RESEARCH ARTICLE

Fire-Smart Territories: a proof of concept based on *Mosaico* approach

Fernando Pulido · Javier Corbacho · Manuel Bertomeu · Álvaro Gómez · Nuno Guiomar · Enrique Juárez · Beatriz Lucas · Gerardo Moreno · Javier Navalpotro · Gonzalo Palomo

Abstract

Context Here we develop a practical framework (*Mosaico*) and report a real-world example of early implementation of a Fire-Smart Territory (FST) in Sierra de Gata-Las Hurdes region of central Spain.

Objectives We aimed to assess the impact of landscape changes induced by Local Land Managers (LLM; indirect prevention) on simulated fire spread under different governance scenarios developed in 2016–2021.

Methods Following a participatory process in the region, we received 250 proposals for intervention (49.6% from agriculturalists, 22.8% from forest producers-mainly resin tappers-, and 27.6% from shepherds). From the 94 (37.6%) proposals implemented by the end of the study, we quantified changes in fuel models over the whole territory (Scenario 1, S1). Then, we simulated fires in 20 ignition points to estimate area burned in S1 and three other governance scenarios.

Results To date, the sole intervention of LLMs results in a low to moderate impact (current mean 10.5; median 1.8), which can be explained by the high frequency of small-scale interventions (agriculture) and the comparatively modest impact on fuel reduction of large-scale interventions (livestock grazing). A combination of LLM and public actions is needed to reach a more substantial reduction of burned area (S2-S3, mean % impact 14.1–18.9; median 6.9–10.8). Relaxing legal/administrative constraints to allow large private intervention would result in the greatest attainable impact on burned area (S4, mean 25.0; median 17.8). Adaptive management of *Mosaico* approach must be focussed on improving LLM capacity to modify larger portions of the territory and prioritizing critical areas such as fire propagation nodes.

F. Pulido (✉) · J. Corbacho · M. Bertomeu · Á. Gómez · E. Juárez · B. Lucas · G. Moreno · J. Navalpotro · G. Palomo
INDEHESA - Instituto de Investigación de la Dehesa Research, Universidad de Extremadura, Plasencia, Spain
e-mail: nando@unex.es

N. Guiomar
MED - Mediterranean Institute for Agriculture, Environment and Development; CHANGE - Global Change and Sustainability; EaRSLab - Earth Remote Sensing Laboratory Institute; IIFA - Institute for Advanced Studies and Research, University of Évora, 7006-554 Évora, Portugal

Introduction

Many regions on Earth are experiencing simultaneous changes in climate and land use leading to the occurrence of high large and severe wildfires in the last decades (e.g., Kirchmeier‑Young et al. 2019; Duane et al. 2021; Collins et al. 2022). Firstly, rural abandonment leads to forest and shrub encroachment, which increases fuel load both at local and landscape scales (Viedma et al. 2015; Li & Li 2017). Secondly, the probability of fire ignition and spread over large areas covered by dry fuels also increases with raising temperatures and decreased precipitation (Barbero et al. 2015; Abatzoglou & Williams 2016). In addition, the long-term application of successful fire suppression policies further exacerbates the problem by reducing the area of small-scale fires that could otherwise maintain pyrodiverse landscape mosaics less prone to large and extreme fires (Collins et al. 2013; Fernandes et al. 2020). As a result, wildfires of unprecedented size are increasingly frequent despite the huge amount of resources allocated to their suppression in developed countries (Rego et al. 2018; Grünig et al. 2022).

Wildfire has been defined as a "wicked problem" due to essential difficulties for its conceptualisation, high complexity and interdependency of different dimensions of the fire management, which in turn lead to lack of consensus between actors on the operational arena (Carroll et al. 2007; Chapin et al. 2008). Furthermore, solutions to high severe wildfires are likely to be site-specific due to the influence of local biophysical conditions, land use, traditional fire culture, population density, attitudes and skills on the design and implementation of fire resilient landscapes. Former conceptual and operational frameworks based on the fire suppression models are now being questioned, not only in view of the limited success of this approach, but also due to the exacerbation of the wildfire problem known as the 'firefighting trap' or the 'fire paradox' (Collins et al. 2013; Fernandes et al. 2020; Xanthopoulos et al. 2020). Authors claiming for a paradigm shift recommend that policy and expenditures be rebalanced between suppression and mitigation and that the effectiveness of fire management policies be measured based on the damage and losses avoided in socio-ecological systems, rather than the burned area (Moreira et al. 2020). In parallel, new approaches considering the social-ecological context and stakeholder engagement to create more resilient landscapes are gaining acceptance (Fischer et al. 2016; Vigna et al. 2021). To overcome de ´fear trap' (defensive strategies based only on the known risks), Castellnou et al. (2019) proposed a proactive approach that integrated, not only the uncertainty in decision-making processes, but also the cost of opportunity taking into account firefighting safety and socio-ecological resilience and values. Campos et al. (2021) highlighted rewilding opportunities that can be undertaken through the use of fire or a more flexible fire suppression policy ('let it burn low intensity fires') where the agricultural policies has failed to support High Nature Value farmlands. According to Fernandes (2020), moving from fire suppression-centered policies to sustainable fire management, among other requirements, demands integrative governance, adaptive approaches and cooperative planning guided by landscape management strategies (see, for example, the collaborative Landscape Strategy Making process proposed by Primdahl et al. [2020] in another context).

What are Fire-Smart Territories? A broadened definition

Novel fire regimes are characterized by high-intensity wildfires that spread above the suppression capacity as a result of increasing risk factors, making silvicultural treatments and fire containment infrastructures increasingly ineffective in stopping fire growth and reduce fire severity (Duane et al. 2021). In this context, the use of preventive (smart) measures modifying the fuelscapes to reduce fire hazard results in Fire Smart Management (FSM). FSM was initially applied to achieve sustainable forest management in fire-prone ecosystems. It involved forest management practices aimed at reducing the area burned and the risk associated with the use of prescribed fires (Hirsch et al. 2001; Fernandes 2013; Corona et al. 2015; Pais et al. 2020; Iglesias et al. 2022). However, many fire-prone territories are made of forest patches intermixed with grazing and agricultural lands, notably in the Mediterranean Region. For such heterogeneous scenarios, smart criteria need to be applied to any silvicultural or farming practice, in such a way that the whole territory (and not only forests) is managed coherently (e.g., Hobbs et al.

2014). Thus, the concept of Fire-Smart Territory (FST) has been recently proposed as "*a territory with a shared governance model, in which empowered communities with high levels of knowledge and skills are able to decide and manage wildfire risk to keep it very low, through economic and social activities that not only can contain (in the end eliminate) wildfire hazard but promote the benefits of fire use*" (Tedim et al. 2016; Leone et al. 2020). The main pillars of this concept are: (1) the social basis of the solution; (2) the interaction between institutions and local communities; (3) the coexistence of multiple land uses allowing fuel reduction; and (4) the communication among agents for an adaptive management of the solution, including regulatory changes and incentives (Tedim et al. 2016). The concept of FST remains elusive to date due to the practical complexity of the approach and the absence of tailored policy measures for cross-sectoral and multi-actor initiatives (Wunder et al. 2021). Here we develop a practical framework and report the initial stages of a real-world example of implementation of an FST. To make the concept operational, we consider FST a territory in which a combination of indirect prevention measures based on forestry, agricultural and livestock practices performed by local actors and direct prevention measures (fuel management by fire agencies) are jointly implemented.

Combining direct and indirect interventions in a Fire-Smart Territory

Fuel reduction can be attained through both direct, strategic interventions funded by public bodies, and indirect, non-strategic interventions whose expected economic returns justify investments by local land managers with or without public support (e.g., grazing, cropping or wood harvesting). Table 1 summarizes the main relevant traits of both approaches. Briefly, the main advantages of direct interventions are related to their strategic location with respect to expected fire behaviour and their rather immediate implementation once they have been officially designed (Oliveira et al. 2016; Salis et al. 2018). However, the high costs and short service life of these fuel management actions usually preclude their application in vast regions. In a study conducted by Davim et al. (2021) in Portugal mainland, the authors concluded that survival of prescribed burning treatments to wildfires decreases with time since treatment (being higher for fuel ages of less than 3 years) and increases with treatment size, and that the encounter rates between prescribed fire patches and wildfires are very high and occur mostly up 4 years after the treatment. By contrast, indirect interventions implemented by local land managers (LLMs) are long-lasting and can cover large areas at no or reduced cost to the public purse (Wunder et al. 2021). They also generate economic returns and promote stakeholder engagement in the territory. Unlike targeted measures, indirect intervention may generate a diffuse effect over larger areas, which has proven effective in reducing wildfire size or severity. Thus, heterogeneous agroforestry landscapes are less affected by large and severe wildfire events than forests, shrublands or grasslands, providing evidence of their large-scale potential to reduce fire hazard and increase fire suppression capacity (Damianidis et al. 2020; Ascoli et al. 2021; Lasanta et al. 2022). Public institutions can further support indirect measures through ad hoc regulations and a variety of incentives such as payments for preventive grazing or supportive

Table 1 Main attributes of direct and indirect approaches for fire prevention in the *Mosaico* territory

Attribute	Direct prevention	Indirect prevention
Funding	Public	Mostly private
Land ownership	Mostly public	Mostly private
Location	Linked to fire behaviour	Independent on fire behaviour
Public cost	High	None or low
Useful life	Short	Long
Governance	Simple	Complex
Products generated	Seldom	Frequently
Social engagement	Seldom	Relevant
Deterrence	No	Relevant

infrastructures for shepherds (Varela et al. 2018; Ascoli et al. 2022).

The strategic value of an area devoted to fuel management can be determined by previous experience, fire history and/or through fire simulations (Oliveira et al. 2016; Salis et al. 2018; Benali et al. 2021). Once it is spatially located, fuel management operations rely on a continued public investment that keeps fuel load under a reasonable threshold. For this reason, a FST based only on direct interventions could in theory be advisable in relatively small public forests where indirect interventions may be undesirable for reasons related to forest conservation. And even in this extreme situation, indirect measures such as prescribed grazing may generate important benefits through fuel reduction and increased surveillance (Varela et al. 2018).

Mediterranean forestlands are usually made up of public forests managed by public agencies and private forests managed by land owners. Thus, any risk reduction plan must necessarily address this duality and allocate resources to both direct (public) and indirect (private) measures. Large and high severe fires are inherently linked to rural abandonment since the mid-twentieth century, which has resulted in an extremely fast forest transition over a traditionally farmed landscape (Viedma et al. 2015; Oliveira et al. 2017; Iriarte & Ayuda 2018). The loss of agroforestry mosaics results in the coalescence of forest patches and increased fuel continuity, pushing many wildfires beyond suppression capacity (San Miguel et al. 2013) and resilience thresholds (Guiomar et al. 2015). Reversal of such processes in extremely depopulated areas is unlikely to occur without a certain degree of public intervention (Wunder et al. 2021). This is the reason why we assume that any given FST depends on a site-specific combination of direct and indirect measures.

The Mosaico approach

The approach illustrated in this study was developed to address a specific problem after a large fire occurred in August 2015 in Sierra de Gata (central Spain). This fire affected 7800 hectares (mainly of shrublands and pine forests) and caused severe losses in local economies (livestock husbandry, orchards and agrotourism). After this event there

was a general consensus concerning the drivers of such wildfire (Bertomeu et al. 2022): rural abandonment, loss of traditional farming practices and the subsequent spread of woody vegetation. Accordingly, our research team from Universidad de Extremadura (UEX) proposed a participatory initiative (project *Mosaico*) aimed to gradually reverse the trend by promoting agroforestry practices of preventive value. The proposal was approved and it has been funded by the regional government of Extremadura for five years (October 2016–September 2021), with risk reduction through participatory landscape change as the main goal. *Mosaico* meets the main attributes of an Integrated Landscape Initiative: acts at a landscape scale, involves inter-sectorial coordination, develops and supports multi-stakeholder processes, and it is highly participatory (García-Martín et al. 2016). The project relies on five main pillars (Wolpert et al. 2022): (1) active search and engagement of LLMs, defined as individuals or groups exploiting a portion of the territory in a way that can reduce fuel load and the probability of fire propagation; (2) interaction among institutional actors, including regional and local agencies and academia; (3) enhancement of cooperation between LLMs by promoting the establishment of formal associations; (4) continued technical support to LLMs offered by centres of knowledge; and (5) periodical evaluation of changes in risk reduction and subsequent adaptation by allocating effort to more cost-effective interventions.

Mosaico is a large-scale, long-term project aimed to gradually generate a FST by engaging all types of LLMs from the agricultural, livestock and forestry sectors. The impact on fuel load of these practices may vary as a function of area exploited and fraction of fuel removed. Also, the impact on fire spread depends on the spatial arrangement of the managed patches (Oliveira et al. 2016; Salis et al. 2018; Ager et al. 2021). Besides these factors, the rate of landscape change depends on the number of LLMs joining the project, which is a function of population density, attitudes, skills, and external support (Wolpert et al. 2022). Therefore, the region-specific rates of landscape change and risk reduction can only be estimated through experience, and it must be improved through adaptive project management. In this paper we aim:

(1) to analyse the response and success of LLMs when invited to participate in an integrated fire prevention initiative;

(2) to describe, qualitatively and quantitatively, the interventions performed by LLMs as compared to public measures;

(3) to compare the effect of different types of interventions on fuel models;

(4) to assess the impact of induced landscape changes on simulated fire spread under different governance scenarios.

By addressing these goals we aim to illustrate and refine the FST concept as well as to suggest practical guidelines for replication and adaptive management in multiple target territories.

Methods

Study area

Mosaico is being carried out in two adjacent but contrasting counties of northern Cáceres province, central-western Spain (Fig. 1). The western region, Sierra de Gata (SG), is located at the border between Spain and Portugal and includes 18 municipalities encompassing 111,024 ha. The eastern region, Las Hurdes (LH), occupies 46,268 ha in five municipalities. Both are mid-elevation (500–1500 m a. s. l.) mountain regions under subhumid Mediterranean climate. Mean annual temperature is 13 °C and annual precipitation is 1000 mm in SG. In LH the values are 14 °C and 1300 mm, respectively. In both regions forestlands (forest, shrubland and grassland) are the dominant land use, covering 91.7% of SG and 81.0% of LH (Fig. 1). We restricted our analysis to fire-prone areas dominated by forests and/or shrublands, excluding some patches of more intensively used grasslands or annual crops. Under this criterium, the area analysed comprises 82,990 ha in SG and 37,477 ha in LH. In these areas shrublands resulting from secondary succession are the main vegetation type (43.8%) due to high fire recurrence and agricultural abandonment. Oak forests including *Quercus pyrenaica*, *Q. suber* and *Q. ilex* cover 15.2%, whereas pine (*Pinus pinaster*) plantations and secondary pine forests are present in 31.1% of the area. The remaining 9.9% corresponds to tree crops, especially olive (*Olea europaea*) and also small-scale and scattered orchards planted with chestnut (*Castanea sativa*), fig (*Ficus carica*) and cherry (*Prunus avium*).

In both regions wildfires larger than 100 ha have been frequent, highlighting some events with fire size larger than 3000 ha, that occurred in 1991,

Fig. 1 Map of the main landscape units in the study area. The solid line in the map differentiates Sierra de Gata (left) and Las Hurdes (right)

Forests
Shrublands
Croplands
Water bodies
Villages

0 5 10 20 Kilometers
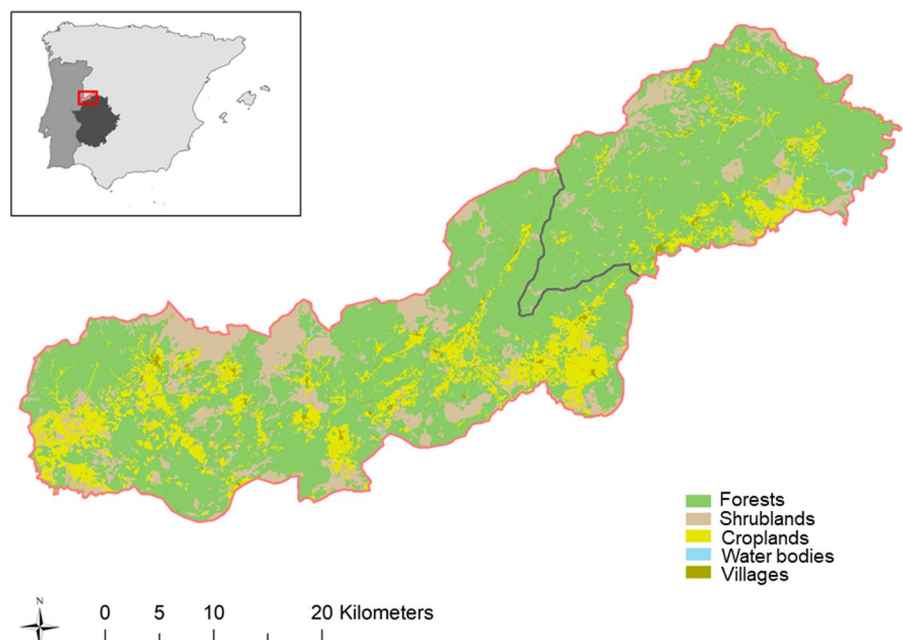
2003, 2009, 2015, and 2022 (Figure S1). According to the official wildfire records (MINECO 2022), the main causes of ignition are intentional fires (49%) and negligence (16%). Typically, shrublands and pine plantations (which in many cases have a dense shrub layer) are the most affected vegetation types. Forest ownership is a relevant factor affecting forest condition, with public pine forests receiving the highest investment for silvicultural treatments and fire suppression infrastructures. Private forests in general lack active management due to high costs, except in those areas managed under public–private agreements. Public forests are owned by local or regional agencies but they are invariably managed by the regional Forest Service. They cover 35,771 ha (45.9% of total forests) in SG and 34,689 ha (79.8% of forests) in LH.

The study area harbours a total population of 17,675 inhabitants (13,040 in SG and 4635 in LH). Global population density is 11.9 persons per square kilometre, which is under the threshold used to define Sparsely Populated Areas in Europe (Le Tourneau 2020). The percentage of people under 20 years old is low (12%) and the largest fraction of people are over 60 years. Population has declined by 41.4% and 48.4% since 1960 in SG and LH, respectively. This depopulation process is still on-going and led to drastic landscape changes observed in the last decades. Nowadays, most inhabitants (55.5%) work in tourism or other type of services. The population linked to direct land management has declined from 48.4% in 1976 to 14.8% in 2021. Most of them are agriculturalists or shepherds, though farmers performing both activities are also frequent. Forest exploitation is mostly linked to timber or biomass harvesting from public pine stands, which is performed by private companies based outside the region. The recent recovery of the pine resin sector due to rising prices is attracting young workers in both SG and LH (Bertomeu et al. 2022). In LH all forests are centrally managed, which precludes participation of local actors. In SG, however, several NGOs were created soon after the 2015 fire, playing a relevant role in the implementation of fire resilient landscapes.

Project implementation

Mosaico was designed in 2016 to promote indirect wildfire prevention through livelihood activities carried out by LLMs: agriculturalists, forest users (timber or resin harvesters), and shepherds (managing herds of goats and/or sheep). Whereas orchards are invariably located in private lands, resin tapping and grazing are mostly performed in public lands by individual LLMs. Public forest lands are managed exclusively by the Regional Forest Service. We considered public treatments as direct prevention if exclusively applied for fuel reduction, whereas timber/biomass harvesting was considered as indirect prevention (Wunder et al. 2021; Ascoli et al. 2022). Forest management interventions performed by the Forest Service were not planned within the *Mosaico* framework, but we used them to define a relevant scenario involving both public and private actors (see below).

Mosaico approach is based in the engagement of LLMs, either acting as individuals or associations. External actors (companies and NGOs) were also included whenever their activities were developed in SG and/or LH. To get these actors involved in the project we conducted, from October 2016 to June 2017, a public process explaining the goals of the project through focus groups in all the municipalities (Wolpert et al. 2022). Focus groups were convened through announcements in public offices and social networks. During these sessions we encouraged the participants to join the project by sending their initiatives through the project's website (https://www.mosaicoextremadura.es). Proposals received were accepted for further support if they could achieve any degree of fuel reduction through the land use practices described above. After acceptance, initiatives were included in a database with their main attributes (type, area managed, goal, relevant skills and contact data of the person/association/institution in charge of the proposal). Spatial information was recorded in ArcGIS® for subsequent evaluation of landscape changes. The information on initiatives was gathered in one or more face to face interviews by an expert technician from our team (a forest engineer, an agricultural engineer or a veterinary depending on the type of initiative). The same technicians monitored and supported every single initiative from the onset to final execution or resignation. Hereafter, we use

the term "intervention" for initiatives that were successfully implemented.

During the project we used an adaptive approach aimed to increase the likelihood of full execution and the area impacted by the interventions. Thus, from June 2017 to June 2019 we supported LLMs by organizing practical sessions and training courses to improve their technical skills. In addition, from June 2019 we selectively supported associations, companies, and municipalities, which usually results in greater areas impacted due to improved professional skills and resources managed by these actors. This differential effectiveness was also achieved by submitting large projects to official calls from regional, national or international programs, especially LIFE EU, the Regional Research Program, and regional/national Operational Groups for Rural Development. Additional communication and engagement tasks were carried out, including recording and dissemination of 60 short movies showing successful stories led by LLMs (https://vimeo.com/user58436665/videos), organization of popular events to promote labelled products generated by LLMs, and public round tables to discuss advances and implementation problems encountered.

Effect of interventions on fuel models

Table 2 shows a description of the way different land use practices modify fuel loads in the studied landscape, as well as the resulting fuel models. Changes in the fuelscape were assessed through changes in Rothermel's (1972) fuel models generated by agricultural, forestry and livestock interventions (Table S1). Official fuel model maps drawn in 2018 through digital photointerpretation and field work were provided by the Regional Fire Service. Subsequent changes in fuel models due to interventions were assessed through orthophotomaps from 2016 and 2020. Complementary field assessment was carried out whenever the original classification raised doubts. In all interventions a single fuel model initially covered the whole area or it was clearly the dominant fuel model. Interventions also resulted in a single/dominant fuel model after vegetation change. Agricultural interventions were usually small in size (< 10 ha) and generally changed from dense forest or shrubland to tilled soil (hereafter model "M0") or transient grassland with scattered fruit trees. Mechanical felling and grubbing of woody vegetation was conducted before soil ploughing for subsequent planting. Forestry interventions (timber harvesting or resin tapping) were intermediate in size (10–100 ha) and transformed dense forests with or without a dense understory to a less dense one without a shrub layer.

Livestock interventions were much larger in size (usually > 100 ha) and comprised a variety of vegetation types, which makes the direct assessment of fuel changes difficult. In addition, five (out of 20) shepherds were engaged in an official program for targeted grazing in fire-breaks, which led them to concentrate their grazing effort on such linear infrastructures. Hence, we made a simplified, qualitative and conservative assessment of livestock-induced fuel model changes based on the estimated fraction of the area used by livestock that showed

Table 2 Description of the ways different Local Land Managers change fuel loads through land use practices

Land use	Type of land use practice	Preventive value	Initial fuel model	Final fuel model
Agriculture	Tree crops (olive, chestnut, cherry, fig, almond)	Scattered trees with tilled (bare) soil or with low herbaceous cover	M2, M4 M5, M7	M0, M1
	Shrub crops (vineyard, red fruits, pistachio, aromatics)	Lines of shrubs separated by tilled lines	M2, M4 M5, M7	M1, M2
Livestock	Small ruminants (goat, sheep)	Continuous shrub layers are kept short and discontinuous	M1, M2, M4 M5, M7, M9	M2, M4 M5, M9
Forestry	Timber harvest	Reduction of tree density	M4, M7	M2
	Resin tapping	Continuous removal of the forest understory	M7	M9

Initial and final fuel models represent actual alternatives observed in the study area. Model M0 correspond to bare (tilled) soil. See Table S1 for description of fuel models

unequivocal evidence of vegetation consumption. This percentage was obtained in the field by sampling randomly distributed points along dirt tracks and noting vegetation consumption (absent or moderate *vs*. severe). This procedure resulted in three categories regarding fuel model change: (1) grazing interventions causing severe plant damage in more than 50% of the sampling points and resulting in a fuel model change over most of the area in recent years; (2) targeted grazing interventions in fire-breaks causing no or little change in fuel model in the surrounding, vegetated area; and (3) interventions implying non-targeted grazing but causing no recent change in fuel model (due to small flock size and/ or use of external food sources; note that significant changes due to grazing could have occurred before the project).

Effects of interventions on burned area

From the changes in fuel models, we estimated the impact of the interventions on fire characteristics trough fire simulations. Simulations with and without landscape interventions were performed using the Wildfire Analyst® software, which provides different descriptors of fire behaviour (see Bertomeu et al. 2022 for a previous application in the study area). Here we focus on changes in fire size to assess the effectiveness of the intervention network (see Oliveira et al. 2016 for a similar approach for a fuel-break network in southern Portugal). Twenty fires were simulated for each scenario using randomly selected ignition points over the whole study area. Fire duration was set at 10 h. We used the most frequent wind direction in the region (22°). Wind speed was set at 25 km/h, air humidity at 30%, temperature at 25 °C, and fine dead fuel moisture (1 h) was 8%.

Effect of governance on burned area

Rather than analysing in detail fire behaviour or burned areas, we focussed on the impact of governance models on fire size. We evaluated the impact of the project interventions on burned area under five governance scenarios resulting from different combinations of direct and indirect measures:

S0: scenario with no landscape intervention ("control" scenario).
S1: scenario with LLM interventions implemented by the end of the study ("private" scenario).
S2: this scenario pools LLM interventions and measures conducted by the Forest Service consisting of mechanical fuel treatments or silvicultural treatments ("mixed" scenario).
S3: this is a foreseen scenario resulting from S2 plus additional measures designed by UEX that will be funded by the Forest Service. These measures have been designed to achieve fuel reductions with public funds, which will subsequently be maintained by LLMs ("cooperation" scenario).
S4: this is a hypothetical scenario including S3 initiatives plus "failed initiatives", that is, initiatives that were proposed by LLMs but could not been implemented within the study period due to legal barriers, administrative burdens, lack of funding or insufficient LLM skills. As shown below, currently failed initiatives are 43.6% of the whole set. We only included in this scenario the subset of failed initiatives for which LLMs had a clear plan with an exact area for intervention, which usually were initiatives promoted by private companies.

S1 corresponds to the narrow-sense definition of FST in which changes are led by empowered local communities (Tedim et al. 2016; Leone et al. 2020). S2 and S3 incorporate public agencies working
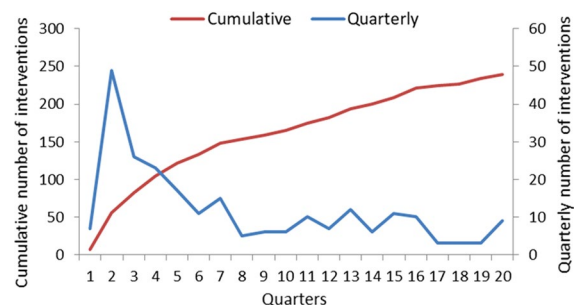
Fig. 2 Cumulative and quarterly number of proposals made by Local Land Managers from October 2016 to September 2021. Data for quarter #10 and quarter #11 were estimated from the total number of proposals received between #9 and #12

independently or in cooperation with LLMs, respectively. S4 is a virtual scenario conceived to gain insight into the obstacles faced by LLMs and the eventual measures needed to circumvent them. Overall, these scenarios represent a wide spectrum of governance structures and adaptive processes that could be replicated elsewhere.

Results

Enrolment and performance of Local Land Managers

We registered 250 valid proposals for intervention in the target territory between October 2016 and September 2021. This number considers 24 interventions by resin tappers that were jointly included at the end of the project. As shown in Fig. 2, the period considered started with a first year (2017) with the highest rate of proposal submission. This led to 104 (41.6%) initiatives received, that is, approximately 10 proposals per month during that year. The subsequent four-year period showed a lower and rather constant rate of proposal reception of ca. 3 proposals per month. By the end of the study the number of proposals was still growing, suggesting that there is still potential for further development. Considering the whole set of proposals (n = 250), 124 (49.6%) came from agriculturalists, 57 (22.8%) from forest producers, and 69 (27.6%) from shepherds.

Regarding the success of the proposals presented, 94 (37.6%) had been implemented by the end of

Fig. 3 Map of interventions implemented in the target regions by Local Land Managers in 2016–2021. Green, red and orange perimeters correspond to agricultural, forestry and livestock interventions, respectively
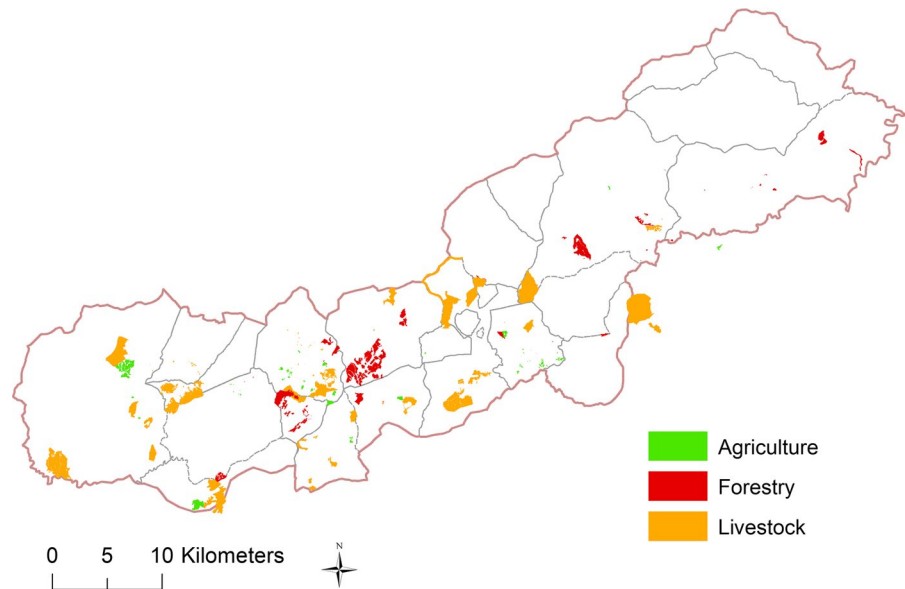
Table 3 Summary statistics for private and public interventions carried in the study area in 2016–2021

	n	Área (ha)	Mean ± SD	Median	Min–Max
Private interventions	94	5754	61.2 ± 112.5	18.6	0.3–552.3
Agriculture	35	350	10.0 ± 14.7	3.7	0.3–69.6
Forestry	39	1244	31.9 ± 41.0	21.0	2.8–253.0
Livestock	20	4160	208.0 ± 170.2	140.0	2.1–552.3
Public interventions	53	2985	56.4 ± 92.8	17.4	0.7–481.1
Fuel removal	30	363	12.1 ± 9.3	9.9	0.7–39.3
Thinning	23	2622	114.0 ± 118.7	58.1	1.5–485
Proposed interventions	35	1617	46.2 ± 75.6	14.1	1.5–268
Failed interventions	17	3807	224.0 ± 507.0	9.1	1.3–1991.2

the study period. The rest of the initiatives (62.4%) were considered as non-implemented, with 43.6% deemed as failed and 18.8% in progress or with insufficient information. Success rates were similar for agriculturalists (28.2%) and shepherds (28.9%), with forest users reaching higher rates (45.4%).

Attributes of interventions

Private interventions performed by LLMs (n=94) were assigned to the following categories: "agriculture" (37.2%), "forestry" (41.4%), and "livestock" (21.3%). The spatial distribution of these interventions is shown in Fig. 3. By far, most (75.5%) interventions were carried out in SG region, where most private land is found. In LH region (24.5% of interventions) public management precluded LLM interventions except in small private enclaves. Agriculture (mean area: 10.0 ha; Table 3) entailed tree or shrub plantations (chestnut, olive, cherry, berries and aromatics) on

bare soil which is tilled annually. Livestock (mean area: 208 ha) initiatives involved mainly goats and sheep either in single- or mixed-species herding. Finally, the forestry category (mean area: 31.9 ha) mostly included pine tappers (85% of interventions) followed by timber operations or two forest tree plantations using mainly tree oak species. Among-type heterogeneity in area of the interventions was statistically significant (ANOVA: F=40.69, df=2, 91, p<0.001).

Public interventions consisted of 23 thinning operations in pine stands (mean area: 114.2 ha; Table 3) and 30 fuel reduction treatments conducted to reduce fire hazard around villages (mean area: 12.1 ha). These interventions were invariably conducted in public forests, with thinning treatments being more frequent in SG (75%) and fuel removal treatments in LH (80%).

Fig. 4 Changes in fuel models in all interventions pooled and in the three types of interventions separately. Initial and final fuel models are shown on axes X and Y, whereas the absolute frequency of each type of change is shown on the Z axis
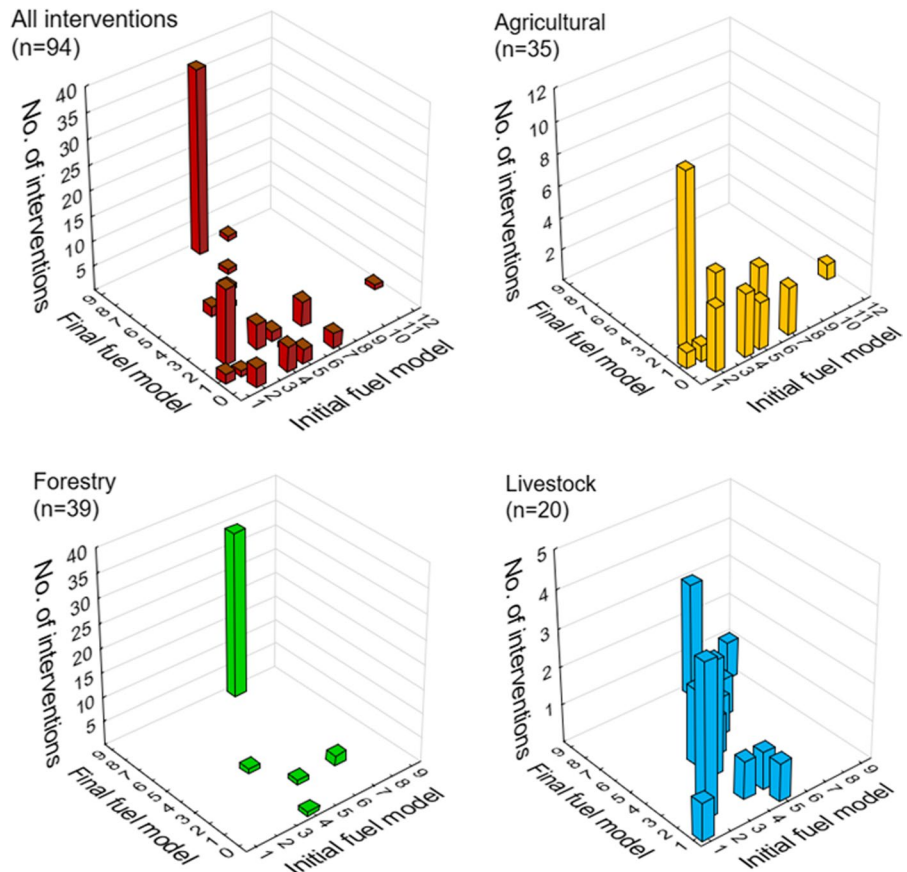
Changes in fuel models

Figure 4 quantitatively depicts the changes in fuel models resulting from the three types of LLM interventions (see also Tables 2, S2). Agricultural interventions affected natural vegetation or human-altered patches, but in either case resulted in fuel models with low or no surface fuel load. Areas used for tree cropping show very low tree densities and frequent tillage, which limits fire spread. Forestry interventions (mainly tapping) reduce the horizontal and vertical continuity of the vegetation through continuous shrub removal, which is required to access the base of pine trees were resin is tapped. Finally, livestock interventions using small ruminants changed fuel model in 8 out of 20 cases (Fig. 4). In the remaining cases, livestock did not noticeably reduce standing woody plant biomass but avoid vertical and horizontal growth through browsing, grazing, and trampling. This may also result in reduced fine fuels availability, though the large spatial scale of our study preclude us to conduct a detailed assessment of the affected area. Across LLM intervention types, a size-effectiveness trade-off can be established. Thus, agricultural interventions were the most effective in reducing fuel loads over small areas (usually < 10 ha). Forestry interventions substantially reduced fuel continuity over areas of intermediate size (10–100 ha). Livestock interventions covered large areas but mainly stabilize rather than reduce fuel loads.

Public interventions for thinning converted high-density pine stands in open forests suited for resin tapping, a practice that requires shrub growth control. Finally, intensive fuel treatments in public forests and around urban areas results in a few isolated trees and a thin layer of woody debris from shrub clearing and chipping.

Governance and effects on area burned

In this section we compare governance scenarios (from S0 to S4) representing a gradient of increasing cumulative area of interventions (Table 3). The area affected by interventions increased from S1 (only LLM interventions, totalling 5754 ha), to S2 (S1 + public interventions; 8739 ha), S3 (S2 + proposed interventions; 10,356 ha) and S4 (S3 + failed interventions; 14,163 ha).
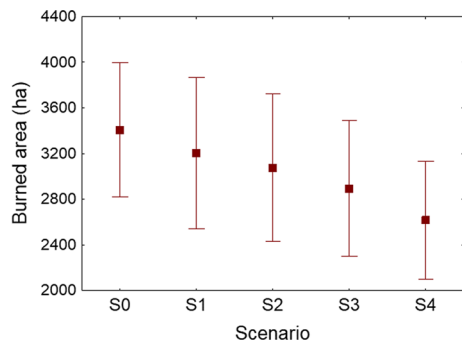
Fig. 5 Mean (±95% CI) burned area in S0-S4 scenarios from 20 random ignitions points. *S0* control scenario, *S1* with private interventions of LLMs, *S2* S1 plus public interventions, *S3* S2 plus mixed interventions proposed; and *S4* S3 plus failed interventions
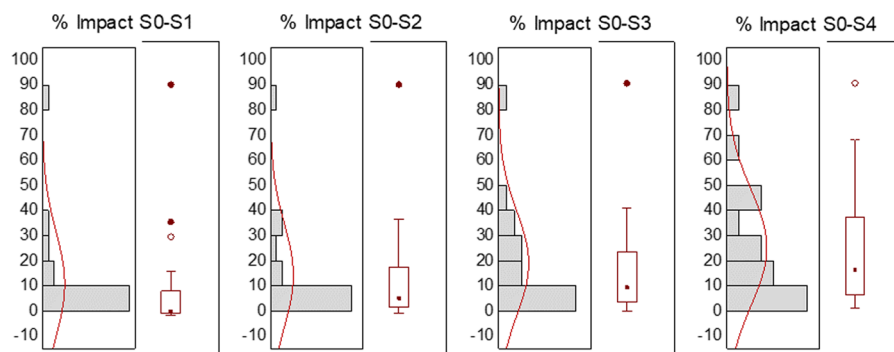
Fig. 6 Frequency distribution and summary statistics of percentage reduction of burned area among scenarios. Box & whiskers plots show median values (solid squares), 25–75% percentiles (boxes), non-outlier ranges (whiskers), outliers (empty circles), and extremes (solid circles). The red line on each graph denotes a normally distributed pattern

Table 4 Summary statistics for the impact (% reduction in burned area) across scenarios

	Impact S0-S1	Impact S1-S2	Impact S2-S3	Impact S3-S4
Mean	10.54	14.08	18.83	25.01
SD	20.89	20.35	20.50	23.05
Median	1.82	6.94	10.77	17.37
25th% percentile	0.78	3.11	5.15	7.97
75th% percentile	9.38	18.47	24.47	37.80
Minimum	0.04	1.01	1.54	2.96
Maximum	88.28	88.58	88.90	88.93
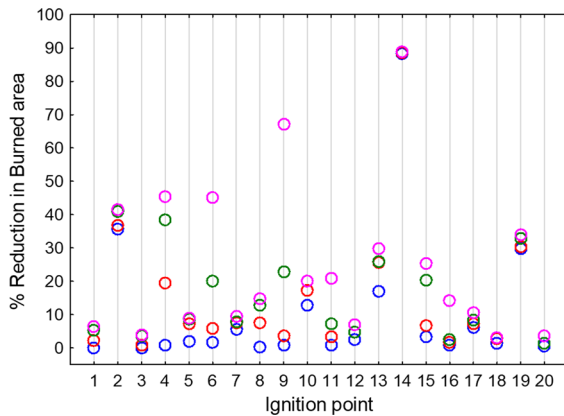
Fig. 7 Variation in cumulative reduction of burned area of each scenario across random ignition points. To improve visualization, lines in the vertical grid join different scenarios for a given ignition point. Blue circles: S1; red circles: S2; green circles: S3; and pink circles: S4

Figure 5 shows mean area burned across scenarios. Values decreased from S0 to S4 in close agreement with the accumulation of area treated across scenarios (r = − 0.97, p = 0.005, adjusted R^2 = 0.93). From the values of area burned in each simulated fire (n = 20), we calculated the individual percentage decrease in area burned among scenarios or "impact". The frequency distributions of impact strongly departed from normality (K-S test, p < 0.01 in all scenarios), and it was highly right-skewed (Fig. 6). Mean impact was 10.5% for S0-S1, 14.1% for S1-S2, 18.8% for S2-S3, and 25.0% for S3-S4. The corresponding median impacts (%) were 1.8, 6.9, 10.8 and 17.4 (Table 4). The number of fires (out of 20) with impact > 10% was 5, 6, 10, and 13, respectively (Fig. 7).

Discussion

LLM enrolment and success

In a previous work based on *Mosaico* (Wolpert et al. 2022), we showed that LLMs feel highly affected by wildfires and are strongly motivated to reduce the effect of land abandonment as the main driver of wildfire hazard. The project was seen to have positive outcomes for individual participants as well as the region, and to stimulate community connectedness (Wolpert et al. 2022). Our region experienced a steady increase in entrepreneurial intentionality, which was very intense during the first year of the project and, to some extent, attenuated the negative consequences of a large wildfire. This attitudinal change was driven by both short term needs of people severely affected by this wildfire and a long-term vision of creating a resilient territory (Bertomeu et al. 2022; Wolpert et al. 2022).

Natural disturbances can create opportunities for entrepreneurial behaviour even as they generate severe negative effects on socioeconomic systems (e.g., Monllor & Murphy 2017). *Mosaico* helped to create value after the wildfire by taking advantage of small business opportunities and providing supporting services required by stakeholders, in agreement with the definition of disaster entrepreneurship (Linnenluecke & McKnight 2017). After a first year of mass reception of proposals, a lower but sustained rate of engagement was found, in such a way that the cumulative curve of proposal reception did not reach asymptotic levels by the end of the study. This is partly due to the continuous arrival of neo-rurals in the area, which show a strong commitment with the project (Wolpert et al. 2022). Lower immigration rates due to remoteness and harsh climate, together with obstacles in accessing land in the

centrally-managed, public forests of LH region, may explain why the overall enrolment in the project was much greater in SG (Fig. 3). In many parts of Europe, neo-rurals moving from urban to rural areas for living and farming play a role in integrated landscape management as they are growing in number and often seek new models of sustainable land management. Forty-two per cent of the LLMs participating in *Mosaico* project with successful initiatives were neo-rurals, showing higher motivations compared to rurals on increasing biodiversity and growing their own food in a healthy way of life (Wolpertz et al. 2022).

Thirty-one per cent of the initiatives had been executed by the end of the study (38% if we include 24 tappers), though initiatives are still open that will increase the overall success rate in the near future. Comparison of such rates showed similar values for agricultural and livestock initiatives and higher values for forestry initiatives. This difference may be explained by the influence of tapping and tree planting interventions, which experience a lower number of administrative barriers. Unfortunately, the lack of similar experiences on bottom-up, multi-sectoral preventive management hampers global comparisons. A recent review in Euromediterranean countries (Ascoli et al. 2022) showed that most of them are based on fuel treatments through mechanical tools, grazing or prescribed burning at local scale. Few of them rely on forestry interventions and none of them promoted simultaneously the three types of practices used in project *Mosaico*. Unfortunately, assessment of the contribution of such initiatives to fire prevention is hampered by their short lifespan derived from transient public funding. Thus, we advocate for the implementation of long term, self-sustainable approaches to develop community-led FSTs.

Failure of 44% of the proposed initiatives was due to multiple causes, though a previous survey based on interview to LLMs showed that maladapted legislation and bureaucratic burdens were generalized (Wolpert et al. 2022). Additional problems stem from lack of funding, poor access to land, and insufficient skills/motivation. Overall, this syndrome also applies to most Integrated Landscape Management initiatives in Europe (García-Martín et al. 2016).

Changes in the fuelscape

Most experiences aimed to manage wildfire hazard focus on fuel reduction treatments at strategic areas to increase fire suppression capacity (e. g., Salis et al. 2018; Palaiologou et al. 2020; Benali et al. 2021; Alcasena et al. 2022; Aparício et al. 2022). LLMs, however, take decisions on the basis of their expected economic return and therefore their interventions are not intended to change fire behavior. Though, as these interventions build up in the territory, they may exert a diffuse, non-targeted effect that may reduce fire intensity, fire rate of spread and/or fire size (Lasanta et al. 2022). By promoting such indirect prevention, project *Mosaico* relies on the massive and complementary implementation of agricultural, forestry and livestock interventions. LLMs involved in the project managed 5774 ha or 4.8% of the target territory, with disparate effects on fuel load. After analyzing the size and impact of different interventions, a size-effectiveness trade-off can be established, as shown below.

Tree/shrub crops (350 ha, or 0.3% of the target territory) tended to be concentrated in fertile soils and thus were small in size but resulted in low-risk fuel models due to tree scatter over tilled plots. Several studies focusing fire selectivity showed that permanent crops (olive groves, orchards, vineyards) are among the least fire-selected land use systems (Moreira et al. 2009; Bajocco et al. 2010; Carmo et al. 2011). Cultivated plots may mitigate fire spread passively or by improving fire suppression (Aquilué et al. 2020; Pais et al. 2020). Unfortunately, implementation or recovery of woody crops to mitigate wildfire damages seems to be an exception in programs for indirect prevention (Ascoli et al. 2022). However, evidence exists that this is a promising tool (see, for example the local network of "cultivated fuel breaks" in eastern Spain led by Fundación Global Nature, https://fundacionglobalnature.org/cortafuego sverde). Enhancement of this preventive role could be achieved through the Common Agricultural Policy (CAP) by designing a payment scheme to farms at strategic locations and adopting fire prevention practices.

Forestry interventions performed mostly by resin tappers (1244 ha, or 1.0% of the area) have a large impact on reducing wildfire hazard due to several reasons. First, the area tapped need to be previously

thinned by the Forest Service to allow sufficient tree growth to ensure resin production. Second, tappers continuously remove the underbrush in pine stands and keep the managed area accessible. Third, they deter intruders that may cause ignitions during the summer period of severe fire-weather. And, finally, they jointly cooperate with surveillance agents by communicating relevant incidents. On the basis of these benefits and the ecosystem services they provide (Soliño et al. 2018), the regional government of Extremadura has recently implemented a new CAP payment scheme for tappers that was designed by project *Mosaico* and could be applied in similar regions. In areas exclusively dedicated to wood production, the vertical continuity of fuels can be effectively reduced and, consequently, the potential fire severity, through underburning (Fernandes 2018) and fire-adapted sylviculture (North et al. 2021; Fernandes 2022), complementing all the effort made in forest stands where resin extraction is the main activity.

Intervention based on livestock (4160 ha, or 3.5% of the area) occurred in large areas (up to 552 ha) where animals play a relevant role by stabilizing plant biomass and preventing transition to more hazardous fuel models. Severe impact on fuel load can only be attained by means of targeted grazing (Varela et al. 2018) or in semi-intensive farms, both of which occur in small areas. However, very dense, old and lignified shrublands limit the success of grazing in reducing fuel loads, as concluded by Ruiz-Mirazo et al. (2011) after an assessment of livestock grazed fuelbreaks. Therefore, the efficiency of "fire shepherds" can be greatly improved by mechanical fuel treatment or prescribed burning, which opens new areas of resprouting vegetation for browsing animals (Ascoli et al. 2013; Fernandes et al. 2013). Combination of mechanical treatments with livestock in our study area confirms that this is a cost-effective action, which could be improved through prescribed burning with additional benefits in soil fertility and ecosystem resilience (Alcañiz et al. 2020). Finally, if supported with small payments or critical infrastructures (e.g., fences, cotes, troughs), shepherds may play a critical role by deterring intentional fires in their lands.

Governance and burned area

One key assumption of *Mosaico* approach is that the success of FSTs depends not only on community initiative and involvement but also on public support, at least in sparsely populated regions. Private–public cooperation is needed to adequately combine direct and indirect prevention. Direct prevention alone may involve unacceptable societal costs, whereas indirect prevention alone needs to be applied in a large portion of the territory to be successful (Table 1; Wunder et al. 2021). This study shows that, in the current policy scenario, a combination of private and public actions is needed to reach a substantial reduction of burned area (14–19%). The interventions of LLMs would ensure a similar impact only in a scenario with no legal restrictions or in a longer time frame. Similarly, the sole intervention of public agents results in a moderate reduction in burned area. Finally, relaxing legal constraints to allow private intervention in public areas would result in the highest attainable impact on fire regime. Below we provide details on the advantages and challenges of these specific scenarios.

On average, private initiatives executed within the *Mosaico* framework (S1) resulted in a 10.5% reduction in burned area. However, the median impact was much lower and only one quarter of the simulated fires experienced an impact above 10%. To date, the limited impact of LLMs can be attributed to the high frequency of small interventions and the low impact on fuel reduction of large interventions. As shown in S4, the inclusion of unperformed LLM interventions would result in a marked reduction of area burned, and this might also be true after implementation of pending initiatives. Interestingly, such reduction could be achieved with the implementation of only three large agricultural interventions (200, 500 and 1500 ha in size; Figure S3) that were not allowed in public land. The Spanish forest legislation (*Ley de Montes*; Gobierno de España 2003) prohibits changing land use from forest to agriculture in areas burned within 30 years after fire occurrence (unless previously planned), which is often the case in the study region due to recurrent fires. In addition, even if plantations do not involve a land use change, they are not allowed when promoted by private companies on public land. Finally, a large fraction of the study area is also protected under Natura 2000 network, which

poses additional restrictions on potentially beneficial interventions. Therefore, relaxing these legal limitations could greatly enhance indirect prevention.

The mixed scenario (S2) combines LLM interventions with public ones consisting of medium-size thinning operation and small fuel treatments around villages. LLMs treated a larger area, whereas public interventions were more effective in reducing fuel loads despite they were not developed in strategic areas based on potential fire behaviour or fire exposure, as several authors propose (e.g., Quílez et al. 2020; Aparicio et al. 2022). Given the high cost and short lifespan of public interventions, performing them in strategic areas for fire prevention as part of Fire Smart Management would increase their cost-efficiency (Fernandes 2013). A similar result could likely be achieved by allowing tappers to reduce fuel load for resin harvesting.

All public interventions were performed in public forests, and this resulted in an aggregated pattern of fuel reduction at the landscape scale (Figure S2). Public intervention would be desirable also in private forests because most of them have remained unmanaged in the last decades due to lack of profitability. In fact, certain private forests (declared by law as *Monte Protector* or Protection Forest) can be publicly managed if this ensures the provisioning of relevant socio-environmental services (Gobierno de España 2003). This constitutes another example of private–public synergy with multiplicative effects on the territory.

The scenario including UEX proposals for future public interventions maintained in the long-term by LLMs (S3) generates a noticeable reduction of burned area despite the relatively small area treated (1.3% of the study region; Figure S3). This can be explained by the large size of most proposed interventions (which makes them more effective in fire containment), their location within large areas of massive fuel build-up that will be fragmented, and the marked reduction in fuel load pursued. The sequential action of different stakeholders has proven extremely effective when the placement of initial public interventions is jointly planned with LLMs that will make a continuous and profitable use of them (Ascoli et al. 2022). A paramount example is that of La Rioja region of northern Spain, in which mechanical fuel removal followed by livestock grazing is associated with an 81% reduction in mean fire size (Lasanta et al. 2022).

Indirect prevention implemented by LLMs is long-lasting and can cover large areas at no or reduced public cost. Initiatives described in this work received only technical advice by *Mosaico* project (funded by the Regional Government of Extremadura), and therefore landscape interventions were generally performed by LLMs with their own funds. Since these private interventions contribute to reduce fire spread in target areas and also in adjacent lands, public investment through technical support to LLMs can be considered as a cost-efficient measure even if they are performed in non-strategic locations. It must be also noted that LLM interventions (5754 ha) almost doubled in area the public ones (2985 ha). Further studies are needed to accurately estimate the cost–benefit ratios of both approaches, though this study points to their complementarity.

Conclusion and future challenges

Spontaneous landscape change takes decades; planned changes may accelerate the process, but it will still be gradual due to the complexity of the social-ecological systems involved. Here we have shown that LLM interventions have a clear potential for large-scale fuel modification. In the context where project *Mosaico* is being developed, the full realization of such potential partly depends on legal/administrative reforms adapting existing regulations to match the needs of megafire-prone territories. In synergy with this objective, harmonization of public and private efforts at the regional and local scale would accelerate the transition towards an FST. Finally, prioritizing public investment according to fire spatial behaviour would further enhance the global effectiveness of the whole strategy.

Besides continuous reporting of obstacles to institutions, adaptive management of *Mosaico* approach in the future must be focussed on improving LLM capacity to modify larger portions of the territory and prioritizing vulnerable areas. To a great extent, this target will require the association of LLMs pursuing similar goals and harmonization of their work with agencies and external actors with adequate financial resources. These conditions would also allow replication of *Mosaico* approach in any fire-prone territory characterized by excessive fuel continuity,

no matter it is provoked by land abandonment or inadequate management.

Author contributions The paper was conceived by FP, who also wrote the first draft. Data collection and analysis were performed by FP, JC, MB, ÁG, EJ, BL, GM, JN and GP. NG made essential contributions to the writing. All authors read and approved the final manuscript.

Declarations

References

Abatzoglou JT, Williams AP (2016) Impact of anthropogenic climate change on wildfire across western US forests. Proc Natl Acad Sci 113:11770–11775

Ager AA, Evers CR, Day MA, Alcasena FJ, Houtman R (2021) Planning for future fire: scenario analysis of an accelerated fuel reduction plan for the western United States. Land Urban Plan 215:104212

Alcañiz M, Úbeda X, Cerdà A (2020) A 13-year approach to understand the effect of prescribed fires and livestock grazing on soil chemical properties in Tivissa NE Iberian Peninsula. Forests 11:1013

Alcasena F, Ager AA, Belavenutti P, Krawchuk M, Day MA (2022) Contrasting the efficiency of landscape versus community protection fuel treatment strategies to reduce wildfire exposure and risk. J Environ Manag 309:114650

Aparício BA, Pereira JM, Santos FC, Bruni C, Sá AC (2022) Combining wildfire behaviour simulations and network analysis to support wildfire management: a Mediterranean landscape case study. Ecol Indic 137:108726

Aquilué N, Fortin MJ, Messier C, Brotons L (2020) The potential of agricultural conversion to shape forest fire regimes in Mediterranean landscapes. Ecosystems 23:34–51

Ascoli D, Moris JV, Marco M, Lorenzo S (2021) Land use change towards forests and wooded land correlates with large and frequent wildfires in Italy. Ann Silv Res 46:177–188

Ascoli D, Oggioni SD, Barbati A, Tomao A, Colonico M, Corona P, Plana E (2022) Smart-solutions for wildfire risk prevention: bottom-up interventions meet top-down policies under EU green deal. 4071721. https://doi.org/10.2139/ssrn.4071721

Bajocco S, Pezzatti GB, Mazzoleni S, Ricotta C (2010) Wildfire seasonality and land use: when do wildfires prefer to burn? Environ Monit Asses 164:445–452

Barbero R, Abatzoglou JT, Larkin NK, Kolden CA, Stocks B (2015) Climate change presents increased potential for very large fires in the contiguous United States. Int J Wildland Fire 24:892–899

Benali A, Sá AC, Pinho J, Fernandes PM, Pereira JMC (2021) Understanding the impact of different landscape-level fuel management strategies on wildfire hazard in central Portugal. Forests 12:522

Bertomeu M, Pineda J, Pulido F (2022) Managing wildfire risk in mosaic landscapes: a case study of the upper Gata river catchment in Sierra de Gata Spain. Land 11:465

Campos JC, Bernhardt J, Aquilué N, Brotons L, Domínguez J, Lomba Â, Marcos B, Martínez-Freiría F, Moreira F, Pais S, Honrado JP, Regos A (2021) Using fire to enhance rewilding when agricultural policies fail. Sci Total Environ 755:142897

Carmo M, Moreira F, Casimiro P, Vaz P (2011) Land use and topography influences on wildfire occurrence in northern Portugal. Land Urban Plann 100:169–176

Carroll MS, Blatner KA, Cohn PJ, Morgan T (2007) Managing fire danger in the forests of the US inland

northwest: A classic "wicked problem" in public land policy. J For 105:239–244

Castellnou M, Prat-Guitart N, Arilla E, Larrañaga A, Nebot E, Castellarnau X, Vendrell J, Pallàs J, Herrera J, Monturiol M, Cespedes J, Pagès J, Gallardo C, Miralles M (2019) Empowering strategic decision-making for wildfire management: avoiding the fear trap and creating a resilient landscape. Fire Ecol 15:1–17

Chapin FS III, Trainor SF, Huntington O, Lovecraft AL, Zavaleta E, Natcher DC, McGuire AD, Nelson JL, Ray L, Calef M, Fresco N, Huntington H, Rupp TS, DeWilde L, Naylor RL (2008) Increasing wildfire in Alaska's boreal forest: pathways to potential solutions of a wicked problem. Bioscience 58:531–540

Collins RD, de Neufville R, Claro J, Oliveira T, Pacheco AP (2013) Forest fire management to avoid unintended consequences: a case study of Portugal using system dynamics. J Environ Manag 130:1–9

Collins L, Clarke H, Clarke MF, Gausden SCM, Nolan RH, Penman T, Bradstock R (2022) Warmer and drier conditions have increased the potential for large and severe fire seasons across south-eastern Australia. Glob Ecol Biogeogr 31:1933–1948

Corona P, Ascoli D, Barbati A, Bovio G, Colangelo G, Elia M, Chianucci F (2015) Integrated forest management to prevent wildfires under Mediterranean environments. Ann Silvic Res 39:1–22

Damianidis C, Santiago-Freijanes JJ, den Herder M, Burgess P, Mosquera-Losada MR, Graves A, Papadopoulos A, Pisanelli A, Camilli F, Rois-Díaz M, Kay S (2020) Agroforestry as a sustainable land use option to reduce wildfires risk in European Mediterranean areas. Agrofor Syst 95:1–11.

Davim DA, Rossa CG, Fernandes PM (2021) Survival of prescribed burning treatments to wildfire in Portugal. For Ecol Manag 493:119250

Duane A, Castellnou M, Brotons L (2021) Towards a comprehensive look at global drivers of novel extreme wildfire events. Clim Change 165:1–21

Fernandes PM (2013) Fire-smart management of forest landscapes in the Mediterranean basin under global change. Lands Urban Plann 110:175–182

Fernandes PM (2020) Sustainable fire management. In: Leal Filho W, Azul A, Brandli L, Lange-Salvia A, Wall T (eds) Life on land encyclopedia of the UN sustainable development goals. Springer, Cham

Fernandes PM (2022) Make Europe's forests climate-smart and fire-smart. Nature 609:32

Fernandes PM, Delogu GM, Leone V, Ascoli D (2020) Wildfire policies contribution to foster extreme wildfires. Extreme wildfire events and disasters. Elsevier, Amsterdam, pp 187–200

Fischer AP, Spies TA, Steelman TA, Moseley C, Johnson BR, Bailey JD, Bowman DM (2016) Wildfire risk as a socioecological pathology. Front Ecol Environ 14:276–284

García-Martín M, Bieling C, Hart A, Plieninger T (2016) Integrated landscape interventions in Europe: Multisector collaboration in multi-functional landscapes. Land Use Policy 58:43–53

Gobierno de España (2003) Ley 43/2003 de 21 de noviembre de Montes, Madrid

Grünig M, Seidl R, Senf C (2022) Increasing aridity causes larger and more severe forest fires across Europe. Glob Change Biol 2022:1–12

Guiomar N, Godinho S, Fernandes PM, Machado R, Neves N, Fernandes JP (2015) Wildfire patterns and landscape changes in Mediterranean oak woodlands. Sci Total Environ 536:338–352

Hirsch K, Kafka V, Tymstra C, McAlpine R, Hawkes B, Stegehuis H, Peck K (2001) Fire-smart forest management: a pragmatic approach to sustainable forest management in fire-dominated ecosystems. For Chron 77:357–363

Hobbs RJ, Higgs E, Hall CM, Bridgewater P, Chapin FS III, Ellis EC, Yung L (2014) Managing the whole landscape: historical hybrid and novel ecosystems. Front Ecol Environ 12:557–564

Iglesias MC, Hermoso V, Campos JC, Carvalho-Santos C, Fernandes PM, Freitas TR, Azevedo JC (2022) Climate- and fire-smart landscape scenarios call for redesigning protection regimes to achieve multiple management goals. J Environ Manag 322:116045

Iriarte-Goñi I, Ayuda MI (2018) Should Forest Transition Theory include effects on forest fires? The case of Spain in the second half of the twentieth century. Land Use Policy 76:789–797

Kirchmeier-Young MC, Gillett NP, Zwiers FW, Cannon AJ, Anslow FS (2019) Attribution of the influence of human-induced climate change on an extreme fire season. Earth's Future 7:2–10

Lasanta T, Cortijos-López M, Errea MP, Khorchani M, Nadal-Romero E (2022) An environmental management experience to control wildfires in the mid-mountain mediterranean area: shrub clearing to generate mosaic landscapes. Land Use Policy 118:106147

Le Tourneau FM (2020) Sparsely populated regions as a specific geographical environment. J Rural Stud 75:70–79

Leone V, Tedim F, Xanthopoulos G (2020) Fire Smart Territory as an innovative approach to wildfire risk reduction. Extreme wildfire events and disasters. Elsevier, Amsterdam, pp 201–215

Li S, Li X (2017) Global understanding of farmland abandonment: a review and prospects. J Geogr Sci 27:1123–1150

Linnenluecke MK, McKnight B (2017) Community resilience to natural disasters: the role of disaster entrepreneurship. J Enterpris Comm 11:166–185

MINECO (2022) Estadística general de incendios forestales. https://datosgobes/es/catalogo/e05068001-estadistica-general-de-incendios-forestales

Monllor J, Murphy PJ (2017) Natural disasters entrepreneurship and creation after destruction: a conceptual approach. Int J Entrep Behav Res 23:618–637

Moreira F, Vaz P, Catry F, Silva JS (2009) Regional variations in wildfire susceptibility of land-cover types in Portugal: implications for landscape management to minimize fire hazard International. J Wild Fire 18:563–574

Moreira F, Ascoli D, Safford H, Adams MA, Moreno JM, Pereira JM, Curt T (2020) Wildfire management in

Mediterranean-type regions: paradigm change needed. Environ Res Lett 15:011001

North MP, York RA, Collins BM, Hurteau MD, Jones GM, Knapp E, Tubbesing CL (2021) Pyrosilviculture needed for landscape resilience of dry western United States forests. J For 119:520–544

Oliveira TM, Barros AM, Ager AA, Fernandes PM (2016) Assessing the effect of a fuel break network to reduce burnt area and wildfire risk transmission. Int J Wildl Fire 25:619–632

Oliveira TM, Guiomar N, Baptista FO, Pereira JM, Claro J (2017) Is Portugal's forest transition going up in smoke? Land Use Policy 66:214–226

Pais S, Aquilué N, Campos J, Sil Â, Marcos B, Martínez-Freiría F, Regos A (2020) Mountain farmland protection and fire-smart management jointly reduce fire hazard and enhance biodiversity and carbon sequestration. Ecosyst Serv 44:101143

Palaiologou P, Kalabokidis K, Ager AA, Day MA (2020) Development of comprehensive fuel management strategies for reducing wildfire risk in Greece. Forests 11:789

Primdahl J, Folvig S, Kristensen LS (2020) Landscape strategy-making and collaboration the hills of northern Mors Denmark; a case of changing focus and scale. Land 9:189

Quílez R, Valbuena L, Vendrell J, Uytewaal K, Ramirez J (2020) Establishing propagation nodes as a basis for preventing large wildfires: the proposed methodology. Front for Glob Change 3:548799

Rego FM, Moreno Rodríguez J, Vallejo Calzada VR, Xanthopoulos G (2018) Forest fires: sparking firesmart policies in the EU. European Commission, Luxembourg

Rothermel R C (1972) A mathematical model for predicting fire spread in wildland fuels. Intermountain Forest & Range Experiment Station Forest Service 115. US Department of Agriculture.

Ruiz-Mirazo J, Robles AB, González-Rebollar JL (2011) Two-year evaluation of fuelbreaks grazed by livestock in the wildfire prevention program in Andalusia (Spain). Agric Ecosyst Environ 141:13–22

Salis M, Del Giudice L, Arca B, Ager AA, Alcasena-Urdiroz F, Lozano O, Duce P (2018) Modeling the effects of different fuel treatment mosaics on wildfire spread and behavior in a Mediterranean agro-pastoral area. J Environ Manag 212:490–505

San-Miguel-Ayanz J, Moreno JM, Camia A (2013) Analysis of large fires in European Mediterranean landscapes: lessons learned and perspectives. For Ecol Manag 294:11–22

Soliño M, Yu T, Alía R, Auñón F, Bravo-Oviedo A, Chambel MR, Del Barrio JMG (2018) Resin-tapped pine forests in Spain: ecological diversity and economic valuation. Sci Total Environ 625:1146–1155

Tedim F, Leone V, Xanthopoulos G (2016) A wildfire risk management concept based on a social-ecological approach in the European Union: Fire Smart Territory. Int J Disaster Risk Reduct 18:138–153

Varela E, Górriz-Mifsud E, Ruiz-Mirazo J, López-i-Gelats F (2018) Payment for targeted grazing: integrating local shepherds into wildfire prevention. Forests 9:464

Viedma O, Moity N, Moreno JM (2015) Changes in landscape fire-hazard during the second half of the 20th century: agriculture abandonment and the changing role of driving factors. Agric Ecosyst Environ 207:126–140

Vigna I, Besana A, Comino E, Pezzoli A (2021) Application of the socio-ecological system framework to forest fire risk management: a systematic literature review. Sustainability 13:2121

Wolpert F, Quintas-Soriano C, Pulido F, Huntsinger L, Plieninger T (2022) Collaborative agroforestry to mitigate wildfires in extremadura Spain: land manager motivations and perceptions of outcomes benefits and policy needs. Agrofor Syst 96:1–15

Wunder S, Calkin DE, Charlton V, Feder S, de Arano IM, Moore P, Vega-García C (2021) Resilient landscapes to prevent catastrophic forest fires: socioeconomic insights towards a new paradigm. For Policy Econ 128:102458

Xanthopoulos G, Leone V, Delogu GM (2020) The suppression model fragilities: the "firefighting trap." In: Tedim F, Leone V, Mcgee TK (eds) Extreme wildfire events and disasters. Elsevier, Amsterdam, pp 135–153