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Potential for CO_2 emissions mitigation in Europe through prescribed burning in the context of the Kyoto Protocol

Caroline Narayan [a,*], Paulo M. Fernandes [b], Jo van Brusselen [a], Andreas Schuck [a]

[a] *European Forest Institute, Torikatu 34, FIN-80100 Joensuu, Finland*
[b] *Departamento Florestal & Centro de Estudos em Gestão de Ecossistemas (CEGE), Universidade de Trás-os-Montes e Alto Douro (UTAD), Vila Real, Portugal*

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Abstract

The current paper analyses the potential for prescribed burning techniques for mitigating carbon dioxide (CO_2) emissions from forest fires and attempts to show quantitatively that it can be a means of achieving a net reduction of carbon emissions in the context of the Kyoto Protocol. The limited number of available studies suggests that significant reductions in CO_2 emissions can be obtained and that prescribed burning can be a viable option for mitigating emissions in fire-prone countries. The present analysis shows that the potential reduction attained by prescribed burning as a percentage of the reduction in emissions required by the Kyoto Protocol varies from country to country. Out of the 33 European countries investigated, only in one the requirements of the Kyoto Protocol could potentially be achieved by applying prescribed burning, while three other nations showed a potential net CO_2 emissions reduction of about 4–8% of the Kyoto requirements and the majority showed a reduction of less than 2%. This implies that prescribed burning can only make a significant contribution in those countries with high wildland fire occurrence. Over a 5-year period the emissions from wildfires in the European region were estimated to be approximately 11 million tonnes of CO_2 per year, while with prescribed burning application this was estimated to be 6 million tonnes, a potential reduction of almost 50%. This means that for countries in the Mediterranean region it may be worthwhile to account for the reduction in emissions obtained when such techniques are applied.

Keywords: CO_2 emissions; Emissions mitigation; Prescribed burning; Wildland fires; Fire management; Kyoto Protocol

1. Introduction

Wildland fires are increasingly becoming a major problem for many European countries, affecting ecosystems and societies and potentially inducing global atmospheric problems, including climate change. Emissions from such disturbances directly affect global or regional carbon cycle by increasing the atmospheric carbon dioxide (CO_2), and in a less indirect fashion, by altering carbon sequestration by terrestrial ecosystems.

In the Mediterranean countries forest fires are more common than in other regions in Europe, affecting between 300,000 and 500,000 ha of forests and other wooded land each year. During the summer of 2003 forest fires were particularly virulent, as the forests were exposed to very hot and dry climatic conditions, causing destruction of about 400,000 ha of forests in Portugal and leaving even well-equipped regions like South-Eastern France in extraordinarily difficult situations despite the available fire suppression resources (Fire Paradox, 2006). According to an analysis of the 1975–2000 statistics, the Mediterranean contributes some 94% of the total burned area in Europe (Xanthopoulos et al., 2006). The reduction of wildfire hazard and the sustainable development of natural and managed ecosystems in Europe require new practices in wildfire management. Integrated wildland fire management solutions should consider not only the traditional approaches focused on the reduction of number of ignitions and suppression of wildfires but also the deliberate and planned use of fire in management (prescribed fire) and in fire fighting (suppression fire). Prescribed and suppression fires can help set the limits for wildfires by controlling their spatial extent, severity and impacts. As a consequence prescribed burning techniques may

* Corresponding author. Tel.: +358 10 7734342; fax: +358 10 7734377.
E-mail address: caroline.narayan@efi.int (C. Narayan).

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also result in a reduction of greenhouse gas (GHG) emissions from biomass burning. In this study we aim to quantify the emissions from wildfires and prescribed burning in Europe and hence to estimate the potential of the prescribed burning techniques to mitigate CO_2 emissions in the context of the Kyoto Protocol.

The current study was undertaken within the framework of the European Commission funded Sixth Framework Project ‘‘Fire Paradox’’, an on-going integrated project aiming to create scientific and technological bases for new practices and policies for integrated wildland fire management in Europe, thus allowing the development of strategies for their implementation at the European level. The project focuses on fire paradoxes, from its negative impacts to its positive effects, from wildland fires to managed fires (prescribed and suppression fires).

This paper is organised into six sections as follows: Section 2 provides an overview of prescribed burning application in Europe, its hazard reduction effects and its potential to reduce CO_2 emissions; Section 3 describes the methodology and data needs, together with the assumptions that were made in computing the emissions; Section 4 presents the analyses and results; Section 5 provides a discussion of the analyses and Section 6 presents the conclusions and an outlook for further studies.

2. Prescribed burning overview

Prescribed burning is the controlled application of fire to vegetation in either its natural or modified state, under specified environmental conditions. This allows the fire to be confined to a predetermined area and at the same time to produce the intensity of heat and rate of spread required to attain planned resource management objectives (IFFN, 2004a). Prescribed fire is a fuel management technique that temporarily reduces damage from wildfire by removing a portion of the accumulated dead and live fuels, hence facilitates fire suppression efforts by reducing the intensity, size and damage of wildfires (Fernandes and Botelho, 2003; Johnson and Miyanishi, 2001; Liu, 2004). In some parts of Europe, mainly in the Mediterranean countries, fuel management techniques have not only been implemented and used, but also the effects of such techniques on trees, forest floor, soil and breeding bird population have been investigated, though not on a very wide scale (e.g. Fernandes and Botelho, 2003; Moreira et al., 2003; Úbeda et al., 2005). Despite being an established practice, it is a technique that is banned in some European countries. The increasing number of wildland fires since the 1970s and the extension of the fire season and fire risk level in Europe in recent years have prompted intensified discussions on preventing or effectively managing destructive wildfires by effective fuel management. Total fire exclusion leads to counter effects in forest ecosystems, such as high fuel accumulation, leading to high intensity fires, and hence an increase in the area burnt, cost of suppressing such fires and their ecological severity. Effectively managing the accumulating dead and live fuels reduces damage from wildfires, as well as enhances the developing under-story of certain ecosystems when burning conditions are not severe (Agee and Skinner, 2005; Baeza et al., 2002; Grady and Hart, 2006; Liu, 2004; Myers, 2006; Perry, 1994; Piñol et al., 2005; Pollet and Omi, 2002; Stocks, 1991).

While extensive literature is available on specific studies regarding the effects of prescribed burning on the ecosystem and alternative fuel management options, such as thinning, mechanical treatment with or without physical removal of the residues, and chemical treatment (FAO, 2005a; Fernandes et al., 1999, 2004), data and information on GHG emissions from such fires is sparse. Previous reports and studies have not given much importance to emissions from fires although they have been acknowledged, among other more obvious and immediate consequences, such as fire management, effects of fires, damage assessment, risk analysis and suppression techniques. Emissions have been investigated in the context of atmospheric pollution or health hazard in some experimental cases, as well as by limited in situ measurements, but not in the context of mitigation of GHGs. Forest fire emissions have been estimated or measured under the broad category of ‘‘forest fires’’, as part of country-based forest inventory reporting. Therefore, data that are available, in most if not all cases include emissions from forest fires in general, without being classified as wildland, prescribed or suppressed fires. Suppression fires are closely related to wildfire burning. From the point of view of emissions a suppression fire is similar to a wildfire because both burn under the same moisture conditions. Some studies have also used a wildland fire emission model, such as the Global Wildland Fire Emission Model (GWEM), to estimate fire emissions on the global scale, using land cover maps, emission factors and satellite input data (Hoelzemann et al., 2004). However, such model-based studies do not distinguish between different types of fires, and in particular, do not include emissions from prescribed burning. This in part is due to lack of data, as well as the complexity of modelling.

Literature on the current state of prescribed burning application in Europe shows that there is hardly any information available for most of the European region, particularly in the Balkans, Eastern Europe and the Mediterranean (Narayan, 2007). This can be attributed to the fact that most countries in the Balkans and Eastern Europe are not highly prone to severe fires and that the fire fighting and suppression techniques, in their view, are sufficient to prevent wildland fires getting out of control. While Western Europe was found to have the highest amount of experimental or limited prescribed burning applications, data on emissions have not been recorded, as the experiments were carried out for investigating other influences or effects of prescribed burning other than measuring emitted gases (for example in previous projects like FIRE TORCH,[1] 1998–2000, FIRESTAR,[2] 2001–2003 and EUFIRELAB,[3] 2003–2006). Although more than 50% of the countries in the different European regions engage in using prescribed

[1] URL: http://www.cindy.ensmp.fr/europe/firetorch/.
[2] URL: http://eufirestar.org.
[3] URL: http://eufirelab.org.

fires, none have kept records of emissions from their experiments.

Recently, a useful study on emissions comparison from wildland fires and prescribed burning was conducted by Fernandes (2005) in maritime pine stands in Portugal. The results indicated that it was reasonable to assume that on the long-term prescribed burning emissions would be lower than the emissions from wildfires, if the wildfire return interval is roughly 40 years, i.e. the annual probability of fire is 0.025 or more. In this study, the relative emissions per unit area of maritime pine stands were estimated for six scenarios of wildfire and prescribed burning with the First Order Fire Effects Model (FOFEM) (Reinhardt, 2003). Typical fuel loading values used in the estimates were obtained from Fernandes and Botelho (2004). The fuel moisture content and the fuel quantity available for combustion distinguished each scenario, as these are the determinants of fuel consumption, and hence the emissions.

Table 1 gives a summary of the results of this study. The release of CO_2 and other compounds from prescribed burning application under normal moisture conditions was estimated to be 38.5% of (i.e. 62% lower than) the emissions from a more severe wildfire. These values correspond to a fraction of biomass burned that was calculated by FOFEM. ''Normal'' conditions here are defined as surface fuels having a moisture content of 20%, under which prescribed fires are usually carried out. Including the scenarios of 12 and 40% moisture content (representing extreme cases), the corresponding range of relative emissions as computed by FOFEM was 23–52% of the wildfire emissions. However, it should be noted that prescribed fire is generally not conducted at moisture conditions below 12% and above 40%. Meaningful comparisons between the scenarios are only possible in the context of a fire regime. The wildfire regime in many regions of Portugal currently approaches a 20-year cycle. Assuming a pine stand with three prescribed fires during its life time (respectively, at the ages of 15, 20 and 25 years), mean annual emissions over the 25-year period will amount to 58% of a wildfire. Only with a wildfire event every 43 years would the prescribed and wildfire emissions be equal.

As wildfires form a significant contribution to GHG emissions, the widespread application of prescribed burning techniques could potentially reduce such emissions. The limited available studies that have been discussed above suggest that reductions of 50% or more could be obtained. Unfortunately, there are not many similar studies that have been reported for Europe. This hinders sound quantitative comparison of the emissions, not only between wildland and prescribed fires but also between the different regions in Europe. In recent decades the number of wildfire occurrences in Europe has increased, leading to the destruction of livelihoods and habitats, as well as having an impact on global atmospheric problems, including climate change. As a consequence there has been an increased interest in fire management through prescribed burning—to frequently burn excess fuel in the form of litter to prevent fuel build-up that would lead to more devastating fires. Prescribed burning is used either locally or sporadically in Portugal and Spain, for example, but is not allowed in Greece and most of Italy, and in some Eastern European countries like Belarus, it is banned by law (Narayan, 2007). Although not widely practised, having a standard methodology for prescribed burning and for estimating the effects of GHG emissions at national levels could nevertheless be useful in case the technique is allowed, or becomes a common practice. Prescribed burning could therefore prove to be a viable management tool for mitigating CO_2 emissions from forest fires.

3. Methodology and data needs

To quantify emissions from vegetation fires four types of parameters are commonly used: the amount of fuel that is available for burning and the percentage of fuel that is actually burned over a specific time period (i.e. carbon density and fraction of carbon consumed), the area burned and emission factors. The amount of fuel and the fraction of the fuel that is burned in a given region depend on vegetation type and density or the biomass, fuel composition and moisture content, and meteorological parameters, such as wind speed, humidity and temperature (Schultz, 2002).

3.1. Modelling of fire emissions

Emissions from wildland fires have gained the attention of the atmospheric chemistry modelling community since the 1980s. One of the first attempts to quantify wildfire emissions was by Seiler and Crutzen (1980) followed by others, such as Cooke and Wilson (1996), Galanter et al. (2000), Hao et al.

Table 1
CO_2 emissions per unit area burned by crown fire for six fire scenarios in maritime pine stands as a percentage of the emissions caused by a severe wildfire

Scenario	% Of area burned by crown fire	% Fuel moisture content		% Of relative CO_2 emissions computed by FOFEM[a] as a function of fuel moisture content
		Surface fine dead fuel	Duff	
Wildfire	90	3	10	100
Wildfire	60	5	10	87.4
Wildfire	30	7	10	74.8
Prescribed fire (drier)	0	12	75	51.5
Prescribed fire (normal)	0	20	150	38.5
Prescribed fire (damper)	0	40	200	23.3

[a] First Order Fire Effects Model (Reinhardt, 2003).

(1990), Hao and Liu (1994), Lavoué et al. (2000) and Lobert et al. (1999). However, these estimates have been made on a global scale using global fire emissions models, such as GWEM that uses data on satellite-observed burnt area, model-derived available fuel load, emission factors, burning efficiency and land cover classification schemes as inputs, to compute emissions from wildland fires (Hoelzemann et al., 2004; Hoelzemann, 2006).

Recent modelling studies focussed on the establishment of links between prescribed burning conditions, fire behaviour and first-order fire effects (Fernandes et al., 2000a,b), and on simulating the behaviour of wildland fires (Morvan et al., 2001). The latter requires measurement of fire emissions but the experiments conducted were primarily designed to study the effect of chemical retardants on fire progression and fire emissions (Miranda et al., 2003).

3.2. Methodology

Fig. 1 summarises the steps required to evaluate emissions from a forest fire. The estimation of emissions from fires is usually based on the commonly used Seiler and Crutzen model (1980):

$$C = ABf_c\beta \quad (1)$$

where C is carbon emitted, A the total area burned (ha), B the biomass (tonne ha^{-1}), f_c the carbon fraction of the biomass and β is the fraction of biomass consumed during biomass burning.

The burning of forest floor fuels, such as litter, lichen and organic soils are not taken into account in Eq. (1). As a result the estimated carbon emissions from this equation are deemed lower than the actual values, as these fuels are believed to be different from those of the above-ground vegetation that contribute to the carbon emissions of forest fires (Lü et al., 2006). In their study Lü and colleagues modified Eq. (1) as follows:

$$C = A(C_a\beta_a + C_g\beta_g) \quad (2)$$

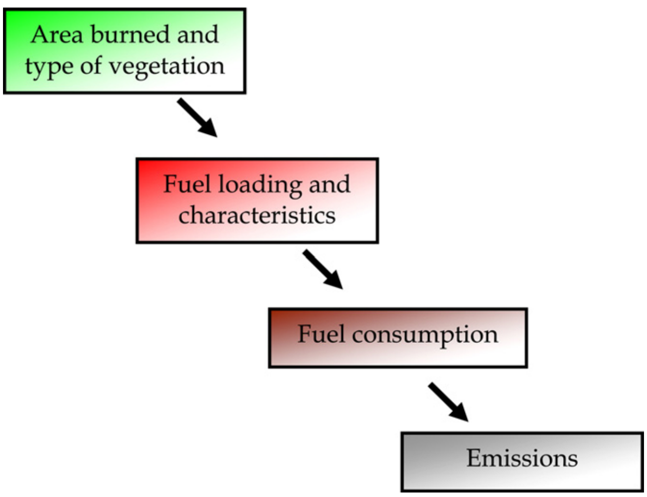

Fig. 1. Steps required for evaluating fire emissions (source: Battye and Byatte, 2002).

where C_a is the average carbon of above-ground vegetation (tonne ha^{-1}), β_a the fraction of above-ground biomass consumed by fire, C_g the average carbon of forest floor fuel (tonne ha^{-1}) and β_g is the fraction of the forest floor fuels consumed by fire.

Thus, the amount of specific trace gas emissions (in this case, carbon emission, E_c) caused by fire was calculated using:

$$E_c = C \times E_{fc} \quad (3)$$

where E_{fc} is the emission factor, in weight of gas released per weight of carbon burned for the gas type.

Lü et al. (2006) in their study assumed that parameters β_a, β_g and E_{fc} are closely related to the forest types. For reasonable quantitative analysis of CO_2 emissions from the different types of forest fires (here, wildfires and prescribed burning), it is important not only to compute but also to compare the emissions resulting from these fires. However, due to lack of sufficient information and available data on prescribed burning, the current study presents estimates of forest fire emissions based on existing databases and published (and to some extent) unpublished literature to illustrate the potential of prescribed burning in mitigating fire emissions in the European region. Eq. (1) was thus modified as follows for the computation of emissions from prescribed burning:

$$C = ABf_c\beta \times 0.38 \quad (4)$$

In Eq. (4) the value 0.38 is based on the study by Fernandes (2005) that was discussed in Section 2, with the estimated reduction in emissions of 62% under prescribed fire application under normal fuel moisture conditions.

However, this reduction factor corresponds to a single fire event only, while over a longer period the reduction in emissions that can be obtained depends on the fire regime and is likely to be lower. In order to compute the long-term reduction in emissions, an estimate has to be made of the frequency at which prescribed burning is applied, as well as of its effects on the reduction of the area burned by wildfires. Based on Finney (2001, 2003), it can be assumed that a typical prescribed fire regime applied annually on strategic locations to 5% of the total forest and shrubland area, or alternatively, to an area amounting to 5–10% of the area annually burned by wildfires leads to a landscape where 20% of it, at any given moment, is adequately fuel managed. This will correspond to a rough decrease in area burned by wildfires of 50%. Note that this estimated reduction in wildfire area is quite conservative and can be viewed as the minimum value possible because it results solely from the passive effect of fuel-reduced areas on fire growth and does not consider the positive effect on fire fighting. The total emissions under a prescribed burning regime are then the sum of the emissions from prescribed fires and the emissions from the remaining wildfires.

3.3. Assumptions

In the current paper Seiler and Crutzen's model (1980) and information from Table 1 was used to estimate emissions from prescribed burning, with the following assumptions:

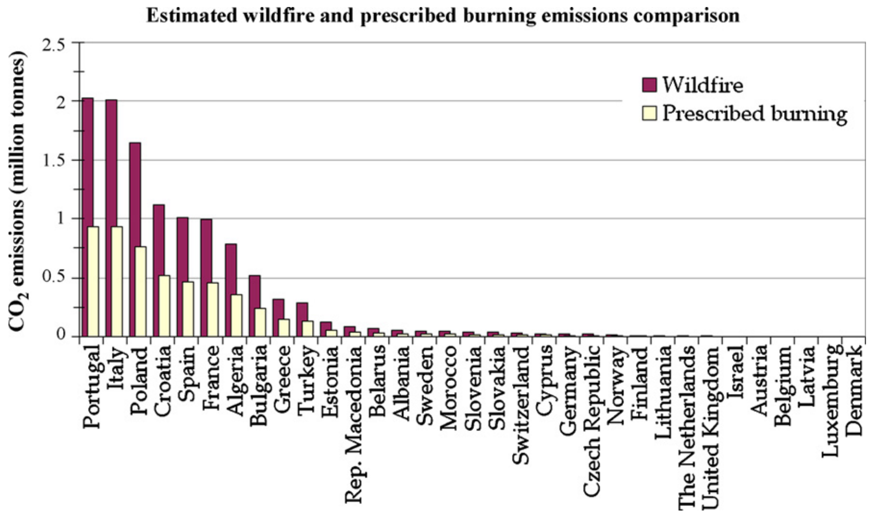

Fig. 2. Estimated wildfire emissions as compared with estimated emissions from prescribed burning assumed under normal conditions of 20% fuel moisture content.

- The carbon fraction is taken as 45% of the biomass, following Seiler and Crutzen (1980).
- An emission factor of 1569 g CO_2/kg dry matter is used, from Andreae and Merlet (2001). The factor was converted to tonnes of CO_2 per tonne of dry matter.
- Biomass in the current estimates implies the biomass of burned area.
- Burning efficiency is taken as 50% of the aboveground biomass (taken from FRA2000 (FAO, 2000)), after Seiler and Crutzen (1980).
- As many vegetation types may in fact not represent a wildfire problem, it is assumed that prescribed burning is applied annually to an area equal to 10% of the area currently burned by wildfires.
- Under normal moisture conditions of fuels, the emissions per unit area from a prescribed fire are 62% lower than wildfire emissions. Thus, the amount of emissions produced by the prescribed burning activity estimated above (by FOFEM) is computed using Eq. (4).
- Based on Finney (2001, 2003), such prescribed fire regime is assumed to lead to a decrease in area burned by wildfires of 50%.

The current estimates are therefore based on the amount and the moisture content of the fuel, as well as area burned under a typical prescribed fire regime. Note that the results that are obtained in this way constitute a rough estimate, based on a single case study in Portugal with conditions that may not apply to other fuel types in Europe. But in the absence of any relevant information this could give at least some indication of the order of magnitude that could potentially be reached by applying prescribed burning as a mitigation measure.

3.4. Data needs

The data used in the present study were in part obtained from the national forest inventories or derived from reports and published and unpublished literature. The main sources are published data in the International Forest Fire News (IFFN, 2001, 2002a,b, 2003a,b, 2004a,b,c), European Forest Fire Information System (EFFIS, 2005) and Terrestrial Ecosystem Monitoring (TEM) database[4] and published Food and Agriculture Organisation (FAO) reports (FAO, 2000, 2001, 2005a,b, 2006a,b,c,d).

4. Results

Using Eqs. (1), (3) and (4) and the outlined assumptions, forest fire emissions were computed on a country-basis where sufficient relevant data were available. The estimates are based on 5-year averages of fire occurrences. In most cases the averages were taken over 1999–2003. Where data were not available from a common period, they were taken over 1997–2001.

Table 2 presents the resulting wildland fire emissions as compared with the emissions from prescribed burning applied under normal moisture conditions of the surface dead fuel (20%) and duff (150%). As discussed above, Table 2 gives an indication of the magnitude of the minimum reduction in emissions resulting from the use of prescribed burning. Overall, roughly 5 million tonnes of emissions could potentially be reduced. This is a very crude estimate for the entire European region, which in reality has very different local environmental conditions and fuel characteristics. Additionally, the table shows that in Western Europe and a few Eastern European nations, where fire is hardly a problem, emissions are comparatively low, both for wildfires, as well as for prescribed burning. A summary of the trend is shown in Fig. 2, whereby the Mediterranean countries dominate the release of emissions, with Poland being the only exception. The results also suggest that while prescribed burning application leads to a reduction in CO_2 emissions, it may not be worthwhile to implement it as a mitigation technique for every European nation. Rather, it would be more practical for those nations where fire occurrences are high and are problematic in terms of damage

[4] URL: http://www.fao.org/gtos/tems/.

Table 2
Wildland fire CO_2 emissions estimates in comparison with emissions from prescribed burning[a]

Region	Country	5-Year period considered	Total number of fires over 5 years	Average area burned over 5-year period (ha)	Forest biomass (tonne ha^{-1})	Biomass consumed by fire[b] (tonne)	Current wildland fire CO_2 emissions (million tonnes CO_2)	Wildland fire CO_2 emissions under a prescribed fire scenario (million tonnes CO_2)			Emissions reduction under the prescribed fire scenario (million tonnes CO_2)
								Prescribed fire	Wildfire	Total wildfire emissions[c]	
Balkans	Albania	1999–2003	2,781	2569.4	58	74,513	0.053	0.002	0.026	0.028	0.025
	Bulgaria	1999–2003	3,709	19486.8	76	740,498	0.523	0.019	0.261	0.280	0.243
	Croatia	1997–2001	2,132	29696.6	107	1,588,768	1.122	0.043	0.561	0.604	0.518
	Greece	1999–2003	9,195	36214.6	25	452,683	0.319	0.012	0.159	0.171	0.148
	Republic of Macedonia	1999–2003	1,959	10236.4	24	122,837	0.087	0.003	0.043	0.046	0.041
	Slovenia	1999–2003	107	659.6	178	58,704	0.041	0.002	0.021	0.023	0.018
	Turkey	1999–2003	10,707	10921.4	74	404,092	0.285	0.011	0.143	0.154	0.131
Western Europe	Austria	1997–2001	294	34.2	250	4,275	0.003	0.000	0.002	0.002	0.001
	Belgium	1997–2001	72	61.4	101	3,101	0.002	0.000	0.001	0.001	0.001
	Denmark	1997–2001	15	2.2	58	64	0.000	0.000	0.000	0.000	0.000
	Germany	1999–2003	6,012	511.0	134	34,237	0.024	0.001	0.012	0.013	0.011
	Luxemburg	1997–2001	13	1.8	101	91	0.000	0.000	0.000	0.000	0.000
	Switzerland	1997–2001	320	476.2	165	39,287	0.023	0.001	0.014	0.015	0.008
	The Netherlands	1997–2001	364	208.8	107	11,171	0.008	0.000	0.004	0.004	0.004
	The UK	1997–2001	1,024	217.8	76	8,276	0.006	0.000	0.003	0.003	0.003
Eastern Europe	Belarus	1997–2001	11,329	2523.4	80	100,936	0.071	0.003	0.036	0.039	0.032
	Czech Republic	1999–2003	5,735	442.4	125	27,650	0.019	0.001	0.009	0.010	0.009
	Estonia	1997–2001	846	4137.0	85	1,75,823	0.124	0.005	0.062	0.067	0.057
	Latvia	1997–2001	5,170	5.8	93	270	0.000	0.000	0.000	0.000	0.000
	Lithuania	1997–2001	2,759	238.0	99	11,781	0.008	0.000	0.004	0.004	0.004
	Poland	1999–2003	178,000	49534.4	94	2,328,305	1.644	0.062	0.822	0.884	0.760
	Slovakia	1999–2003	3,003	785.4	142	5,578	0.039	0.002	0.019	0.021	0.018
Scandinavia	Finland	1999–2003	9,590	615.0	50	15,375	0.011	0.000	0.005	0.005	0.005
	Norway	1997–2001	453	940.4	49	23,040	0.016	0.001	0.008	0.009	0.008
	Sweden	2000–2004	28,803	2263.4	63	71,297	0.050	0.002	0.025	0.027	0.023
Mediterranean	Algeria	1996–2000	8,300	29496.8	75	1,106,130	0.781	0.029	0.390	0.419	0.361
	Cyprus	1999–2003	1,274	3482.6	21	36,567	0.026	0.001	0.013	0.014	0.012
	France	1999–2003	19,873	30631.0	92	1,409,026	0.995	0.038	0.497	0.535	0.460
	Israel	1999–2003	4,591	3469.6	3	5,204	0.004	0.000	0.002	0.002	0.002
	Italy	1999–2003	39,289	76891.0	74	2,844,967	2.009	0.076	1.004	1.080	0.929
	Morocco	1995–1999	1,940	3118.2	41	63,923	0.045	0.002	0.023	0.025	0.021
	Portugal	1999–2003	140,242	173802.0	33	2,867,733	2.025	0.077	1.012	1.089	0.936
	Spain	1999–2003	100,737	118714.8	24	1,424,578	1.006	0.038	0.503	0.541	0.465
Total for all countries							11.369	0.431	5.684	6.115	5.254

[a] Data presented in this table are derived from the following publications: Andreae and Merlet (2001), Fernandes and Botelho (2004), Seiler and Crutzen (1980), Ward and Hardy (1991), FAO (2006b,c,d), FAO (2000).
[b] Fifty percent of total biomass of the burned area. 50% is assumed to be the biomass burning efficiency (from Seiler and Crutzen, 1980). Total biomass is the product of area burned and biomass.
[c] Sum of prescribe fire and wildfire with prescribed burning.

Table 3
Potential CO_2 emissions reduction obtained by applying prescribed burning

Region	Country	Kyoto targets for European countries (% above or below 1990 levels)	Reported 1990 CO_2 levels of the emissions from LULUCF (million tonnes CO_2)	Amount of emissions reduction required by Kyoto (million tonnes CO_2)	Estimated wildfire emissions of the total reported LULUCF emissions (%)	Reduction in emissions achieved with prescribed burning application (%)
Balkan	Albania	–	–	–	–	–
	Bulgaria	8	72.99	5.84	1.69	4.14
	Croatia	5	8.59	0.43	18.01	120.55
	Greece	25	81.07	20.27	0.31	0.73
	Republic of Macedonia	–	–	–	–	–
	Slovenia	8	–	–	0.38	–
	Turkey	8	–	–	–	–
Western Europe	Austria	13	49.95	6.49	0.01	0.02
	Belgium	7.5	117.65	8.82	0.00	0.01
	Denmark	21	54.59	11.46	0.00	0.00
	Germany	21	1001.62	210.34	0.00	0.01
	Luxemburg	28	–	–	–	–
	Switzerland	8	42.73	3.42		0.38
	The Netherlands	6	161.78	9.71	0.00	0.04
	United Kingdom	12.5	593.24	74.15	0.00	0.00
Eastern Europe	Belarus	8	90.63	7.25	0.17	0.45
	Czech Republic	8	163.28	13.06	0.02	0.07
	Estonia	8	–	–	1.11	–
	Latvia	8	2.09	0.17	0.00	0.05
	Lithuania	8	–	–	0.05	–
	Poland	6	–	–	0.57	–
	Slovakia	8	58.13	4.65	0.10	0.39
Scandinavia	Finland	1990 level	35.31	2.82	0.02	0.18
	Norway	8	20.16	1.61	0.09	0.47
	Sweden	4	34.31	1.37	0.13	1.69
Mediterranean	Algeria	8	–	–	–	–
	Cyprus	8	–	–	–	–
	France	1990 level	367.98	29.44	0.27	1.56
	Israel	–	–	–	–	–
	Italy	6.5	354.58	23.05	0.52	4.03
	Morocco	8	–	–	–	–
	Portugal	27	46.73	12.62	3.22	7.42
	Spain	15	205.54	30.83	0.31	1.51
Total for all countries				477.80		

to livelihoods, environment and the economy. In these countries, not only devastating fires can be prevented but also mitigation of CO_2 emissions under the Kyoto Protocol can be achieved.

Table 3 presents for every country the percentage of the reduction in emissions required under the Kyoto Protocol that can potentially be achieved by applying prescribed burning, while Fig. 3 visualises the information in Table 3. It should be noted that the high potential reduction for Croatia (121%, which can be attributed to the low Kyoto requirement of 5% or 0.429 million tonnes, and the low 1990 emissions level of 8.598 million tonnes of CO_2, in combination with a high fire incidence) is not shown completely in order to be able to compare the reductions for other countries.

It is important to keep in mind when interpreting Fig. 3 that the reductions in emissions shown here present only a rough and conservative estimate, assuming that a typical prescribed burning regime would be able to protect half of the area burned by wildland fire. The actual reductions that can be obtained over a longer period should be higher because here we have neither considered the effect of fire fighting on wildfire size nor the effect of fuel-reduced areas on the effectiveness of fire suppression. Nevertheless, it is estimated that for a country like Portugal about 7.5% of the emission reductions required by the Kyoto could be obtained with prescribed burning. A potential of about 4% may be achieved by two other nations, while for the majority the potential reduction is below 2% of the Kyoto requirements. This implies that in most of the European countries the potential for prescribed burning as a mitigation technique is low. However, in countries with a high fire incidence, i.e. in the Mediterranean region, prescribed burning could be a viable way of mitigating CO_2 emissions under the Kyoto Treaty.

5. Summary and discussions

The present study attempted to quantify and compare CO_2 emissions from wildland fires and prescribed burning in Europe

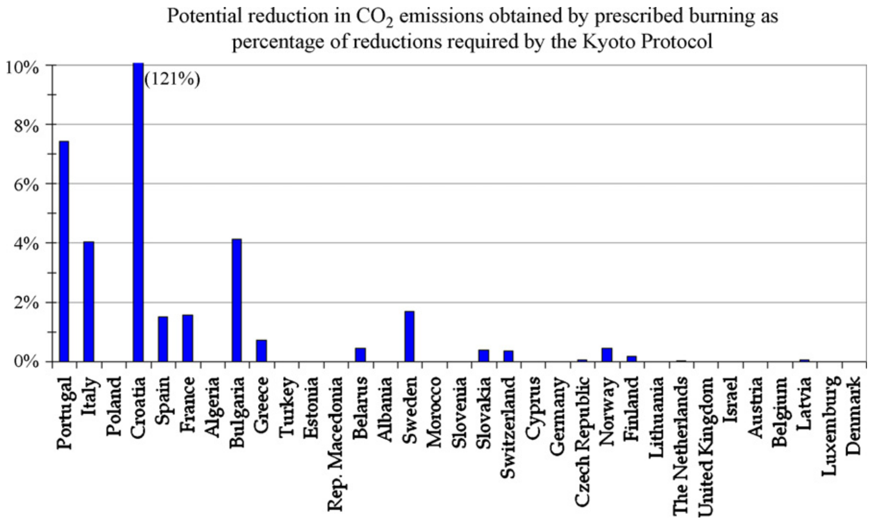

Fig. 3. Potential CO_2 emissions reduction that could be achieved by prescribed burning, shown here as a percentage of reductions required by the Kyoto agreement. The high potential reduction for Croatia is not shown completely but is labelled next to the bar.

contributing to the overall emissions. From the limited data that was available, it was estimated that over a 5-year period approximately 11 million tonnes of CO_2 were released annually from wildfires in Europe. Based on the outlined assumptions and the single case study of Portugal where wildfire emissions were compared with the emissions from prescribed burning (Fernandes, 2005), these emissions could potentially be reduced by almost 50% if prescribed burning would be widely used as a mitigation technique. In the current study, it was estimated that with a widespread application of prescribed burning under normal fuel moisture conditions, a reduction in emissions of up to 5 million tonnes could potentially be achieved. However, studies have shown that both the nature and the amount of emissions from forest fires are directly related to the intensity and the direction of the fire, and indirectly related to the rate of spread of the fire, which is affected mainly by the weather (wind velocity, ambient temperature and relative humidity), fuels (fuel types, fuel bed array, moisture content and fuel size), and topography (slope and profile). These conditions are highly variable, both in space and time, which brings about considerable uncertainty in the results that we have found.

The estimations in the current study clearly show a lack of appropriate data for the different countries. Prescribed burning, for most of Europe, apart from the Mediterranean region, is not a regular practice and therefore records of emissions from these fires were so far not deemed important, or were assumed to be negligible. The current study could therefore only make a very rough estimate of the emissions from wildland fires and from prescribed burning. Nevertheless, with the limited available data and some key assumptions where appropriate, the study has shown that there are countries in certain European regions where wildland fires are common, and where prescribed burning would be useful not only for reducing damages and risks, but also for mitigating CO_2 emissions.

The potential reductions in emissions that were estimated in the present study are marred by assumptions and severe lack of data. At this stage it can only be hypothesised that countries with devastating wildfires could mitigate CO_2 emissions by adopting prescribed burning on a meaningful spatial scale. However, for most European countries it seems that the emissions reductions that could potentially be obtained with prescribed burning are insignificant compared to the requirements of the Kyoto Protocol.

While good support systems, such as fire science and fire models, fire danger rating systems and modern fire suppression systems (IFFN/GFMC, 2006) for prescribed burning have emerged in the recent past, its full realisation has yet to come. Prescribed burning application may prove to be a viable forest management technique to achieve a net reduction in GHG emissions, which, if a country chooses to, could be reported as a reduction in the emissions of national GHGs in their reporting for the Kyoto Protocol. Additionally, the development of a good prescribed fire framework involving both prescribed fire projects, as well as stakeholders, will support not only a more targeted use of fire in the management of land in fire vulnerable regions of Europe, but also help inform policy makers about the factors that influence fire behaviour and consequent fire effects, hopefully leading to the creation of a more sustainable policy framework for prescribed fires in high fire risk regions of Europe. Even if mitigating CO_2 emissions may not be a convincing argument for applying prescribed burning, it can still be regarded as having an added value in its entirety.

6. Conclusions and outlook

6.1. Conclusions

The current paper analysed the potential for prescribed burning technique for mitigating CO_2 emissions from forest fires. The stance of prescribed burning as mitigation for CO_2 emissions can be seen as a valid measure. In a previous study it was found that for pine stands in Portugal the emissions from prescribed burning application under normal fuel moisture conditions can be 62% lower than for a more severe wildland fire (Fernandes, 2005). Current analyses have shown that the potential reduction attained by prescribed burning techniques as a percentage of the reduction in emissions required by the Kyoto Protocol varies from country to country, implying that prescribed burning can only make a significant contribution where fire occurrence is high. In most countries the reduction in emissions that can be obtained with prescribed burning application is therefore not significant compared to the requirements of the Kyoto Protocol, with the exception of some countries in the Mediterranean region. Over a 5-year period the emissions from wildfires in the European region were estimated to be approximately 11 million tonnes of CO_2 per year, while with prescribed burning application this was estimated to be 6 million tonnes per year, a potential reduction of almost 50%. However, the emissions that were calculated in the present study should be regarded only as a very rough estimate. The actual reductions that can be obtained will likely be higher.

Although the current study estimated the potential of prescribed burning technique for CO_2 emissions mitigation to be rather low for most countries, there may be more reasons for its application, such as to prevent wildfires and the related losses of biodiversity and of economic value, and for some regions in Europe, most notably in the South, it may prove to be a viable means to start accounting for the reduction in emissions that may be obtained at the same time.

6.2. Outlook

More research is needed specifically on GHG emissions quantification from prescribed burning in order to establish, not only for specific areas but on a national scale or Europe-wide, and over a longer period of time, to what extent net CO_2 emissions from prescribed burning are lower when compared to the baseline.

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