forests

MDPI

Article

A Choice-Modeling Approach to Inform Policies Aimed at Reducing Wildfire Hazard through the Promotion of Fuel Management by Forest Owners

José L. Santos, Ana Martins *, Ana Novais and Maria João Canadas

Centro de Estudos Florestais, Instituto Superior de Agronomia, Universidade de Lisboa, Tapada da Ajuda, 1349-017 Lisboa, Portugal; jlsantos@isa.ulisboa.pt (J.L.S.); ananovais@isa.ulisboa.pt (A.N.); mjcanadas@isa.ulisboa.pt (M.J.C.)

* Correspondence: anacostamartins@gmail.com

Abstract: The public-good nature of benefits of fuel management explains its current undersupply and the consequent wildfire blow. Policies to promote fuel management are thus required. To be cost-effective, they need to be informed by context-specific estimates of forest owners' willingness-to-accept (WTA) for managing fuel. This study develops a choice-modeling approach to this problem. A survey of forest owners was undertaken in a wildfire-prone parish in Portugal. Respondents were asked about their willingness to subscribe different management contracts. A choice model was estimated and used to predict owners' WTA for different fuel management commitments, and the marginal cost of reducing burned area in the parish. Estimated WTA amounts depend on owner type and commitment. Active owners demanded lower amounts for adopting silvicultural intervention commitments, and higher for those implying income foregone. The marginal cost of reducing burned area through fuel management increases with area, but it currently is yet smaller than the corresponding marginal benefit. Our results suggest that zero burned area is not an option and optimum fuel management lies beyond the current level. It will be shifted even beyond by targeted (key-spot) fuel management approaches; WTA differences across owners can be used to design context-specific policies that are more cost-effective.

Keywords: cost-effectiveness; willingness-to-accept; fuel management commitments; choice modeling; marginal cost–benefit analysis; avoided burned area; wildfire prevention; public goods; private forest owners; context-specific policy

check for updates

Citation: Santos, J.L.; Martins, A.; Novais, A.; Canadas, M.J. A Choice-Modeling Approach to Inform Policies Aimed at Reducing Wildfire Hazard through the Promotion of Fuel Management by Forest Owners. *Forests* **2021**, *12*, 403. https://doi.org/10.3390/f12040403

Academic Editor: Donald G. Hodges

Received: 3 February 2021
Accepted: 25 March 2021
Published: 29 March 2021

1. Introduction

1.1. The Policy Problem

The risk of larger and more severe wildfires has been increasing, namely in Mediterranean Europe [1]. Besides climate change, fuel accumulation associated with changes in rural activities and land use over the last decades explain this increase [2,3]. Fuel management to reduce the amount or modify the kind and arrangement of fuel loads is thus key to reduce wildfire hazard and risk [2,4–6]. There is a growing claim, in the academic community, for a paradigm shift from fire suppression to damage prevention, including fuels treatments [3].

The benefits of wildfire hazard reduction are mostly captured by society collectively in the form of less human lives lost, lower costs for the local economy, including property destruction and job losses, and the conservation of many regulating ecosystem services, such as water flow and water quality regulation and carbon stocks protection [2,3,7]. In addition, the avoided losses in terms of burned wood often go much beyond the ownership boundaries [8]. Therefore, only a small share of the benefits of wildfire hazard reduction accrues to the forest owner, who is often requested to undertake fuel management actions at his or her own cost [9]. In some particularly wildfire-prone regions, in particular in rainy and hilly Mediterranean areas, such as Portugal, the costs of fuel management are very significant. These forest regions compete, in the global wood market, with many other areas where such costs are much lower, and thus global wood prices tend not to reflect the former regions' extra costs [10]. In these circumstances, the small share of the benefits of wildfire hazard reduction accruing to the forest owner is often insufficient to support the full costs of fuel management in these wildfire-prone regions.

Therefore, the public-good, nonexcludable nature of the social benefits of fuel management explains the current systematic undersupply of fuel management in parts of Mediterranean Europe, in particular. A cost-sharing policy intervention may thus be required to correct this market failure [11]. This need for policy support may be stronger in areas dominated by small-scale owners, who tend to capture an even smaller share of those social benefits.

The emergence of this need for policy support for fuel management is related to several historical trends, such as: (1) raising labor costs; (2) declining value of the byproducts of fuel management (firewood, grazing, manure), which were used in the past as inputs to farming systems and rural livelihoods; and (3) declining economic viability of agriculture in hilly areas, which led to the obliteration of the forest–farmland mosaic [10,12,13].

Most economic analyses that looked at wildfire hazard reduction by fuel treatments as a public benefit have been guided by the main goal of justifying public expenditure in fuel management in (mainly) public lands. Two different types of studies have been done in this context. The first includes a set of economic valuation studies that assessed public preferences for several options of fuel treatments with impact on perceived landscape attributes or with undesirable side-effects such as, e.g., smoke from prescribed burning [14–20]. The second type of studies evaluated the positive and negative externalities among adjacent owners, namely public ownership and private owners [8,9,21,22].

Two main arguments converge to justify a broadening of scope in the analysis of fuel management costs and their public benefits. The first derives from the growing claim for a broader and multidimensional analysis of wildfire damages [3] to better inform about the benefits of policies that promote fuel management. The second is the need for widening the range of territorial contexts where studies of public benefits of fuel management have typically been undertaken—from settings dominated by public land ownership to those where private ownership prevails—and from exploring issues raised by the expansion of the wildland–urban interface as a relevant driver of wildfires, to addressing problems related to the abandonment of land management in Mediterranean Europe [3].

Emerging public policies and public debates in Europe and elsewhere, e.g., the idea of using public funds to pay for public-good delivery [23–25], as well as the growing claim to fully consider fire hazard reduction as an ecosystem service [26] are creating a favorable policy setting for considering the use of public payments to promote fuel management whenever significant public benefits result from it. Within the European Common Agricultural Policy (CAP), support to forest owners who subscribe management commitments related to environmental and climate-related objectives (sylvo-environmental measures) and investment support aimed at reducing the susceptibility of forests to wildfire hazard have emerged in the last decade as an exception to the general parsimony of CAP measures related to forests [27]. As opposed to agriculture, the EU Treaties and the CAP do not allow for direct payments to forest owners, and there is not a common forest policy in the EU. Recently, the strongest objections to a truly integrated common forest policy, including those of Member States such as Sweden, are fading away [28]. In a broader geographic context, payments for ecosystem services (PES) and tax incentives are also used to incentivize forest owners to adopt management prescriptions that are associated with increased ecosystem service provision or environmental public good delivery [29,30]. Different countries in Mediterranean Europe, such as Spain, are also incentivizing fuel management action by forest owners, farmers who break the continuity of big forest blocks, or shepherds that graze fuel management strips [29].

1.2. Valuation Methods

An essential requirement for these emerging policies for fuel management by forest owners and other land managers to be effective, is getting valid and reliable estimates of the minimum amount required by forest owners and other land managers—that is willingness-to-accept (WTA)—to subscribe particular management commitments. This is essential to inform policy design so that sufficient uptake by forest owners is achieved while keeping public expenditure at the lowest possible level (cost-effective policy). It is also essential to estimate the total policy cost for each level of fuel management intensity, in order to decide how far should we go, that is: what is the most reasonable or optimal level of fuel management intensity.

The estimation of owners' WTA for subscribing fuel management commitments can be based on pragmatic approaches, such as the budget method, which relies on existing (tabulated) estimates of standard per-unit costs of forest operations. This approach is often used, in practice, for developing and budgeting forest policies [31]. A natural alternative candidate for this task would be using stated-preference valuation methods, such as choice modeling [32,33], where respondents (e.g., farmers or forest owners) are asked to select their preferred option among several alternatives involving, e.g., different levels of management commitments and policy payments in an hypothetical choice experiment.

Until recently, most choice-modeling studies in this area have been focused on the public's (local residents, visitors, the general public) willingness-to-pay (WTP) for (often environmental) public goods related to agriculture or forest management, including fire hazard reduction [11,17,18,34,35], rather than on farmers' or forest owners' WTA to subscribe management commitments. The usual aim of these studies is integrating social preferences in sustainable agricultural or forest management, or to establish policy priorities among different public goods (PG), rather than to inform policy about cost-effective payment levels. For example, Santos et al. [11] compared several PG of agriculture at the EU level, showing that WTP for wildfire hazard reduction, through the contribution of farmland to the landscape mosaic, was the most valued PG of agriculture in their Portuguese sample, but not in other countries.

A smaller group of choice modeling studies valued the WTA of farmers or forest owners, as suppliers of environmental PG, to subscribe the management commitments that are required to supply them. Most of these studies have concentrated on agri-environmental contracts [36–44]. Fewer studies have addressed forest owners' WTA [45–49].

No study, which we are aware of, has yet estimated forest owners' WTA for subscribing fuel management commitments. The use of choice modeling for this purpose has, however, several potential advantages. One of them is the usual familiarity of forest owners with the forest operations (and their costs) that are involved in hypothetical choices they would be asked to undertake. This is an essential condition for a satisfactory hypothetical transaction sensu Fischhoff and Furby [50], and thus for the validity of any stated-preference valuation study. Lack of familiarity of the respondents with the hypothetical choices they are asked to perform was indeed, very early identified as a major factor of bias in stated preference valuation studies [51].

Stated-preference WTA studies have considered management commitments that either constrain owners' land-use decisions, by, e.g., set aside, buffer strips, constraints to forest plantations or livestock densities [36,38,44,45,47,49,52], or require active management for environmental benefits [37,40–43,48]. These two types of management commitments lead to two types of costs that need to be offset by policy payments, respectively: (1) opportunity cost or income foregone, such as where land is set aside or productivity is affected by constraints; and (2) direct costs, where the management commitment does not imply an income loss, but rather to employ costly production factors (e.g., labor) to carry out, e.g., additional silvicultural interventions. These valuation studies also show that the minimum WTA required by landowners also depend on transaction costs, e.g., time spent on compliance checks, meetings, and paperwork. In contexts where small forest owners prevail, nonpaid family labor may represent an important element of opportunity cost.

The conventional budget method that is often used to value the costs of forest plans, projects, or operations at the stand level [31] tends to focus on available, standard (usually tabulated) estimates of financial or opportunity costs; not to consider transaction costs; and not to fully consider the variability of costs across owners, i.e., the fact that costs are context-dependent. On the other hand, by asking each respondent to make a hypothetical choice between subscribing or not to a particular commitment for a given payment, choice-modeling provides an opportunity for each forest owner to consider all compliance costs under his or her particular circumstances. Possibly, owners' knowledge about these costs better matches his or her local context than the tabulated standard cost figures used in the budget method. Choice modeling may thus help including owner-specific costs, such as, e.g., traveling to negotiate with forest contractors for owners living far from their forests.

A better knowledge of costs faced by each owner type in each area would help in designing more context-specific policies, which may be expected to get a higher uptake of fire management commitments by owners at the lowest possible cost in terms of public expenditure. Choice modeling is thus expected to help designing more cost-effective policies to reduce wildfire hazard through context-specific payments to fuel management by private owners.

1.3. The Study and Its Objectives

In this study, we carried out a survey of forest owners in the Alvares parish. Owners were presented different forest management contracts, each of which included particular fuel management commitments and a particular payment level. Respondents were asked to state whether they would sign each of these contracts. Commitments and payment levels varied across contracts, according to the survey design, and forest owners with different characteristics were included in the survey sample. This variability of contracts and owners allowed us to model the response (uptake decision) of different owners to different management commitments, and eventually to estimate the minimum payment required (WTA) by each type of owner to subscribe each fuel management commitment. The estimated (uptake) choice model was then used to analyze the relationship between payment level and percentage of the parish forest area under shrub clearing. Using a fire model presented in a companion article, within this same issue, we estimated the reduction in average per year burned area for each percentage of the parish under shrub clearing. Eventually, we estimated the marginal cost, in terms of public expenditure, of reducing the overall burned area in the parish by one hectare.

The study area (the Alvares parish) corresponds to a mix of conditions that makes it the perfect-storm case of recurrent, dramatic wildfires caused by systematic undersupply of fuel management activities due to the public-good, nonexcludable nature of the social benefits of fuel management. These conditions are, among others: (i) high costs of fuel management, due to a rainy Mediterranean climate and a hilly landform; (ii) the dominance of small ownership size contributes to reduce the share of the benefits of fuel management that accrue to the owner, who is nevertheless required to support the full costs of his/her fuel management activities; and (iii) the majority of forest owners live far from the parish, which may significantly increase transaction costs (e.g., traveling to negotiate with forest contractors) and risks related to subscribing fuel management commitments (e.g., nonsupervised forest operation by contracting may lead to noncompliance and thus to the need to return policy payments).

With this study we aimed at: (1) comparing the minimum payment (WTA) amounts required by owners to perform fuel management, across types of fuel management commitments and across owner types, and exploring the economic logics, or rationalities underlying differences across commitments and owners; (2) using the understanding gained about these differences and economic logics to develop some implications for a more context-sensitive, and thus cost-effective policy, which would promote fuel management by forest owners to reduce wildfire hazard and risk; and (3) developing an exploratory marginal cost–benefit approach to discuss how far to go concerning (optimal) fuel management intensity, and to explore the effects of a more targeted approach to fuel management on the location of this optimum.

2. Materials and Methods

2.1. Study Area and Its Context

This study took place in Alvares (Góis municipality in central Portugal), a parish affected by a violent wildfire in 2017. In the last 40 years, there were 42 wildfires, recurrent in some places at least three times. They have burned more than 20,000 hectares, twice the area of the parish [53]. The prevalence of steep hillsides (slope above 25%) on extensive mountainous areas contributes to high fire hazard in one of the most wildfire susceptible areas in Portugal, which includes Alvares [54].

Forests cover more than 90% of the parish, dominated by eucalyptus (53%) and pine (30%) plantations for wood production. Nonindustrial private forest (NIPF) owners individually manage most of the forest area (84%), while two paper pulp companies manage the remaining 16%. In most of the area under NIPF management, the owner lives outside the municipality (61% of NIPF owners). Population density has declined by 83% since 1940, and the parish currently has only 812 inhabitants, grouped in 34 settlements of varying size [55,56]. Nearly half of the residents (47%) are more than 65 years old, and only 16% are young people (up to 24 years of age) [56].

2.2. Survey and the Choice Experiment

In early 2018, we applied a choice experiment questionnaire to 221 NIPF owners in Alvares to assess their willingness to subscribe fuel management commitments in the context of a hypothetical governmental cost-share program. Following the choice experiments, the respondents were asked about forest structure and management practices, the owner' sociodemographic characteristics, and forest importance for the household. A face-to-face survey was applied to both local and nonlocal residents.

Owners were asked to choose between the current situation (status quo), with no payment, and subscribing a contract including a set of hypothetical fuel management commitments for a given payment. The selection of these commitments was based on the opinions of Portuguese forest ecosystem experts, elicited in an online survey whose results were discussed in two focus groups held on January 2018. Following the recommendation in Riera et al. [57], six forest ecosystem experts from the academia and national forest authority, and three local owners participated in this consultation.

To reduce both horizontal and vertical continuity of fuels and the consequent fire propagation throughout the landscape [4,58–60], the following three commitments were initially considered: increasing the area of native broadleaved trees, keeping a proportion of area without trees or shrubs (as fuel breaks), and increasing the frequency of shrub clearing. Three payment levels—50, 100 and 150 EUR/ha—were considered to reasonably cover the expected range of costs that would be incurred by forest owners to comply with these fuel management commitments. After a pretest of the questionnaire with 15 forest owners, only two management commitments—fuel breaks and shrub clearing—remained in the final version of the questionnaire, to reduce complexity and cognitive burden of the choice task for the respondents. Payment levels were also adjusted to better cover the full range of compliance costs that came out in the pretest (Table 1). An aid card (Card A1) supported the explanation of all of these attributes: both fuel management commitments and the payment level. The per hectare annual payment levels were converted in absolute values (EUR/year), during each interview, by multiplying these unit payment levels by the area reported by each respondent.

Table 1. Attributes and attribute levels used in the choice experiment.

Attributes	Variable	Attribute Levels	Description
Delivering a proportion of land area to be included in fuel breaks; these would be implemented and kept by a common entity, which would support the implementation and maintenance costs	Fuel break	0 15 30	No loss of productive area 15% loss of productive area 30% loss of productive area
Clean shrubs each 5 years in all area managed by the owner	Shrub clearing	No, yes	Not required by law, but would become mandatory after subscribing the contract
Payment level	Payment	20 80 200 500	Monetary value (EUR/ha/year) to be received for the subscription and compliance with the fuel management commitments

Following an orthogonal factorial design [61], 20 different combinations of attributes ($3 \times 2 \times 4$ levels of the Fuel break, Shrub clearing, and payment attributes, respectively, minus the four meaningless combinations without management commitments and with a payment level) were considered and represented in choice cards, such as the one depicted in Figure 1. These 20 possible contracts were then arranged into four blocks of five choice cards each. These blocks were randomly assigned to respondents, so that each made only five choices, a number that aligns with recommendations to reduce respondents' fatigue [57]. When grouping and sequencing the cards within each block, some logical rules were employed to reduce cognitive dissonance and potential upward biases due to anchoring [57]. First, do not use three consecutive cards that are increasingly demanding on management commitments and with increasing payments. Second, using in each block, at least the two extreme levels of each attribute (0, 30; 0, 1; and 20, 500). Third, the highest payment level should preferably be presented in the last choice card. After reading each of the five cards, the respondent was simply asked whether he or she would sign the proposed contract. Before the choice experiments, the respondent was invited to fully consider all costs and risks involved in subscribing each fuel management contract, by showing him or her Card A1 (Figure A1).

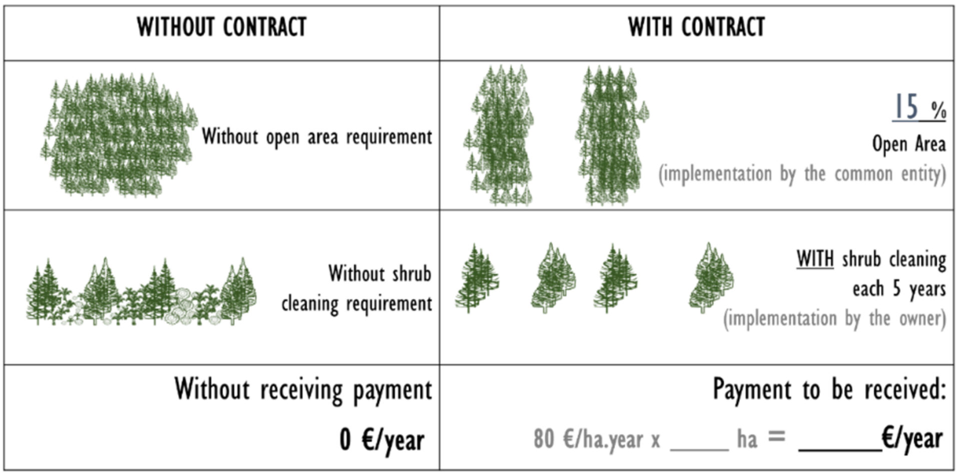


Figure 1. Example of a choice card (to be completed before the choice) according to the area of each respondent).

Prior to completing the choice task, an introductory script was presented by the interviewer, with the support of an aid card (Card A2-Figure A2), where the frame for the hypothetical contracts was better explained. Two parties were involved in the agreement, the government and the owner; the latter would receive a monetary payment for the subscribed fuel management commitments; a third party, specified as a local common institution, would administer the payments, implement, and keep the fuel breaks at its own cost. Contract details were also specified: length of the commitments (10 years), frequency of the payment (annual), supervision by national authorities, and the consequences of rule breaking (suspension and total devolution of the entire amounts received).

Surveyed NIPF owners were familiar with all silvicultural operations involved in the choice tasks they were asked to perform (including contracting prices, or amounts of family labor involved in each parcel), as they were the ones responsible for forest management in their parcels. The choice between accepting or declining the contract was thus dependent upon a fully informed, personal evaluation of the choice attributes presented to them: fuel management commitments and payment. This ensured "satisfactory transactions" were made, where individuals were "fully informed, not coerced, and able to identify their own best interests" [50], which are important validity requirements in any valuation study.

2.3. Data Analysis I: Estimating the Choice Model and Marginal WTA to Subscribe Particular Fuel Management Commitments

The conditional probability of an owner subscribing a particular fuel management contract, depending on contract attributes X (fuel management commitments and payment level) and owner's characteristics Z was modeled using binomial logistic regression (BLR) analysis. This is an appropriate modeling approach given the observations of (1) a dichotomous dependent variable, the choice by the respondent to subscribe (or not) the fuel management contract that was presented to him/her, and (2) a series of (continuous or dichotomous) explanatory variables characterizing the contract (X) and the respondent (Z) [62,63].

Following the standard random utility approach, the BLR model was specified as a functional relationship between the natural logarithm of the odds ratio $p/(1-p)$ (where p is the probability of choosing to sign the contract, a "yes" response) and a linear (in parameters) combination of the independent variables (X, Z) plus a random term:

$$Y^* = \ln(p/(1-p)) = \alpha + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 Z_1 X_1 + \beta_5 Z_1 X_2 + \mu \quad (1)$$

where $\ln(p/(1-p))$ is the logit link function (Y^*); X_1 and X_2 are management commitments, with X_1 being a continuous variable and representing the percentage of own land to deliver for fuel breaks, and X_2, a dichotomous variable = 1 when the shrub-clearing commitment is in the contract (Table 1); X_3 is the amount offered to the owner as the counterpart for the commitments; $\alpha, \beta_1, \ldots, \beta_5$ are the model parameters to be estimated through a maximum likelihood procedure and μ is a random term with zero average. The intercept α is set equal to zero and the variable describing a characteristic of respondents (Z_1 = 1 when the respondent is an active owner, 0 otherwise) only enters the model as interactions with the two fuel management attributes X_1 and X_2. These constraints imposed on the model specification are based on the idea that WTA to subscribe no management commitment whatsoever is equal to zero. Incorporating this idea into model specification is more straightforward when using Cameron and James's modeling approach [64]. Santos [65] transposed the way to implement it within the Hanemann's approach [66], which is the one used here. The characteristics of each owner are, in this way, allowed to play a moderating effect, by affecting the probability of that owner accepting a particular contract with specific values for the management commitments X_1 and X_2.

Model estimation was carried out using SPSS version 25. The Pearson chi-square statistic was used to inform about the goodness-of-fit of the estimated model.

From (1), the probability of an owner with specific characteristic Z_1 accepting a contract with attributes X (management commitments and payment level) is:

$$p = \frac{e^{y*}}{1 + e^{y*}} = \frac{1}{1 + e^{-y*}} \quad (2)$$

In this study, the interpretation of the logistic regression results focused on the identification of explanatory variables with significant effects and the signs of these effects.

A positive (negative) sign for the effect β_j of a particular explanatory variable, X or Z_1X, means that, holding all other variables constant, an increase in this variable leads to raise (reduce) the relative probability of that owner accepting the proposed fuel management contract [67].

Using the classical application of the random utility model to valuation [66], the average of the minimum amount required by a respondent to subscribe a particular management commitment X_1 or X_2—that is, his/her marginal willingness-to-accept ($mgWTA_{1,2}$) to adopt this commitment—was estimated as:

$$mgWTA_1 = -(\beta_1 + \beta_4)/\beta_3 \text{ or } mgWTA_2 = -(\beta_2 + \beta_5)/\beta_3 \quad (3)$$

where β_1 and β_2 are the marginal effects (on the log of the odds ratio) of the two management commitments, β_4 and β_5 are the marginal effects of the corresponding interactions with the owner characteristic Z_1, and β_3 is the marginal effect of the payment level.

2.4. Data Analysis II: Estimating the Marginal Cost of Avoided Burned Area for Two Higher Levels of Fuel Management at the Parish Level

Multiplying the probability of each particular owner accepting a particular fuel management contract (obtained using (2)) by the area of land managed by this owner yields the expected value of the area where the management commitments in this contract would be implemented, given the corresponding payment level and the owner's characteristics. This was done for a contract only including the commitment of shrub clearing once in each five years. Aggregating across all owners and taking into account the ratio of sampled area to total area in the parish, we obtained the expected value of the area under a shrub-clearing contract for the whole parish (*Expected_uptake_area*). Multiplying this area by the per hectare payment corresponding to this contract yielded the total public expenditure to get this area under contract. By keeping the fuel management commitments constant (shrub clearing alone) and varying the payment level over the whole range of reasonable per hectare payments, we got the full curve that relates total public expenditure with the expected percentage of the parish area where the corresponding fuel management commitments (that is, shrub clearing once in each five years) would be applied.

The delivery of land by owners for fuel-break implementation would need to be mandatory for fuel breaks to be technically coherent at the landscape scale. Therefore, this study focused on predicting the increased *Expected_uptake_area* under the shrub-clearing commitment with increasing payment levels. In fact, shrub clearing can be implemented on a voluntary basis, which better corresponds to our choice experiment scenario, without jeopardizing its landscape-scale effectiveness. This allowed us to simulate the effect of the per hectare payment level on (1) the expected area under shrub clearing (uptake area) and (2) total public expenditure, using the owner's uptake behavior that is captured in the estimated choice model. To link expected uptake area with its effect on reducing wildfire hazard, we used the results of two companion articles in this issue [68,69]. In the former, Barreiro et al. developed a simple algorithm to reproduce the spatiotemporal distribution of very large wildfires (>1000 ha) in the study area. The algorithm distributes the spatial perimeters of individual wildfires simulated using FUNC-SIM [69,70] over a 40-year period and considering 100 possible time trajectories. The same trajectories were repeated with two fuel management options, which change the fuel distribution in the landscape, thus reducing wildfire size, time between consecutive wildfires, and the extent of total burned area. Barreiro et al. estimated that, from the 4025 hectares of eucalyptus stands run by nonindustrial owners, about 40% has some degree of fuel management, totaling 1610 hectares. This figure corresponds to 22.0% of the 7311 hectares currently managed by NIPF owners that are not subject to mandatory shrub clearing. This level of fuel management was taken as the baseline for two additional fuel management options: the "moderate" and "high" level options, which add 754 and 1370 ha of forest area under fuel management, respectively [69]. These increases raise the percentage of NIPF area under fuel management to 32.3% and 40.8%, respectively. The expected burned area per year was simulated for each of these management options [69]. As the use of FUNC-SIM only simulates very large wildfires, we divided the resulting burned area by the historical proportion of very large wildfires on total burned area (0.88) to produce our estimates of total burned area under those two management options. Subtracting the expected yearly burned areas under the moderate and high level options from that under the present management conditions, we obtained the avoided burned areas (ABA) under each of these two management options when compared to the present management conditions.

Using our choice model iteratively and aggregating across owners, we identified the per hectare payment level that would be required to achieve the share of the land managed by NIPF owners under shrub clearing that corresponds to each of the abovementioned two management options.

The total public expenditure required to achieve the uptake levels corresponding to these two options were estimated as:

$$\begin{gathered}\text{Public expenditure (EUR/year)} = \text{payment level (EUR/ha/year)} \\ \times \text{ share of area of NIPF owners under shrub clearing} \times \text{total\_land\_area managed by NIPF owners (ha)}, \\ \text{for each management level}\end{gathered} \tag{4}$$

The marginal cost per hectare of avoided burned area (MgC_ABA) was estimated as:

$$\text{MgC\_ABA of moderate level} = \text{public expenditure to achieve the moderate level/ABA of moderate level} \tag{5}$$

$$\begin{gathered}\text{MgC\_ABA of high level} = \text{(public expenditure to achieve the high level} \\ - \text{public expenditure to achieve the moderate level)/(ABA of high level} - \text{ABA of moderate level)}\end{gathered} \tag{6}$$

3. Results

We begin by characterizing our sample of owners, their relationships with their forests, and the way they manage them. We then present the estimated choice model, which predicts the probability of any particular owner subscribing any combination of fuel management commitments and payment levels. Our estimates of marginal willingness-to-accept or minimum per hectare payment required for subscribing particular management commitments are presented next. We then present our estimates of the per hectare payment level that is required to achieve the parish-level area under shrub clearing that matches each of the two management intervention levels for which we could predict the corresponding avoided burned area. Finally, we present the marginal cost of each of these two wildfire hazard reduction levels.

3.1. Owner's Characteristics and Forest Management

Our sample included 221 owners who manage 36% of the total forestland in Alvares. They are mainly men (75%), more than 65 years old (54%), mostly without a college degree (75%), and economically inactive (52%) (Table 2). Most are nonresidents, i.e., their primary home is outside the municipality, mostly Lisbon or Coimbra, although they often keep a second inherited family home within the parish. More than 40% of owners own less than 4 ha of forest, and only about one third more than 10 ha. Eucalyptus and pine are the dominant species of this forest area and 70% of owners in the sample use one or both of these species. In the last 10 years, 63% of the landowners planted eucalyptus and 9%, maritime pine, and most of them (81%) harvested their forest stands for wood. During this period, the main productive interventions carried out were shrub clearing by the majority (65%), thinning and pole selection (48%) and pruning (37%). However, only 29% of the owners carried out shrub clearing at least once in all parcels. We take this variable as a proxy of active management.

Table 2. Owners, forest management and wildfires (number and % of respondents, total = 221).

Variable	Categories	Respondents	
		n	%
Sociodemography and relationship with the forest			
Gender	Female	55	25
	Male	166	75
Age	<55 years	42	19
	55–65 years	60	27
	≥65 years	119	54
Place of Residence	At the parish (Góis)	87	39
	Outside the parish (Lisbon or Coimbra)	134	61
Education	Without primary education	13	6
	Primary—High school	153	69
	College degree	55	25
Socioeconomic group/Occupation	Active (entrepreneurial or independent activity, dependent activity, unemployed)	105	48
	Nonactive (retired, domestic, student)	116	52
Forest income is one of the main reasons why forest is important (1st or 2nd)		87	39
Forest income weight on the household income during the last 10 years	0%	102	46
	0–10%	108	49
	>10%	11	5
Forest structure and management practices			
Ownership size	<4 ha	86	42
	4–10 ha	53	26
	≥10 ha	66	32
Dominant forest species	Only eucalyptus	67	30
	Only pine	48	22
	Only eucalyptus and pine	47	21
	Other type of forest stands or no response	59	27
Last planted species	Eucalyptus	139	63
	Pine	20	9
	Other species	19	9
	Does not know	43	19
Shrub clearing in the past 10 years in all land parcels (active management *)	Yes	65	29
	No	156	71
Productive interventions in the last 10 years	Shrub clearing	143	65
	Fertilization	52	24
	Chemical treatment	35	16
	Thinning and poles selection	106	48
	Pruning	82	37
	Harvesting	179	81
Family work—executes productive interventions and only uses family work	Yes	58	26
	No	163	74
Manual work—executes productive interventions and only uses manual or mechanically assisted work	Yes	127	58
	No	94	43
Impact of the 2017 fires			
Affected by 2017 wildfires		194	88
Intervention on forest spaces after 2017 wildfires		103	47
Choice experiment			
Fuel management attribute that would cost more	Keep a % area without trees or shrubs (15% reference level) (fuel break)	42	19
	Shrub clearing every 5 years (shrub clearing)	174	79
	No answer	5	2

* Variable included in the choice model.

Most of the owners (88%) were affected by the 2017 violent wildfires. Besides having lost timber, animals, or trees in their land parcels, they also lost other assets, such as houses, infrastructure, or equipment, which greatly affected their wellbeing and productive capacity. In the aftermath of these wildfires, nearly half of the owners (47%) carried out or planned interventions in their forests either by harvesting burned wood or by conducting reforestation projects.

Faced with the request to indicate the most costly fuel management commitment, only 19% selected delivering (15% of) productive land for fuel breaks, while most (79%) selected increasing shrub-clearing frequency.

3.2. Choice Model and Estimated Minimum Payment Required (Willingness-to-Accept) for Particular Owners to Subscribe Particular Fuel Management Commitments

We tested several owners' characteristics as candidates for the moderator variable Z_1 in (1). Considering statistical significance, magnitude of the effect, and causal interpretability (validity) of the effects, we selected *Active management*, identified at the owner level as having made shrub clearing at least once in all their parcels during the last 10 years.

The estimated BLR model, which is the choice model, estimated from 1030 choices made by 206 respondents, is presented in Table 3. All parameters for contract attributes are statistically significant and have the expected signs. Positive values for *Payment* indicate that more forest owners would, ceteris paribus, be willing to increase the level of fuel management commitments if per hectare payments are increased. Negative values for fuel management commitments (*Fuel break* and *Shrub clearing*) indicate that putting this commitment in the contract (shrub clearing once in five years, a dichotomous variable) or increasing the commitment's intensity (higher percentage of land delivered for fuel breaks) would decrease, ceteris paribus, the odds of accepting the contract. The negative and positive signs of the parameters for the interactions of *Active management* with the *Fuel break* and *Shrub clearing* variables, respectively, mean that being an owner with active management decreases, ceteris paribus, the likelihood of accepting to deliver more land for fuel breaks, but increases the likelihood of accepting to clear shrub at least once in five years in all land.

Table 3. Estimated parameters of the binomial logistic regression model.

Attributes	**Model β**	***p***	**Effect on Probability of Choosing the Contract Exp (β)#**
Fuel break	−0.010 *	<0.047	0.990 (1.010)
Shrub clearing	−1.373 ***	<0.000	0.253 (3.947)
Payment	0.004 ***	<0.000	1.004
Fuel break × Active management	−0.016 (*)	<0.060	0.984 (1.016)
Shrub clearing × Active management	0.627 **	<0.006	1.871
Number of observations: 1030 Number of respondents: 206	Overall goodness-of-fit: −2Log-Likelihood: 1240.414 Chi-square: 187.469 *** R square Cox and Snell: 0.166 R square Nagelkerke: 0.222 Predictive capacity: 69.2% of all replies correctly predicted		

Legend: significant at (*) $p < 0.10$; * $p < 0.5$; ** $p < 0.01$; *** $p < 0.001$; # for readability purposes in the case of significant negative Exp (β) values, we also present in brackets the equivalent odd ratio value for the inverse in the variable, as it would have a positive (driver) effect calculated by Exp (−β).

All the estimated parameters have signs in accordance to our theoretical expectations, with the inclusion of a management commitment (shrub clearing) or the raising of another (percentage of land required for fuel breaks) reducing the probability of the owner signing the contract and the raise in the per hectare payment received increasing that probability. On the other hand, being an active owner increases (in relation to nonactives) the probability of signing a contract if it includes shrub clearing and reduces it if the area set aside for fuel breaks increases. All these signs are statistically significant (except the interaction fuel break × active management, which is only marginally above the 5% *p*-level). These theoretical expectations are fully explored in the first section of the discussion. Accordance with theoretical expectations has been used in the stated-preference literature, since Mitchell and Carson's [51] seminal book, as a major (theoretical) validity test of valuation studies and their results.

The estimated BLR model has an overall percentage of correct predictions of 69.2%, which is acceptable in behavioral predictions. Its goodness-of-fit (pseudo-R^2 indicators) is acceptable, and the null hypothesis that the model's independent variables do not add explanatory power to the simplest possible model that uses the overall percentage of those who accepted the fuel management contract is rejected with a very high level of significance (chi-square variable for the log-likelihood ratio test of this hypothesis). These overall indicators of the model allow us to assess the level of reliability [51,65] of this valuation study and its results as acceptable.

Based on the estimated model parameters and using the method described in the methods section, we estimated the minimum payment required, on average, by an owner to subscribe some particular fuel management commitments (marginal willingness-to-accept, WTA, for those commitments), separately for active and nonactive owners; also estimated was the effect of being active on this marginal WTA (Table 4).

Table 4. Estimated minimum payment required by an owner to subscribe each particular commitment.

Commitment	Owner Type		Marginal Effect of Being Active
	Nonactive	Active	
Delivering 15% of land to be integrated in a fuel break	37.5	97.5	60.0
Delivering 30% of land to be integrated in a fuel break	75.0	195.0	120.0
Delivering 50% of land to be integrated in a fuel break	125.0	325.0	200.0
Delivering all land to be integrated in a fuel break	250.0	650.0	400.0
Scrub clearing once in 5 years in all land	343.3	186.5	−156.8

Notes: All figures in the table are average willingness-to-accept in EUR/hectare of owned land/year, as predicted with the estimated model. Note that our WTA estimates for 50% and all land delivered for a fuel break correspond to predictions outside our data range. Although the null hypothesis of a linear relationship between the dependent and X_1 variables could not be rejected for the data range, this may hold or not outside this range.

These results reveal that the WTA to subscribe a management commitment depends heavily on owner characteristics that are associated with our indicator of active management. An active owner requires, on average, a minimum per hectare payment to deliver land to be integrated in a fuel break that is much higher (650 EUR/ha/year) than a nonactive owner (250 EUR/ha/year). However, actives would require a much lower minimum per hectare payment to carry out shrub clearing once in five years in all his/her forestland (187 versus 343 EUR/ha/year). Being active has thus the effect of increasing by 400 EUR/year the minimum payment that is required to deliver one hectare of land for fuel breaks. On the other hand, being active leads to a decline of 157 EUR/ha/year in the minimum required payment to subscribe a shrub-clearing commitment. The difference between active and nonactive owners is greater in WTA to giving up land than in WTA to undertake shrub clearing.

Comparing WTA across commitments for the same owner type, our results imply that, for a nonactive owner, it would be less costly to deliver all land for fuel breaks (250 EUR/ha/year) than to subscribe a shrub-clearing commitment in all land (343 EUR/ha/year). On the other hand, for an active owner, giving up only 30% of owned land for fuel breaks is slightly more costly (195 EUR/ha/year) than subscribing a shrub-clearing commitment in all land (187 EUR /ha/year); delivering all land for fuel breaks would be three times more costly than subscribing the shrub commitment in all land.

3.3. Marginal Costs of Avoided Burned Area at the Parish Level

As explained in the methods section, we used the estimated model to predict Y * = log (p/1–p); replacing this Y* in (2), we computed, for each owner, the probability (p) of subscribing the shrub-clearing commitment as a function of the owner's characteristics (with or without active management) and for one payment level. By multiplying this probability by the owner's area, and aggregating across owners, we computed the parish-level *Expected_uptake_area* of the shrub-clearing commitments for each payment level.

In this way, our choice model was then iteratively used to predict the per hectare payment level that would be required to achieve 32.3% (2364 ha) and 40.8% (2980 ha) of the parish-level area of NIPF owners under shrub clearing, which correspond to the moderate and high fuel management level options of Benali et al. [69]. These payment levels are 111.5 and 207.5 EUR/ha/year, respectively, and the total public expenditure for each scenario is 263,069 and 618,993 EUR/year, respectively (Table 5).

Table 5. Marginal cost calculation using combined fire and choice models for shrub clearing every five years.

		Shrub-Clearing Levels		
		Present Situation	Moderate	High
Parish area under shrub management (%)	(1a)	22.0%	32.3%	40.8%
Parish area under shrub management (ha)	(1b)	1610	2364	2980
Avoided burned area (ha/year) [68,69]	(2)	-	68.3	102.7
Marginal reduction in burned area (ha/year)	(3)	-	68.3	34.4
Using our Choice Model				
Payment level (EUR/ha/year)	(4)	0	111.5	207.5
Total public expenditure (EUR/year)	(5) = (4) × (1b)	0	263,069	618,993
Marginal Cost (MgC)				
MgC, marginal expenditure to increase shrub management from the previous level (EUR/year)	(6)	0	263,069	355,924
MgC per avoided burned area (EUR/ha/year)	(7) = (6)/(3)	0	3852	10,347

The public expenditure curve required to promote shrub clearing by forest owners (Figure 2) shows that the relationship between public expenditure and the expected percentage of the parish's forest area under shrub clearing is nonlinear and convex. This means that the increase in the area under shrub clearing will require a more than proportional increase in expenditure, that is: marginal expenditure grows with the area already under shrub clearing. The moderate (32.3%) and high (40.8%) management level options and the corresponding public expenditure levels are highlighted in Figure 2. Note that the percentage of NIPF area under shrub clearing predicted by the model for a zero per hectare payment (23.7%) is not far from the currently observed 22.0%, without any payment, which contributes to a positive assessment of the model's validity and reliability.

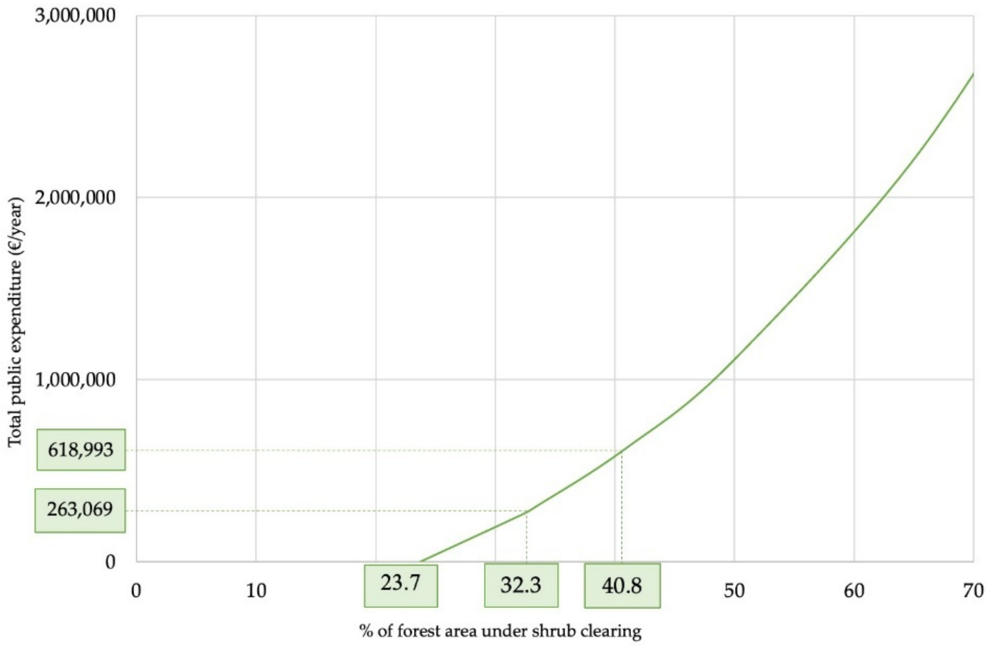


Figure 2. Public expenditure curve for shrub clearing by forest owners in the parish as a whole.

Remember that the 111.5 EUR/ha would be paid to the whole of the 32.3% of land under shrub clearing for this payment level, including the 22.0% that would be under shrub clearing even without payment. This means that a part of the payment would not have an additional effect when compared with the policy-off situation. Doing it otherwise would mean rampant administrative (transaction) costs for policy administration, as it would imply, for example, identifying all owners that are already doing shrub clearing and discriminating against them, which would also raise ethical problems.

According to the wildfire simulations developed by Benali et al. and Barreiro et al. [68,69], moderately (highly) increasing the level of shrub management at the parish level yields an expected reduction in burned area of 68.3 ha/year (102.7 ha/year) when compared to present management conditions (Table 5). This means that the marginal effect on burned area declines with fuel management level; 68.3 ha of burned area/year is avoided by passing from current management to the moderate management level (+10.3% of total area under management), while passing from the latter to the high level (+8.5% of total area under management) has a marginal effect of avoiding only 34.4 ha of burned area/year. Finally, the marginal costs for policy (marginal public expenditure) of each additional hectare of avoided burned area are 3852 and 10,347 EUR/ha/year, respectively. Therefore, the marginal cost of avoiding burned area is increasing with shrub management intensity, because of both the increasing marginal cost of expanding the area under shrub clearing, and the declining marginal effect of this expansion on avoided burned area.

4. Discussion

4.1. Comparing Fuel Management Costs Across Commitments and Owner Types: What Do These Differences Tell Us about the Owners' Contexts and Rationalities?

For nonactive owners (the majority in the sample), delivering land for fuel breaks and giving up the future income from forest on that land appears as less costly than paying the shrub-clearing expenditure, in the present, whatever the percentage of their land is requested for fuel breaks. Shrub clearing is, however, less costly for active owners (29% of owners). On the other hand, for them, delivering land for fuel breaks is more costly than subscribing to the shrub-clearing commitment, unless only a minor share of their land is to be given up for that purpose.

To explain these results, several traits distinguishing the two commitments, as regards the nature of the corresponding costs and that of the associated policy support measures, must be taken into account: direct versus opportunity costs, immediate and certain expenditure versus losses of future and uncertain income, and policy payments to cover management costs versus a policy rent to compensate for income foregone. For this discussion, we resort to some insights on NIPF owners' objectives and practices from studies undertaken in similar socioeconomic contexts (e.g., [71–73]).

The fuel break commitment corresponds to an opportunity cost, or giving up an expected flow of forest revenues into the (more or less) far future. These revenues depend, however, on market-dependent factors such as uncertain timber prices and loggers' margins, and other risks related with losses to wildfires and pests [10]. The nature of the costs involved in the shrub-clearing commitment is more complex: besides opportunity costs related with the use of family labor and capital, they comprise direct costs (wage labor, payments to contractors, fuel, equipment amortization) and transaction costs (the time to negotiate and supervise the services provided by forest contractors).

Opportunity costs may be perceived as less tangible than direct costs, and thus tend to be less considered by owners. Moreover, the loss of revenue in the far future may be associated with higher risk. It tends to be discounted when compared to another in a very near future. The risk analysis literature also reveals that we care more about losing what we already have (expenditure) than about gaining what we do not have yet [74], i.e., "losses are typically assigned a higher value than equivalent gains" [75].

Lower levels of owners' management activity tend to be associated with conditions where direct and transaction costs of active management are higher and yields lower, with the opportunity cost of land (land revenue—cost) being thus lower. From the literature on NIPF owners, we know that nonactive owners are often associated with higher slope and other biophysical constraints, lower availability of family labor, or dissociation from the local social context—either by living outside the municipality, in a distant urban center, or by missing other bounds such as keeping an inherited second home or participating in local social networks [71–73]. In a similar context, in Portugal, it was found that, for instance, forest plots of active and nonactive owners had an average slope of 16% and 25%, respectively, the latter often combined with more rocky outcrops, imposing higher direct costs for stand establishment and silvicultural operations and eventually decreasing wood yields [76]. For pine stands of medium quality, the cost of manual shrub clearing with paid labor (125 EUR/ha/year) is often far from being offset by wood revenue (50 EUR/ha/year) [77]. More recently, for eucalyptus stands in low productivity sites, the results in Pra et al. [10] imply that shrub-clearing costs contribute to negative forest income in these sites, while positive returns to investment are secured in very high productivity sites, where thus forest revenues offset shrub-clearing costs as well as total management costs. Direct and transaction costs of shrub clearing for "nonactive" owners are thus higher than for active ones, while the reverse is true for the opportunity cost of land set aside, independently of the scale of the operation.

For the majority of our owners, forest is perceived more as a heritage than as a source of income: only for 5% of the owners does forest income represent more than 10% of the household income; only 39% perceive forest income as the first or second reason why forest is important for them (Table 2). What contributes more to distinguish their WTA is not their stated objectives (heritage or income) or ownership size, but rather their silvicultural practices, namely whether they have a more active management, indicated by shrub clearing in all land parcels at least once in the last ten years. These differences in the system of practices are related to the abovementioned differences in costs, and express distinct management logics. Facing higher direct costs, nonactive owners minimize silvicultural interventions, viewed as an immediate expenditure without close or certain return in higher wood productivity or lower wildfire hazard, and tend to discount a future income they view as more risky. On the other hand, active owners, for whom forest may represent a more relevant source of income or a household asset (savings) that can be mobilized if needed, assign more value and certainty to forest income.

Carrying out active management affects the uptake of the two management commitments in distinct ways, positively for shrub clearing and negatively for fuel breaks. Active owners (that already perform clearing) require smaller economic incentives to subscribe the clearing commitment, implying that timber yields and market signals may be closer to the threshold that leads to fuel management execution. On the other hand, these factors increase the perceived opportunity cost of giving up land for fuel breaks [73,78].

Considering the results of previous studies of fuel management costs or investment returns [10,31,79], the variation in WTA across different management situations is not surprising. What deserves mention is the importance assumed by the variable "active management" to explain this variation, as existing empirical analyses have often found out that the size/scale of the operation explains a large share of the variation in per hectare cost or profitability [79]. There are two possible reasons for this difference from previous studies. First, in our study area, ownership size is hardly a proxy of operation scale, as large ownership size often results from many noncontiguous, scattered land parcels, and also because contracting is used by both small and large owners [71]. Second, the choice between mechanical or manual shrub clearing (the latter requiring considerably more labor time) depends on factors such as slope, existence of rocky outcrops, and stand attributes such as alignment and tree density. When mechanical treatment is not possible, manual intervention depends usually on the availability of family labor. While contracting the operation represents a direct cost/expenditure for the owner, the family labor used in manual clearing is an opportunity cost, whose level largely depends on the owner's personal circumstances.

4.2. Policy Implications

The following discussion of the policy implications of this study's results assumes that, as noted in the introduction, significant policy incentives are required to solve the problem of systematic undersupply of shrub clearing and the consequent dramatic and recurring wildfires.

4.2.1. Context-Sensitive, Cost-Effective Policies to Promote Fuel Management

Our results on preference differences between more or less active managers are in line with previous studies of forest owners' WTA to subscribe similar conservation commitments [45,47,52]. This supports the claim for the reinforcement of studying owners' management practices rather than simply studying their perceptions, as a basis to build typologies of NIPF owners that have practical utility to inform policy [80]. Differences in owners' preferences and the cost contexts and management logics underlying those differences should not be ignored in the design of policy measures if the aim is achieving high uptake levels at the lowest possible cost. That is, to be cost-effective, policies need to be context-sensitive.

To illustrate this claim, we start by recalling that, according to our results, nonactive owners' expectations concerning their forest income, and thus the opportunity costs of giving up land, are much lower than those of active owners. This means that, contrarily to common wisdom, "nonactive" owners may not be an effective obstacle to local structural adjustment, by either land renting, land selling, or delegating land management to a common managing entity, as already contended [81]. As, on the other hand, nonactive owners require large payments for active management commitments, our results suggest, in accordance with Canadas et al. [78], that cost-effective policies for contexts where nonactives prevail require buying management or property rights from most of the owners and managing fuels at a broader scale with lower (in particular, transaction) costs.

Contrarily, for active owners, for whom the opportunity costs of giving up land for fuel breaks and possibly also for other passive management commitments, such as delivering land to plant with slow-growing native broadleaved trees, are much higher, the required incentive payments may be prohibitively costly for policy. Small active owners may, in fact, pose a considerable challenge concerning fuel breaks or local structural adjustment initiatives [81]. On the other hand, active owners tend to demand much lower policy payments for active management commitments, such as shrub clearing. These results together suggest that, in accordance with Canadas et al. [13], in contexts where active owners prevail, although fuel management actions may need to be planned at a broader scale, they can be implemented on a cost-effective manner by incentive policy payments to owners that accept to carry out fuel management actions that are inscribed in the common plan.

A caveat needs to be applied here regarding the use of the proposed choice-modeling approach to estimate the payment levels that are required by cost-effective policy. The estimates in this study correspond to the WTA concept, which is reflected in our valuation scenario, where owners are free to subscribe (or not) the proposed commitments in exchange for the proposed payment. In the case of the fuel break commitment, however, a less voluntary and more compulsory approach might be required to ensure the technical effectiveness of the policy. In fact, to be technically effective at the landscape scale, regional networks of fuel breaks need contiguous areas at the right locations, just as buffer zones for nature conservation do, and thus should not depend on the owners' consent. Previous studies focused on buffer conservation zones [47,52] suggest that, when asked to subscribe set-aside commitments on a voluntarily basis, forest owners tend to avoid setting aside the most productive land. In our context, this trend would mean that unprofitable areas, which have been accumulating fuel loads, are the ones supplied, mostly by nonactive owners, at a low policy cost. However, if discontinuities are technically needed not there but on more profitable areas, the effect of the network on wildfire hazard reduction may be insignificant. If nonvoluntary measures are required for this purpose, the role of policy payments is different from the previously discussed. It is not anymore an incentive payment, but a total or partial compensation of income foregone in land mandatorily set aside. This compensation is essentially done for equity reasons—because some owners will be requested to incur all the costs for the benefit of all owners and society in general. In this case, the payment concept does not exactly match the WTA concept, which is the minimum amount that is required to voluntarily accept doing something. The appropriate payment level in this context of total or partial compensation for income foregone in land mandatorily set aside is probably lower than our estimates based on the WTA (voluntary) frame. Nevertheless, both figures should be correlated over commitments and owner types, because, as suggested in the previous subsection, opportunity cost is the main common underlying cost affecting owners' WTA for giving up land for fuel breaks.

4.2.2. How Far Should We Go in Fuel Management? (The Socially Optimal Fuel Management Level)

This study's results suggest that the public-expenditure cost of increasing the area where shrub clearing is carried out by forest owners grows more than proportionally with the area under fuel management. Therefore, the marginal cost of an additional hectare with shrub clearing rises with the area under fuel management. Moreover, there is a declining marginal effect of expanding the area under shrub management on avoided burned area. These two relationships together mean that the marginal public-expenditure cost of reducing the burned area by an additional hectare increases with avoided burned area even faster than the marginal costs of increasing the area under fuel management. This result supports, on sound economic grounds, the claim by Moreira et al. [3], for Mediterranean areas, for a paradigm shift towards damage prevention. As far as we are aware, this is the first time this need for paradigm change is supported in a full economic analysis of the marginal costs of wildfire hazard reduction.

How far should we go in fuel management and the corresponding wildfire damage reduction? Marginal cost–benefit analysis (CBA) has a long tradition of applied studies aimed at addressing this type of problem in environmental and natural resource economics [65].

By comparing our estimations of the marginal cost of each additional hectare of avoided burned area with the corresponding marginal benefit, in terms of reduced wildfire damage, we illustrate how marginal CBA could be used to answer that policy question in the spirit of the new paradigm defended by Moreira et al. [3]. In our study, a literature-based, approximate estimate for the marginal benefit of avoided burned area was developed by dividing the wildfire damage cost resulting from the wildfires of 2017 in the Góis municipality (which includes the Alvares parish) by the area burned in this municipality in this particular year (46,161 hectares of forestland). The used damage cost values correspond to the cost of the measures needed to restore the pre-fire situation, taken from the report of the Portuguese authorities [82], which amounts to 318,289,791 EUR, that is, 6895 EUR/ha of burned area.

This per hectare estimate of the benefit of avoided burned area is probably conservative, in that it does not include other indirect economic effects, such as lost human lives and nonmarket ecosystem services, the acceleration of rural demographic decline, the loss of attractiveness to tourists, indirect job losses, and the interim loss of household income from local forest resources. On the other hand, the 2017 severe fire season may not correspond to the average fire-season cost pattern in the area.

There is another possible limitation in using this average, per hectare damage cost of wildfires as a proxy for the marginal benefit per hectare of avoided burned area. However, if we assume an increasing, sigmoid benefit curve with an inflection point, the average benefit of avoided burned area is lower than the corresponding marginal benefit for low levels of fuel management intensity. By assuming we are still in those lower levels of fuel management intensity (which is a more than reasonable assumption in Alvares), we can deduce that the use of average benefits as a proxy will lead to a conservative estimate of marginal benefit.

The abovementioned 6895 EUR per hectare of avoided burned area was thus cautiously taken as a proxy for the marginal benefit for the current fuel management context (22% of forestland under shrub management). It can be compared with the marginal cost of avoiding burned area by moving from the current to the moderate fuel management option (32.3%), and that of moving from the latter to the high fuel management level (40.5%), that is, 3852 and 10,347 EUR/ha/year, respectively (Figure 3).

Even ignoring the rate of the downward slope of the marginal benefit curve (in red), we can deduce from this comparison that, despite the high levels of marginal cost of avoiding each hectare of burned area from $Q_{22.0\%}$ to $Q_{32.3\%}$ and from $Q_{32.3\%}$ to $Q_{40.8\%}$, the marginal benefit (given the abovementioned factors of underestimation) would probably be higher than the former, but not very likely higher than the latter, which places the social optimal level of fuel management Q_1 (Figure 3) beyond the current 22.0% of NIPF forestland under shrub clearing, somewhere between the 32.3% and the 40.8% of NIPF forestland under shrub clearing.

Our estimates of marginal public-expenditure cost per each additional hectare of avoided burned area are based on generalized shrub management across all the parish area (MgC_1 curve in Figure 3), because neither our calculations and valuation scenarios nor the used fire simulations have included spatially explicit fuel management commitments. Some wildfire specialists have argued that fuel management targeted to priority areas where the effect of each hectare under shrub clearing on avoided fire area is maximized would enable the policy to get the same reduction in fire hazard with much lower costs [83]. The MgC_2 curve (Figure 3) illustrates the location of the marginal cost curve if such a strategy of targeted fuel management is adopted. The consequences are clearly seen in Figure 3; with this lower marginal cost of avoiding the same (additional) hectare of burned area, we could afford a higher optimal level of fuel management, the consequent higher reduction of burned area Q_2, and an increase in the net social benefit of fire management (this increase in net benefit is represented by the area of the triangle ABC, in Figure 3). This net benefit represents the returns to investment in better knowledge about targeted fuel management.

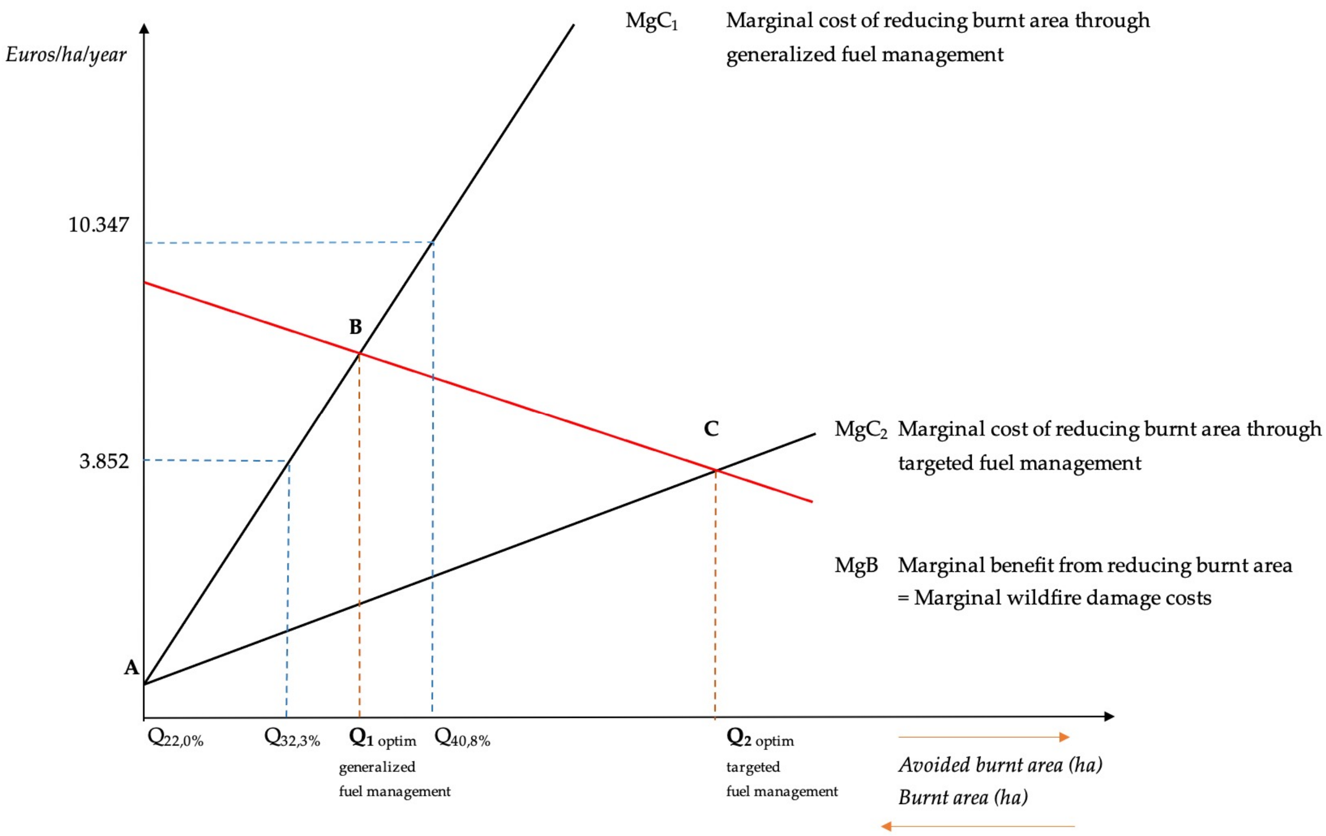


Figure 3. Marginal benefits and marginal costs of avoided burned area (EUR/ha/year). Avoided burnt areas corresponding to three fuel management levels: $Q_{22.0\%} = 0$, current situation, $Q_{32.3\%}$, moderate level, and $Q_{40.8\%}$, high level. Two optimal levels of fuel management: Q_1, with generalized fuel management, and Q_2, with targeted fuel management (only where it has the highest effect). Note these are simplified (not empirically estimated) curves, for illustrative purposes alone.

For this targeted approach to fuel management to be cost-effective, a spatially explicit policy design with differentiated per hectare payments depending on the ratio (avoided burned area)/(ha of uptake) would be required. This implies mapping this ratio for the whole area, which would imply knowledge that is not available yet, and may cause ramping transaction costs for the policy, which need to be assessed before adopting this approach.

This example developed from the Alvares case study and respective results helps to illustrate the potential of the choice-modeling and marginal CBA of fuel management to support decision-making in damage-prevention policies inspired in the new paradigm defended by Moreira et al. [3].

5. Conclusions

This study developed a choice-modeling approach to deliver context-specific estimates of particular forest owners' willingness-to-accept (WTA) to subscribe particular management commitments, which may inform the design of more cost-effective policies to reduce wildfire hazard and risk through fuel management by owners. This policy information need is particularly felt in rainy Mediterranean areas with prevailing hilly landform and small ownership, where fuel management is costly, the share of fuel management benefits accruing to the owner is small, and, consequently, wildfires are recurrent.

To develop and test the approach, a survey of forest owners was carried out in a Portuguese parish with the abovementioned perfect-storm characteristics. Owners were invited to undertake hypothetical choice experiments where they could sign (or not) different fuel management contracts created by survey design. Respondents' choices were then analyzed, in a choice-modeling frame, to estimate an uptake choice model. Based on this model, we estimated the average WTA of different owner types to subscribe different management commitments, and the marginal cost of increasing the parish area under fuel management. Combining the latter with the results of a fire model in a companion article in this issue, we also estimated the marginal cost of reducing the average annually burned area in the parish.

By comparing the estimated WTA amounts across owners and commitments, active owners were revealed to demand lower amounts than nonactives to adopt silvicultural-intervention commitments, namely periodical shrub clearing, and higher amounts for commitments implying income forgone, namely giving up land for fuel breaks. The different WTA amounts required by these two owner types are clearly rational given the different levels of context-dependent (direct, opportunity and transaction) costs each of these groups face. These cost differences across contexts recommends that, to be cost-effective, fuel management policies need to use context-specific payment levels; also recommended are two differentiated policy approaches for implementing a cost-effective fuel management plan in small ownership regions: (1) when active owners prevail, pay owners to carry out the planned fuel management actions; and (2) when less active owners prevail, pay owners to give up their management rights, so that fuel management actions can be carried out by a third-party entity, who will implement the plan at a broader scale.

In the case of fuel breaks, a compulsory approach is required to ensure the technical effectiveness of the policy, which is not fully compatible with using the WTA concept as a basis to calculate the payment to owners. In this case, it is not an incentive payment, but a total or partial compensation of income foregone in land mandatorily set aside, which is essentially done for equity reasons, and which is probably lower than our WTA estimates.

Our result of increasing marginal costs of avoided burned area demonstrates, on economic grounds, that, as others had already claimed on technical grounds, zero burned area is not an option and, therefore, we need a new paradigm oriented towards the reduction of damage caused by wildfires. The marginal social CBA proposed and illustrated in this article, using our marginal cost estimates, provides an analytical framework to support decisions about how far to go in fuel management under this new paradigm. Concerning our study area, our results suggest that we currently are below the optimal fuel management level, where the marginal cost of avoiding the last hectare of burned area would be equal to the corresponding marginal benefit (i.e., marginal wildfire damage cost avoided). The illustrative cost–benefit diagram in the discussion section suggests the potential of more targeted approaches to fuel management for reducing marginal cost, and thus for increasing the optimum level of fuel management. More investment in knowledge and innovation in this direction is thus warranted, as it will probably pay back by making higher levels of wildfire damage reduction affordable, with the consequent net benefits for society.

Author Contributions: Conceptualization, J.L.S., A.M., A.N., and M.J.C.; methodology, J.L.S., A.M., A.N., and M.J.C.; validation, J.L.S., A.M., A.N., and M.J.C.; formal analysis, J.L.S., A.M., A.N., and M.J.C.; investigation, J.L.S., A.M., A.N., and M.J.C.; data curation, A.M.; writing—original draft preparation, J.L.S., A.M., A.N., and M.J.C.; writing—review and editing, J.L.S., A.M., A.N., and M.J.C.; visualization, J.L.S., A.M., A.N., and M.J.C.; supervision, M.J.C. and J.L.S.; project administration, A.M. All authors have read and agreed to the published version of the manuscript.

Funding: The "Observador" newspaper funded the fieldwork and the publication of this article. Fundação para a Ciência e Tecnologia (FCT) financed this research through the Ph.D. fellowship (PDBD/113930/2015), at the Ph.D. Program in Climate Change and Sustainable Development Policies, and through the project "People and Fire (FCT - PCIF/AGT/0136/2017).

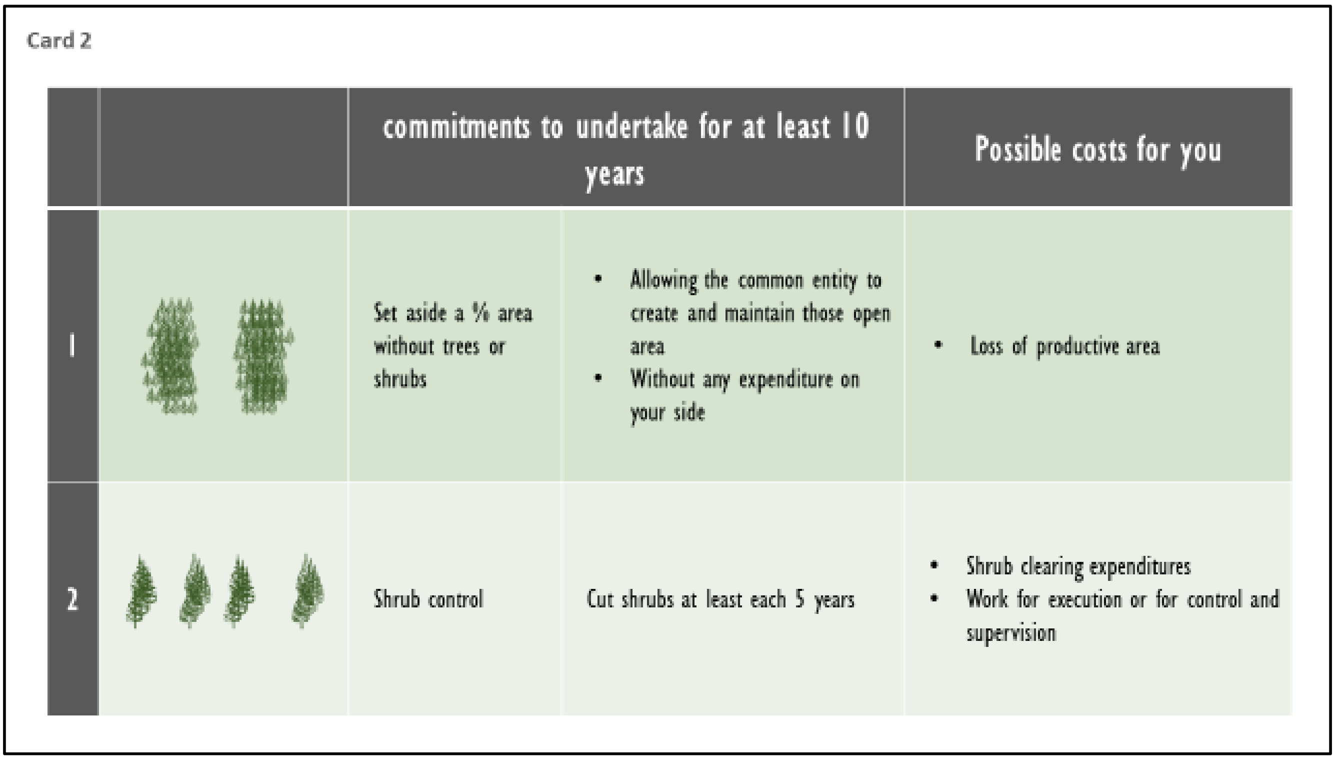
Data Availability Statement: Data is not available due to confidentiality and privacy issues given the extremely small size of the study area, and relatively small number of forest owners in the study area, that would made some of them identifiable even if the data were anonymous.

Acknowledgments: We are grateful to all colleagues and people from the Alvares community who helped us during the field work, in particular to all forest owners who participated in our survey. We also thank to two anonymous reviewers whose comments very much contributed to the quality of the article.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

Appendix A

The length of the commitment was described as a minimum of 10 years, the frequency of the payment as annual, the program supervision as being done by national authorities, and the consequences for serious rule breaking as the suspension of payments and recovery of the received amounts. For clarity purposes, a note was produced, which indicated that selling or renting would be considered a contract breach, unless the commitments were formally transferred to the buyer or tenant.



Card 2

		commitments to undertake for at least 10 years		Possible costs for you
1		Set aside a % area without trees or shrubs	• Allowing the common entity to create and maintain those open area • Without any expenditure on your side	• Loss of productive area
2		Shrub control	Cut shrubs at least each 5 years	• Shrub clearing expenditures • Work for execution or for control and supervision

Figure A1. Card 1—Visual presentation of the commitments to be subscribed by the respondent for at least ten years and possible costs, for each commitment. The choice experiment only proceeded after careful presentation of each attribute and all doubts explained.

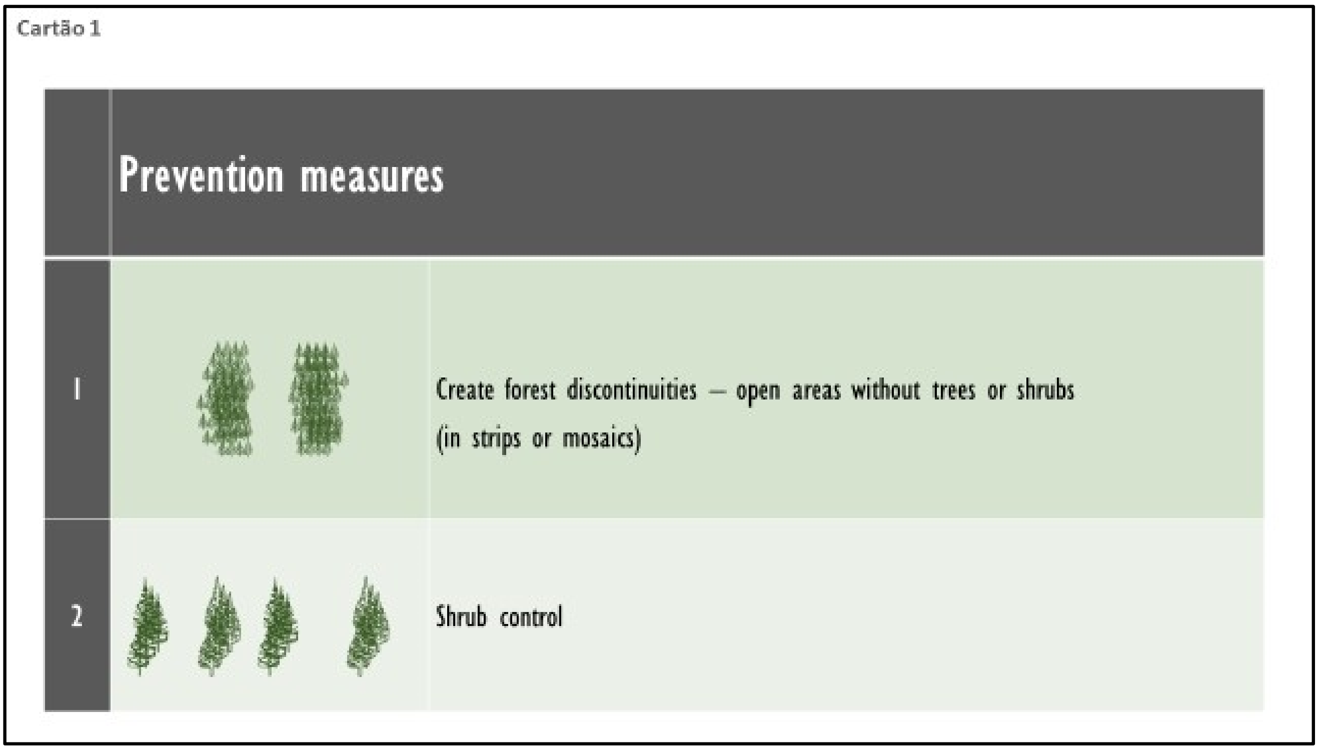


Figure A2. Card 2—visual presentation of the prevention measures (i.e., the choice experiment's attributes shrub and fuel break) under the contract explained to the respondents.

References

1. Rossi, J.L. *Evolving Risk of Wildfires in Europe: The Changing Nature of Wildfire Risk Calls for a Shift in Policy Focus from Suppression to Prevention*; UN Office for Disaster Risk Reduction: Brussels, Belgium, 2020.
2. Lee, C.; Schlemme, C.; Murray, J.; Unsworth, R. The cost of climate change: Ecosystem services and wildland fires. *Ecol. Econ.* **2015**, *116*, 261–269. [CrossRef]
3. Moreira, F.; Ascoli, D.; Safford, H.; Adams, M.; Moreno, J.; Pereira, J.; Catry, F.X.; Armesto, J.; Bond, W.; González, M.E.; et al. Wildfire management in Mediterranean-type regions: Paradigm change needed. *Environ. Res. Lett.* **2020**, *15*, 011001. [CrossRef]
4. Fernandes, P. Fire-smart management of forest landscapes in the Mediterranean basin under global change. *Landsc. Urban Plan.* **2013**, *110*, 175–182. [CrossRef]
5. Fernandes, P.M.; Guiomar, N.; Rossa, C.G. Analysing eucalypt expansion in Portugal as a fire-regime modifier. *Sci. Total Environ.* **2019**, *666*, 79–88. [CrossRef] [PubMed]
6. Collins, R.D.; de Neufville, R.; Claro, J.; Oliveira, T.; Pacheco, A.P. Forest fire management to avoid unintended consequences: A case study of Portugal using system dynamics. *J. Environ. Manag.* **2013**, *130*, 1–9. [CrossRef]
7. Badgon, B.; Huang, C.H. *Review of Economic Benefits from Fuel Reduction Treatments in Fire Prone Forests on the Southwestern US*; Southwest Fire Science Consortium, Northern Arizona University: Flagstaff, AZ, USA, 2016; 11p.
8. Busby, G.; Albers, H. Wildfire risk management on a landscape with public and private ownership: Who pays for protection? *Environ. Manag.* **2010**, *45*, 296–310. [CrossRef]
9. Prante, T.; Little, J.M.; Jones, M.; McKeed, M.; Berrens, R. Inducing private wildfire risk mitigation: Experimental investigation of measures on adjacent public lands. *J. For. Econ.* **2011**, *17*, 415–431. [CrossRef]
10. Pra, A.; Masiero, M.; Barreiro, S.; Tomé, M.; De Arano, I.M.; Orradre, G.; Onaindia, A.; Brotto, L.; Pettenella, D. Forest plantations in Southwestern Europe: A comparative trend analysis on investment returns, markets and policies. *For. Policy Econ.* **2019**, *109*, 102000. [CrossRef]
11. Santos, J.L.; Madureira, L.; Ferreira, A.C.; Espinosa, M.; Paloma, S.G. Building an empirically-based framework to value multiple public goods of agriculture at broad supranational scales. *Land Use Policy* **2016**, *53*, 56–70. [CrossRef]
12. Radich, M.C.; Baptista, F.O. Floresta e Sociedade: Um Percurso (1875–2005). *Silva Lusit.* **2005**, *13*, 143–157.
13. Canadas, M.J.; Novais, A.; Marques, M. *Proprietários florestais, políticas e Territórios: Incêndios e a gestão do Espaço Rural [Forest Owners, Policies and Territories: Wildfires and Rural Areas Management]*; ANIMAR: Lisboa, Portugal, 2014.
14. Loomis, J.; González-Caban, A. Contingent valuation of fuel hazard reduction treatments. In *The Economics of Forest Disturbances: Wildfires, Storms and Invasive Species*; Holmes, T.P., Prestemon, J.P., Abt, K.L., Eds.; Springer: Newton, NC, USA, 2008; pp. 229–243.

15. Loomis, J.; Hung, L.; González-Caban, A. Willingness to pay function for two fuel treatments to reduce wildfire acreage burned: A scope teste and comparison of White and Hispanic households. *For. Policy Econ.* **2009**, *11*, 155–160. [CrossRef]
16. Loomis, J.; González-Caban, A. Forest service use of nonmarket valuation in fire economics: Past, present and future. *J. For.* **2010**, *108*, 389–396.
17. Varela, E.; Jacobsen, J.B.; Soliño, M. Understanding the heterogeneity of social preferences for fire prevention management. *Ecol. Econ.* **2014**, *106*, 91–104. [CrossRef]
18. Varela, E.; Giergiczny, M.; Riera, P.; Mahieu, P.A.; Soliño, M. Social preferences for fuel break management programs in Spain: A choice modelling application to prevention of forest fires. *Int. J. Wildland Fire* **2014**, *23*, 281–289. [CrossRef]
19. Durán-Medraño, R.; Varela, E.; Garza-Gil, D.; Prada, A.; Vázquez, M.; Soliño, M. Valuation of terrestrial and marine biodiversity losses caused by forest wildfires. *J. Behav. Exp. Econ.* **2017**, *75*, 88–95. [CrossRef]
20. Alló, M.; Loureiro, M.L. Assessing preferences for wildfire prevention policies in Spain. *For. Policy Econ.* **2020**, *115*, 102145. [CrossRef]
21. Jarret, A.; Gan, J.; Johnson, C.; Munn, I. Landowner awareness and adoption of wildfire programs in the Southern United States. *J. For.* **2009**, *107*, 113–118.
22. Crowley, C.; Malik, A.; Amacher, G.; Haight, R. Adjacency externalities and forest fire prevention. *Land Econ.* **2009**, *85*, 162–185. [CrossRef]
23. Cooper, T.; Hart, K.; Baldock, D. *Provision of Public Goods through Agriculture in the European Union*; Institute for European Environmental Policy: London, UK, 2009.
24. Zahrnt, V. *Public Money for Public Goods: Winners and Losers from CAP Reform*; ECIPE working paper No. 739-2016-50917; European Centre for International Political Economy (ECIPE): Brussels, Belgium, 2009.
25. Bateman, I.J.; Balmford, B. Public funding for public goods: A post-Brexit perspective on principles for agricultural policy. *Land Use Policy* **2018**, *79*, 293–300. [CrossRef]
26. Czúcz, B.; Arany, I.; Potschin-Young, M.; Bereczki, K.; Kertész, M.; Kiss, M.; Aszalós, R.; Haines-Young, R. Where concepts meet the real world: A systematic review of ecosystem service indicators and their classification using CICES. *Ecosyst. Serv.* **2018**, *29*, 145–157. [CrossRef]
27. Alliance Environnement. *Evaluation Study if the Forestry Measures Under Rural Development*; European Comission, Directorate-General for Agriculture and Rural Development: Brussels, Belgium, 2017.
28. Bjärstig, T. The Swedish forest sector's approach to a formalized forest policy within the EU. *For. Policy Econ.* **2013**, *26*, 131–137. [CrossRef]
29. Varela, E.; Górriz-Mifsud, E.; Ruiz-Mirazo, J.; López-i-Gelats, F. Payments for targeted grazing: Integrating local sheperds into wildfire prevention. *Forests* **2018**, *9*, 464. [CrossRef]
30. Kilgore, M.; Ellefson, P.; Funk, T.; Frey, G. Private forest owners and tax incentive programs in the United States: A national review and analysis of ecosystem services promoted, landowner participation, forestland area enrolled, and magnitude of tax benefits provided. *Forest Policy Econ.* **2018**, *97*, 33–40. [CrossRef]
31. Rummer, B. Assessing the cost of fuel reduction treatments: A critical review. *For. Policy Econ.* **2008**, *10*, 355–362. [CrossRef]
32. Bennett, J.; Blamey, R. (Eds.) *The Choice Modelling Approach to Environmental Valuation*; Edward Elgar Publishing: Cheltenham, UK, 2001.
33. Bateman, I.J.; Carson, R.T.; Day, B.; Hanemann, M.; Hanley, N.; Hett, T.; Jones-Lee, M.; Loomes, G.; Mourato, S.; Özdemiroglu, E.; et al. *Economic Valuation with Stated Preference Techniques: A Manual*; Edward Elgar Publishing: Cheltenham, UK, 2002.
34. Mavsar, R.; Japelj, A.; Kovač, M. Trade-offs between fire prevention and provision of ecosystem services in Slovenia. *For. Policy Econ.* **2013**, *29*, 62–69. [CrossRef]
35. Madureira, L.; Magalhães, P.; Silva, P.G.; Marinho, C.; Oliveira, R. *Economia dos Serviços de Ecossistema: Um Guia para Conhecer e Valorizar Serviços de Agroecossistemas em Áreas Protegidas de Montanha*; Quercus–Associação Nacional de Conservação da Natureza: Lisboa, Portugal, 2013; 146p.
36. Christensen, T.; Pedersen, A.B.; Nielsen, H.O.; Mørkbak, M.R.; Hasler, B.; Denver, S. Determinants of farmers' willingness to participate in subsidy schemes for pesticide-free buffer zones: A choice experiment study. *Ecol. Econ.* **2011**, *70*, 1558–1564. [CrossRef]
37. Duke, J.M.; Borchers, A.M.; Johnston, R.J.; Absetz, S. Sustainable agricultural management contracts: Using choice experiments to estimate the benefits of land preservation and conservation practices. *Ecol. Econ.* **2012**, *74*, 95–103. [CrossRef]
38. Le Coent, P.; Préget, R.; Thoyer, S. Compensating environmental losses versus creating environmental gains: Implications for biodiversity offsets. *Ecol. Econ.* **2017**, *142*, 120–129. [CrossRef]
39. Ruto, E.; Garrod, G. Investigating farmers' preferences for the design of agri-environment schemes: A choice experiment approach. *J. Environ. Plan. Manag.* **2009**, *52*, 631–647. [CrossRef]
40. Espinosa-Goded, M.; Barreiro-Hurlé, J.; Ruto, E. What do farmers want from agri-environmental scheme design? A choice experiment approach. *J. Agric. Econ.* **2010**, *61*, 259–273. [CrossRef]
41. Broch, S.W.; Vedel, S.E. Using choice experiments to investigate the policy relevance of heterogeneity in farmer agri-environmental contract preferences. *Environ. Resour. Econ.* **2012**, *51*, 561–581. [CrossRef]
42. Vedel, S.E.; Jacobsen, J.B.; Thorsen, B.J. Contracts for afforestation and the role of monitoring for landowners' willingness to accept. *For. Policy Econ.* **2015**, *51*, 29–37. [CrossRef]

43. Lienhoop, N.; Brouwer, R. Agri-environmental policy valuation: Farmers' contract design preferences for afforestation schemes. *Land Use Policy* **2015**, *42*, 568–577. [CrossRef]
44. Santos, R.; Clemente, P.; Brouwer, R.; Antunes, P.; Pinto, R. Landowner preferences for agri-environmental agreements to conserve the montado ecosystem in Portugal. *Ecol. Econ.* **2015**, *118*, 159–167. [CrossRef]
45. Horne, P. Forest owners' acceptance of incentive based policy instruments in forest biodiversity conservation: A choice experiment based approach. *Silva Fenn.* **2006**, *40*, 169–178. [CrossRef]
46. Lindhjem, H. 20 years of stated preference valuation of non-timber benefits from Fennoscandian forests: A meta-analysis. *J. For. Econ.* **2007**, *12*, 251–277. [CrossRef]
47. Vedel, S.E.; Jacobsen, J.B.; Thorsen, B.J. Forest owners' willingness to accept contracts for ecosystem service provision is sensitive to additionality. *Ecol. Econ.* **2015**, *113*, 15–24. [CrossRef]
48. Stevens, T.H.; White, S.; Kittredge, D.B.; Dennis, D. Factors affecting NIPF landowner participation in management programs: A Massachusetts case study. *J. For. Econ.* **2002**, *8*, 169–184.
49. Kang, M.J.; Siry, J.P.; Colson, G.; Ferreira, S. Do forest property characteristics reveal landowners' willingness to accept payments for ecosystem services contracts in southeast Georgia, US? *Ecol. Econ.* **2019**, *161*, 144–152. [CrossRef]
50. Fischhoff, B.; Furby, L. Measuring values: A conceptual framework for interpreting transactions with special reference to contingent valuation of visibility. *J. Risk Uncertain.* **1988**, *1*, 147–184. [CrossRef]
51. Mitchell, R.C.; Carson, R.T. *Using Surveys to Value Public Goods: The Contingent Valuation Method*; Resources for the Future: Washington, DC, USA, 1989.
52. Lindhjem, H.; Mitani, Y. Forest owners' willingness to accept compensation for voluntary conservation: A contingent valuation approach. *J. For. Econ.* **2012**, *18*, 290–302.
53. Pereira, J.M.; Benali, A.; Sá, A.; Le Page, Y.; Barreiro, S.; Rua, J.; Tomé, M.; Santos, J.L.; Canadas, M.J.; Martins, A.; et al. *Alvares—um Caso de Resiliência ao Fogo (Relatório Técnico)*; Instituto Superior de Agronomia: Lisbon, Portugal, 2019.
54. Verde, J.C.; Zêzere, J.L. Assessment and validation of wildfire susceptibility and hazard in Portugal. *Nat. Hazards Earth Syst. Sci.* **2010**, *10*, 485–497. [CrossRef]
55. INE. X Recenseamento Geral da População. Tomo I. Vol1. Prédios e fogos. In *População—Dados Retrospectivos (Distritos, Concelhos e Freguesias)*; Instituto Nacional de Estatística: Lisboa, Portugal, 1960.
56. INE. *Censos 2011 Resultados Definitivos-Portugal*; Instituto Nacional de Estatística: Lisboa, Portugal, 2012.
57. Riera, P.; Signorello, G.; Thiene, M.; Mahieu, P.A.; Navrud, S.; Kaval, P.; Rulleau, B.; Mavsar, R.; Madureira, L.; Meyerhoff, J.; et al. Non-market valuation of forest goods and services: Good practice guidelines. *J. For. Econ.* **2012**, *18*, 259–270. [CrossRef]
58. Pereira, J.S. (Ed.) *Incêndios Florestais em Portugal: Caracterização, Impactes e Prevenção*; Instituto Superior de Agronomia: Lisbon, Portugal, 2006; ISBN 972-8669-17-8.
59. Moreira, F.; Viedma, O.; Arianoutsou, M.; Curt, T.; Koutsias, N.; Rigolot, E.; Barbati, A.; Corona, P.; Vaz, P.; Xanthopoulos, G.; et al. Landscape—Wildfire interactions in Southern Europe: Implications for landscape management. *J. Environ. Manag.* **2011**, *92*, 2389–2402. [CrossRef] [PubMed]
60. Oliveira, T.; Barros, A.; Ager, A.; Fernandes, P. Assessing the effect of fuel break network to reduce burnt area and wildfire risk transmission. *Int. J. Wildland Fire* **2016**, *25*, 619–632. [CrossRef]
61. Holmes, T.P.; Adamowicz, W.L.; Carlsson, F. Choice experiments. In *A Primer on Nonmarket Valuation*; Springer: Dordrecht, The Netherlands, 2017; pp. 133–186.
62. Jaccard, J. *Interaction Effects in Logistic Regression (No. 135)*; Sage University Papers Series on Quantitative Applications in the Social Sciences, 07-135; Sage: Thousand Oacks, CA, USA, 2001.
63. Hair, J.F.; Black, W.C.; Babin, B.J.; Anderson, R.E.; Tatham, R.L. *Multivariate Data Analysis*; Prentice Hall: Uppersaddle River, NJ, USA, 2010; 816p.
64. Cameron, T.A.; James, M.D. Efficient estimation methods for "closed-ended" contingent valuation surveys. *Rev. Econ. Stat.* **1987**, *69*, 269–276. [CrossRef]
65. Santos, J.L. *The Economic Valuation of Landscape Change: Theory and Policies for Land Use and Conservation*; Edward Elgar Publishing: Cheltenham, UK, 1998.
66. Hanemann, M. Welfare Evaluations in Contingent Valuation Experiments with Discrete Responses. *Am. J. Agric. Econ.* **1984**, *66*, 332–341. [CrossRef]
67. Borrooah, V.K. *Logit and Probit: Ordered and Multinomial Models*; Sage University Papers Series on Quantitative Applications in the Social Sciences; Series no 07-138; Sage: Thousand Oaks, CA, USA, 2001.
68. Barreiro, S.; Benali, A.; Rua, J.C.P.; Tomé, M.; Pereira, J.C. Assisting landowners in building fire-resilient landscapes using forest management driven simulations. *Forests* **2021**, in press.
69. Benali, A.; Sá, A.; Le Page, Y.; Pinto, M.M.; Nunes, S.; Pinho, J.; Pereira, J.C. Understanding the impact of different landscape-level fuel management approaches on wildfire exposure. *Forests* **2021**, in press.
70. Finney, M.A. *FARSITE: Fire Area Simulator–Model Development and Evaluation*; Research Paper RMRS-RP-4 Revised; U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: Ogden, UT, USA, 2004; 47p.
71. Novais, A.; Canadas, M.J. Understanding the management logic of private forest owners: A new approach. *For. Policy Econ.* **2010**, *12*, 173–180. [CrossRef]

72. Canadas, M.J.; Novais, A. Bringing local socioeconomic context to the analysis of forest owners' management. *Land Use Policy* **2014**, *41*, 397–407. [CrossRef]
73. Canadas, M.J.; Novais, A. Forest owners and fuels management coordination. When neighbours' actions matter. *Scand. J. For. Res.* **2019**, *34*, 67–77. [CrossRef]
74. Greenberg, M.; Haas, C.; Cox, A.; Lowrie, K.; McComas, K.; North, W. Ten Most Important Accomplishments in Risk Analysis, 1980–2010. *Risk Anal.* **2012**, *32*, 771–781. [CrossRef]
75. Wilson, R.S.; Arvai, J.L.; Arkes, H.R. My Loss Is Your Loss Sometimes: Loss Aversion and the Effect of Motivational Biases. *Risk Anal.* **2008**, *28*, 929–938. [CrossRef]
76. Baptista, F.O.; Novais, A.; Canadas, M.J.; Marques, M.; Reis, P.; Oliveira, T. *Proprietários, Gestão Florestal e Incêndios*; Project report; ISA: Lisboa, Portugal, 2015.
77. DGRF. *Estratégia Nacional para as Florestas*; Direcção Geral de Recursos Florestais: Lisboa, Portugal, 2006.
78. Canadas, M.J.; Novais, A.; Marques, M. Wildfires, forest management and landowners' collective action: A comparative approach at the local level. *Land Use Policy* **2016**, *56*, 179–188. [CrossRef]
79. Calkin, D.; Gebert, A. Modeling fuel treatment costs on Forest Service Lands in the western US. *West. J. Appl. For.* **2006**, *21*, 217–221. [CrossRef]
80. Ficko, A.; Lidestav, G.; Dhubháin, A.; Karppinen, H.; Zivojinovic, I.; West, K. European private forest owner typologies: A review of methods and use. *For. Policy Econ.* **2019**, *99*, 21–31. [CrossRef]
81. Martins, A.; Novais, A.; Santos, J.M.; Canadas, M.J. Modelling private owners' choices for alternative options to achieve landscape-level management coordination. Case study in a context of high wildfire hazard. *For. Policy Econ.*. submitted.
82. CCDRC. *Relatório de Incêndios na Região Centro. 17 a 21 de Junho de 2017*; Pedrógão Grande, Castanheira de Pêra, Figueiró dos Vinhos, Pampilhosa da Serra, Sertã, Góis e Penela, Comissão de Coordenação e Desenvolvimento Regional do Centro: Coimbra, Portugal, 2017.
83. Ager, A.; Finney, M.; McMahan, A. A wildfire risk modeling system for evaluating landscape fuel treatment strategies. In *Proceedings of the Fuels Management-How to Measure Success: Conference Proceedings, Portland, OR, USA, 28–30 March 2006*; Proceedings RMRS-P-41; Andrews, P.L., Butler, B.W., Eds.; US Department of Agriculture, Forest Service, Rocky Mountain Research Station: Fort Collins, CO, USA, 2006; pp. 149–162.