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RESEARCH PAPER

Prescribed burning as a cost-effective way to address climate change and forest management in Mediterranean countries

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Abstract

• ***Key message*** **As climate change and forest management become the focus of various development agendas and the price of carbon rises in the market, the need for improving carbon sequestration and avoiding wildfires emissions increases. Prescribed burning interventions might play an important role in this context, as in some situations, it has been suggested that it can reduce overall fire emissions. In this study, the potential economic benefits associated with the practice are analyzed for five Mediterranean countries. Despite the uncertainty in the estimates, the results suggest that under some circumstances these interventions can be cost-effective from a carbon management perspective.**

• ***Context*** Wildland fires are becoming a major concern for many European countries and are expected to become more prevalent due to climate change, affecting societies, ecosystems, and various ecosystem services provided by forests that are not valued by traditional markets, such as carbon sequestration.

• ***Aims*** The objective of this study is to evaluate the possibility of using carbon taxation to fund fire management measures in Mediterranean countries.

• ***Methods*** The analysis is done by converting prescribed burning savings in carbon emissions into their economic value. This is performed for France, Greece, Italy, Spain, and Portugal, which is studied in more detail, since the country has a National Prescribed Burning Program (NPBP) and a specific tax on carbon in place.

• ***Results*** The results indicate that most countries could potentially have benefits in the order of millions of euros from employing prescribed burning measures. In Portugal, NPBP has the potential to be a relevant policy instrument to reduce wildfire emissions, as well as economically since the carbon emissions savings can outweigh the prescribed burning costs in some circumstances. Also, the revenue from the country's Addition Tax on Carbon Emissions would be able to accommodate the foreseen prescribed burning costs.

• ***Conclusion*** There are still many uncertainties regarding the benefits of prescribed burning in terms of overall emission reductions, and more studies should be conducted on this topic. However, as the price of carbon rises in the markets and climate change becomes a more pressing concern, even small emissions reductions might be economically interesting. The analysis framework used in this study has the potential to be useful for other countries, especially in Mediterranean-type ecosystems.

Keywords Forest management · Carbon sequestration · Prescribed burning · Emissions · Ecosystem services

1 Introduction

Wildfires are an increasing concern worldwide, especially over the last decades (Moritz et al. 2014; Jolly et al. 2015) and are expected to become more frequent in the future given climate change (Vilén and Fernandes 2011; Duane et al. 2019). These changing fire regimes are causing substantial environmental, social, and economic impacts due to the destruction of infrastructure, degradation of ecosystem services, loss of life, and smoke-related health effects

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(Bowman et al. 2011). Considering the magnitude of these impacts, forest and fire must be effectively managed (Jolly et al. 2015). This is particularly important in the Mediterranean region, in which fire is not only a natural component of the environment but also perhaps one of the most relevant evolutionary forces (Castri and Mooney 1973).

Wildfires affect carbon cycles by increasing the concentration of carbon dioxide (CO_2) in the atmosphere and reducing the sequestration by terrestrial ecosystems (Narayan et al. 2007; Guo et al. 2019). Forestry is considered an effective way to mitigate climate change, as it decreases greenhouse gas emissions and improves their absorption, behaving as a carbon sink, storing carbon-containing chemicals for unspecified periods (Liu and Wu 2017), be it in the forest biomass or the soil, both in the organic and inorganic forms (Lal 2005).

Climate change adaptation is a form of disaster risk reduction, and measures to address it should be supported by other sustainable development policies (Kelman 2017). In this sense, the European Commission acknowledges that the biodiversity crisis and the climate crisis are directly connected. Climate change accelerates the destruction of the natural world through more extreme climatic events, such as wildfires, while the loss and unsustainable use of nature are drivers of climate change (European Commission 2020). Under these harsher climate conditions, it is likely that current fire suppression will not be able to control all wildfires and its capability to do so in the future might be compromised (Duane et al. 2019).

Wildland fires affect ecosystems and societies, and in Mediterranean countries, they are more common than in other regions in Europe (Narayan et al. 2007). In this sense, there is the need to shift the fire management paradigm towards the development of adaptive strategies focusing on the reduction of negative fire impacts rather than focusing on the total removal of this disturbance from the system (Duane et al. 2019). In fact, Fernandes (2015) states that while the persistent nature and ecological role of fire prevents its eradication, fire management activities try to regulate the fire regime to minimize its potential negative impacts and optimize its benefits for both ecosystems and the population. In addition, there is a tendency for governments to allocate most of the fire management investment to the suppression of unwanted fires, which can paradoxically exacerbate the problem, as fuels accumulate to levels that prevent effective fire-fighting operations regardless of the resources available (Collins et al. 2013). Managing vegetation fuels is the sole option available to fire managers to modify fire behavior characteristics, simply because the other influences (weather and topography) are beyond human control.

One of the most economic and effective ways to manage fuels is through prescribed burning (Fernandes 2015). In southern Europe, prescribed burning is used to reduce wildfire risk and to manage habitats for grazing and wildlife, but it is still underused in contrast with other regions of the world (Fernandes et al. 2013). In Australia, for example, prescribed burning is widely employed, including by the indigenous peoples, and it is now applied strategically to reduce wildfires emissions (Edwards et al. 2021; Sangha et al. 2021).

The technique, besides reducing the risk of destructive wildfires, also 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 (Defossé et al. 2011). Besides the potential for emission reductions, prescribed burning benefits also include improved wildlife habitat, enhanced biodiversity, reduced threat of destructive wildfire, and enhanced ecosystem resilience. However, prescribed fire can also come with costs, such as reduced air quality and impacts to fire-sensitive species (Hunter and Robles 2020).

Portugal is considered a relevant case study for forest-management interventions (Oliveira et al. 2017), as it is highly representative of the Mediterranean region. In alignment with the European guidelines, Portugal has developed policies to tackle climate change, wildfires, and biodiversity recovery in the past decades. In terms of emissions, Law N. 82-D/2014 changed environmental fiscal norms and created the Addition Tax on Carbon Emissions applied over specific energy sources. The income from this taxation is directed to the Portuguese Environmental Fund, which was designed to sponsor sustainable development actions in the country. As for wildfires, Resolution of the Council of Ministers (RCM) N. 59/2017 instated the National Prescribed Burning Program, intending to reduce fire events' extensions. This policy seeks to avoid losses in terms of biodiversity, real-estate, and possibly lives, but it can potentially reduce overall fire emissions in some Mediterranean countries, like Portugal, as studies have suggested (Narayan et al. 2007; Vilén and Fernandes 2011).

One way to materialize actions to reduce CO_2 emissions by forests is to appropriately reward them through economic incentives (Cairns and Lasserre 2004). By instating incentives for carbon sequestration, for example, a more robust economic rationale can be made for expanding forest restoration (Wu et al. 2011), and in this sense, policy-makers are pushed to modify forest policies to include both climate change mitigation and adaptation (Hoberg et al. 2016). In this regard, carbon taxation has been suggested as a means to fund forest conservation measures around the world (Barbier et al. 2020).

Forest carbon policies can be integrated into an emissions trading scheme (Lintunen et al. 2016), and new governance arrangements have been developed to jointly address climate change and forest policies, both from the optics of adaptation and mitigation (Doelle et al. 2012). More recently, literature

emerged in the support of using taxes on fossil fuels to fund the restoration of ecosystems aiming to curb climate change (Barbier et al. 2020).

In this context, the objective of this study is to evaluate the possibility of using carbon taxation to fund fire management measures, by comparing the carbon emissions savings from avoided fires and the income of the carbon taxation with the costs of prescribed burning. This analysis is performed in two parts. First, to estimate the monetary benefits of prescribed burning in Mediterranean countries, the prescribed burning scenarios proposed in the work of Vilén and Fernandes (2011) are used along with the average auction price in the European Union Emissions Trading System (EU ETS) in 2020. Next, Portugal is further investigated by using the scenarios proposed by Vilén and Fernandes (2011), along with the Addition Tax on Carbon Emissions between 2016 and 2021, and contrasting the emissions monetary savings with the costs of prescribed burning estimated in RCM N. 59/2017. As Portugal is considered to be highly representative of the Mediterranean region for forest-management interventions (Oliveira et al. 2017), this part of the analysis can be a useful approach for other countries in the region, and even in other Mediterranean-climate regions of the world.

2 Methods

2.1 Approach

The approach illustrated in Fig. 1 was used to estimate the economic benefits of employing prescribed burning measures in Mediterranean countries, and in Portugal with more detail.

This study is divided into two parts. In the first one, the auction price of the EU ETS carbon market and the benefits of prescribed burning in terms of emissions reductions were used to estimate the economic benefits of adopting such preventive fire practices. In the second, Portugal is further studied, since the country already has carbon and prescribed burning policies in place, and is considered a relevant case study in the western world for forest-management-related issues (Oliveira et al. 2017). This part of the study aims to illustrate the synergies between these pieces of legislation and how other Mediterranean countries might benefit from adopting such a joint policy approach. The following sections show the data sources used and calculations performed in this study. For simplicity, considering that the forest fire gases emitted will not be assessed individually, the carbon dioxide equivalents emissions analyzed in this study will be referred to collectively as CO_2 emissions.

2.2 Carbon value

For the first part of the analysis, regarding Mediterranean countries, data from the European Carbon Market was used. For the second part, regarding Portugal, the Addition Tax on Carbon Emissions values were used. This is described in more detail in the following subsections.

2.2.1 Mediterranean countries

To estimate the monetary benefits of avoiding CO_2 emissions through prescribed burning measures, the average auction

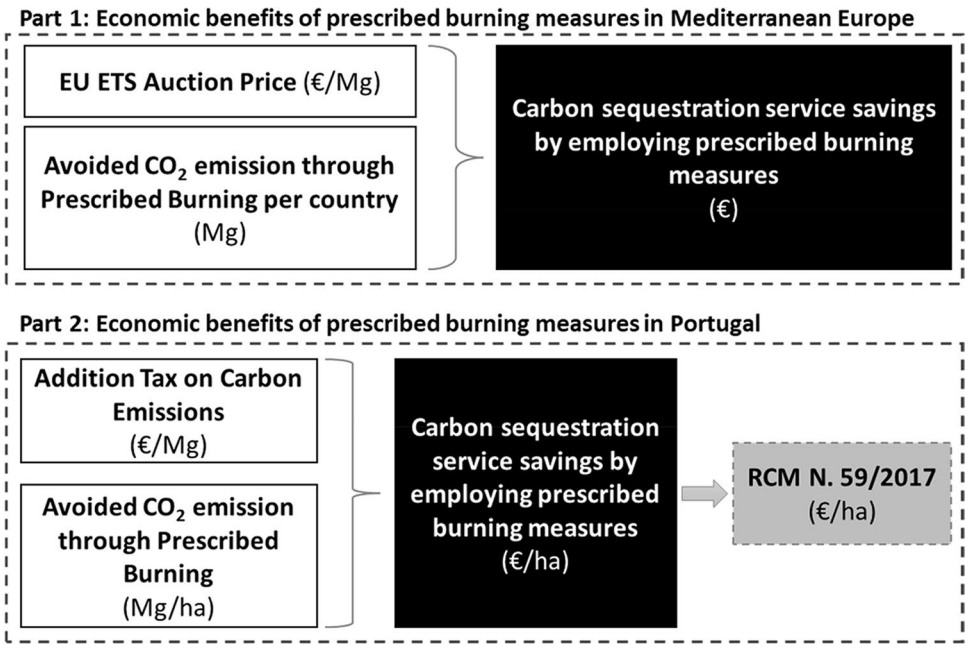

Fig. 1 Analysis framework employed. The white boxes represent data input, the black boxes the results of the calculations, and the grey box the legislation used to compare and discuss the results

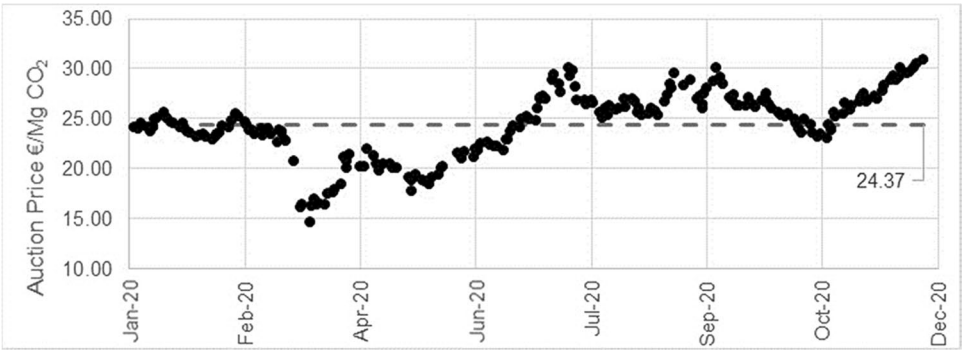

Fig. 2 Variation of the auction price in the EU ETS throughout the year 2020. The dashed grey line shows the mean auction price value for 2020. Data source: EEX (2021)

price in the EU ETS in 2020 was used as the reference. Fig. 2 shows the variation of the auction value throughout 2020.

Carbon markets are a popular instrument to mitigate CO_2 emissions and are considered a cost-effective alternative. However, their constitution is a learning-by-doing process and needs regular regulatory updates to deliver optimal effects, which has been occurring since 2005 in the EU ETS (Fan et al. 2017). Following the Paris Climate Conference (COP21), the prices of carbon permits have been rising and reached all-time highs after EU leaders reached a deal on more ambitious emissions cuts for this decade (Chestney 2020). As is illustrated in Fig. 2, the auction prices in 2020 varied between 14.60 €/Mg CO_2 and 30.92 €/Mg CO_2. The mean value of 24.37 €/Mg CO_2 is used in the following calculations.

2.2.2 Portugal

To calculate the monetary benefits of employing prescribed burning measures in Portuguese forests, the Addition Tax on Carbon Emissions was used as a reference. Table 1 shows the values this tax has had since 2016, the year it started, until 2021.

Law N. 82-D/2014 instates that the value of the Addition Tax for each year (n) is calculated in the previous year (n-1) as the arithmetic mean of the price resulting from auctions of greenhouse gas emission allowances, carried out within the framework of the European Union Emissions Trading System, between July 1 of year n-2 and June 30 of year n-1. This tax is applied over petroleum and specific energy sources, and the revenue collected is directed to the Portuguese Environmental Fund. As seen in the overall increasing trend in the auction prices in the year 2020, the Addition Tax values have also been increasing through the years.

2.3 Prescribed burning savings

The data on the emissions reductions expected by adopting prescribed burning measures is from the study by Vilén and Fernandes (2011). The authors employed published data to quantify the average annual wildfire CO_2 emissions in France, Greece, Italy, Portugal, and Spain, according to the Intergovernmental Panel on Climate Change (IPCC) guidelines. Previous studies had suggested that these countries were among the ones that could benefit the most from applying prescribed burning measures (Narayan et al. 2007). Table 2 shows the total wildfire emissions estimates for each country.

They then modeled the effect that prescribed burning interventions would have on the final emissions for four scenarios of treatment effectiveness based on data from Portugal. To create these scenarios, the authors employed empirical data and simulation to identify the extreme burn

Table 1 Evolution of the addition tax on carbon emissions

Year	Addition Tax on Carbon Emissions (€/Mg of CO_2)	Reference
2016	6.67	Ordinance N. 420-B/2015
2017	6.85	Ordinance N. 10/2017
2018	6.85	Ordinance N. 384/2017
2019	12.74	Ordinance N. 6-A/2019
2020	23.619	Ordinance N. 22/2020
2021	23.921	Ordinance N. 277/2020

Table 2 Annual average fire emissions estimate for each country. Adapted from Vilén and Fernandes (2011)

Country	Annual average fire emissions (Mg CO_2)
France	1,340,682
Greece	358,509
Italy	5,816,367
Portugal	4,408,808
Spain	1,719,108
Total	13,643,474

leverages. The burn leverage effect of prescribed burning (or its return for effort) quantifies how much unplanned burned area is reduced per unit treated area, i.e., the unit reduction in fire area produced by one unit of prescribed fire. Leverage is expected to increase with fire incidence (Fernandes 2015).

Vilén and Fernandes (2011) distinguished the burn leverage by ecoregions displaying low (mean annual burned area < 2%) and high (mean annual burned area > 5%) incidence of fire. Wherever wildfire incidence was low, a 1 ha decrease in the area burned by wildfire for each treated ha was assumed, meaning that the odds of a wildfire coming across a previously burned land is low. Wherever wildfire incidence is high, a 3-ha wildfire area decrease per ha treated was assumed, since the spatial pattern of prescribed burning is optimized.

This information was then associated with the effects of two levels of prescribed burning treatment efforts, respectively 2 and 20% of the mean annual area burned by wildfire. This reflects the present degree of prescribed fire development in Portugal and in France, respectively. Table 3 describes the four scenarios and results in terms of emission reduction obtained in their work.

Their results suggested that prescribed burning could have a significant effect on decreasing wildfire emissions in all countries. Still, the authors acknowledge that the uncertainty in emission estimates is considerable, and more precise input data for the models, such as deadwood and litter, is necessary.

2.3.1 Uncertainties

The main uncertainties that affect the results derive from the base study of Vilén and Fernandes (2011). The authors assess the uncertainty in wildfire emissions according to IPCC guidelines (IPCC 2006) and estimate it to be in the order of ± 58%. According to the authors, this uncertainty is derived from the lack of data for all fuel compartments and corresponding combustion factors. This uncertainty is explicitly included in all calculations and discussed along with the results.

2.3.2 Monetary savings in the Mediterranean countries

To estimate the monetary savings of each scenario for every country, the percentage reduction expected was multiplied by the annual average emission (see Table 4 in the Results section), and this value was then multiplied by the mean auction price of the EU ETS for 2020. The following calculation (Equation 1) is performed for every scenario and every country:

$$Savings(\in) = Emission\ savings\left(MgCO_2\right) \times Mean\ 2020\ auction\ price\left(\frac{\in}{MgCO_2}\right) \quad (1)$$

The results of these calculations are shown in Table 5.

2.3.3 Monetary savings in Portugal

For Portugal, to allow a better comparison with RCM N. 59/2017 (National Prescribed Burning Program), the annual average CO_2 emissions in wildfires (4,408,808 Mg) was multiplied by the emission reduction factors (Table 3) and divided by 2% (scenarios I and II) and 20% (scenarios III and IV) of the average burnt area (109,327 ha) of the years studied (1980–2008) by Vilén and Fernandes (2011). To translate these emission cuts to the monetary savings they embody, the emission savings in every scenario are multiplied by the Addition Tax value for every year, following Equation 2:

$$Savings\left(\frac{\in}{\text{treatedha}}\right) = Emission\ savings\left(\frac{MgCO_2}{treatedha}\right) \times Addition\ tax\ value\left(\frac{\in}{MgCO_2}\right) \quad (2)$$

These results are presented in Table 6.

Table 3 Scenarios' description and calculated overall emission reductions for all simulated countries. Adapted from Vilén and Fernandes (2011)

Scenarios	Calculated overall emission reductions
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	1%
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	5%
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	13%
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	52%

3 Results

As mentioned previously, the results are divided into two parts. First, the results for the Mediterranean countries are presented, followed by Portugal. The same structure is used in the Discussion section.

3.1 Prescribed burning monetary savings in the Mediterranean countries

Table 4 shows the total emission reductions expected by employing prescribed burning measures in each of the studied Mediterranean countries, according to the simulated scenarios.

In the most favorable reduction scenario, the total mass of CO_2 that could be saved by employing prescribed burning measures in these five Mediterranean countries is expected to be in the order of 7 billion Mg. To put it into perspective, that is close to 70% of car emissions in Portugal in 2018 (NIR 2020). Besides the environmental benefits in reducing emissions, this reduction also has economic advantages. The monetary equivalents of these emissions savings are shown in Table 5.

The results indicate that all countries studied potentially benefit from adopting prescribed burning practices. Greece is expected to economically benefit the least, as little as 87 thousand euros in the least favorable scenario, possibly as low as 36 thousand euros, considering the uncertainty in the emission estimates. Italy, in contrast, is the country that is expected to benefit the most by employing prescribed burning measures, being able to save annually more than 73 million euros in emissions. Considering the uncertainty in the results, this value could be as high as 115 million euros. Portugal comes in second place, with savings expected to be somewhere between 450 thousand and 88 million euros per year.

3.2 Prescribed burning monetary savings in Portugal

For Portugal, the monetary savings associated with the avoided CO_2 emissions per each prescribed burning treated hectare were estimated for the four scenarios proposed by Vilén and Fernandes (2011). The results account for the scenarios uncertainties and are presented in Table 6.

Considering the uncertainties in the scenarios estimates, the value of the savings related to the treatment could vary from 56 €/ha, in the least favorable setting, reaching 3963 €/ha, in the most favorable. Scenarios I and III simulated a burn leverage of 1-ha decrease in the area burned by wildfire for each treated ha, while Scenarios II and IV employed a 3-ha decrease in the area burned for each treated ha. This led their results to be similar. Even so, Scenarios III and IV showed slightly improved results, suggesting that treating larger areas (20% of the annually burned area, instead of 2%) is economically more promising.

4 Discussion

4.1 Climate change, carbon emissions, and prescribed burning in Mediterranean countries

Fire regimes are shifting or are expected to do so under global change. Current fire suppression strategies are not able of controlling all wildfires, and their power to do so might be compromised under harsher climate conditions (Duane et al. 2019). In this sense, the focus is shifting towards prevention strategies, such as fuel management through prescribed burning. Research on prescribed burning and its use in southern Europe is somewhat less developed than in other regions of the world. There are still considerable institutional and cultural challenges preventing its widespread adoption in the Mediterranean region (Fernandes et al. 2013).

Another main concern in the region is biodiversity conservation, especially considering future threats such as the impacts of climate change and forest fires (European Commission 2020). One way to jointly tackle these issues is through forest carbon enhancement, which presents a low-cost opportunity in climate policy but needs efficient strategies to be implemented (Gren and Zeleke 2016). Studies

Table 4 Estimated fire emission reduction (in Mg CO_2) and associated uncertainty (± 58%) according to each scenario and country

Scenario	I	II	III	IV
Reduction	1%	5%	13%	52%
France	13,407 ± 7,776	67,034 ± 38,880	174,289 ± 101,087	697,155 ± 404,350
Greece	3,585 ± 2,079	17,925 ± 10,397	46,606 ± 27,032	186,425 ± 108,126
Italy	58,164 ± 33,735	290,818 ± 168,675	756,128 ± 438,554	3,024,511 ± 1,754,216
Portugal	44,088 ± 25,571	220,440 ± 127,855	573,145 ± 332,424	2,292,580 ± 1,329,696
Spain	17,191 ± 9,971	85,955 ± 49,854	223,484 ± 129,621	893,936 ± 518,483
Total	136,435 ± 79,132	682,174 ± 395,661	1,773,652 ± 1,028,718	7,094,606 ± 4,114,872

Table 5 Expected monetary savings related to the adoption of prescribed burning practices, according to the country and scenarios proposed by Vilén and Fernandes (2011). The minimum and maximum values correspond to 42% and 158% of the expected value, accounting for the ± 58% uncertainty in the scenarios estimates

Prescribed Burning Scenarios		France	Greece	Italy	Portugal	Spain
Scenario I	Minimum	137,224 €	36,695 €	595,330 €	451,260 €	175,958 €
	Expected	326,725 €	87,369 €	1,417,451 €	1,074,429 €	418,947 €
	Maximum	516,225 €	138,043 €	2,239,573 €	1,697,597 €	661,937 €
Scenario II	Minimum	686,122 €	183,474 €	2,976,648 €	2,256,300 €	879,790 €
	Expected	1,633,624 €	436,844 €	7,087,257 €	5,372,143 €	2,094,737 €
	Maximum	2,581,126 €	690,214 €	11,197,865 €	8,487,985 €	3,309,685 €
Scenario III	Minimum	1,783,918 €	477,034 €	7,739,284 €	5,866,380 €	2,287,453 €
	Expected	4,247,423 €	1,135,795 €	18,426,867 €	13,967,571 €	5,446,316 €
	Maximum	6,710,928 €	1,794,555 €	29,114,450 €	22,068,762 €	8,605,180 €
Scenario IV	Minimum	7,135,670 €	1,908,135 €	30,957,137 €	23,465,519 €	9,149,811 €
	Expected	16,989,691 €	4,543,178 €	73,707,469 €	55,870,284 €	21,785,265 €
	Maximum	26,843,711 €	7,178,221 €	116,457,800 €	88,275,049 €	34,420,719 €

have shown that prescribed burning can be a valuable tool in this context since it has been suggested to reduce overall wildfire emissions in Mediterranean countries (Narayan et al. 2007; Vilén and Fernandes 2011) by avoiding larger fire events. Indeed, all countries analyzed in this study can economically benefit by employing prescribed burning measures.

It should be highlighted that, despite being encouraging, these results are highly dependent on the assumptions made by Vilén and Fernandes (2011) on the prescribed burning leverages, that is, the number of hectares saved from wildfire per unit area treated. The authors estimated the leverage based on wildfire data available at the time, which since then has started to increase. More recent studies have put the reduction in overall fire emissions under question. While prescribed burning has been shown to reduce emissions in savannahs in northern Australia (Edwards et al. 2021; Sangha et al. 2021), that might not be the case in every ecosystem. In biomes with little fire incidence, it is doubtful that prescribed fire will reduce unplanned fire extension, while for many others, the return for effort is expected to be low. Lessons derived from one biome do not necessarily translate to others (Price et al. 2015). Moreover, further studies have suggested that, above a certain leverage threshold, prescribed burning might even contribute to additional emissions (Fernandes et al. 2013), others did not find any emission reduction benefits from prescribed fires (Bradstock et al. 2012; Volkova et al. 2021), and another found that the activity needs to be conducted in a large scale to effectively contribute to decrease wildfire sizes (Davim et al. 2021).

Despite the uncertainties regarding the emissions estimates and the associated economic benefits, prescribed burning is linked to other financial advantages, such as the decrease in suppression costs, and additional economic

Table 6 Annual monetary savings (in €/ha) linked to the prescribed burning interventions, according to the Addition Tax values and the scenarios proposed by Vilén and Fernandes (2011). The minimum and maximum values correspond to 42% and 158% of the expected value, accounting for the ± 58% uncertainty in the scenarios estimates

Prescribed burning scenarios		CO_2 tax - 2016	CO_2 tax - 2017	CO_2 tax - 2018	CO_2 tax - 2019	CO_2 tax - 2020	CO_2 tax - 2021
Scenario I	Minimum	56	58	58	108	200	203
	Expected	134	138	138	257	476	482
	Maximum	212	218	218	406	752	762
Scenario II	Minimum	282	290	290	539	1000	1013
	Expected	672	691	691	1284	2381	2412
	Maximum	1062	1091	1091	2029	3762	3810
Scenario III	Minimum	73	75	75	140	260	263
	Expected	175	180	180	334	619	627
	Maximum	276	284	284	528	978	991
Scenario IV	Minimum	294	302	302	561	1040	1053
	Expected	699	718	718	1336	2476	2508
	Maximum	1105	1135	1135	2111	3913	3963

losses associated with wildfires. Studies have also concluded that for a 5-year prescribed fire return interval, a yield cost saving in terms of reducing the need for debris basin cleanout would also happen (Hunter and Robles 2020). Furthermore, prescribed fire has neutral or positive effects on soils and biodiversity, in contrast to wildfires, which can be extremely damaging (Fernandes et al. 2013). In this context, especially considering the concerns of the EU Biodiversity Strategy for 2030, prescribed burning in southern Europe is justified by the need to manage fire-prone vegetation types and maintain cultural landscapes that provide a range of ecosystem services (Fernandes et al. 2013). Next, we look at Portugal in further detail, as the country already has established guidelines for the use of prescribed burning.

4.2 Prescribed burning, fuel management, and carbon taxation in Portugal

In Portugal, the National Prescribed Burning Program, approved by the RCM N. 59/2017, is the primary fire prevention policy instrument, and it is part of the National Plan for the Defense of the Forest Against Fires. It not only helps in avoiding losses in terms of biodiversity, real-estate, and potentially lives, but it also recognizes that it is essential to increase the area of active management to achieve an effective defense against fires. This is to be achieved through the creation of fuel breaks and mosaics with low fuel load strategically situated to support firefighting (ICNF 2017).

The Portuguese National Prescribed Burning Plan (ICNF 2017), part of the National Prescribed Burning Program, asserts that it is vital to increase the area of active management, focusing on structural prevention. Fuel management networks have an elevated cost that thwarts their execution. In this sense, it is desirable to employ techniques with lower costs and high benefits, such as prescribed burning. This is in alignment with what is proposed by Fernandes (2015) that states that it is more effective to invest in fuel management than only in fire suppression and that one of the most economic and effective ways to manage fuels is through prescribed burning.

The plan estimates that the treatment cost is 120 euros per hectare. Considering this, prescribed burning measures are not only an attractive option for their potential emission reductions (Narayan et al. 2007; Vilén and Fernandes 2011) but also in economic terms since the value of the carbon savings can surpass the treatment investments in some scenarios, in addition to other possibly averted costs related to suppression, economic losses, and the reduced necessity for debris basin removal (Hunter and Robles 2020).

It is true that not every ecosystem benefits from prescribed burning reducing emissions (Price et al. 2015), and that uncertainties related to fire emission estimates are large and more data on fuel load and fuel consumption in different fuel layers are needed (Vilén and Fernandes 2011). However, even considering the ± 58% uncertainty reported Scenarios II and IV, the most optimistic, pay off economically for all Addition Tax values to date. Still, only for the Addition Tax value of 2020 and 2021, all scenarios pay off.

Also, despite the proportionality of the results between Scenarios I and III and Scenarios II and IV, the latter displayed somewhat improved results, likely related to the larger extent of the treated areas. This agrees with the findings of Davim et al. (2021) that underlines the need to scale up prescribed burning in Portugal and guide its spatial planning by strategic considerations to effectively contribute to decreasing wildfire sizes.

Considering that the estimated prescribed burning costs are in the order of 120 €/treated ha, Fig. 3 shows the overall reduction in emissions necessary for it to economically break even, according to the Addition Tax value.

The curve illustrates the emission reduction necessary for prescribed burning to break even from an economic perspective, being that points above the line are cost-effective. As the Addition Tax values increase, the need

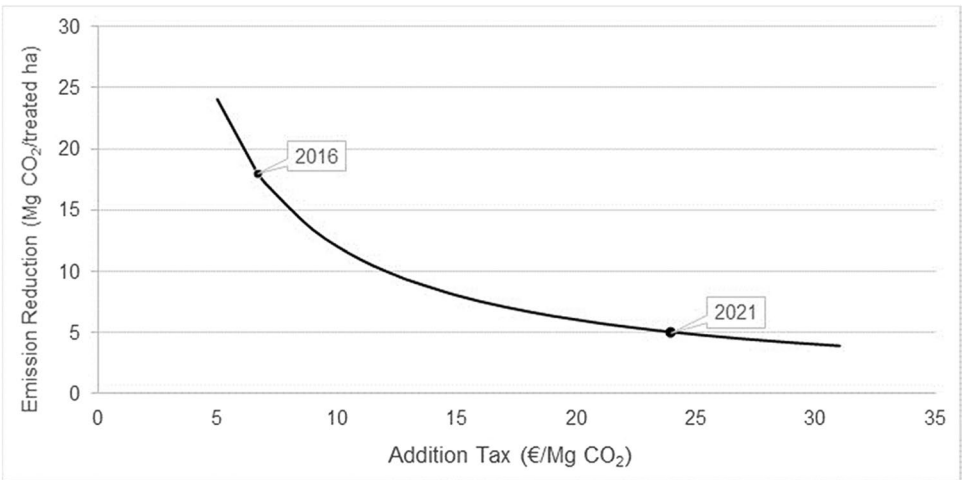

Fig. 3 Average reduction in emissions per treated hectare needed for prescribed burning to be cost-effective (considering the cost of 120 €/treated ha) according to the Addition Tax values. The first and the latest Addition Tax values are indicated in the curve. Points above the line are cost-effective, while the points below provide an economic benefit that is under the cost of the treatment

for higher treatment efficiency regarding emission reductions decreases. For reference, the average fire emissions in untreated areas estimated for Portugal is in the order of 40 Mg CO_2/burned ha (Vilén and Fernandes 2011).

As the tax values have almost steadily risen since its creation, it increases the likelihood that prescribed burning will be a cost-effective treatment provided that the treatment costs do not increase as well. Currently, the auction price value is averaging 60 €/Mg CO_2 (Silva 2021), which can make even small prescribed burning treatment reductions economically interesting. Furthermore, as studies emerge urging for the expansion of the use of prescribed burning (Davim et al. 2021), the treatment costs may go down due to scale effects.

4.3 Economic and conservation considerations: Portugal's example

For the years of 2017 and 2018, the Portuguese National Prescribed Burning Plan establishes that the prescribed burning interventions should concentrate on eight priority areas of the country, amounting to 10,000 treated hectares. Therefore, the total investment for this season (2017–2018) is in the order of 1.2 million euros. As for the revenues from the Addition Tax on Carbon Emissions, the sums collected from the same period are shown in Table 7.

The revenue from the taxation is much higher than the costs of the prescribed burning intervention planned for the same season. It should be mentioned that after 2018, the Addition Tax value has continued to rise, which likely increase the total revenue collected. This Addition Tax revenue is directed to the Portuguese Environmental Fund, which has the objective of supporting environmental policies aligned with the Sustainable Development Goals, such as carbon sequestration. In this sense, there is the opportunity for applying this type of ecosystem services-based solution, which is often overlooked or underexploited (Yang et al. 2020). Prescribed burning interventions in Portugal are currently financed through the Permanent Forest Fund. Still, as the tax revenue far exceeds the total treatment investments, these measures could have an additional source of financial support, especially since the overall benefits of prescribed burning align with the Environmental Fund's objective. Furthermore, it is expected that for 2022 the Environmental Fund budget availability will amount to one billion euros, more than double the sum available for 2021, a direct effect of the rise in emissions allowances prices (Silva 2021).

Table 7 Addition Tax on carbon emissions revenue through the years of 2017 and 2018

Year	Revenue
2017	136 M€
2018	138 M€

Source: (UTAO 2019)

It should be mentioned that Barbier et al. (2020) point to three main criticisms related to funding natural climate solutions through carbon taxes. One, they may lead to the shift of forest degradation to other areas. Two, they may discourage investing in reducing emissions through renewable energy. And three, the tax income should be applied in other ventures. Still, the authors advocate that these issues can be addressed. National taxation arrangements can lessen the chances of displacements within each country. Renewable energy generation and natural climate solutions are both crucial. Finally, regardless of the many valuable applications the tax revenue could have, the gravity of biodiversity loss and climate change makes it urgent to address them jointly.

This is likely also true in Portugal's case. First, the tax income would be applied in the protection of the forest (and the residing population) against extreme fire events, following the areas' vulnerability. Second, as the results have highlighted, the tax revenue far surpasses the investment needed for the prescribed burning interventions, leaving enough financial assets to be spent on renewable energies or other climate-focused initiatives. Finally, biodiversity and climate actions are key concerns in the European and Portuguese environmental agenda, and they should have precedence in accessing these resources.

It is also recognized that it can be politically difficult to create measures that raise living costs, such as carbon taxes (Barbier et al. 2020). However, in Portugal's instance, this barrier has already been surpassed, and other ecosystem services provided by forests, like food provision, drinking-water supply, and cultural services, are deemed to contribute between 50 and 90% to the income and subsistence of those who live in forests and the rural population (Convention on Biological Diversity 2016). This strengthens the argument that applying the revenue from carbon taxes to fund prescribed burning intervention is beneficial not only for potentially curbing climate change but also for protecting rural livelihoods and biodiversity.

5 Conclusions

Among the terrestrial ecosystems, forests are considered the most efficient carbon sequestration systems, as the various services they offer contribute significantly to reducing CO_2 in the atmosphere (Liu and Wu 2017). In this sense, Mediterranean forests provide various ecosystem services and goods that are valued by traditional markets, such as timber and cork. However, essential services provided by forests, such as carbon sequestration, are not valued by traditional economies. In this sense, the potential benefits from prescribed burning include reducing biodiversity and

economic value losses, and for some regions in Europe, notably in Southern Europe, the technique may also prove to be a viable means to start accounting for the reduction in CO_2 emissions within the Kyoto Protocol context (Narayan et al. 2007).

The adoption of prescribed burning in the Mediterranean region has been slow, unequal, and inconsistent, and its employment is constrained by cultural and socioeconomic factors, as well as by specific aspects related to demography, land use, and landscape structure (Fernandes et al. 2013). Considering that novel climates can increase the potential of large wildfire events, the use of prescribed burning has the potential to offset large wildfire events forecasted for the twenty-first century (Duane et al. 2019).

Despite the intrinsic uncertainties typical of policies that target carbon sequestration (Gren and Zeleke 2016), the results of this study have suggested that prescribed burning can be an interesting policy not only from a carbon sequestration perspective, but it also can represent a benefit potentially in the order of hundreds of million euros for most analyzed countries. Specifically, in Portugal's case, the value of the carbon sequestered by prescribed burning exceeds the treatment costs for the four analyzed scenarios almost always. As the Auction Prices and the Addition Tax values have been showing an overall increasing trend, this suggests that this benefit is likely sustainable in time.

Finally, the results have demonstrated that the Addition Tax revenues are more than enough to finance prescribed burning interventions in Portugal and could perhaps be further invested in other carbon sequestration-focused actions and biodiversity conservation efforts in the Portuguese forests, including more scientific research on the topic. As there are still uncertainties regarding burning leverages, which in some cases might even lead prescribed burning to contribute to additional emissions (Fernandes et al. 2013), and there have been studies that did not report any emission reduction benefits from the treatment (Bradstock et al. 2012; Volkova et al. 2021), more studies on the topic would invaluable for guiding and informing future policies on the matter.

Considering that protecting biodiversity and combating climate change are international priorities, explicitly addressed by the United Nations, European Union policies, other countries, especially in the Mediterranean basin, can profit from the analysis and results of this study. There is a need for new governance arrangements connecting climate change to forest policy (Doelle et al. 2012), and the analytical framework employed in this study integrates environmental policies in a way that illustrates the possibility of positive synergies between their objectives, potentially improving their benefits to society.

Author contribution RMP wrote and created the scope of the study under the close supervision and guidance of JC.

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