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Wildfire mitigation and adaptation: Two locally independent actions supported by different policy domains

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A R T I C L E I N F O

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A B S T R A C T

There is a broad consensus in the academic and policy communities over the need to shift the focus from fire suppression to fire prevention. To inform policies that effectively promote this shift, we distinguish between prevention actions aimed at more fire-resilient landscapes and those focused on the protection of people, i.e., wildfire mitigation and adaptation (WM&A), respectively. With the goal of discussing the usefulness of this distinction and identifying local factors and external resources that promote each of those preventive actions, we developed an analysis of collective WM&A actions across 116 parishes in a wildfire-prone region in Portugal, using primary and secondary data. Two principal component analyses were used to explore relationships between variables expressing collective WM&A actions. Random forest, a machine learning technique based on multiple decision trees, was used to model how those actions are related to local factors (land use/land cover, population, institutions) and access to policy funding for wildfire prevention. Our results showed that collective mitigation and adaptation responses to wildfire are locally independent, in coherence with their distinct goals, actors involved, and institutional and policy framing. Mitigation through owners' collaboration proved to be strongly related to policy funding (notably that exclusively addressed at mitigation), local socioeconomic dynamism, and ownership structure, whereas adaptation responses are related with leadership by local governments. Considering these differences, the incipiency of adaptation actions, and the difficulties in expanding owner's collaboratives beyond the most favourable local conditions, we conclude that mitigation and adaptation actions are currently supported by two distinct policy domains with unequal consolidation but equally underfunded.

1. Introduction

Wildfires are an integral component of Mediterranean Europe due to its climate and vegetation cover (Amraoui et al., 2015; Ganteaume et al., 2013). The most affected countries (Portugal, Spain, Italy, Greece, and France) have largely relied upon centralised suppression strategies, focused on enhancing firefighting capabilities and reducing burnt area (Busenberg, 2004; Calkin et al., 2014; Collins et al., 2013; Fernandes et al., 2020; North et al., 2015). Suppression has nevertheless been accused of originating a "fire paradox", i.e., creating favourable conditions for high-magnitude events that cause large burnt areas in years with adverse weather (Carlucci et al., 2019; Jiménez-Ruano et al., 2020; Montiel-Molina, 2013; Silva et al., 2019). In fact, despite the costly investments in suppression, recent decades have witnessed a steadily

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increase in the extent and severity of wildfires in Mediterranean Europe, as well as in the frequency of extreme events due to land use/land cover (LULC) and climate changes that are expected to continue (García-Llamas et al., 2019; González-De Vega et al., 2016).

Consequently, there is a broad consensus in the academic and policy communities over the need to shift the focus from fire suppression to fire prevention (Ager et al., 2018; EC, 2018; Fernandes et al., 2020; Leone and Tedim, 2020; Moreira et al., 2020). Prevention includes fuel management by forest owners to reduce the amount and continuity of fuels (Fernandes et al., 2014; Martins et al., 2021; Moreira et al., 2011; Oliveira et al., 2013) and the creation of defensible or survivable space by homeowners to make their lives, livelihoods and property less vulnerable to wildfire damage (Stasiewicz and Paveglio, 2021). We name these mitigation and adaptation, respectively.

Wherever small-scale owners prevail, mitigation and adaptation require the actions of many individuals and entities at the local level, such as landowners, homeowners, and the organizations and institutions representing them (Busenberg, 2004; Gill, 2005; Weber et al., 2019). Besides involving distinct stakeholders, wildfire mitigation and adaptation (hereafter WM&A) actions can be undertaken at distinct levels (Gill, 2005; Haynes et al., 2020; Jakes et al., 2007; Labossière and McGee, 2017; McCaffrey et al., 2020): 1) the individual level, by private homeowners and landowners; 2) the collective level, by private owner groups, local (e.g., village) communities, and local governments; and 3) the organizational/national level, mainly by national governments implementing preventive or regulatory measures, such as wildfire risk assessments, rules on the location of buildings and infrastructures, funding of action at the individual or collective levels, and educational programs to improve people's awareness (Montiel-Molina, 2013). Our research is focused on the second, collective level.

The collective level is relevant because, to be effective, WM&A actions need to be coherently implemented at a scale larger than the individual. For example, mitigation actions need to consider the landscape scale due to non-linearity of the hazard-managed area relationship (Canadas et al., 2016; OECD, 2013) and because the location of fuel management actions matters (Santos et al., 2021); in small-scale ownership contexts, acting at this broader scale asks for the coordination of multiple owners' actions (Ager et al., 2018; Alcasena et al., 2019; Busenberg, 2004; Charnley et al., 2020; Palaiologou et al., 2018).

The collective level has nevertheless received scant attention in the extensive literature on human response to wildfires. Most empirical studies have focused on individual responses by either landowners (e.g., Fischer, 2011; Rodríguez-Carreras et al., 2020) or homeowners (e.g., Bardsley et al., 2021; Brenkert-Smith et al., 2012; Martin et al., 2009; McCaffrey et al., 2011; McGee et al., 2009; Olsen et al., 2017). The limited research at the collective level considered, for instance, landowner groups (Canadas et al., 2016), voluntary citizen groups (Everett and Fuller, 2011; Górriz-Mifsud et al., 2019; Haynes et al., 2020), and "communities" more broadly (Fairbrother et al., 2013; Jakes et al., 2007; Mockrin et al., 2018; Paveglio et al., 2015, 2019).

Likewise, the identification of the factors that promote WM&A actions has been mostly carried out at the individual rather than the collective level, focusing on cognitive factors and homeowners' response (e.g., Bardsley et al., 2021; Charnley et al., 2020; Edgeley et al., 2020; Fischer et al., 2019; Mockrin et al., 2020; Paveglio et al., 2019). For our collective-level analysis, and with the support of collective action (CA) theories, we explored factors characterizing the territorial context of the action, which were grouped in several dimensions: LULC, population, institutions, and external resources (Bihari and Ryan, 2012; OECD, 2013; Poteete and Ostrom, 2008). External resources mainly refer to public policies and access to public funding, which are expected to play a major role in enabling collective action (Canadas et al., 2016; OECD, 2013). This role has however been scantly analysed, because the policy-oriented literature is still focused on demonstrating the failure of wildfire suppression, in many geographical contexts (Busenberg, 2004; Collins et al., 2013; Fernandes et al., 2020; Galiana et al., 2013; Leone and Tedim, 2020; Montiel-Molina, 2013; Moreira et al., 2020; Otero and Nielsen, 2017), rather than on implementing prevention strategies. This study aims to contribute to an effective implementation of the shift in focus from suppression to prevention by analysing the diversity of collective WM&A actions within a Portuguese region frequently affected by wildfires: Pinhal Interior.

The main innovation in our study is introducing a framework that: 1) distinguishes between mitigation and adaptation based on the nature and objectives of the action and the actors; 2) addresses both mitigation and adaptation in the same analysis using the same set of explanatory factors; and 3) considers both local context (natural resources, population, and institutions) and external resources (such as access to policy funding) among such factors. In addition, this framework is developed and tested in a territorial context that has received scant attention: Mediterranean Europe. The main goal of this research is thus to explore the usefulness of this framework to discuss the effectiveness of different governance and policy options for wildfire prevention.

2. Literature review

In this section we build our conceptual framework, by, first, justifying and clarifying our use of the mitigation and adaptation notions, and, second, identifying the factors influencing collective actions/responses to wildfire.

2.1. Distinguishing wildfire mitigation by landowners and adaptation by community members

Mitigation and adaptation are concepts with distinct and even contradictory definitions in different research fields. For the United Nations Office for Disaster Risk Reduction (UNISDR), mitigation can be understood as "the lessening or limitation of the adverse impacts of hazards and related disasters", while adaptation is "the adjustment in natural or human systems in response to actual or expected stimuli or their effects, which moderates harm or exploits beneficial opportunities" (UNISDR, 2009). In this context, e.g., purely natural disasters like earthquakes, mitigation as hazard reduction is not a possibility, and thus both mitigation and adaptation have to do with impact reduction. On the other hand, the Intergovernmental Panel on Climate Change (IPCC), which deals with an anthropogenic hazard, climate change, defines mitigation as "the human intervention to reduce the sources or enhance the sinks of greenhouse gases" (IPCC, 2014), thus reducing climate change (the hazard), while adaptation is "the process of adjustment to actual or expected climate and its effects" (Noble et al., 2014).

Wildfires are more similar to climate change than to purely natural disasters in that an anthropogenic hazard (wildfire and climate change, respectively) can be reduced through human action. As an analogy with the climate change framework (Sharifi, 2021), we use the term mitigation to designate action aimed at reducing the magnitude of wildfire hazard through fuel management. Accordingly, the term adaptation is used, in this paper, for action aimed at decreasing the exposure and vulnerability of people and goods to wildfires. The heuristic power of the mitigation-adaptation dichotomy is not jeopardized by the fact that some particular actions may contribute for both mitigation and adaptation. Contrarily, synergies and overlaps are extensively searched for in the climate change literature (Kongsager, 2018; Sharifi, 2021).

The recent focus shift from suppression to prevention has changed the overall purpose of wildfire policy from damage reduction to hazard reduction. Of course, both mitigation and adaptation contribute to reduce wildfire damage, and thus selecting an appropriate damage reduction strategy requires finding the right mix of mitigation and adaptation for each context. By reducing burnt area, mitigation directly reduces the damage to forests. It is possible that this direct, more visible link between mitigation and the protection of forest interests has led forest-oriented policies to focus on mitigation. Of course, by creating fire-resilient landscapes, mitigation also indirectly (but effectively) contributes to protect people, their goods, and the local economy. On the other hand, it is probable that policies aimed at the protection of people and the local economy have focused on reducing the exposure and vulnerability of local people and infrastructure to wildfires, or adaptation, because the link to the relevant damage is more direct.

Our distinction between mitigation and adaptation takes into consideration the action itself, its objectives, and the actors involved, in line with the need to identify the policy recipients. Mitigation actions are primarily designed to reduce the susceptibility of the landscape to wildfire, while protecting forest assets. Adaptation actions mainly seek to safeguard people and goods through reducing their exposure and vulnerability. Mitigation includes actions taken by landowners to reduce the amount or modify the kind and arrangement of fuel loads in forest and agricultural areas, thereby contributing to reduce wildfire hazard (Fernandes et al., 2014; Martins et al., 2021; Moreira et al., 2011; Oliveira et al., 2013). Examples include thinning or understory scrub clearing, networks of fuel breaks, or mosaics with different land uses, and converting stands into less flammable tree species. Adaptation actions are taken by residents, homeowners, local communities, or local governments to create defensible space on their properties and territories (Alcasena et al., 2019; Bihari and Ryan, 2012; Stidham et al., 2014) or to get insurance policies that allow a quicker recovery after a damaging event (Gan et al., 2015). Adaptation includes actions taken to reduce wildfire-caused loss and impact on locale people and economy, such as fuel treatments and protection strips in the surroundings of rural settlements and infrastructure, material investments in local firefighting capacity, escape strategies, evacuation routes, and shelters (Everett and Fuller, 2011).

This use of the proposed mitigation and adaptation notions, inspired by Gan et al., (2014, 2015), is almost absent within the social-science approaches to wildfires, despite the frequent use of both notions, sometimes interchangeably. For instance, Paveglio et al. (2016) describe wildfire adaptation as "the enactment of context-specific processes and actions local people undertake in the face of wildfire risk" and mitigation as a component of "larger adaptation processes (…) referring to specific actions that reduce the future impact of hazards [e.g., fuel reduction around homes, establishment of community-wide fire breaks, etc.]" (p. 1247).

In addition, mainstream wildfire studies have almost never considered the response and actions of both community members and landowners within the same study and analytical framework. Actually, they have focused much more on the response-action of residents living at the wildland urban interface (WUI) (Bardsley et al., 2021; Brenkert-Smith et al., 2017; Champ et al., 2013; Koksal et al., 2019; Martin et al., 2007, 2009; McCaffrey, 2008; McFarlane et al., 2011; McNeill et al., 2013; Wilson et al., 2017) than on the response of landowners and land managers (Fischer, 2012, 2011; Fischer et al., 2014; Gan et al., 2015; Jarrett et al., 2009; Wyman et al., 2012).

2.2. Factors that may influence collective mitigation and adaptation actions

The identification of factors influencing collective WM&A actions by groups of citizens and/or by local governments requires some preliminary considerations on the burgeoning body of research on human responses to wildfires (for a review, see McCaffrey, 2015; McCaffrey et al., 2020). This literature has been mostly focused: 1) on the individual rather than the collective level (e.g., Weber et al., 2019); 2) on cognitive rather than structural factors (Novais and Canadas, 2022); and 3) on territorial contexts such as the United States (US) rather than the European Mediterranean. That is why few studies have investigated collective responses by local governments (Harris et al., 2011; Labossière and McGee, 2017; Muller and Schulte, 2011). In addition to representing the residents, local governments act as conduits between larger, national scale resources, policies and incentives, and WM&A efforts on the ground (McCaffrey et al., 2020). This study aims to fill the abovementioned gaps by exploring structural factors underlying collective WM&A responses of citizen groups and local governments in Mediterranean Europe.

That literature has outlined various factors that may foster (or hinder) collective WM&A responses. Cognitive factors such as perceived wildfire risk, perceived damage, wildfire experience, place attachment, and access to scientific or technical knowledge, amongst others, have received a considerable attention (Bardsley et al., 2021; Fischer, 2011; Gan et al., 2015; Harris et al., 2011; Jakes et al., 2007; Jarrett et al., 2009; Labossière and McGee, 2017; Martin et al., 2009; McGee et al., 2009; McGee and Russell, 2003; Olsen et al., 2017; Paveglio et al., 2012, 2016; Schultz and Moseley, 2019; Steelman and Kunkel, 2004; Stidham et al., 2014; Weber et al., 2019). The effect of these factors has not always been consistent across studies. For instance, some have found that wildfire experience and risk perception increase WM&A efforts (Haynes et al., 2020; Jakes and Sturtevant, 2013; Labossière and McGee, 2017; Mockrin et al., 2018), while no effect or the reverse has been found by others (Martin et al., 2009; McCaffrey et al., 2020; McGee et al., 2009; Paveglio et al., 2012). The impacts of experience and awareness on action tend to be higher immediately after a wildfire event and quickly subside as time passes (Martin et al., 2009).

To compare collective WM&A actions across distinct territorial units, the factors considered in this study characterize the territorial context of those actions. Their selection benefited from a wider perspective on rural areas dynamics and typologies (Arnalte-Alegre et al., 2012; Baptista, 2010; Elands et al., 2004) and combined the previously reviewed literature on wildfire responses with the conceptual framework of CA. This framework has increasingly integrated both ecological and socioeconomic factors to explain what fosters or inhibits effective CA (Agrawal, 2001; Canadas et al., 2016; Meinzen-Dick et al., 2004; Poteete and Ostrom, 2008; Ratner et al., 2013; Sapkota et al., 2015), and has already been used in wildfire response analysis (Canadas et al., 2016; Charnley et al., 2020; Fischer et al., 2019).

The factors considered have been grouped into four dimensions. First, natural resources and their use (e.g., spatial and temporal distribution, biophysical and ecological conditions and trends), which are expected to influence the need for WM&A actions as well as their profitability (Canadas et al., 2016; Harris et al., 2011; Jakes et al., 2007; Olsen et al., 2017; Paveglio et al., 2012, 2016). Second, socioeconomic and demographic characteristics of the population that depends on or benefits from the resource (e.g., population size, dynamics, structure, occupation; primary or secondary home ownership; tourism; presence of local champions), which influences vulnerability, capacity to act or willingness to collaborate (Canadas and Novais, 2019; Fischer, 2011; Gan et al., 2015; Harris et al., 2011; Martin et al., 2009; McGee and Russell, 2003; Oliveira et al., 2017; Paveglio et al., 2016, 2012). Third, institutional or governance regimes through which resources are managed and used (e.g., ownership size and regime, land registry, multi-layered partnerships and collaborations) that may affect the transaction costs of collective action (Charnley et al., 2020; Harris et al., 2011; Labossière and McGee, 2017; Paveglio et al., 2012; Steelman and Kunkel, 2004). Finally, external resources (e.g., financial and non-financial support, public policies) that are decisive to offset those costs (Charnley et al., 2020; Fischer, 2011; Harris et al., 2011; Jakes et al., 2007; Jarrett et al., 2009; Labossière and McGee, 2017; Schultz and Moseley, 2019; Steelman and Kunkel, 2004; Stidham et al., 2014). To these, an additional dimension related to wildfire experience has been added (Charnley et al., 2020; Gan et al., 2015; Harris et al., 2011; Jarrett et al., 2009; Martin et al., 2009; McCaffrey et al., 2020; McGee et al., 2009; McGee and Russell, 2003; Paveglio et al., 2012).

The mix of WM&A actions is considered context-dependent by Paveglio et al. (2012, 2015, 2016), who developed what they call an interactional approach to emphasise how unique local contexts and community characteristics could variably influence different adaptation strategies across communities. They contend that adaptative capacity reflects the combination of complex, interdependent local social characteristics and extra-local forces, to which fire management approaches and policies need to be tailored. In fact, each community may be characterized by a particular constellation of factors leading to a unique action mix. However, this does not necessarily mean that the effects of these factors (and even their interactions) on the action mix cannot be modelled to produce more generalized knowledge of the effect of each factor across contexts, as we intend to do in this study. Our analysis of collective responses across territorial contexts aims to get a better understanding of the diversity of factors underlying these responses, which will help selecting the right policy for each context.

Our study contributes to these discussions in a region wherein research has been incipient: Mediterranean Europe (cf. Górriz-Mifsud et al., 2019). In fact, most of the literature on responses to wildfires has drawn predominantly on case studies from the US, Australia and Canada (McCaffrey, 2015; McCaffrey et al., 2020). However, there are important differences between these Anglo-Saxon countries and Mediterranean Europe that hinder generalizable lessons across case studies. In the US and Australia, for instance, there has been an increasing migration from urban areas into more fire-prone rural landscapes, thus expanding the WUI and increasing social diversity (Eriksen and Gill, 2010; Everett and Fuller, 2011; Paveglio et al., 2015). In Mediterranean European countries, such as Portugal, the opposite has happened: high rates of rural-to-urban migration have led to land management abandonment, depopulation, and aging of the remaining population (Arnalte-Alegre et al., 2012; Baptista, 2010).

3. Methodology

3.1. Regional context. Study area

Among the European Mediterranean countries, Portugal recorded the highest number of fires and the largest weighted burnt area during the 1980–2019 period, when nearly one third of the country's total area was burned (Oliveira et al., 2017; Rodrigues et al., 2019). In 2017, two unprecedented wildfire events, in June and October, destroyed around 500 thousand hectares of forests, shrubland and agricultural land and claimed over 100 civilians' lives (San-Miguel-Ayanz et al., 2020). Pinhal Interior was the most seriously hit area. These tragic fire events have also led to questions on mainstream policies mostly focused on fire suppression, which triggered a series of government reforms more directed to prevention, some of which have yet to be enacted.

Pinhal Interior is in the Centre of Portugal, comprising an area of 5% of the mainland Portugal, spread over 19 municipalities and 121 parishes (Fig. 1). Climate is Mediterranean, elevation ranges between 23 m a.m.s.l. and 1418 m a.m.s.l., and 46% of the region has a slope of 25% or more. Landscape is dominated by forest and scrubland (83% of the Pinhal Interior's surface), mostly under private ownership. Maritime pine (*Pinus pinaster*) and eucalyptus (*Eucalyptus globulus*) account for almost 2/3 of the study area. Agricultural areas occupy 13% of this region, most of which are small-sized farms (67% are smaller than 5 ha). Commons have a very small share of the whole region, although they can be more relevant in specific parishes (Baptista, 2010; JCI, 1939).

Like in most rural steep areas of the central parts of inland Portugal, population has been declining and aging over the last decades. The number of residents decreased by 19% between 1981 and 2011 and 9% between 2011 and 2021. In 2011, the region presented 38.1 inhabitants/km^2, a value significantly lower than the Portuguese average in the same year: 114.5 inhabitants/km^2. The primary sector (farming, livestock production and forestry) employed 7% of the working population in 2011, a number significantly lower than the 68% in 1960.

As a result of these socioeconomic changes, there has been an expansion of uncultivated, abandoned land and the consequent accumulation of high levels of fuel. Moreover, small-sized built-up areas are scattered throughout the region (3% of the area) and interspersed with wildland, making them highly exposed and vulnerable to wildfires. The sum of the areas burnt between 1975 and 2019 represented 1.57 times the Pinhal Interior's surface. That sum represented 0.85 times the region's surface during the 2003–2019 period, when three devastating wildfires occurred, in the critical years of 2003, 2005 and especially 2017 (which burned almost half the region's surface). The fires of June and October 2017 caused more than 80 casualties in this region.

3.2. Local collective actors and policy context for WM&A

A preliminary identification of local collective actors (citizen collaboratives and local governments) in Pinhal Interior and extra-local entities framing WM&A actions was carried out (Table 1).

Regarding mitigation, the most important local collective actor is the so-called Forest Intervention Zones (FIZ). Legally created in 2005 to increase Portuguese territorial fire resilience, FIZ corresponds to a formal multi-ownership collaboration. Each FIZ has a contiguous minimum surface and a minimum number of enrolled owners (Canadas et al., 2016). The FIZ's managing body is frequently a forest owners' association (FOA), which is responsible for designing a single forest management plan for the whole area. This plan includes and maps fuel breaks, water points, and other collective infrastructures, as well as stand-level constraints on forest management by owners (e.g., species, interventions). Once approved by the National Forest Authority, the plan is supposedly mandatory for all owners, including those who are not FIZ members but have their land within the FIZ boundaries (Canadas et al., 2014, 2016).

Many FOAs, which operate most frequently at the municipal level, also have teams of forest sappers (workers). These teams are responsible, for instance, for carrying out shrub clearing, pruning, and thinning of vegetation, controlled fires, implementing fuel breaks, and developing awareness campaigns. Besides FOAs, forest sappers can also be sponsored or managed by local associations at the parish level or by local governments (Beighley and Hyde, 2018). The latter also play other roles in mitigation. For instance, municipalities are responsible for updating municipal fire management plans, which operationalize the norms contained in the national legislation pertaining to forest defence against wildfires at the local and municipal levels (Anon, 2012). These plans are implemented by the municipal Technical Forest Offices (TFO) (Beighley and Hyde, 2018).

In Portuguese rural areas such as Pinhal Interior, the weakness or even absence of formal or informal collective initiatives involving local inhabitants and other community members (second homeowners, regular tourists and visitors) in WM&A actions, has given particular importance to the role played by local governments (Municipalities and Parish Councils) (Peixoto, 2019; Rego et al., 2020; Viegas et al., 2017).

Extra-local entities pertain mostly to the policy programmes that currently address WM&A actions and their respective executing/funding. These programmes include funding instruments (e.g., Rural Development Programme) and other measures that establish monitoring and education priorities (e.g., "Secure Forests operation"), both at the national level, and are predominantly or exclusively directed at the promotion of either adaptation or mitigation (Table 2). Monitoring at the WUI is assured by the Police Service for the Protection of Nature and the Environment (Beighley and Hyde, 2018).

3.3. Data collection and analysis

Data collection and analysis were carried out at the local scale, using the parish as the unit of analysis. In most cases, collective action under FIZ takes place at the parish level because FIZ jurisdiction falls within the parish boundaries (Canadas et al., 2016). The parish also seems to be a pertinent level for the identification of adaptation strategies such as the implementation of shelters or evacuation routes or perimeter strips for village defence (Viegas et al., 2017).

The variables used in this study were gathered from primary and secondary sources. A phone survey conducted in July 2020 with the presidents of the Parish Councils of Pinhal Interior was the source for the

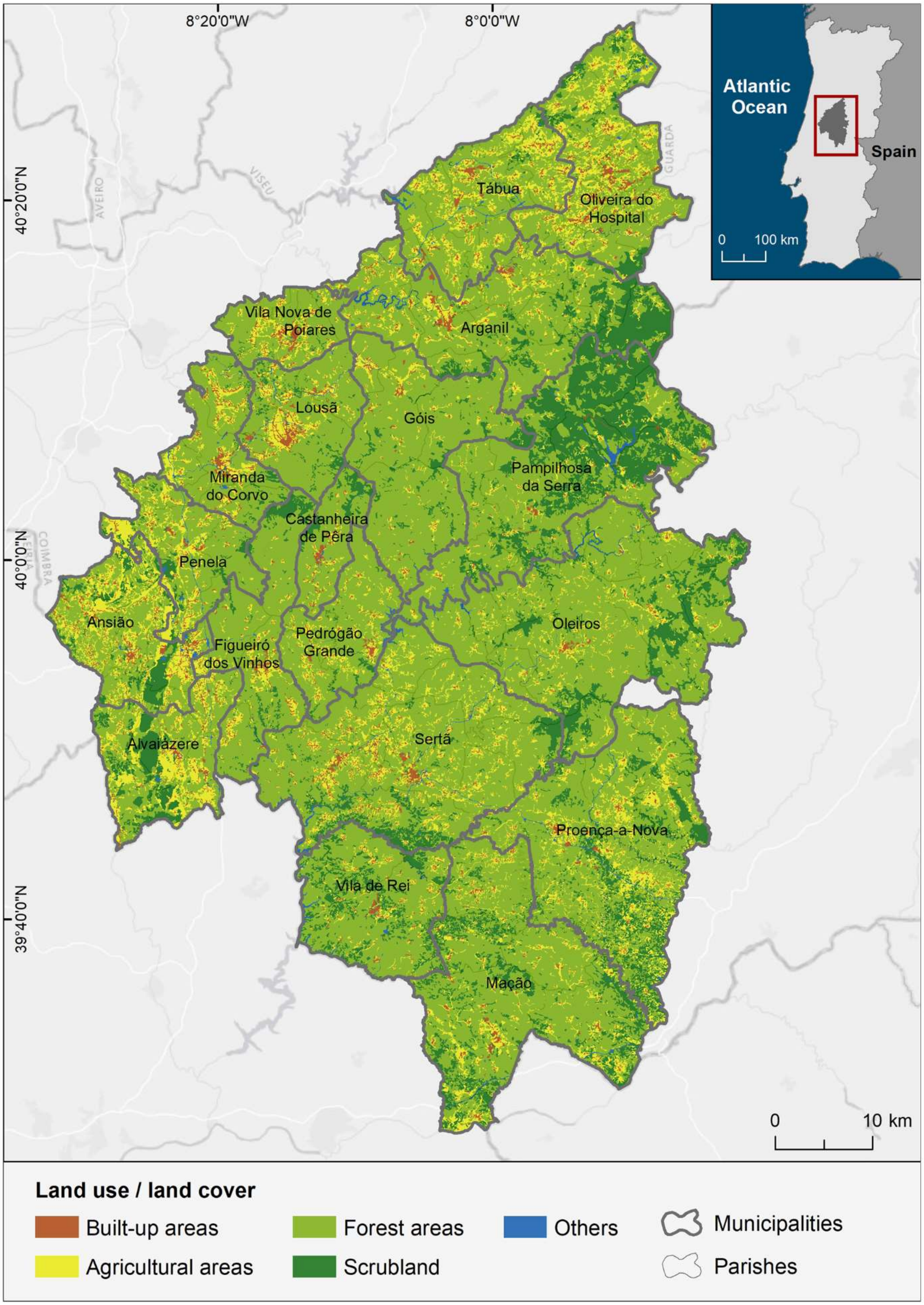

Fig. 1. Study area.

Table 1
Institutions responsible for collective WM&A actions at different territorial levels.

Territorial level	Wildfire mitigation entities	Wildfire adaptation entities
Parish (several villages)	Forest Intervention Zones (FIZ) (landowners' collaboration)	Parish Council (local community representation and responsibility over Local Civil Protection Units) Formal or informal groups of residents
Municipal	Forest owners' associations (FOA) Forest sappers Municipal Technical Forest Offices (TFO)	Civil protection service (Municipality Council) Volunteer firefighters Police Service for the Protection of Nature and the Environment
National	National Forest Authority (ICNF) (Agricultural policy, Ministry of Agriculture)	National Emergency and Civil Protection Authority and National Republican Guard (Ministry of Internal Administration) Ministry of Environment

primary data. The survey focused on the WM&A actions implemented in the 2015–2020 period at the parish level, by Parish Councils, local associations, and communities. Five of the 121 Parish Councils' presidents did not answer the survey and, therefore, these parishes were not included in this study. Secondary data includes information on FIZ, LULC, population (including housing and tourism), institutions, public funding, or burnt areas.

Two principal component analyses (PCA) were applied to the WM&A actions implemented in the 116 parishes to better comprehend how community adaptation and landowners' mitigation under FIZ were related (Fig. 2).

The first PCA was performed to explore relationships among 14 different categories of WM&A actions reported by the presidents of the Parish Councils, which were regrouped into seven categories for simplicity, which were classified as mitigation or adaptation (Table 3). These seven categories have been coded as binary variables to enter the PCA.

The second PCA, which combined the number of WM&A actions reported by the Parish Council's presidents and collective mitigation under FIZ, aimed to know whether the wildfire problem is dealt with in the same way throughout this region or whether there are different approaches (community adaptation vs. landowners' mitigation under FIZ). This PCA used four variables (Fig. 2 and Table 4): 1) the number of WM&A actions (from the initial 14 actions reported in the survey, cf. Table 3) (*Numb_actions*); 2) the existence of an approved Forest Management Plan (*FMP_approved*); 3) proportion of the parish covered by FIZ (*FIZ_extent*); and 4) age of FIZ (*FIZ_age*). Variables 2–4 are intended to express the FIZ's success in the implementation of collective mitigation actions. When two or more FIZ were present in a parish, FIZ age was weighted according to the area occupied in the parish by each FIZ.

PCA were performed using *SPSS* software. The principal components (PC) with eigenvalues greater than 1 were extracted. The component matrix rotation method was chosen based on the results presented by the software. The unrotated component matrix presented the best results for the second PCA, while the rotated (varimax) component matrix was the best solution for the first PCA.

A set of 51 indicators was used as independent variables, which were organized in five dimensions (Table 5 and appendix 1), as explained in the literature review: 1) LULC or resource system characteristics (forest, farming, and livestock); 2) population or people and their relationships (including buildings' characteristics and tourism); 3) institutions (institutional capacity in place); 4) external resources (funding and technical support for WM&A actions); and 5) wildfires (historic and recent burnt areas). Most independent variables are available at the parish level, except for night stays, which are only available at the municipality level. The number of night stays in each parish was estimated by weighting the night stays of the respective municipality by the accommodation capacity of the parishes. Likewise, for funding, in the cases where the amounts were only available at the municipality and/or FIZ levels, the amount per parish was estimated by weighting the total area of the respective municipality or FIZ by the total area of the parish (or forest area, for the Permanent Forest Fund).

A random forest modelling approach (Breiman, 2001) was used to establish relationships between the PC scores extracted from the second PCA (dependent variables) and the 51 independent variables (Fig. 2 and Table 5). Random forest is a popular machine learning technique that has been extensively used for modelling spatial and spatiotemporal data (Hengl et al., 2018), having also been applied in recent wildfire research (e.g., Eskandari et al., 2020; García-Llamas et al., 2019; Ma et al., 2020; Oliveira et al., 2017). Since we were mostly interested in exploring the effects of the independent variables on the PC scores, rather than in using the model to make predictions, we used the entire dataset to estimate the model, with no major concerns about overfitting issues (Shmueli, 2010). Mean squared residuals (MSR) and the percentage of variance explained were used to assess the global model fit. Lower MSR values indicate stronger model fit, as predicted values are closer to observed ones. Variable importance measures (mean squared error – MSE) were used to assess the effect of each independent variable in the model; higher MSE values show that the variable is important in the model, in the sense that it significantly contributes to the model's accuracy (Friedman, 2001). The marginal effect of each variable was examined using partial dependence plots, based on a visual analysis of the fitted function for each independent variable (Ribeiro et al., 2021).

4. Results

4.1. Mitigation and adaptation actors and existing policies

There are 26 FIZ in the study area, occupying 17% of the region (774 km^2). Most of them (24, corresponding to 16% of the total surface of Pinhal Interior) were created between 2006 and 2011 and only 2 FIZ were established in 2020. This has implications on the approval of the respective FMP that usually takes place considerably later than the collaborative establishment. Only half of the FIZ (13) have an approved plan. Eleven FOA are the managing body of those FIZ, while the most representative in the region manages 9 FIZ (62% of the surface occupied by FIZ in the study area).

Formal or informal groups of homeowners (of primary or second homes) with wildfire-related adaptation activities have only arisen recently, after the 2017 fires (Rego et al., 2020), and are now present in nearly 6% of the parishes. Only 3% of the parishes have Local Civil Protection Units. In 35% of the parishes there is at least one village included in the "Safe Village, Safe People" programme, although one of its main measures is much less implemented: only in 14% of the parishes there is at least one village where a resident has been designated as responsible for the community security.

Considering the policy programmes and funding mechanisms directly applied to collective WM&A in Pinhal Interior over the period considered (Table 6), the largest amount comes from rural development policies (55%). Environmental policy only accounts for less than a fifth (18%) and sectoral forest funds account for near a quarter.

4.2. Landowners' collaboration for mitigation and community adaptation

4.2.1. First PCA. Actions reported by Parish Councils' presidents: predominantly adaptation

From the seven aggregated categories of WM&A actions reported by the Parish Councils' presidents (Table 3), *scrub clearing around villages and roadsides* and *opening and maintaining forest roads* and *fuel breaks at villages' vicinity* are the most reported (92% and 83% of the parishes, respectively) over the last five years (Table 7). They are followed by *information, protection, and escape strategies* (49%), *material investments in*

Table 2
Measures supporting collective WM&A included in different programmes.

Programme and executing/funding entities	Starting date and period considered	Description	Domain
"Secure Forests" Operation ***[Operação"Floresta Segura"]*** **Entity:** National Republican Guard (Ministry of Internal Administration and Ministry of National Defence)	Started in 2012 Period: 2015–2020	This annual operation aims to prevent the occurrence of fire outbreaks and to guarantee the safety of people and their goods in the urban-forest interface. It entails: i) Awareness campaigns; ii) Inspection and signalling of situations of non-compliance with the legal obligation of private landowners to reduce the fuel load in the properties within a 100 m buffer around built-up areas; iii) Patrolling and surveillance of forest areas. Since 2018, the priority areas for intervention are the parishes that are identified each year in a legal diploma as being at very high risk of wildfires. The classification of high-priority parishes draws upon a methodology developed by the National Forest Authority that includes three variables: fire hazard, species' flammability, and areas with the highest forest value (conservation and production forest). Beneficiaries: N/A	Adaptation
"Safe Village, Safe People" Programme ***[Programa "Aldeia Segura, Pessoas Seguras"]*** **Entities:** National Emergency and Civil Protection Authority (Ministry of Internal Administration), National Associations of Municipalities and Parishes	Started in 2017 Period: 2017–2020	This programme aims to protect people and their goods in the urban-forest interface, through: i) The implementation and management of protection zones and shelter/refuge areas; ii) The definition and simulation of emergency evacuation plans; iii) Awareness campaigns to prevent risky behaviours and to promote the adoption of self-protection and preparedness measures against wildfires. Beneficiaries: Municipalities and Parish Councils	Adaptation
Rural Development Programme 2014–2020 (RDP 2020) ***[Programa de Desenvolvimento Rural 2020]*** **Entity:** Ministry of Agriculture Co-financed by the European Agricultural Fund for Rural Development (EAFRD) and the Portuguese State Budget	Started in 2014 Period: 2015–2020	The Rural Development Programme, which is the national programming of measures under the "second pillar" of the Common Agricultural Policy, provides incentives for the sustainable development of rural areas by fostering the competitiveness of the agriculture and forestry sectors, ensuring a sustainable management of the environment, natural resources, and climate action, and supporting local development initiatives. It includes the following measures directly or indirectly related to wildfire management: i) Restoration of agricultural land and the production potential damaged by wildfires (agriculture, livestock, beekeeping) (measure 6.2.2.); ii) Prevention of damage to forests from wildfires (measure 8.1.3.); iii) Restoration of forest areas affected by wildfires (measure 8.1.4.); iv) Improvement of the resilience and environmental value of forest ecosystems (measure 8.1.5.). Beneficiaries: Municipalities, Parish Councils, forestry/landowner associations, agricultural associations/cooperatives and local associations.	Predominantly Mitigation
Permanent Forest Fund ***[Fundo Florestal Permanente]*** **Entity:** National Forest Authority	Started in 2004 Period: 2013–2019	This Fund aims to support the forestry sector and the sustainable management of forests, in line with the Portuguese National Forest Strategy. Financial support from the Fund that is directly or indirectly related to wildfires includes: i) Awareness campaigns; ii) Wildfire prevention and forest protection measures (e.g., functioning of forest sappers' teams and municipal Technical Forest Offices, creation of forest buffers, etc.); iii) Forest management and planning (e.g., creation of Forest Intervention Zones, land consolidation, etc.). Beneficiaries: Municipalities, Parish Councils, FOAs and local associations.	Mitigation
Programme for Sustainability and Efficient Use of Resources ***[POSEUR - Programa Operacional Sustentabilidade e Eficiência no Uso de Recursos]*** **Entity:** Ministry of Environment Financed by the European Commission's Cohesion Fund	Started in 2014 Period: 2014–2020	POSEUR is a tool of the Europe 2020 Strategy for Sustainability and Resource Use Efficiency. It aims to promote a more efficient use of resources and a greater resilience to climate risks and disasters. This programme includes the following measures directly related to wildfires: i) Risk prevention and management (e.g., video surveillance system and fire detection, risk cartography, acquisition of vehicles and individual protection equipment for firefighting, and fuel management in forest areas, particularly in protected and public areas); ii) Recovery of burnt areas within Protected Areas (e.g., Protected Landscape of Serra do Açor). Beneficiaries: Municipalities, Intermunicipal Communities, official authorities (National Authority for Civil Protection, Voluntary Firefighters Associations, National Republican Guard) and Institute for Nature Conservation and Forests.	Predominantly Adaptation

firefighting (42%), *plantations of fire-resistant trees around villages* (36%), *commons' clearing* (24%) and *grazing* (3%). It is also worth noting the lower relevance of material investments in firefighting at the parish level (firefighting corporations normally have a municipal geographical scope) and the plantations of native fire-resistant species, even though it is only around the villages.

The five components extracted from the first PCA (Table 7), which considers those seven aggregated WM&A actions, comprise 82% of the variance. PC1, PC2, PC3 and PC5 clearly correspond to adaptation actions. Plantations of indigenous fire-resistant trees is the variable with the highest loading to PC1 followed by far by bush clearing in communitarian properties. Because most of these plantations take place in the proximity of the villages, we consider it as mainly an adaptation axis. PC2 is mainly associated with material investments in firefighting and the opening and maintenance of forest roads and fuel breaks at villages' vicinity. These are complementary actions as the latter allow the access and circulation of firefighting vehicles and equipment in case of wildfires. The PC3 axis is associated with safety strategies (information, protection, and escape) while PC5 is related to scrub clearing around villages and roads. The axis characterized by extensive grazing for fuel management (PC4) is the only one that could be considered as representing mitigation actions. However, the number of parishes having reported extensive grazing is very low (4).

The results of this PCA lead to consider the actions reported by the Parish Councils' presidents as mostly adaptation actions and support the use of the variable 'number of collective WM&A actions' (*Numb_actions*) as a proxy for adaptation effort.

4.2.2. *Second PCA: Mitigation under FIZ and Adaptation at the community (parish) level*

The second PCA (Table 8) resulted in two unrotated axes or PCs, which together retain 88% of the variance in the data. PC1, representing 64% of variance, is positively associated with the variables *FMP_approved*, *FIZ_extent* and *FIZ_age* (the negative association of *Numb_actions* to this PC is extremely weak). As FIZ are exclusively about mitigation, PC1 is interpreted as the progression of *Mitigation under FIZ*. On the other hand, PC2, which represents 24% of variance, is only associated with *Numb_actions*, and is thus interpreted as *Community adaptation* effort.

Therefore, all variables related to progression of *Mitigation under FIZ* only contribute to the first PC and the variable related to *Community adaptation* effort only contributes to the other (orthogonal) PC, which means there is no association whatsoever between progression of mitigation and adaptation effort (Table 8), in the sense that the progression of mitigation does not tell anything about adaptation effort and vice versa. The frequencies of observations over the factorial plan (Table 9) also show that many different combinations of levels of progression of mitigation and adaptation effort do occur with no significant association between them (chi-square test).

4.3. *Local context attributes and external resources for collective WM&A actions*

A random forest model was performed for the second PCA (Fig. 2), using the PC scores as dependent variables, against the 51 predictors (independent variables) in Table 5. The model for *Mitigation under FIZ* (PC1) showed a much better fit, with a MSR of 0.41% and 58.5% of variance explained, compared with 0.92% and 6.8% for the *Community adaptation* axis (PC2), respectively.

The variables' importance assessment revealed that most of the top variables in the mitigation under FIZ model are in the fourth dimension – external resources (Fig. 3), with two of Rural Development Programme variables in the top two positions (*RDP value assigned to associations* and *total value assigned under RDP2020*). The average farm size (*AvgUAA*) came in third place, followed by recent burnt area (*Fire1719*). The marginal effects of these four top variables are all positive, as inferred from the partial dependence plots (see appendix 2 for supplementary information). Although the entire study area is rural, the highest scores of mitigation under FIZ were obtained for the parishes with larger proportions of built-up areas (*Built_up*) and higher population densities (*PopDens*). Additionally, high scores of mitigation under FIZ can also be found where there are larger areas with agriculture (*Agricult* and *AgricBuff*), more heterogeneous landscapes (*Shannon*), younger people (*Young*), larger livestock units (*LivStock*), higher importance of tourism (*AccomCap* and *NightSty*), larger properties/farms (*AvgUAA*), and greater capacity to raise (forest sector) public funding (*ForFund*). On the other hand, mitigation under FIZ is negatively associated with some funding programmes (*RDP assigned to the municipalities* and *POSEUR*), priority for inspection (*PubInspe*), priority-vulnerability levels (*PrioVuln*), eucalyptus (*Euc*), forest/wildland buffers around built-up areas (*ForBuff*), elderly people (*Aging*, *Elderly* and *EldAlone*), and historic wildfires (*Fire0316*). Therefore, the propensity for landowners' collective mitigation under FIZ seems to be strongly encouraged by public policies, larger properties, and recent experience of wildfires. In brief, the highest levels of FIZ/landowners' collaboration occur in parishes with more fragmented/heterogeneous landscapes, larger built-up and agricultural areas, higher social dynamism, larger properties, higher amounts of money from public funding, and recent wildfires. On the contrary, there are no FIZ in parishes where people are older (and more vulnerable), landscape is more homogeneous, eucalyptus predominates, properties are smaller, and there have been fewer recent fires.

For the second model (community adaptation), associated with the number of adaptation actions (*Numb_actions)* reported by the Parish Councils' presidents, only land registry (*LandReg*) stands out in variable importance (Fig. 3). This suggests that the existence of a land registry (which is absent/outdated in most of the region) can promote adaptation actions, according to the interpretation of the partial dependence plots (appendix 3). Besides, wildfire adaptation actions do not seem to be strongly related to most of the potential explanatory variables considered at the outset (Table 5). There are about 10 variables in the mitigation under FIZ model with percentages of variance explained greater than or equal to the second most relevant variable (*Agricult*) for community adaptation (Fig. 3).

5. Discussion

Conceptual, methodological and policy implications can be drawn from our main results, namely local independence of collective mitigation and adaptation, strong association between mitigation and local demographic and economic vitality, and unequal consolidation of the two action spheres and policy domains.

5.1. *Collective mitigation and adaptation: two locally independent dynamics*

The fact that, in the second PCA, all variables related to progression of mitigation only contribute to the same PC and the variable related to adaptation effort only contribute to a different PC means that there is no association between progression of mitigation and level of adaptation effort. Mitigation and adaptation can thus be seen as locally independent actions, which suggests the territorial factors they depend on are different (an issue that is systematically addressed in the next section).

This independence also means that, at least in our study area, there are two independent dynamics at the local level regarding collective wildfire prevention actions, in the sense that local collective dynamism concerning mitigation does not necessarily go along with dynamism concerning adaptation. This innovative result was only made possible because both responses to wildfire hazard (mitigation and adaptation, as defined in this study) were, for the first time, included in a same study and explicitly compared across different territorial units. We recall that research on collective responses to wildfires are usually confined to single territorial contexts and case studies (as noticed by Danley et al., 2021), and that mitigation by landowners and adaptation by residents

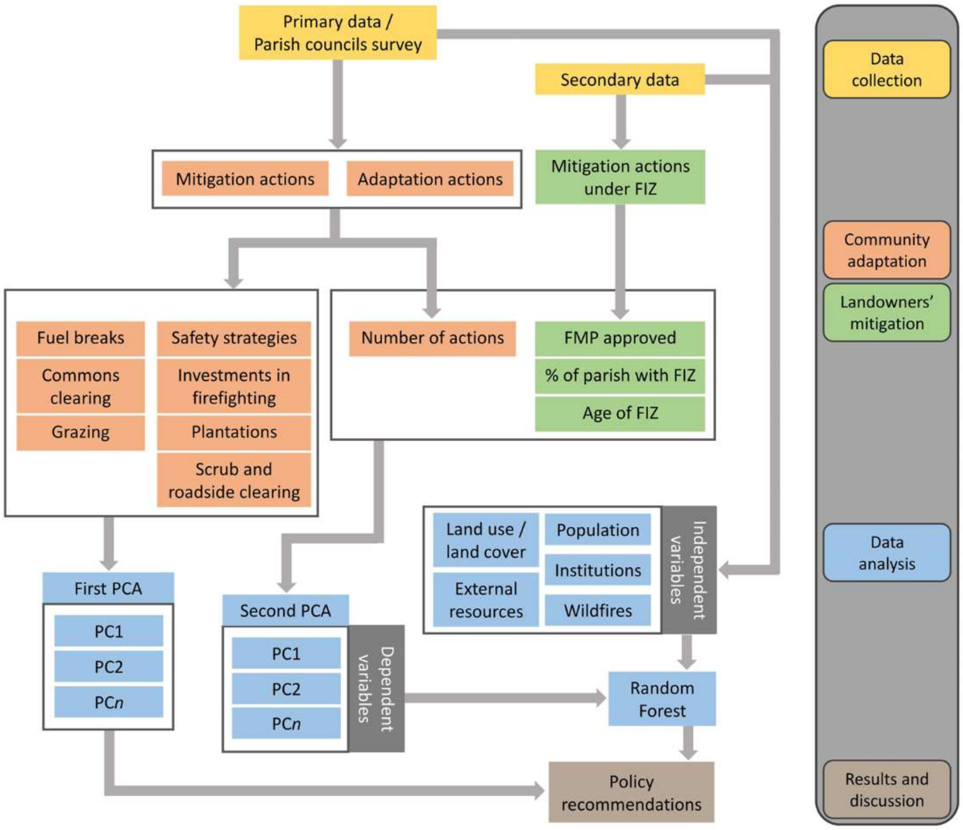

Fig. 2. Methodological framework.

Table 3
Correspondence between WM&A actions reported by the Parish Councils' presidents and the simplified set of 7 categories used in the analysis.

Reported actions	Simplified set of categories	Mitigation / adaptation
1. Clearing/maintenance of forest roads 2. Opening and/or maintenance of fuel breaks	1. Opening/maintaining forest roads and fuel breaks at villages' vicinity	Adaptation
3. Commons' clearing	2. Commons' clearing	Mitigation
4. Extensive grazing for fuel management	3. Extensive grazing for fuel management	Mitigation
5. Construction/recovery of water points 6. Acquisition of vans and kits with fire hoses for first intervention 7. Fire hydrants' maintenance/checking	4. Material investments in firefighting	Adaptation
8. Implementation of awareness campaigns 9. Definition of evacuation plans/training and implementation of shelters 10. Implementation of fire signs (e.g., evacuation routes, shelter, information placards) 11. Distribution of self-protection kits and individual protection collars	5. Information, protection, and escape strategies	Adaptation
12. Scrub clearing around villages 13. Roadside clearing	6. Scrub clearing around villages and roadside clearing	Adaptation
14. Plantation of native fire-resistant trees around villages	7. Plantations of native fire-resistant trees around villages	Adaptation

are either analysed in different studies or included in a same study but assimilated (Everett and Fuller, 2011; Górriz-Mifsud et al., 2019; McLennan and Birch, 2005), as if mitigation and adaptation were not different (as regards the nature and objectives of the actions, as well as actors involved) and did not possibly depend on different factors.

In fact, mitigation and adaptation, as defined in this study, are different in terms of: scale and cost of the action (fuels management at the landscape/parish scale versus in a perimeter strip for village defence, e.g., 100 m vicinity) (Everett and Fuller, 2011); direct objectives of the action (wildfire hazard reduction and forest protection, versus the protection of people's lives, livelihoods and belongings) (Hartsough et al., 2008; Koksal et al., 2019); the voluntary or mandatory character of those actions (Santos et al., 2021); and, finally, the collective actors involved (landowner groups that manage fuel loads to reduce landscape susceptibility to wildfires versus resident groups, who are impacted by fire spread in the WUI) (Fernandes et al., 2014; Viegas et al., 2017). These differences are given more relevance by the finding that the dynamics of mitigation and adaptation are independent, at the local level, and possibly depend on different factors, which confirms the usefulness of our definitions of mitigation and adaptation.

5.2. Local context versus wildfire experience as explanatory factors for collective WM&A action

Random forest models were used to find relationships between a set of independent variables and landowners' mitigation and community adaptation. The model undoubtedly better fits the mitigation than the adaptation data. This difference can be partly explained by the distinct sources of information for each action: secondary, administrative data for FIZ and primary survey data for adaptation, which depends on the respondent memory for the time span considered. The number of adaptation actions as a measurement of adaptation effort also has some weaknesses resulting to some actions being implemented at a level

Table 4
Variables used in the second PCA.

Acronym	Variable name	Year/period	Unit	Source	Average	Max – min	Std. deviat.
Numb_actions	Number of wildfire mitigation and adaptation (WM&A) actions	2015–2020	Nr.	(1)	5.8	13 – 1	2.3
FMP_approved	Forest Management Plan (FMP) approved	2020	Binary	(2)	0.3	1 – 0	0.5
FIZ_extent	Proportion of the parish covered by Forest Intervention Zones (FIZ)	2020	%	(2)	30.8	100 – 0	41.7
FIZ_age	Age of the FIZ	2020	Nr.	(2)	5.5	14 – 0	5.9

(1) Survey to the Presidents of the Parish Councils of Pinhal Interior; (2) Portuguese Institute for Nature Conservation and Forests.

higher than the parish (municipal, e.g., in awareness campaigns), while others are implemented at a lower level (e.g., perimeter strip for village defence) (Almeida, 2012; Peixoto, 2019; Viegas et al., 2017), which may have led Parish Councils to underreport them. In addition, the variable adaptation effort (number of actions) varies significantly less than the variables measuring progression of mitigation (Table 5), which may have hindered the identification of the correlates of the former. Another difficulty in establishing the factors associated with adaptation may be related with the fact that data for some of the variables characterizing the local context (e.g., night stays) and external resources (e.g., RDP funds for municipalities) aimed at explaining adaptation effort were only available at the municipal level (Table 2), while the dependent variable (adaptation) is measured at the parish (lower) level. The identification of correlations in the mitigation model was not affected so much by these hindrances.

Mitigation under FIZ is strongly and positively correlated to policy funding, which will be discussed in the next section, and to larger properties, higher economic dynamism and social vitality, and more historic wildfires. Higher livestock density, weight of agricultural areas, and landscape heterogeneity (more built-up areas, less forest in the vicinity of those areas, and higher Shannon index) can be associated with higher levels of income from the land and consequently more economic dynamism concerning land and fuel management (Baptista, 2010; Cordovil, 2021; Rolo and Cordovil, 2014). Regarding the population variables, less social vitality (older population, older buildings), lower population density and less tourists (accommodation supply and demand) seem, on the contrary, to act as obstacles to progression of mitigation (Fig. 3). Social vitality has in fact been identified as favouring trust, knowledge sharing and in general reducing transaction costs in collective action (OECD, 2013; Ratner et al., 2013). An aging and declining population may also affect the collective ability to respond to wildfires, although in other studies these characteristics have been found to have a mixed effect on landowners' action (Gan et al., 2015; McGee and Russell, 2003; Poteete and Ostrom, 2008).

Concerning institutions, a larger ownership structure reduces the number of owners involved in FIZ-like collaboratives, thus lowering its implementation costs (Canadas et al., 2016; Meinzen-Dick et al., 2004; OECD, 2013; Poteete and Ostrom, 2008). Although land registry has often been considered a condition for the effectiveness of coordinated fuels management (by providing an easier identification of owners and ownership boundaries), our results show that it is less important to explain FIZ constitution and progression than the ownership structure itself and local socioeconomic vitality (Canadas et al., 2014, 2016).

The number of adaptation actions reported by the Parish Councils' presidents is in general weakly correlated to local socioeconomic attributes, institutions, external resources, or wildfires. Nevertheless, land registry clearly stands out as an important positive correlate of adaptation effort. The active role played by local governments in the promotion of land registry through the mobilization of residents suggests that community adaptation significantly depends on stronger leadership by local governments (Harris et al., 2011; Labossière and McGee, 2017).

Considering that the area burnt in historic wildfires (2003–2016) is very concentrated in 2003 and 2005, and that FIZ legislation and most FIZs emerged in the immediate aftermath of these two years, the negative association of progression of mitigation under FIZ with historic wildfires (2003–2016 Fig. 3) rules out the hypothesis that FIZ were mostly constituted in the local territories most affected by those wildfires. Therefore, while these catastrophic events triggered new wildfire policies, they were not the triggers of local mitigation action implementing those policies.

The progression of mitigation (24 FIZs created in 2006–2011; 2 in 2020) was found to be positively associated with recent wildfires (2017–2019). This suggests that most FIZs suffered more the effects of a catastrophic year (2017) precisely because they were more effective in fire prevention, and thus fuel accumulation, in normal years. However, this finding is not key for this article, because we are discussing the effect of wildfires as a trigger of preventive action and not the effectiveness of this action. What is actually a key finding is that only 2 new FIZs have been created after the catastrophic year of 2017, which suggests that, while leading again to FIZ policy reforms, the wildfires of 2017 were not major drivers of local mitigation progression through the FIZ constitution.

Both historic and recent fires were found to have no significant effect on the progression of adaptation effort (reported by Presidents of Parish Councils for the 2015–2020 period).

The fact that both historic and recent fires, namely the catastrophic years of 2003, 2005 and 2017, did not locally trigger collective mitigation or adaptation actions means that wildfire experience and awareness at the local level may not represent an effective trigger of collective mitigation and adaptation action, contrary to what has been suggested in other studies (Jakes and Sturtevant, 2013; Labossière and McGee, 2017; Mockrin et al., 2018; Muller and Schulte, 2011; Prater and Lindell, 2000; Steelman and Kunkel, 2004). No or inconsistent effects of wildfire experience on wildfire response have indeed been reported in other studies (Harris et al., 2011; Jarrett et al., 2009; Martin et al., 2009; McGee et al., 2009; Novais and Canadas, 2022; Paveglio et al., 2012).

The results of this study strongly suggest the local context, namely the economic and social vitality, ownership structure, and leadership by local governments are the key factors to explain why some territories are more involved in collective WM&A action than others, while wildfire experience and awareness seem to play a minor role.

5.3. Mitigation and adaptation: two unequally consolidated but equally underfunded policy domains

5.3.1. Two action spheres supported by distinct and unequally consolidated policy domains

Our analyses show that mitigation and adaptation on the ground are related to different policy domains, which are promoted by different policy actors (Table 2) and tend to protect different types of interests. Mitigation under FIZ has a strong association with many variables included in the external resources dimension, revealing the essential role of public funding in the progression of collective mitigation (Canadas et al., 2016; OECD, 2013). There is a positive association between mitigation progression and policy funding addressed at mitigation (i.e., the RDP 2020, particularly the value assigned to FOAs, and the Permanent Forest Fund), and a negative association with policies directed at adaptation (e.g., RDP 2020 funds assigned to municipalities, and the POSEUR). This reveals that the distinction between two action spheres (mitigation and adaptation) corresponds to a distinction between two policy domains (OECD, 2016). Progression of collective mitigation is strongly associated with a policy domain more focused on reducing the

Table 5
Independent variables used for random forest modelling.

Acronym	Variable name	Year/ period	Unit	Source	Average	Max - min	Std. deviat.
DIMENSION 1 – Land use/land cover (LULC)							
Built_up	Proportion of built-up areas	2015	%	(1)	3.6	16.3 – 0.4	2.9
Agricult	Proportion of agricultural areas	2015	%	(1)	14.9	40.6 – 1.6	9.3
Forest	Proportion of forest/wildland areas	2015	%	(1)	79.9	97.8 – 48.3	11.6
AgricBuff	Farming in a 100 m buffer around built-up areas	2015	%	(1)	54.1	84.0 – 22.2	12.3
ForBuff	Forest/wildland in a 100 m buffer around built-up areas	2015	%	(1)	44.9	76.9 – 16.0	12.2
Euc	Proportion of eucalyptus	2015	%	(1)	21.5	67.0 – 0.4	16.2
EucVar	Variation of eucalyptus area	1995–2015	%	(1)	6.9	39.1 – -6.7	7.7
Pin	Proportion of maritime pine	2015	%	(1)	38.4	72.9 – 1.9	16.7
PinVar	Variation of maritime pine area	1995–2015	Nr.	(1)	-8.2	16.8 – -50.5	12.3
Shannon	Shannon index	2015	%	(1)	1.1	1.5 – 0.6	0.2
EucProd	Net primary productivity of eucalyptus	2000–2014	Kg of carbon /m^2/ year	(1)	1.1	1.4 – 0.8	0.1
PinProd	Net primary productivity of maritime pine	2000–2014	Kg of carbon /m^2/ year	(1)	1.0	1.3 – 0.7	0.1
LivStock	Livestock units (sheep, goats, and cattle)	2009	Nr/km^2	(2)	2.2	11.2 – 0.0	2.1
Traction	Mechanical traction/horse-power availability	2009	Nr/ha of rural area	(2)	1.3	4.3 – 0.0	1.0
DIMENSION 2 – Population							
PopDens	Population density	2011	Nr/km^2	(3)	46.8	255.3 – 4.0	43.2
RPopVar	Variation of rural population density	1981–2011	%	(3)	-33.5	41.9 – -68.6	19.1
Young	Proportion of young population (< 15 years)	2011	%	(3)	9.9	17.4 – 1.9	3.4
Elderly	Proportion of elderly population (≥ 65 years)	2011	%	(3)	34.3	58.8 – 17.1	10.0
Aging	Aging index	2011	%	(3)	455.3	2250.0 – 105.3	374.1
EldAlone	Proportion of elderly living alone or with others in the same age group	2011	%	(3)	23.6	49.6 – 10.0	8.7
Illitera	Illiteracy rate	2011	%	(3)	11.3	27.6 – 2.3	5.0
Educat	Proportion of the population with secondary or higher education	2011	%	(3)	17.9	35.0 – 3.9	5.7
PrimSect	Proportion of the population working in the primary sector	2011	%	(3)	5.8	36.4 – 0.0	5.5
LiveOutP	Proportion of the population that lived outside the parish 5 years ago	2011	%	(3)	9.9	35.3 – 1.3	4.3
WorkOutP	Proportion of the population that works or studies in another parish in the same municipality	2011	%	(3)	16.2	16.2 37.8 – 0.6	8.4
Seasonal	Proportion of seasonal/secondary dwellings	2011	%	(3)	38.6	72.9 – 9.5	14.5
BuildAge	Average age of buildings	2011	Nr. years	(3)	43.3	66.1 – 20.5	8.1
FamLabor	Proportion of farm family labour - annual work unit (AWU)	2009	%	(2)	93.8	99.9 – 50.1	7.3
TourisAg	Tourist entertainment companies	2021	Nr/100 km^2	(4)	1.5	12.4 – 0.0	2.7
AccomCap	Accommodation capacity (number of beds/people)	2021	Nr/1000 inhabitants	(4)	67.8	438.2 – 0.0	80.8
NightSty	Night stays	2020	Nr/km^2	(4)	70.4	1170.9 – 0.0	136.4
RivBeach	River beaches and bathing areas	2020	Nr/1000 inhabitants	(5)	0.9	16.9 – 0.0	2.1
DIMENSION 3 - Institutions							
AvgUAA	Average utilised agricultural area (UAA) - farms	2009	ha	(2)	2.0	6.1 – 0.7	0.8
Commons	Existence of commons	2015–2020	Binary	(6)	0.6	1 – 0	0.5
PulpPape	Existence of areas managed by pulp paper companies	2015–2020	Binary	(6)	0.4	1 – 0	0.5
MunSeat	Parish is coincident or not with the municipality seat	2021	Binary	n.a.	0.1	1 – 0	0.4
HistVill	Number of classified traditional (historical and schist) villages	2021	Nr.	(7)	0.2	5.0 – 0.0	0.7
LocAssoc	Number of local associations with wildfire-related initiatives	2015–2021	Nr.	(6) (8)	0.4	4.0 – 0.0	0.7
LandReg	Existence of simplified land registry	2015–2020	Binary	(6)	0.4	1 – 0	0.5
DIMENSION 4 – External resources							
PubInspe	Number of years that the parish was a priority for inspection of mandatory fuel management around villages	2018–2020	Nr.	(9)	1.5	3.0 – 0.0	1.1
PrioVuln	Combined priority-vulnerability levels	2020	Nr.	(9) (10)	1.6	2.0 – 0.0	0.6
SecFores	Parish included in the “Secure Forests” programme	2015–2020	Binary	(6)	0.6	1 – 0	0.5
SafeVill	Proportion of villages in the parish included in the “Safe Village, Safe People” programme	2017–2020	%	(11)	3.6	100.0 – 0.0	12.0
RDP2020	Value assigned under the Rural Development Programme (RDP2020)	2015–2020	€/km^2	(12)	4842.44	22449 – 0	4742.62
RDPMunic	Value assigned to the municipalities under the RDP2020	2015–2020	€/km^2	(12)	1809.97	10648 – 0	2615.56
RDPAssoc	Value assigned to wildfire-related associations under the RDP2020	2015–2020	€/km^2	(12)	1579.57	17957 – 0	3468.19
ForFund	Value assigned under the Permanent Forest Fund	2013–2019	€/ha of forest area	(13)	31.91	245.50 – 9.60	27.65
POSEUR	Value assigned under the Programme Sustainability and Efficiency in the Use of Resources (POSEUR)	2014–2020	€/km^2	(14)	1362.45	7648.62 – 118.58	1214.70
ForSappr	Existence of forest sappers' teams	2015–2020	Binary	(6)	0.2	1 – 0	0.4
DIMENSION 5 – Wildfires							
Fire0316	Accumulated burnt area during the 2003–2016 period (historic burnt area)	2003–2016	%	(13)	31.7	128.2 – 0.0	28.1
Fire1719	Accumulated burnt area during the 2017–2019 period (recent burnt area)	2017–2019	%	(13)	53.0	100.0 – 0.0	37.8

(1) Land Cover Map, Portuguese Directorate-General for Territory; (2) General Agricultural Census, Statistics Portugal; (3) Population and building Census, Statistics Portugal; (4) Portuguese National Tourism Institute; (5) River beaches of Portugal; (6) Survey to the Presidents of Parish Councils of Pinhal Interior; (7) Schist/historical villages of Portugal; (8) Local media; (9) Portuguese Republic Diary (Orders nr. 1913/2018, 744/2019 and 2616/2020); (10) Portuguese Republic Diary (Decree order nr. 301/2020); (11) National Emergency and Civil Protection Authority; (12) Management Authority of the RDP 2020; (13) Portuguese Institute for Nature Conservation and Forests; (14) Management Authority of POSEUR; n.a. not applicable.

Table 6
Average annual funding or number of villages included in programmes supporting collective WM&A.

Programmes	Period considered	Average annual funding (thousand euros)	
		Portugal mainland	Pinhal Interior
Rural Development Programme 2020	2015–2020	27,129	3 194
Permanent Forest Fund	2013–2019	20,982	1 354
POSEUR - Programme for Sustainability and Efficient Use of Resources	2014–2020	10,906	880
Programme	**Period considered**	**Number of villages**	
		Portugal mainland	**Pinhal Interior**
"Safe Village, Safe People" Programme	2017–2020	1992	116

Note: the funding figures only include the measures supporting collective WM&A actions (cf. Table 2).

Table 7
Rotated component matrix extracted from the first PCA.

WM&A actions	% of the parishes	Components				
		PC1	PC2	PC3	PC4	PC5
7. Plantations of native fire-resistant trees around villages	36%	**0.921**	-0.041	-0.090	0.040	-0.054
2. Commons clearing	24%	**0.599**	-0.070	0.449	0.176	0.199
4. Material investments in firefighting	42%	-0.062	**0.805**	-0.245	0.298	-0.055
1. Opening/ maintaining forest roads/ fuel breaks at villages' vicinity	83%	-0.043	**0.733**	0.323	-0.290	0.215
5. Information, protection, and escape strategies	49%	0.010	0.006	**0.896**	0.076	0.027
3. Extensive grazing for fuel management	3%	0.114	0.045	0.112	**0.925**	0.042
6. Scrub clearing around villages and roadside clearing	92%	0.029	0.075	0.053	0.035	**0.978**
Explained variance (%)		*18*	*17*	*17*	*15*	*15*

Table 8
Unrotated component matrix extracted from the second PCA.

Acronym	Variable	Component	
		Mitigation under FIZ (PC1)	Community adaptation (PC2)
Numb_actions	Number of wildfire adaptation actions	-0.264	**0.964**
FMP_approved	Forest Management Plan (FMP) approved	**0.915**	0.151
FIZ_extent	Proportion of the parish covered by Forest Intervention Zones (FIZ)	**0.910**	0.085
FIZ_age	Age of the FIZ	**0.909**	0.042

Table 9
Distribution of parishes by classes of scores obtained from the second PCA: Mitigation under FIZ (PC1) and Community adaptation (PC2).

Score intervals on PC1	Score intervals on PC2						Total	
	[-2.18 – -0.71]		]-0.71 – 0.07]		] 0.07 – 3.36]			
	N	%	N	%	N	%	N	%
[-1.06 – -0.66]	17	28.3	15	25.0	28	46.7	**60**	**100**
]-0.66 – 1.21]	10	33.3	6	20.0	14	46.7	**30**	**100**
]1.21 – 1.72]	5	19.2	10	38.5	11	42.3	**26**	**100**
Total	**32**	**27.6**	**31**	**26.7**	**53**	**45.7**	**116**	**100**

p-value for the Pearson's chi-square test = 0.553
Note: classes were obtained by combining the natural breaks criterion with the meaning of the PC scores.

wildfire susceptibility/hazard.

The consolidation of these two policy domains seems quite unequal. The mitigation domain is framed by an ensemble of well-established public and private agencies, policy measures and funding allocation. For instance, the Forest Fund, established in 2004 (Mourato et al., 2020), together with the RDP, represents the largest funding share for wildfire prevention both in the study area and in Portugal (Table 6). An associative capacity in place (e.g., FOAs), promoted by public policies during the 1990 s (Canadas et al., 2014), and the existence of forestland managed by pulp and paper companies also translates into the ability to compete for public funds allocated to wildfire mitigation. The adaptation domain is more recent and less consolidated, contrary to Anglo-Saxon countries (Everett and Fuller, 2011; Haynes et al., 2020; McLennan and Birch, 2005). Until 2017, human casualties were mainly firefighters, and the success of wildfire policies was mostly assessed by the reduction in burnt areas (Moreira et al., 2020; Stephens et al., 2013). Despite abundant legislative production in the aftermath of the 2003 and 2005 wildfires, the implementation of adaptation measures on the ground, such as perimeter strips around villages (mandatory by law since 2006), was almost inexistent (Viegas et al., 2017). After 2017, the need for adaptation gained more visibility, yet the achievements have been modest (Peixoto, 2019; Rego et al., 2020).

5.3.2. *Drawbacks of both action spheres and policy domains*

Fire suppression has persistently attracted most of the public funds related with wildfires, thereby constraining the availability of resources for prevention (Beighley and Hyde, 2018; Calkin et al., 2011; Fernandes et al., 2020; North et al., 2015; Viegas et al., 2017). Underfunding is among the main drawbacks associated with mitigation policies (Santos et al., 2021). Despite the strong legal status of the FIZ, the implementation of its FMP is not ensured, as it requires costly interventions for fuel management (Busenberg, 2004; Hartsough et al., 2008; Novais and Canadas, 2022) and the mechanisms to finance these have not yet been fully developed. This implementation failure is more evident concerning active fuel management at the stand/owner level, usually perceived as part of good forest management itself, than for collective infrastructures (Santos et al., 2021). Another hindrance concerns a still very sectoral view of the mitigation problem, focused on forest rather than landscape management (Cordovil, 2021; Martins et al., 2021), although there was a recent shift towards new policy tools targeting the latter (Mourato et al., 2020).

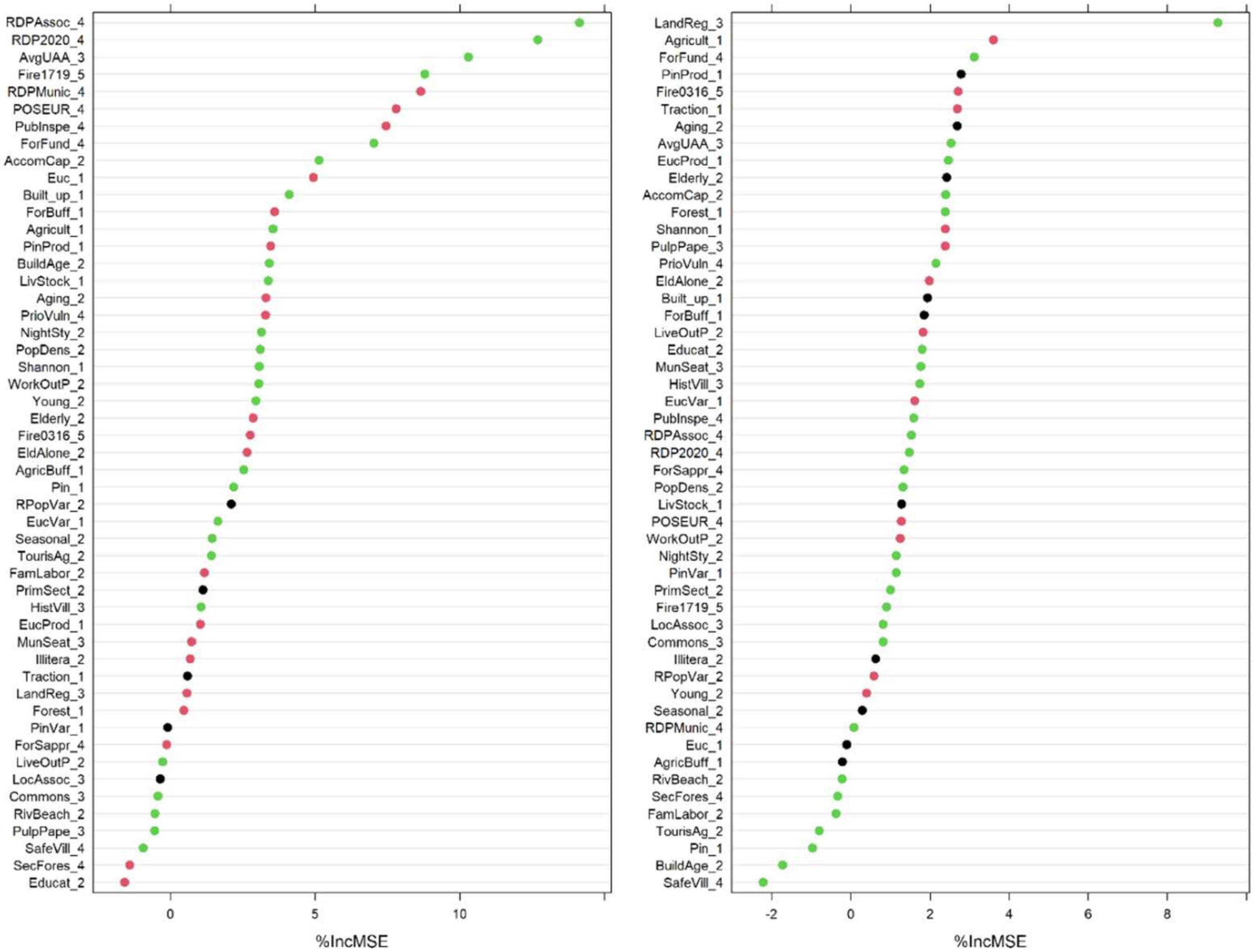

Fig. 3. Variable importance for the random forest models for the mitigation under FIZ - PC1 (left) and community adaptation - PC2 (right). Values describe the effect of the variable in contributing to improve the mean squared error (MSE) of the model. Green, red, and black dots identify positive, negative, or unclear marginal effects of the variable on the scores of the PCs, respectively. Numbers following variable names refer to the corresponding "dimension" (Table 5).

Our results show that adaptation effort on the ground has no strong association with any funding nor policy priority. Even though data limitations can partly explain this weak association, it probably reflects the fragile consolidation of the policy domain directed to people's protection at the local level. For instance, there has been an almost complete lack of funding of the "Safe Village, Safe People" program (Rego et al., 2020). This contrasts with the case of California, where one of the main tasks of the Fire Safe Councils is to find support for their activities, with 80% of their funding coming from governmental sources (Everett and Fuller, 2011). The expectation that the inclusion of villages in this program would be related to more adaptation actions is not verified because many of its prescribed measures have not yet been implemented, such as the designation of a person responsible for the village safety, hindered by the reduced capabilities of an aging population. The absence of a fully consolidated policy domain in the adaptation sphere is also indicated by the fact the only significant predictor of collective adaptation effort is related with stronger leadership of individual local governments.

5.3.3. *Socioeconomic constraints on governance by self-organization*

One third of the population (almost two thirds in some parishes) in the study region is over 65 years old. Reduced demographic and economic vitality, land management abandonment, and low land profitability, in a context where non-industrial private ownership largely dominates, generally distinguish our study setting from those that prevail in the literature. In Anglo-Saxon countries, there has been an increasing urban-to-rural migration with housing developments extending into wildlands (Everett and Fuller, 2011; Moreira et al., 2020; Paveglio et al., 2015) and small private ownership is often confined to the proximity of built-up areas (Charnley et al., 2020; Fischer and Charnley, 2012) rather than extended to the whole of the landscape, as it is the case in our study area.

These territorial differences are relevant for the selection of context-sensitive analytical perspectives and conceptual frameworks that allow to identify solutions and governance arrangements under which they are expected to be implemented. Whatever the context, education for awareness and self-responsibility is among the main proposed solutions (Beighley and Hyde, 2018; Paveglio et al., 2016). Although needed, the educative solution may overlook other aspects of the problem, such as the decrease of response capacity by community members and landowners due to the reduced demographic vitality (Oliveira et al., 2017) and lack of economic profitability of land management (Novais and Canadas, 2022). Concerning governance arrangements, we recall that mitigation under FIZ is being applied mostly in parishes with lower susceptibility/hazard from the LULC point of view (Canadas et al., 2016) and lower vulnerability due to the demographic and socioeconomic features of the population. In other words, public funding of self-organized responses does not counteract territorial disadvantages.

Self-organization is largely recognized as requiring considerable public support to prosper (Villamayor-Tomas et al., 2019), particularly for collective adaptation (Everett and Fuller, 2011; Labossière and McGee, 2017). From our results, there is nevertheless reasonable doubt about the possibilities of assuring the implementation of both mitigation and adaptation solely based on self-organized initiatives in regional contexts like the one studied. Moreover, it is not reasonable to blame a stronger State role and tradition for less self-organization in the Mediterranean context (Górriz-Mifsud et al., 2019), in particular in cases of extremely low social and economic vitality. For example, in our study area, even a strong tradition of popular involvement in volunteer firefighting has been recently affected by aging and population decline (Beighley and Hyde, 2018). A general prejudice on reduced government intervention and funding in any context may therefore be a major hindrance to the promotion of effective WM&A action in socioeconomically weakened territories.

6. Conclusions

The policy debate on wildfire strategies has been dominated by the prevention-suppression duality, within which suppression policies have often been viewed as promoting a fire paradox. Departing from that duality, the mitigation-adaptation distinction we propose is centred on the risk components involved in each: mitigation is associated with susceptibility/hazard and adaptation is associated with exposure and vulnerability. This distinction enabled us to reveal that action concerning collective mitigation does not necessarily go along with action concerning collective adaptation (i.e., they are independent at the local level), and they are associated to different territorial and policy variables.

The progression of mitigation and the adaptation effort seem to be promoted by different policies and policy domains. Our results suggest the policy domain supporting adaptation is less consolidated in the study region than the mitigation policy domain. For example, FOAs, TFO, FIZ, along with the implementation of firebreaks at the landscape level (mitigation domain) are already locally established, while Local Civil Protection Units and the implementation of measures such as perimeter strips for village defence (adaptation domain) are yet to be established.

Owners' collaboration for mitigation action developed in the areas with higher demographic vitality and economic dynamism. Self-organization (residents' collaboratives) for collective adaptation is practically inexistent in the study region and elsewhere in Portugal. High levels of population aging, low profitability of land-using activities, and land management abandonment hinder both mitigation and adaptation on strictly self-governance grounds. In fact, self-organization will hardly arise and prosper in similar regions, where local socioeconomic conditions markedly differ from those reported in the WUI literature.

Our results have emphasized the importance of policy funding and local structural factors that both constrain collective WM&A actions and establish different levels of need for those actions. Another implication that stems from this is that awareness campaigns, intended to spread knowledge and increase the sense of citizens' self-responsibility towards wildfires, are needed but may prove insufficient. Whichever the goal of collective intervention (wildfire mitigation or adaptation), and the corresponding nature of the actors and institutions involved (residents/homeowners or forest owners, associations, or local governments), more government intervention and public funding are needed to overcome territorial disadvantages in demographically and economically depressed regions, as well as to incentivize fuel management to reach effective mitigation results.

CRediT authorship contribution statement

Maria João Canadas: Conceptualization, Methodology, Validation, Investigation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration. **Miguel Leal:** Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization. **Filipa Soares:** Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization. **Ana Novais:** Methodology, Formal analysis, Validation, Investigation, Writing – review & editing. **Paulo Flores Ribeiro:** Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization. **Luísa Schmidt:** Methodology, Validation, Investigation, Writing – review & editing. **Ana Delicado:** Methodology, Validation, Investigation, Writing – review & editing. **Francisco Moreira:** Validation, Writing – review & editing. **Rafaello Bergonse:** Validation, Data curation, Writing – review & editing. **Sandra Oliveira:** Validation, Data curation, Writing – review & editing. **Paulo Miguel Madeira:** Investigation, Data curation. **José Lima Santos:** Conceptualization, Methodology, Validation, Investigation, Writing – review & editing, Supervision, Project administration.

Data availability

We do not have permission to share the primary data (survey to the Presidents of the Parish Councils). Secondary data can be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.landusepol.2022.106444.

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