time period (Boer and others 2009; Price and Bradstock 2011). The burn leverage estimates were compared with those calculated from the output of the BehavePlus fire modelling system (Andrews and others 2008).

Estimation of the prescribed burning effect considered two levels in treatment effort, respectively 2 and 20% of the mean annual area burned by wildfire, and reflecting the current degree of prescribed fire development in Portugal (http://www.afn.min-agricultura.pt) and in France (Lázaro 2010). While the treatment effort in Spain is comparable to Portugal, prescribed fire programs are absent from Greece and Italy. The two levels in treatment effort were combined with the two burn leverage extremes, hence resulting in four emission scenarios for prescribed burning.

Combustion factors for prescribed burning were assumed to be 0.5 for litter and 0.2 for deadwood. Although prescribed burning should not damage overstory trees, a combustion factor of 0.05 was used for foliage biomass to avoid overestimating the mitigation effect of prescribed burning. These combustion factors were based on an extensive database of experimental fires (Fernandes and others 2009). The mitigation effect of each scenario was then calculated by comparing emissions with and without prescribed burning.

Kyoto Protocol

To evaluate the effectiveness of prescribed burning in the Kyoto Protocol context, we compared the emissions mitigation with the year 2007 carbon stock losses of the LU-LUCF sector, as reported in the 2009 National Inventory submissions for UNFCCC (2009). There the gains and losses of living biomass and net carbon stock change of dead organic matter are reported. Under Article 3.4 of the Kyoto Protocol, Parties may elect additional human-induced activities related to LULUCF specifically, forest management, cropland management, grazing land management and revegetation, to be included in their accounting of anthropogenic GHG emissions and removals for the first commitment period. Upon election, this decision by a Party is fixed for the first commitment period.

When LULUCF activities under Article 3.4 result in a net removal of GHGs, an Annex I Party can issue removal units (RMUs) on the basis of these activities as part of meeting its commitments. Thus we considered the mitigation effect also in regards to the Article 3.4 of the Kyoto Protocol, comparing the mitigated wildfire emissions with the Article 3.4 maximum eligible sink in the countries studied.

Uncertainty Analysis

To get an estimate of the overall uncertainty in wildfire emission estimates, we combined the uncertainty of different factors using the error propagation equation (IPCC 2006)

$$U_{\text{total}} = \sqrt{U_1^2 + U_2^2 + \cdots + U_n^2}$$

where U_{total} is the percentage uncertainty in the product of the quantities and U_i are the percentage uncertainties associated with each quantity.

In error propagation, we used uncertainty estimates from Andreae and Merlet (2001): 50% uncertainty for burned biomass, mainly attributable to the biomass estimate in the burned area and the biomass consumption by fire, and 30% uncertainty for the emission factor.

Results

Wildfire Emissions

Estimated annual average fire emissions in the Mediterranean countries ranged from 5816 Gg CO_2 in Italy to 359 Gg CO_2 in Greece (Table 2). Litter produced most of the emissions, around 49%, and deadwood and aboveground biomass represented around 36 and 15% of emissions in all countries, respectively. Lack of data precluded consideration of the emissions coming from soil. Average fire emissions were largest in Italy (Table 2) although Spain registers the highest average burned area (Table 1), because the mean aboveground biomass stock (average of forest and other wooded land) in Italy is 94.3 t/ha whereas in Spain it is 18.5 t/ha only, based on FRA 2005 data (FAO 2005). High fuel loads in France also lead to quite high emissions although the annually burned area is the lowest of the studied countries.

Prescribed Burning Leverage

Mean annual wildfire incidence over the 13-year period varied from 0.66 to 6.81% across the Portuguese ecoregions, with an overall mean of 3.62% and means of 0.94

Table 2 Annual average burned biomass, carbon stock losses and CO_2 emissions in wildfires

Country	Burned biomass (Mg)					C stock losses (Mg C)	CO_2 emissions (Mg CO_2)
	Foliage	Branches	Deadwood	Litter	Total		
France	112,588	29,878	311,466	438,207	892,140	389,103	1,340,682
Greece	16,328	12,133	93,576	115,717	237,754	103,834	358,509
Italy	147,720	199,714	1,459,460	2,061,238	3,868,13	1,666,105	5,816,367
Portugal	368,163	134,152	930,810	1,499,848	2,932,974	1,271,507	4,408,808
Spain	174,859	57,972	412,515	492,126	1,137,472	504,759	1,719,108

Table 3 Fire incidence models: significance (P-values) of the independent variables effects and regression coefficients (±std. error) for past fire incidence

Fire incidence models	Variable		
	Ecoregion	FWI 95th perc.	6-year wildfire incidence
Low ($n = 39$, $R^2 = 0.37$)	0.004	0.004	0.048
			−0.167 ± 0.078
High ($n = 52$, $R^2 = 0.74$)	0.001	<0.001	<0.001
			−0.306 ± 0.077

and 5.96% for the ecoregions with low and high fire incidence. The variables selected for inclusion in the fire incidence model were the FWI 95th percentile and the % area burned in the past 6 years. Both variables, as well as ecoregion, were statistically significant at the $P < 0.05$ level (Table 3).

The regression coefficients for 6-year fire incidence imply burn leverages of 1.0 and 1.8, respectively when wildfire incidence is low and high. The extent and spatial organization of fuel treatments affect how landscape fire spread is disturbed. If the treatment effect persists for 6 years and an annual treatment rate of 5% is assumed, then fire spread will be disrupted or delayed over 30% of the landscape at any given time. The corresponding BehavePlus simulation indicates burn leverages of 1.5 and 2.9, respectively when prescribed burning placement is random or strategic. Based on these results, emissions are calculated for two extremes in prescribed burning leverage: a 1 ha decrease in the area burned by wildfire for each treated ha, where low wildfire incidence determines that the chance of a wildfire encountering a previously burned area is low; and a 3-ha wildfire area decrease per ha treated, where wildfire incidence is high and the spatial pattern of prescribed burning is optimized.

Mitigation of Emissions by Prescribed Burning

The effect of prescribed burning is based on four scenarios for treatment effort and impact on wildfire area:

(I)   2% of the annually burned area treated by prescribed fire, assuming 1 ha decrease in the area burned by wildfire for each treated ha

(II) 2% of the annually burned area treated by prescribed fire, assuming 3 ha decrease in the area burned by wildfire for each treated ha

(III) 20% of the annually burned area treated by prescribed fire, assuming 1 ha decrease in the area burned by wildfire for each treated ha

(IV) 20% of the annually burned area treated by prescribed fire, assuming 3 ha decrease in the area burned by wildfire for each treated ha.

Figure 1 compares CO_2 emissions for the four prescribed burning scenarios and the situation without prescribed burning (baseline). Figure 1 shows that a small treated area corresponds to minor decreases in emissions, even for the highest prescribed burning leverage. Prescribed burning over an area equal to 2% of the average annually burned area would lead to a reduction in emissions of only 1–5%, depending on the assumed leverage of the treatment (Scenarios I and II). Conversely, the mitigation effect of the other two prescribed burning scenarios both resulted in a substantial decrease in emissions; fire emissions are around 13% lower with Scenario III and around 52% lower with Scenario IV.

In the Kyoto Protocol, emissions from forest fires are part of the LULUCF sector balance and are calculated as losses from forest carbon stocks. Therefore we compared our results with the LULUCF data from the UNFCCC National Inventory Submissions 2009 to assess the magnitude of the mitigation effect accomplished by prescribed burning. In addition, we compared the emissions reduction with the Article 3.4 largest eligible sink (Table 4). Here we present the results as carbon, because sinks and losses as well as Article 3.4 largest eligible sinks are presented as carbon (Mt C) in the Kyoto Protocol.

Table 4 shows that the decrease in emissions resulting from prescribed burning scenario IV is also substantial in the context of the Kyoto Protocol. Compared to the LULUCF sector reported losses in 2009, the decrease in carbon stock losses were 1–11%, depending on the country

Fig. 1 CO_2 emissions (Gg CO_2) in the five investigated countries under different scenario assumptions. Baseline refers to the situation without prescribed burning and Scenario I–IV to the prescribed burning scenarios. *Error bars* represent the standard error ($\pm 58\%$) of the wildfire emission estimates
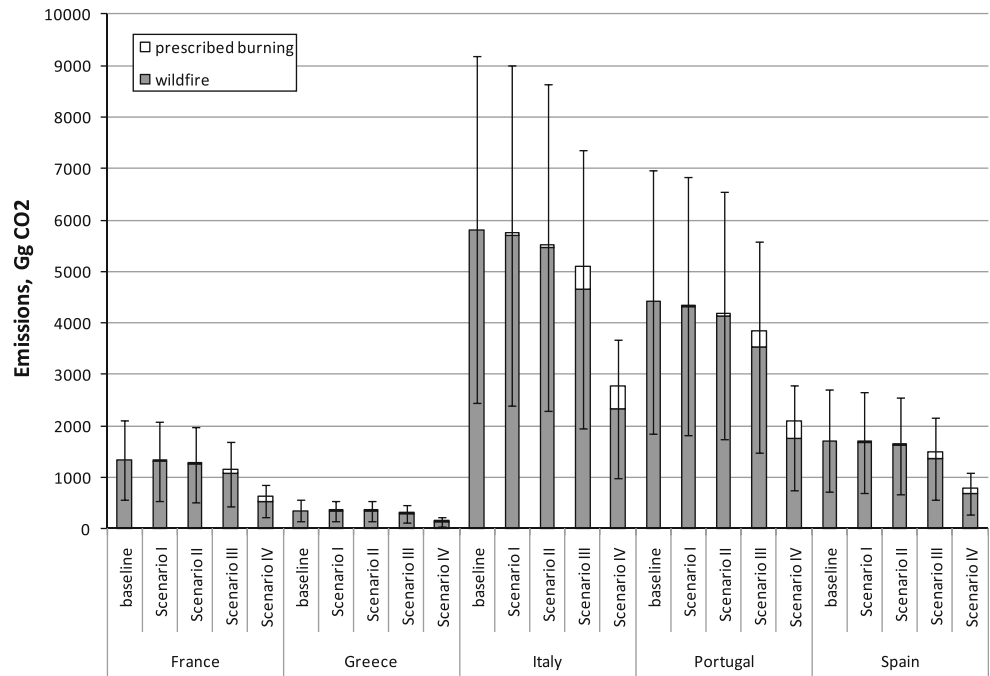

Table 4 Comparison of the effectiveness of prescribed burning in the context of the Kyoto Protocol

Country	2007 LULUCF sector losses (Mt C)	Emission reduction through prescribed burning (Mt C)				Emission reduction/ reported LULUCF C losses (%)				A 3.4 Largest eligible sink (Mt C)	Emission reduction from Article 3.4 largest sink (%)			
		I	II	III	IV	I	II	III	IV		I	II	III	IV
France	20.49	0.0052	0.0208	0.0521	0.2078	0.03	0.10	0.24	1.01	0.88	0.59	2.36	5.92	23.61
Greece	1.31	0.0014	0.0055	0.0138	0.0554	0.11	0.42	1.06	4.24	0.09	1.54	6.15	15.36	61.51
Italy	20.91	0.0215	0.0882	0.2151	0.8815	0.10	0.42	1.03	4.22	0.18	11.95	48.97	119.48	489.73
Portugal	6.12	0.0170	0.0678	0.1695	0.6781	0.28	1.11	2.77	11.09	0.22	7.70	30.82	77.05	308.23
Spain	n.a.	0.0070	0.0272	0.0704	0.2723	n.a.	n.a.	n.a.	n.a.	0.67	1.05	4.06	10.51	40.64

Reported 2007 LULUCF sector carbon losses (Mt C), estimated emission reduction through prescribed burning, emission reduction compared with LULUCF sector losses (%), Article 3.4 largest eligible C sink (Mt C) and emission reduction compared with Article 3.4 largest eligible sink (%). n.a. = Spain has reported only net change, not losses separately (UNFCCC National Inventory Submissions 2009). Numbers I–IV refer to the prescribed burning scenarios

(Table 4). If prescribed burning would be accounted for as an Article 3.4 forest management activity, even Scenarios I and II would lead to a 0.6–31% reduction in emissions of the Article 3.4 largest eligible sink, depending on country. For Scenarios III and IV, the largest eligible sink would be achieved in Italy and Portugal. Thus, prescribed burning could have a considerable effect on the carbon balance of the LULUCF sector.

Discussion

Uncertainties

The annually burned area used in the calculations was the annual average for the period 1980–2008 based on official

statistics (European Commission 2009) including both forests and other wooded lands. To estimate the biomass in the burned area, we calculated the average biomass of the forest and other wooded land based on the FAO Forest Resource Assessment data (FAO 2005). Because data for all fuel compartments was not available for all of the studied countries, we had to estimate the missing values based on existing data. Furthermore, we excluded understorey vegetation from the calculations due to lack of data. Understorey vegetation can be an important fuel compartment, especially in open Mediterranean forests, and its exclusion underestimates CO_2 emissions. However, because understorey vegetation is burned in both wildfires and prescribed fires, its absence from the calculations has only a minor effect on the results when comparing wildfire and prescribed burning emissions.

The combustion factor used in the calculations has a large impact on the results. Since only a fraction of the aboveground biomass is consumed by fire, usually the foliage and the finer branches, we used biomass allocation shares (Vilén and others 2005) to estimate the aboveground biomass fractions of foliage and branches. Then separate combustion factors were used for foliage and branches instead of applying a single combustion factor to the whole aboveground biomass. Emission factors used in this study were suited for Mediterranean ecosystems (Carvalho and others 2007).

The results reliability is thus affected by multiple factors. To get a rough estimate of the overall level of uncertainty in our results, we estimated total uncertainty by using published estimates of uncertainty for the burned biomass and emission factor. The results indicate that the degree of uncertainty in our fire emission estimates is very high, the error propagation calculation resulting in a total uncertainty of ±58%.

Wildfire Emissions

Wildfire emissions in the Mediterranean countries have been previously studied. Narayan and others (2007) estimated emissions in 33 European countries when investigating the potential for CO_2 emissions mitigation through prescribed burning. Miranda and others (2005) used models NFDRS and EMISPREAD to estimate the emissions for the 2001 Southern European forest fires. A comparison of the results (Table 5) shows that our study yields the highest country level estimates for all countries but Greece. Different reference periods explain part of the differences; our results are based on the long-term average burned area, while the others are either for a single year (Miranda and others 2005) or a shorter time period average (Narayan and others 2007). Individual years can deviate substantially from the long-term average. Miranda and others (2005) studied the year 2001, when the burned area was quite low compared to the long-term average, e.g. in Spain 93,297 ha burned compared to a long-term average of 179,043 ha

Table 5 Comparison of wildfire emission (Gg CO_2) results of different studies

Country	This study	NFDRS	EMISPREAD	Narayan and others
France	1,341	415	211	995
Greece	359	466	230	319
Italy	5,816	1,236	951	2,009
Portugal	4,409	2,712	2,596	2,025
Spain	1,719	1,555	1,225	1,006

NFDRS and EMISPREAD refers to the results of the two fire emission models used by Miranda and others (2005)

(European Commission 2009). Furthermore, the use of country level average biomass in the calculations presumably lead to an overestimation of emissions, at least in Italy, where the highest incidence of fire (in the South) is not coincident with the highest biomass stocks (in the North).

The differences between this study results and those of Narayan and others (2007) are explainable by differences in methodology. Narayan and others (2007) converted the combusted biomass into carbon before multiplying the values by the emission factor. However, since the emission factor is the amount of a compound released per amount of dry fuel consumed (Andreae and Merlet 2001), multiplying the consumed dry mass by the carbon content leads to incorrect results. Furthermore, we took into account the combustion of deadwood and litter instead of just estimating the emissions from aboveground tree biomass.

Effectiveness of Prescribed Burning

Prescribed burning creates fuel-modified areas where the intensity of subsequent wildfires is decreased, increasing the likelihood of fire suppression and leading to a decrease in the number and size of large wildfires. Although many study cases are available on the effects of prescribed burning on wildfire intensity and severity (e.g., Fernandes and Botelho 2003; Finney and others 2005) it is difficult to assess the overall effect of prescribed burning on wildfire incidence at the country level. Prescribed burning effectiveness is not easy to estimate since it varies between ecosystems and is affected by the overall fire management process (Fernandes and Botelho 2003). The highest return for effort of prescribed burning is expected in litter-dominated systems (e.g., Collins and others 2009) as opposed to shrub-dominated systems (e.g., Keeley 2002). Pinol and others (2005, 2007) used a simple simulation model to investigate whether large wildfires in the Mediterranean region are a result of extreme weather conditions or the cumulative effect of a policy of fire suppression over time. Their results suggest that the total area burned is much the same regardless of fire suppression and prescribed burning efforts; however, prescribed burning reduced fire intensity over the landscape. Boer and others (2009) studied a 52-year fire history from a eucalypt forest region in southwestern Australia to quantify the impact of prescribed burning on the occurrence, extent and size distribution of wildfires. Their results indicate that prescribed burning has significantly reduced the incidence and extent of unplanned large fires, hence providing strong empirical evidence for its effectiveness in the mitigation of wildfire hazard. However, because of differences in the fire environment, ignition density and fire suppression, their results cannot be extrapolated to forests elsewhere.

Narayan and others (2007) based their assumptions about prescribed burning effectiveness on landscape fire spread modelling (Finney 2001, 2003), where a prescribed burning effort around 10% of the annual wildfire area would decrease wildfire incidence by 50%. Defossé and others (2011) studied the prescribed burning effect in Patagonia and followed the assumptions adopted by Narayan and others (2007). Finney and others (2007) worked with four case study areas in the western USA and found that strategically placing fuel treatments reduces modelled landscape fire growth rates under severe weather conditions more effectively than the random allocation of fuel treatments. In fact, random fuel treatments had to be implemented at about twice the treatment rate of optimally placed fuel treatments to achieve the same reduction in fire growth rates. Our adopted scenarios are consistent with these findings. It is reasonable to expect that strategically placed prescribed burning treatments will perform better than random treatments, namely in the heterogeneous and fragmented Mediterranean Basin landscapes (Fernandes and Botelho 2003).

There are also contradictory views about how reasonable it is to use prescribed burning as a tool to maximize forest carbon stocks. Mitchell and others (2009) found that fuel treatments can be effective in decreasing fire severity, but fuel removal almost always reduces C storage more than the additional C that a stand is able to store when made more resistant to wildfire. North and others (2009) studied the carbon released by different fuel treatments in the western United States and suggest modifying current treatments to focus on reducing surface fuels, actively thinning most small trees and removing only fire-sensitive species in the merchantable, intermediate size-class. That would result in the development of large, fire resistant trees and reduce emissions from potential future wildfire.

Climate change is expected to result in more extensive and severe wildfires throughout southern Europe (Carvalho and others 2010; Lindner and others 2010). Consequently there is a pressing need for landscape-level fuel treatments, including prescribed burning, which has been recognized by the IPCC (2007). The potential of prescribed burning to manage forests and wildlands in Europe remains largely unfulfilled. Future development of prescribed burning will require higher awareness of the role of fire on ecosystems, changes in fire management policies, and acceptance by stakeholders and the general public (Galiana and Lázaro 2010).

This study analysed the potential of prescribed burning to mitigate CO_2 emissions in the Mediterranean countries by taking into account its impact on the area burned by wildfire. Results indicate that an increase in the use of prescribed burning would limit wildfires more effectively than in other Mediterranean ecosystems (Boer and others 2009; Price and Bradstock 2011). However, our estimates

of prescribed burning leverage (the total area protected from wildfire per unit area treated) were based on wildfire data. Accurate estimation of the mitigation effect would need long-term data on prescribed burning leverage. In the absence of such data, research should strive to quantify to what extent vegetation and fuel accumulation and connectivity contribute to large fire spread in Europe.

Uncertainties related to fire emission estimates remain large and more data on fuel load and fuel consumption in different fuel layers are needed. So far, most of the studies have taken into account only the aboveground tree biomass although understorey vegetation, litter and soil remarkably contribute to emissions. Estimating the forest floor emissions is the most uncertain component when modelling carbon emissions from forest fires, since its consumption can range from near zero to 100% (de Groot and others 2007). This should be a minor source of uncertainty in the Mediterranean, where fire activity largely coincides with the summer drought period when the forest floor is totally available to burn (Camia and Amatulli 2009). Explicitly accounting for emissions from soil and understorey vegetation would improve our estimates of both wildfire emissions and the effect of prescribed burning. However, the current data and understanding already allows concluding that prescribed burning can have a considerable effect on the carbon balance of the LULUCF sector. More accurate assessments would require partitioning area burned by vegetation type and appraising fuel loading and consumption by vegetation type.

References

Ager AA, Vaillant NM, Finney MA (2010) A comparison of landscape fuel treatment strategies to mitigate wildland fire risk in the urban interface and preserve old forest structure. Forest Ecology and Management 259:1556–1570

Albuquerque JPM (1961) Divisão regional do Continente Português. Agricultura 9:1–11

Andreae MO, Merlet P (2001) Emission of trace gases and aerosols from biomass burning. Global Biogeochemical Cycles 15(4):955–966

Andrews PL, Bevins CD, Seli RC (2008) BehavePlus Fire Modeling System, version 4.0: user's guide. USDA Forest Service, Rocky Mountain Research Station, General Technical Report RMRS-GTR-106WWW Revised, Ogden

Arno SF, Brown JK (1989) Managing fire in our forests—time for a new initiative. Journal of Forestry 87(12):44–46

Boer MM, Sadler RJ, Wittkuhn RS, McCaw L, Grierson PF (2009) Long-term impacts of prescribed burning on regional extent and incidence of wildfires—evidence from 50 years of active fire

management in SW Australian forests. Forest Ecology and Management 259(1):132–142

Bradstock RA, Williams RJ (2009) Can Australian fire regimes be managed for carbon benefits? New Phytologist 183:931–934

Camia A, Amatulli G (2009) Weather factors and fire danger in the Mediterranean. In: Chuvieco E (ed) Earth observation of wildland fires in Mediterranean ecosystems. Springer, Berlin, pp 71–82

Carrión JS, Sánches-Gómez P, Mota JF, Yll J, Chaín C (2003) Holocene vegetation dynamics, fire and grazing in the Sierra de Gádor, Southern Spain. The Holocene 13(6):839–849

Carvalho A, Monteiro A, Flannigan M, Solman S, Miranda A, Borrego C (2007) Forest fire emissions under climate change: impact on air quality. In: Seventh symposium on fire and forest meteorology, Extended abstract. http://ams.confex.com/ams/7firenortheast/techprogram/paper_126854.htm

Carvalho A, Flannigan M, Logan K, Gowman L, Miranda A, Borrego C (2010) The impact of spatial resolution on area burned and fire occurrence projections in Portugal under climate change. Climatic Change 98:177–197

Collins BM, Miller JM, Thode AE, Kelly M, van Wagtendonk JW, Stephen SL (2009) Interactions among wildland fires in a long-established Sierra Nevada natural fire area. Ecosystems 12:114–128

De Groot WJ, Landry R, Kurz WA, Anderson KR, Englefield P, Frase RH, Hall RJ, Banfield E, Raymond DA, Decker V, Lynham TJ, Pritchard JM (2007) Estimating direct carbon emissions from Canadian wildland fires. International Journal of Wildland Fire 16:593–606

Defossé GE, Loguercio G, Oddi FJ, Molina, JC, Kraus PD (2011) Potential CO_2 emissions mitigation through forest prescribed burning: a case study in Patagonia, Argentina. Forest Ecology and Management. doi:10.1016/j.foreco.2010.11.021

European Commission (2009) Forest Fires in Europe 2008. JRC Scientific and Technical Reports No 9

FAO (2005) Global Forest Resources Assessment (FRA) 2005. http://www.fao.org/forestry/fra/fra2005/en/. Accessed 3 Jan 2011

FCCC (2006) Report of the individual review of the greenhouse gas inventory of Portugal submitted in 2005. FCCC/ARR/2005/PRT. http://unfccc.int/resource/docs/2006/arr/prt.pdf. Accessed 17 Feb 2010

Fernandes PM (2008) Forest fires in Galicia (Spain): the outcome of unbalanced fire management. Journal of Forest Economics 14:155–157

Fernandes PM (2009) Examining fuel treatment longevity through experimental and simulated surface fire behaviour: a maritime pine case study. Canadian Journal of Forest Research 39:2529–2535

Fernandes P, Botelho H (2003) A review of prescribed burning effectiveness in fire hazard reduction. International Journal of Wildland Fire 12:117–128

Fernandes P, Botelho H (2004) Analysis of prescribed burning practice in the pine forest of northwestern Portugal. Journal of Environmental Management 70:15–26

Fernandes P, Loureiro C, Botelho H (2004) Fire behavior and severity in a maritime pine stand under differing fuel conditions. Annals of Forest Science 61:537–544

Fernandes P, Botelho H, Rego F, Loureiro C (2009) Empirical modelling of surface fire behaviour in maritime pine stands. International Journal of Wildland Fire 18:698–710

Finney MA (2001) Design of regular landscape fuel treatment patterns for modifying fire growth and behavior. Forest Science 47(2):219–228

Finney MA (2003) Calculation of fire spread rates across random landscapes. International Journal of Wildland Fire 12:167–174

Finney MA, McHugh CW, Grenfell IC (2005) Stand- and landscape-level effects of prescribed burning on two Arizona wildfires. Canadian Journal of Forest Research 35:1714–1722

Finney MA, Seli RC, McHugh CW, Ager AA, Bahro B, Agee JK (2007) Simulation of long-term landscape-level fuel treatment effects on large wildfires. International Journal of Wildland Fires 16:712–727

Flannigan MD, Harrington JB (1988) A study of the relation of meteorological variables to monthly provincial area burned by wildfire in Canada 1953–80. Journal of Applied Meteorology 27:441–452

Galiana L, Lázaro A (2010) Potential barriers and factors for success. In: Montiel C, Kraus D (eds) Best practices of fire use—prescribed burning and suppression fire programmes in selected case-study regions in Europe. European Forest Institute Research Report 24, Joensuu, pp 155–162

IPCC (2006) In: Eggleston HS, Buendia L, Miwa K, Ngara T, Tanabe K (eds.) 2006 IPCC guidelines for national greenhouse gas inventories, prepared by the National Greenhouse Gas Inventories Programme. Volume 4. Agriculture, forestry and other land use. IGES, Japan

IPCC (2007) In: Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE (Eds) Contribution of Working group II to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge

Ito A, Penner JE (2004) Global estimates of biomass burning based on satellite imagery for the year. Journal of Geophysical Research 109:D14S05

Keeley JE (2002) Fire management of California shrubland landscapes. Environmental Management 29:395–408

Lázaro A (2010) Development of prescribed burning and suppression fire in Europe. In: Montiel C, Kraus D (eds) Best practices of fire use—prescribed burning and suppression fire programmes in selected case-study regions in Europe. European Forest Institute Research Report 24, Joensuu, pp 17–31

Lindner M, Maroschek M, Netherer S, Kremer A, Barbati A, Garcia-Gonzalo J, Seidl R, Delzon S, Corona P, Kolström M, Lexer MJ, Marchetti M (2010) Climate change impacts, adaptive capacity, and vulnerability of European forest ecosystems. Forest Ecology and Management 259:698–709

Loehle C (2004) Applying landscape principles to fire hazard reduction. Forest Ecology and Management 198:261–267

MCPFE (2007) State of Europe's forests 2007. The MCPFE report on sustainable forest management in Europe 2007

Miranda AI, Borrego C, Sousa M, Valente J, Barbosa P, Carvalho A (2005) Model of forest fire emissions to the atmosphere. Deliverable D252 of SPREAD Project (EVG1-CT-2001-00043). Department of Environment and Planning, University of Aveiro AMB-QA-07/2005, Aveiro

Miranda AI, Marchi E, Ferretti M, Millán MM (2009) Forest fires and air quality issues in Southern Europe. In: Bytnerowicz A, Arbaugh M, Riebau A, Andersen C (eds) Wildland fires and air pollution, developments in environmental science, vol 8. Elsevier, Amsterdam, pp 209–232

Mitchell SR, Harmon ME, O'Connell KEB (2009) Forest fuel reduction alters fire severity and long-term carbon storage in three Pacific Northwest ecosystems. Ecological Applications 19(3):643–655

Narayan C, Fernandes P, van Brusselen J, Schuck A (2007) Potential for CO_2 emissions mitigation in Europe through prescribed burning in the context of the Kyoto Protocol. Forest Ecology and Management 251:164–173

North M, Hurteau M, Innes J (2009) Fire suppression and fuels treatment effects on mixed-conifer carbon stocks and emissions. Ecological Applications 19(6):1385–1396

Nunes MCS, Vasconcelos MJ, Pereira JMC, Dasgupta N, Alldredge RJ, Rego FC (2005) Land cover type and fire in Portugal: do fires burn land cover selectively? Landscape Ecology 20:661–673

Pausas J (2004) Changes in fire and climate in the Eastern Iberian Peninsula (Mediterranean Basin). Climatic Change 63:337–350

Pausas J, Llovet J, Rodrigo A, Vallejo R (2008) Are wildfires a disaster in the Mediterranean basin? A review. International Journal of Wildland Fire 17:713–723

Pinol J, Terradas J, LLoret F (1998) Climate warming, wildfire hazard, and wildfire occurrence in coastal Eastern Spain. Climatic Change 38:345–357

Pinol J, Beven K, Viegas DX (2005) Modelling the effect of fire-exclusion and prescribed fire on wildfire size in Mediterranean ecosystems. Ecological Modelling 183:397–409

Pinol J, Castellnou M, Beven KJ (2007) Conditioning uncertainty in ecological models: assessing the impact of fire management strategies. Ecological Modelling 207:34–44

Price O, Bradstock R (2011) Quantifying the influence of fuel-age and weather on the annual extent of unplanned fires in the Sydney region of Australia. International Journal of Wildland Fire 20:142–151

Reinhard ED, Keane RE, Brown JK (1997) First order fire effects model: FOFEM 4.0 user's guide. USDA Forest Service General Technical Report INT-GTR-344

Seiler W, Crutzen PJ (1980) Estimates of gross and net fluxes of carbon between the biosphere and the atmosphere from biomass burning. Climatic Change 2:207–247

Smith JE, Heath LS (2002) A model of forest floor carbon mass for United States forest types. USDA Forest Service Research Paper NE-722

Sorensen CD, Finkral AJ, Kolb TE, Huang CH (2011) Short- and long-term effects of thinning and prescribed fire on carbon stocks in ponderosa pine stands in northern Arizona. Forest Ecology and Management 261:460–472

Stephens SL, Moghaddas JJ (2005) Experimental fuel treatment impacts on forest structure, potential fire behavior, and predicted tree mortality in a California mixed conifer forest. Forest Ecology and Management 215:21–36

Stephens SL, Moghaddas JJ, Hartsough BR, Moghaddas E, Clinton NE (2009) Fuel treatment effects on stand-level carbon pools, treatment-related emissions, and fire risk in a Sierra Nevada mixed-conifer forest. Canadian Journal of Forest Research 39:1538–1547

UNFCCC National Inventory Submissions (2009) http://unfccc.int/national_reports/annex_i_ghg_inventories/national_inventories_submissions/items/4771.php. Accessed 21 Sep 2009

Van Wagner C (1987) Development and structure of the Canadian Forest Fire Weather Index System. Canadian Forestry Service, Forestry Technical Report 35, Ottawa

Vilén T, Meyer J, Thürig E, Lindner M, Green T (2005) Improved regional and national level estimates of the carbon stock and stock change of tree biomass for six European countries (Deliverable 6.1 of the CarboInvent Project). CarboInvent Deliverable 6.2, European Forest Institute, Joensuu

Wiedinmyer C, Hurteau MD (2010) Prescribed fire as a means of reducing forest carbon emissions in the Western United States. Environmental Science and Technology 44:1926–1932