Forest Policy and Economics 128 (2021) 102458

Contents lists available at ScienceDirect

Forest Policy and Economics

journal homepage: www.elsevier.com/locate/forpol

Resilient landscapes to prevent catastrophic forest fires: Socioeconomic insights towards a new paradigm☆

Sven Wunder [a,*], Dave E. Calkin [b], Val Charlton [c], Sarah Feder [a], Inazio Martínez de Arano [a], Peter Moore [d], Francisco Rodríguez y Silva [e], Luca Tacconi [f], Cristina Vega-García [g]

[a] *European Forest Institute, Spain*
[b] *Rocky Mountain Research Station, USA*
[c] *LANDWORKS, South Africa*
[d] *Food and Agriculture Organization of the United Nations, Italy*
[e] *University of Cordoba, Spain*
[f] *Australian National University, Australia*
[g] *University of Lleida, Spain*

ARTICLE INFO

Keywords
Wildfire drivers
Fire prevention
Suppression
Integrated fire management
Risk
Megafires

ABSTRACT

Extreme wildfires are a major environmental and socioeconomic threat across many regions worldwide. The limits of fire suppression-centred strategies have become evident even in technologically well-equipped countries, due to high-cost and a legacy of landscape transformations, yet with ultimately low-efficient solutions vis-à-vis extreme fires. Many practitioners and policymakers thus increasingly recognize the need to develop novel, integrated fire management approaches that shift emphasis towards the root causes of extreme fires. Here we provide from the socioeconomic angle a collective, science-informed vision about to what extent landscapes and people could become more fire-resilient through integrated fire prevention strategies. Based on our insights from around the globe, we highlight the need for interdisciplinary approaches, multiple stakeholder perspectives, and systems thinking, so as to break down a wicked problem with complex linkages into manageable nodes of information. We illustrate this, using Mediterranean forests as an example. New fire regimes will predictably make our societies more exposed and vulnerable to the risk of extreme wildfires. Proactive, innovative strategies are thus needed to provide adaptive and cost-efficient policy responses, whether based on direct changes in landscape and fuel-load management, or indirect changes in rural development models.

1. Introduction

Over the last decades, trends in global burnt areas have been regionally highly variable (Andela et al., 2019); no clear long-term trend in fire impacts has been detectable (Doerr and Santín, 2016). However, successively unprecedented megafire events have occurred over the last three years: Portugal (2017), Chile (2017), California (2018, 2019, 2020), and Australia (2019, 2020). Even smaller wildfires can produce locally unprecedented impacts (ecological, socio-economic, human lives), and hence extreme wildfire events (e.g. Greece 2018), often in newly fire-prone, less risk-aware areas. Extreme wildfires are thus a major environmental, economic and social threat in Southern Europe[1] – and increasingly becoming so elsewhere in Europe (Lidskog et al., 2019) and Eurasia (Andela et al., 2019). The Mediterranean comprises 85% of the annual area burnt in Europe, yet about 2% of all fires result in over 80% of the extent burnt (Rego et al., 2018; San-Miguel-Ayanz et al.,

☆ In this article, we further elaborate on presentations and discussions at the European Forest Institute's (EFI) event "Resilient landscapes to face catastrophic forest fires" (Madrid, Spain, 14–15 October 2019. Opinions expressed are ours, and do not reflect institutional positions.

* Corresponding author.
E-mail address: sven.wunder@efi.int (S. Wunder).

[1] Over the last two decades, annual costs have totaled three billion EUR in the Mediterranean (Rego et al., 2018).

https://doi.org/10.1016/j.forpol.2021.102458
Received 6 September 2020; Received in revised form 10 March 2021; Accepted 24 March 2021

2013). As extreme fires start consuming vast areas, impacts on suppression costs (Molina et al., 2019)[2] and human values, assets, and ecosystem services accelerate (Moritz et al., 2014). Globally, some 300 major wildfire events over the past 30 years have cost around 50 billion USD in direct losses to an estimated five million affected people (Guha-Sapir et al., 2015).

Climate change transforms fire regimes in multiple ways (Fargeon et al., 2020; Liu et al., 2010), resulting in longer fire seasons and newly vulnerable ecosystems, such as in Central and Northern Europe (Flannigan et al., 2009; Molina et al., 2019). It also impacts weather patterns more widely, exacerbating meteorological anomalies (e.g. heatwaves, winds, droughts), making it more difficult to cope with fire behaviour and effects (Alcasena et al., 2019; Duane and Brotons, 2018). As we write (August 2020), there have been 11,000 lightning strikes in California in 3 days, and 0.5 Mha have been burnt in 700 wildfires over 10 days (The Economist, 2020).

An analysis of the “largest, longest and fastest fires” in this millennium (Andela et al., 2019) identified large-scale climate forcing as a dominating driver, but anthropic effects of e.g. urban sprawl and rural exodus also left human societies and the environment more fire-exposed and -vulnerable (Ganteaume et al., 2013; Moritz et al., 2014). In Mediterranean countries with rising incomes and urbanization, rural land abandonment has created continuous areas of unmanaged regrown forest on abandoned agricultural lands, nurturing dense fuel loads. Increased ex-urban development in wildland-urban interface (WUI) areas in the United States (Radeloff et al., 2018) and Australia (Weber et al., 2019) have increased exposure of homes and people to catastrophic wildfire. In tropical southeast Asia, peatland conversion to plantations greatly increases fire risks and smoke hazards (Page and Hooijer, 2016). Biophysical and anthropic drivers can thus become analytically hard to disentangle (Bowman et al., 2017), but combined they can create a perfect storm of larger regions becoming increasingly exposed over extended fire seasons (Castellnou et al., 2019).

Faced with these recent worryingly reinforcing events, the economic limits of fire suppression-centred strategies have become evident: costs become exorbitant (Myers, 2006). New decision-making tools could make suppression more cost-effective (Rodríguez y Silva et al., 2020). Yet, reactive suppression strategies alone usually prove ineffective to stop extreme fires (Williams et al., 2011). They could actually exacerbate the “wildfire suppression paradox”: the more immediate success, the higher the fuel build-up (Calkin et al., 2015). Many practitioners and policymakers thus recognize the need to develop more proactive, people–centred and integrated fire management (IFM) along the entire risk management cycle of prevention, preparedness, response and recovery (Myers, 2006; Rego et al., 2010). This shifts emphasis towards the root causes of extreme fires, including resilient landscape management for fire prevention (Calkin et al., 2014; Moritz et al., 2014; Moreira et al., 2020; Tedim et al., 2016). However, this recognition notably comes more from an observed failure of focusing exclusively on traditional zero-fire tolerance and suppression-only strategies, than from a proven track record of fire-resilient landscape strategies: the widespread intuition is that there must be a better way, yet this new exploratory-resilient pathway remains still in the making (Ager et al., 2011; McWethy et al., 2019; Tedim et al., 2016); many challenges (Higuera et al., 2019) and barriers (Calkin et al., 2011; Smith et al., 2016) remain before we can tailor resilience models to real-world scenarios.

In this article, we focus on socioeconomic dimensions that will be needed for constructing more fire-resilient landscapes. First, we describe why extreme fire events constitute a wicked problem (Section 2). Second, we discuss the cost-benefit gaps and externalities of wildfire risks (Section 3). We then outline an example of an integral theory of change towards resilient landscapes for Europe's Mediterranean region (Section 4). Finally, we outline emerging policy implications (Section 5).

2. Extreme wildfires: a wicked problem

Landscape fires are an essential component of healthy ecosystem function worldwide. Generally, the occurrence and characteristics of forest fires are shaped by weather, vegetation fuel, topography, and anthropogenic influences that restrict or enhance the inception and spread of fire in the landscape, in a complex and dynamic mix of social and biophysical factors (Moritz et al., 2014). Even across similar forest types, wildfire drivers may differ substantially according to the socio-demographic context (Salis et al., 2019). The causes and determinants of fire impacts relate to risks of ignition, e.g. agricultural practices, electrical infrastructure (Costafreda-Aumedes et al., 2018) and of fire spread, e.g. high fuel loads in continuous and flammable vegetation types (Ager et al., 2011). New potentially catastrophic fire regimes are emerging from these dynamic interactions; impacts are much harder to predict once fire regime changes have occurred (Castellnou et al., 2019).

Managing wildfire risk constitutes what is often referred to as a “wicked problem” (Carroll et al., 2007): a highly customized, hard-to-frame and scientifically disputed phenomenon, interconnected to other problem spheres with moving parts that change the ‘rules of the game’ (e.g. climate change, rural exodus, urban sprawl) – triggering events that in isolation appear improbable, yet will have socioeconomically dire consequences whenever they occur. Hence, the options to learn from history are limited by the diffusely evolving nature of a higher-order problem, and by possible contradictions where short-term success links to long-term failure (Rittel and Webber, 1973).

Wicked problems have no unambiguous, optimal, final solution. Hence, proposed mitigating solutions cannot be fully tested through trial and error. The wildfire problem is commonly diagnosed to worsen under a business-as-usual scenario (Moreira et al., 2020). However, the scale of increased risk and the cost of mitigating it are relatively location-dependent; thus consensus on ‘how much worse’ is lacking. Consequently, progress made is also hard to track objectively. Multiple stakeholders – climate scientists, foresters, firefighters, mayors, landowners, etc. – will have different perspectives on causes, problems and solutions: their different mental models need to be made explicit and reconciled (Daniel, 2007; Higuera et al., 2019), envisaging also different benefits and costs (see next section). In traditional wildfire science, the wickedness is seen as biophysical, but it should equally include the complexity of human values and perspectives of stakeholders affected by, and affecting wildfires (Higuera et al., 2019; Smith et al., 2016). Wildfires are thus best addressed through systems thinking, breaking down complex information into nodes of information (objects, people or concepts), and establishing the links between them.

3. Externality dimensions of wildfires

Alongside a systems-based approach emerges also a basic economic-institutional question: why are extreme wildfires not effectively prevented by the relevant (groups of) local landowners and users, whether their ownership is private or public (communal, state)? After all, local people would stand to lose first from burnt homes, forests, fields, and infrastructure, and thus should have a fundamental self-interest in effectively avoiding both ignition and fire spread potentials. Are risk aversion and risk ownership ill-aligned to mitigation responsibilities and management incentives within the local institutional settings?

In wildfire science, risk is an *ex ante* non-measurable probability, but we can model it through scenarios with tangible outcomes. Wildfire risk at the landscape level encompasses three components: *hazard* (the likelihood of ignition and spread, affecting fire size and intensity), *exposure* (assets localized so that fire could affect them), and *vulnerability* (susceptibility of fire-exposed assets to suffer damage) (Finney, 2005; Lavell et al., 2012). From a people-oriented perspective on disaster risk,

[2] In Andalusia (Spain), from 1999 to 2005 to 2005–2015 average suppression costs per unit area (€/ha) increased from 139.25 to 168.44; per unit of time (€/h), the rise from 6555 to 11,014 (Molina et al., 2019).

coping capacity may be added as a fourth, vulnerability-reducing dimension (UNDRR, 2021). Hence, by multiplying alleged likelihoods of hazard by exposed, vulnerable assets, we can estimate the expected consequences, i.e. the physical damage and possibly monetized risk of fire events. Yet, in disaster management practices, multiple risk conceptualizations continue to coexist.[3]

Nevertheless, fire-related drivers, impacts, and response strategies can trigger notable cost-benefit gaps between local landowners/users and external fire-exposed societies (Donovan and Brown, 2007). Table 1 provides some examples. Starting with locally originating trends (1–3), in Europe's Mediterranean region, around two thirds of all fires originate in agriculture: farmers traditionally use fire, e.g. removing crop residues or rejuvenating pastures, because it makes economic sense for them (1). This implies risks of unintended fire spread, but also options to better manage risky fuel load accumulation. Conversely, rural exodus and land abandonment lower risk of out-of-control agricultural fires, but accumulate vegetative fuel (2). Active forest management and fire prevention works may not be worthwhile to absentee landowners, especially when their families are no longer directly exposed (Viedma et al., 2015). Obviously, resident landowners might also lack sufficient knowledge about low-probability yet high-impact extreme wildfire risks (3), and/or they may overestimate firefighters' suppression potential (Diaz et al., 2015). Community collective action may also be locally underdeveloped, thus hampering fire-preventive actions (Thompson et al., 2016). Additionally, fire managers rarely receive credit for fixing or preventing problems that never come to occur (Collins et al., 2013). If so, local actors, whether private or public, may come to underinvest in prevention and preparedness, thus increasing their own and others' exposure and vulnerability (Daniel, 2007).

As for external drivers of wildfire risk, some increased ignition risks are caused by tourists, accidents in electrical infrastructure, etc. (4). But risk may also escalate through advancing human settlement in the WUI (higher exposure), especially when built houses and infrastructure are insufficiently fire-resistant (high vulnerability). Opportunities and responsibilities for managing risk factors vary across federal and state land management agencies, local planning agencies, incident responders, and private landowners (Calkin et al., 2014).[4] (5). Last but not least, spatial externalities surge when extreme wildfire events expose assets across neighbouring regions, cities or businesses: accumulated asset values at stake may grossly exceed those of local landowners, especially when lost ecosystem services (e.g. biodiversity, carbon) and health effects (smoke damages) are considered (6) (Reisen et al., 2015). These factors, separately or jointly, may cause local landowners and -managers to underinvest in fire prevention.[5]

Overall, the economics of the ecosystem disservice provided by the fire risk from forests and landscapes may thus to some extent resemble that of ecosystem services, such as watershed and biodiversity protection: society may have an interest in modifying the first-best land management and fire practices that landowners autonomously would adopt, investing more to mitigate social costs (Watts et al., 2019). A pilot example of paying pastoralists for targeted fire-preventing grazing exists (Varela et al., 2018). But one could apply any combination of incentives (e.g. rewarding landowners for voluntary fire-preventing actions), disincentives (e.g. fining landowners for not undertaking legally mandated management measures) and enabling measures that target landowner decisions more indirectly (e.g. environmental education, organizational support, or land-use zoning policies).[6]

Correspondingly, societies may also need to reassess the adequacy of the assignment of post-fire costs: 'who owns the fire' (Eburn and Cary, 2017)? In other words, who can, by default, be held responsible for the economic costs of an extreme fire, be it through attributed causes of ignition, or insufficient fuel-load management to arrest fire spread? Globally, quite distinct models have been adopted here, reflecting distinct political realities. In Europe's Mediterranean region, much dominated by small forest owners, costs are widely externalized to insurance companies and the public sector; in the USA, Australia and South Africa, ignition-causing companies, as well as fuel load-negligent large landholders, have indeed been held responsible for major costs (Water and Forestry, 2005). Another game-changing factor could be if properties on land projected to be fire-affected were to be charged higher home insurance premiums (as e.g. in Australia), or if insurance coverage was contingent on fire-preventing actions. While command-and-control regulation (e.g. vis-à-vis WUI zoning or agricultural fires) are key policy tools, incentive-changing economic instruments often remain under-utilized in bridging cost-benefit gaps hindering effective fire-preventive action.

4. A theory of change for fire resilience

Traditional fire science, management and policies have tended to operate in silos, focusing only on 'their' targeted aspects (e.g. physical, biological, or social) of the wicked wildfire problem (Smith et al., 2016). However, many divergent and intersecting factors make clear that the envisaged transformation of landscapes towards greater fire resilience requires a holistic, transdisciplinary frame to better enable systems thinking. A 'Theory of Change' (ToC) framework (Fig. 1) allows abstruse information to be broken down into nodes for developing stepwise, logically sequenced solutions to complex social or socioenvironmental problems (Weiss, 1997). A ToC fleshes out how intermediate accomplishments relate to longer-term goals, particularly when hoped-for longer-term impacts such as reduced fire risks and damage are hard to measure objectively in the present, given their probabilistic and/or perceptive nature. For instance, with respect to the aforementioned "wildfire suppression paradox", if we were to register fewer fires occurrences than in the past, this could constitute a contrarian indicator foreshadowing greater future risk of extreme fires and less landscape resilience (Donovan and Brown, 2007; Calkin et al., 2014). Hence, the

[3] The Forest Fire Management Group of land-management agencies in Australia/ New Zealand noted that no internationally agreed risk management standard covering all types of fire associated with forest and rural land management exists (Dudfield, 2012). The disaster risk-generic ISO standard expressed risk in terms of sources, potential events, their consequences, and likelihood (ISO, 2021). In the USA, the risk assessment outlined in Scott et al. (2013) has been widely adopted, using the key term Highly Valued Resources and Assets (HVRA) –"resources" being ecological values of interest and "assets" referring to built infrastructure. These efforts define exposure through probabilistic fire simulation and vulnerability by eliciting expert-derived functions (how HVRA responds to fire of different intensities), and the relative weight of different HVRAs. Monetization is often not attempted; focus is on how individual HVRAs contribute to overall risk scores. This method shares many similarities with risk assessments in Canada (McFayden et al., 2019) and Spain (Chuvieco et al., 2014).

[4] As for externalities between levels of government, fire suppression costs likely accrue centralized, while local governments may expect increased property tax revenues from developing WUI in fire-prone landscapes.

[5] Conversely, misguided external policies could also jeopardize effective local fire management: a flat no-fire policy may prevent landowners from using controlled fire safely as a cost-efficient tool of wildfire prevention on their lands, thus acting eventually as a perverse disincentive to the local alignment of risk ownership.

[6] The classical discussion from environmental economics about when Pigouvian (polluter pays principle) versus Coasian solutions (provider gets principle) are preferable to address social costs (e.g. Engel et al., 2008) is thus also relevant to fire prevention.

Table 1
Wildfire risk components and externalities: examples of drivers and impacts.

Risk component	**Hazard**		**Exposure**		**Vulnerability**	
Problem/trend	**Ignition**	**Spread**	**Local**	**External**	**Local**	**External**
1. **Local** fire-using agricultural practices as fire drivers/ managers	↑	↓				
2. **Local** driver**:** land abandonment, landholder absenteeism	↓	↑	↓			
3. Low **local** risk perception	↑	↑	↑	↑	↑	↑
4. More **externally** driven ignitions (tourism, electricity, etc.)	↑					
5. **External** driver: settlement in the wildland-urban interface (WUI)	↑		↑			
6. Extreme fires impact distant **external** regions (incl. assets, health, ecosystem services)				↑		↑

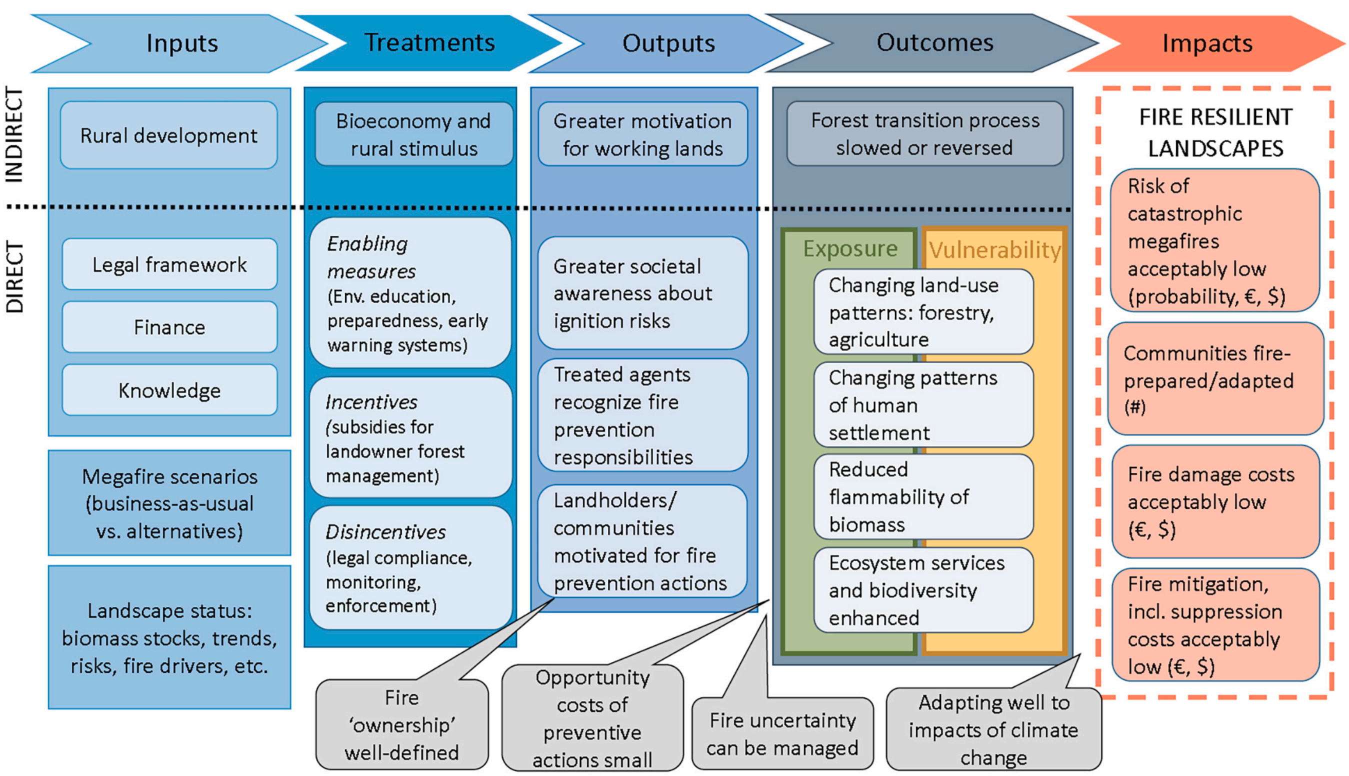

Fig. 1. A Theory of Change for fire-resilient landscapes: the example of Europe's Mediterranean region.

ToC will make explicit how these system nodes allegedly are interlinked.

Through a ToC exercise, planned interventions can inter alia be mapped backwards: from a bundle of desirable long-term impacts and outcomes (right-hand side), one can identify the necessary outputs (centre), treatments, and inputs (left-hand side) to reach stated goals. This is consistent with the incremental system improvements proposed by Carroll et al. (2007) for analysing wicked wildfire problems. We explore what is required to make sequential progress in a chain of socio-environmentally interdependent actions leading to the super-goal of "fire-resilient landscapes" using Europe's Mediterranean region as an example. Improved fire resilience implies reduced fire risk and (material and ecological) damage, lower suppression costs, and more fire-adapted communities – all expressed relative to customized business-as-usual baseline scenarios. Yet, even taking comprehensive fire-preventive measures may not provide complete protection against new super-potent fire regimes (Castellnou et al., 2019), emerging in so-called "black swan" (Taleb, 2007), or climate-induced "green swan" type of low-probability, extreme-impact events (Bolton et al., 2020). Society's expectations about future risks thus also need to be managed.

The desired Mediterranean risk-mitigating land- and resource-use outcomes are to occur in the productive sectors (forestry, agriculture) and in human settlement patterns (WUI, rural zones). In turn, these changes will have implications for ignitions, flammability of biomass, and for the ecosystem services landscapes provide. Outcomes are the make-or-break part of our ToC: do changes on the ground materialize as intended? On limited spatial and temporal scales, 'success' in reducing wildfire risks will be defined at the outcomes, rather than the impact level – and require explicit (e.g. modelled) assumptions about how outcomes and impacts are allegedly interlinked.

Notably, landscape outcomes could be triggered by any combination of direct (fire-targeted) and indirect (rural development-motivated) lines of actions. Indirect benefits on forest and fuel management would be yielded from rural income generation that slows down the secular "forest transition" process in developed economies: abandonment of marginal agricultural lands, matched by spontaneous forest regrowth (Mather and Needle, 1998). An innovative, more profitable rural economy might halt rural exodus, through investing in value-added renewable biological resources, with the bioeconomy as umbrella concept (McCormick and Kautto, 2013). As a desirable side-effect, more actively worked rural lands and better managed forestlands could mitigate fuel load build-up and continuity, thus curbing the risk of wildfire spread (Verkerk et al., 2018) (Fig. 1, upper part).

These indirect effects are potentially powerful triggers of landscape transformation at large scale enhancing fire resilience. However, reversing forest transition is extremely ambitious: it has for decades been driven by higher-order economic development, such as agricultural technologies, rising wages, globalisation, urbanization, etc. Drastic course changes in rural economies could hardly be motivated by firefighting alone: they would require effective alliances around broader models of rural development strategies (incl. Climate, biodiversity, cultural and economic goals). Absent these multiple benefits, indirect strategies are likely excessively expensive solutions for fire resilience. Conversely, not every bioeconomic innovation (e.g. in plantation forestry), nor all retained agriculture (e.g. traditional pastoralism using fire) will automatically increase fire resilience: spatial targeting and managed tradeoffs in multipurpose objective functions would be needed to make sure indirect rural development strategies genuinely pay off for fire prevention.

In turn, direct strategies of fire prevention (Fig. 1, lower part) seek to achieve targeted changes in awareness, behaviour and ultimately landscape composition and configuration, from reducing ignition risks to diminishing fuel loads. As a side-effect, these changes may also raise rural incomes, which may politically ease their implementation, but different from indirect strategies, this is not their primary purpose. Their more targeted nature, however, increases options for designing them cost-effectively. As mentioned, treatments may include incentives and disincentives (aimed at changing behaviour), as well as enabling measures (fire-use training, land-use planning, evacuation strategies, etc.), requiring inputs stretching from legal and financial means, to participatory community engagement empowering localized knowledge about landscape dynamics. Additionally, direct strategies will only work when certain assumptions hold (cf. bubbles in Fig. 1), related to biophysics (adapting to climate change, managing insecurity) as well as socioeconomics (keeping costs of actions low, aligning fire-related responsibilities).

Also, direct landscape strategies encounter non-trivial challenges. Forest management reducing biomass density and fuel-load continuity can reduce wildfire spread importantly (Parisien and Moritz, 2009), including through prescribed burning (Fernandes et al., 2013). But this result holds more for convective, heat-driven fires, while wind-driven fires more strongly relate to topographic and climate factors, as found in California (Jin et al., 2014) and Catalonia (Duane et al., 2015). The role of tree species composition is equally debated: rapidly expanding eucalypt plantations seemingly did not increase burnt area in Portugal (Fernandes et al., 2019); in Chile, non-native monostand plantations were one contributing driver to the 2017 fires (McWethy et al., 2018). In some forest contexts, logging and associated forest management can exacerbate fire risks, rather than reducing them (Nepstad et al., 1999; Lindenmayer et al., 2020).

Fuel treatment options also face controversial questions (Alcasena et al., 2019): what type of treatment, how often and how much, and where to treat the fuelscape? Some landscapes may require intervention at scales never attempted before, requiring long-term monitoring and learning (Carroll et al., 2007; Steelman, 2016), and a change in paradigm: policy performance should be evaluated in terms of avoided socio-ecological damage (Moreira et al., 2020). Biophysical approaches require complementary visions of landscape and communities, integrating subjective dimensions (Higuera et al., 2019) and bridging adaptive governance gaps between communities and institutions, especially under climate change constraints (Niekerk, 2014; Steelman, 2016).

5. Conclusion: Wildfires, socioeconomics, and policies

Much research has been done about the biophysical drivers of forest wildfires, trying to develop technical blueprints for how landscapes can be better managed to prevent wildfire risks (Alcasena et al., 2019; Fernandes et al., 2013; Moreira et al., 2020). However, it is essential to make socioeconomic considerations a centrepiece in these efforts: we want people to organize and behave differently on the ground, yet human organization and behaviour are strongly linked to socioeconomic options (Watts et al., 2019). These needs will have to inform also the type of capacities (e.g. innovative profiles of landscape managers) and territorial governance (e.g. modified relationships between political entities/ jurisdictions) that will be required for implementing a new paradigm. Hence, consider that to date no blueprints for fire-resilient landscapes exist: the concept is promising, but in practice it remains widely untested (Higuera et al., 2019). Policymakers should thus also generally encourage diverse, tentative, and learning-oriented solutions, rather than searching for a singular and impossible one-size-fits-all model.

Diagnostically, extreme wildfires constitute a wicked problem, which due to its many moving parts has no single 'optimized' solution. First, this adds to the attractiveness of experimental and adaptive approaches. Second, the goal becomes to achieve "long-term system improvements rather than short-term fixes" (Carroll et al., 2007:239). Yet, arguably little attention has been paid to the cost-benefit gap and spatial externality dimensions of wildfires. The often-convenient default assumption that 'everybody is in the same boat' may conceal at least partial conflicts of interest. Mapping the distribution of fire- and response-related costs and benefits is a key first step towards resilient solutions. While economic instruments are generally no panacea, economists and other social scientists can help to identify respective designs of incentives and disincentives, to promote (individual or collective) behavioural change. The established field of ecosystem services can here provide valuable policy lessons for wildfires, constituting an environmental disservice with potentially high social costs.

Walking backwards through a theory of change for Mediterranean fire-resilient landscapes served us to identify critical pathways and nodes in a complex transition. One key strategic distinction surfaced: are we trying to directly achieve landscape changes for preventing catastrophic fires, hoping it will also raise rural incomes – or are we, conversely, trying to reinvigorate rural economies, incomes, and settlement, hoping it will also indirectly keep landscapes open and fuel loads down? Both strategies certainly should be complementary to some extent, but also each faces critical drawbacks. Fighting powerful long-term forest transition processes of rural exodus may often become a Sisyphean challenge. Conversely, targeted direct strategies may offer better prospects of effectiveness, but lack consolidation.

Author statement

SW – Conceptualization, writing – original draft, writing – review and editing, visualization; SF – conceptualization, visualization, writing – review and editing; DEC, VC, IMA, PM, FRS, LT, and CVG – conceptualization, writing – review and editing.

Funding

We appreciate support from Diputació de Barcelona and the Spanish Ministry for Ecological Transition and Demographic Challenge (MITECO). (Not involved in research design).

Declaration of Competing Interest

The authors declare to have no conflicts of interest.

References

Ager, A.A., Vaillant, N.M., Finney, M.A., 2011. Integrating fire behavior models and geospatial analysis for wildland fire risk assessment and fuel management planning. J. Comb., 572452 https://doi.org/10.1155/2011/572452.

Alcasena, F., Ager, A.A., Bailey, J.D., Pineda, N., Vega-García, C., 2019. Towards a comprehensive wildfire management strategy for Mediterranean areas: Framework development and implementation in Catalonia, Spain. J. Environ. Manag. 231 (1), 303–320.

Andela, N., Morton, D.C., Giglio, L., Paugam, R., Chen, Y., Hantson, S., van der Werf, G. R., Randerson, J.T., 2019. The global fire atlas of individual fire size, duration, speed and direction. Earth Syst. Sci. Data 11 (2), 529–552.

Bolton, P., Despres, M., Pereira da Silva, L.A., Samana, F., Svartzman, R., 2020. The Green Swan: Central Banking and Financial Stability in the Age of Climate Change. Bank for International Settlements.

Bowman, D.M.J.S., Williamson, G.J., Abatzoglou, J.T., Kolden, C.A., Cochrane, M.A., Smith, A.M.S., 2017. Human exposure and sensitivity to globally extreme wildfire events. Nat. Ecol. Evolut. 1 (3), 0058. https://doi.org/10.1038/s41559-016-0058.

Calkin, D.E., Finney, M.A., Ager, A.A., Thompson, M.P., Gebert, K.G., 2011. Progress towards and barriers to implementation of a risk framework for Federal wildland fire policy and decision making in the United States. Forest Policy Econ. 13 (5), 378–389.

Calkin, D.E., Cohen, J.D., Finney, M.A., Thompson, M.P., 2014. How risk management can prevent future wildfire disasters in the wildland-urban interface. Proc. Natl. Acad. Sci. 111 (2), 746–751.

Calkin, D.E., Thompson, M.P., Finney, M.A., 2015. Negative consequences of positive feedbacks in US wildfire management. Forest Ecosyst. 2 (1), 9.

Carroll, M.S., Blatner, K.A., Cohn, P.J., 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 (5), 239–244. https://doi.org/10.1093/jof/105.5.239.

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), 31.

Chuvieco, E., Aguado, I., Jurdao, S., Pettinari, M.L., Yebra, M., Salas, J., Hantson, S., de la Riva, J., Ibarra, P., Rodrigues, M., Echeverría, M., Azqueta, D., Román, M.V., Bastarrika, A., Martínez, S., Recondo, C., Zapico, E., Martínez-Vega, F.J., 2014. Integrating geospatial information into fire risk assessment. Int. J. Wildland Fire 23 (5), 606–619.

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

Costafreda-Aumedes, S., Vega-Garcia, C., Comas, C., 2018. Improving fire season definition by optimized temporal modelling of daily human-caused ignitions. J. Environ. Manag. 217, 90–99. https://doi.org/10.1016/j.jenvman.2018.03.080.

Daniel, T.C., 2007. Perceptions of wildfire risk. In: Daniel, Terry C. (Ed.), People, Fire and Forests. Oregon State University Press, ISBN 978-0-87071-184-8.

Diaz, J.M., Steelman, T., Nowell, B., 2015. Local ecological knowledge and fire management: what does the public understand? J. For. 114 (1), 58–65. https://doi.org/10.5849/jof.14-026.

Doerr, S.H., Santín, C., 2016. Global trends in wildfire and its impacts: perceptions versus realities in a changing world. Philos. Trans. R. Soc. B: Biol. Sci. 371 (1696), 20150345.

Donovan, G.H., Brown, T.C., 2007. Be careful what you wish for: the legacy of Smokey Bear. Front. Ecol. Environ. 5 (2), 73–79.

Duane, A., Brotons, L., 2018. Synoptic weather conditions and changing fire regimes in a Mediterranean environment. Agric. For. Meteorol. 253-254, 190–202. https://doi.org/10.1016/j.agrformet.2018.02.014.

Duane, A., Piqué, M., Castellnou, M., Brotons, L., 2015. Predictive modelling of fire occurrences from different fire spread patterns in Mediterranean landscapes. Int. J. Wildland Fire 24 (3), 407–418. https://doi.org/10.1071/WF14040.

Dudfield, M., 2012. Integrating the Management of Wildfire-Related Risks in Rural Land and Forest Management Legislation and Policies. ANZ Forest Fire Management Group. May. https://gfmc.online/globalnetworks/wfag-ilc-ifag/Wildfire-Risk-Management-Position-Paper-06-July-2012.pdf.

Eburn, M., Cary, G.J., 2017. You own the fuel, but who owns the fire? Int. J. Wildland Fire 26 (12), 999–1008. https://doi.org/10.1071/WF17070.

Engel, S., Pagiola, S., Wunder, S., 2008. Designing payments for environmental services in theory and practice: an overview of the issues. Ecol. Econ. 65 (4), 663–675.

Fargeon, H., Pimont, F., Martin-St. Paul, N., De Caceres, M., Ruffault, J., Barbero, R., Dupuy, J.L., 2020. Projections of fire danger under climate change over France: where do the greatest uncertainties lie? Clim. Chang. 160 (3), 479–493. https://doi.org/10.1007/s10584-019-02629-w.

Fernandes, P.M., Davies, G.M., Ascoli, D., Fernández, C., Moreira, F., Rigolot, E., Stoof, C. R., Vega, J.A., Molina, D., 2013. Prescribed burning in southern Europe: developing fire management in a dynamic landscape. Front. Ecol. Environ. 11 (1), 4–14.

Fernandes, P.M., Guiomar, N., Rossa, C.G., 2019. Analysing eucalypt expansion in Portugal as a fire-regime modifier. Sci. Total Environ. 666, 79–88.

Finney, M.A., 2005. The challenge of quantitative risk analysis for wildland fire. Forest Ecology and Management 211 (1), 97–108. https://doi.org/10.1016/j.foreco.2005.02.010.

Flannigan, M., Stocks, B., Turetsky, M., Wotton, M., 2009. Impacts of climate change on fire activity and fire management in the circumboreal forest. Glob. Chang. Biol. https://doi.org/10.1111/j.1365-2486.2008.01660.x.

Ganteaume, A., Camia, A., Jappiot, M., San-Miguel-Ayanz, J., Long-Fournel, M., Lampin, C., 2013. A review of the Main driving factors of Forest fire ignition over Europe. Environ. Manag. 51, 651–662.

Guha-Sapir, D., Below, R., Hoyois, P., 2015. EM-DAT: international disaster database. In: Centre for Research on the Epidemiology of Disasters (CRED). University of Louvain, Belgium. Available from: http://www.emdat.be/.

Higuera, P.E., Metcalf, A.L., Miller, C., Buma, B., McWethy, D.B., Metcalf, E.C., Ratajczak, Z., Nelson, C.R., Chaffin, B.C., Stedman, R.C., McCaffrey, S., Schoennagel, T., Harvey, B.J., Hood, S.M., Schultz, C.A., Black, A.E., Campbell, D., Haggerty, J.H., Keane, R.E., Krawchuk, M.A., Kulig, J.C., Rafferty, R., Virapongse, A., 2019. Integrating subjective and objective dimensions of resilience in fire-prone landscapes. BioScience 69, 379–388.

ISO, 2021. ISO 31000:2018(en) Risk management — Guidelines. https://www.iso.org/obp/ui#iso:std:iso:31000:ed-2:v1:en. Accessed 16 February 2021.

Jin, Y., Randerson, J.T., Faivre, N., Capps, S., Hall, A., Goulden, M.L., 2014. Contrasting controls on wildland fires in Southern California during periods with and without Santa Ana winds. J. Geophys. Res. Biogeosci. 119 (3), 432–450. https://doi.org/10.1002/2013JG002541.

Lavell, A., Oppenheimer, M., Diop, C., Hess, J., Lempert, R., Li, J., Muir-Wood, R., Myeong, S., Moser, S., Takeuchi, K., Cardona, O.D., Hallegatte, S., Lemos, M., Little, C., Lotsch, A., Weber, E., 2012. Climate change: New dimensions in disaster risk, exposure, vulnerability, and resilience. In: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation: Special Report of the Intergovernmental Panel on Climate Change, 9781107025066. Cambridge Uni Press, pp. 25–64. https://doi.org/10.1017/CBO9781139177245.004.

Lidskog, R., Johansson, J., Sjödin, D., 2019. Wildfires, responsibility and trust: public understanding of Sweden's largest wildfire. Scand. J. For. Res. 34 (2), 319–328.

Lindenmayer, D.B., Kooyman, R.M., Taylor, C., Ward, M., Watson, J.E.M., 2020. Recent Australian wildfires made worse by logging and associated Forest management. Nat. Ecol. Evolut. 4 (7), 898–900.

Liu, Y., Stanturf, J., Goodrick, S., 2010. Trends in global wildfire potential in a changing climate. For. Ecol. Manag. 259 (4), 685–697. https://doi.org/10.1016/j.foreco.2009.09.002.

Mather, A.S., Needle, C.L., 1998. The forest transition: a theoretical basis. Area 30 (2), 117–124. https://www.jstor.org/stable/20003865.

McCormick, K., Kautto, N., 2013. The bioeconomy in Europe: an overview. Sustainability 5 (6), 2589–2608.

McFayden, C.B., Boychuk, D., Woolford, D.G., Wheatley, M.J., Johnston, L., 2019. Impacts of wildland fire effects on resources and assets through expert elicitation to support fire response decisions. Int. J. Wildland Fire 28, 885–900.

McWethy, D.B., Pauchard, A., García, R.A., Holz, A., González, M.E., Veblen, T.T., Stahl, J., Curre, B., 2018. Landscape drivers of recent fire activity (2001-2017) in South-Central Chile. PLoS One 13 (8), e0201195.

McWethy, D.B., Schoennagel, T., Higuera, P.E., Krawchuk, M., Harvey, B.J., Metcalf, E. C., Schultz, C., Miller, C., Metcalf, A.L., Buma, B., Virapongse, A., Kulig, J.C., Stedman, R.C., Ratajczak, Z., Nelson, C.R., Kolden, C., 2019. Rethinking resilience to wildfire. Nat. Sustain. 2, 797–804.

Molina, J.R., González-Cabán, A., Rodríguez y Silva, F., 2019. Potential effects of climate change on fire behavior, economic susceptibility and suppression costs in Mediterranean ecosystems: Córdoba Province, Spain. Forests 10, 679.

Moreira, F., Ascoli, D., Safford, H., Adams, M.A., Moreno, J.M., Pereira, J.M.C., Catry, F. X., Armesto, J., Bond, W., González, M.E., Curt, T., Koutsias, N., McCaw, L., Price, O., Pausas, J.G., Rigolot, E., Stephens, S., Tavsanoglu, C., Vallejo, V.R., Van Wilgen, B. W., Xanthopoulos, G., Fernandes, P.M., 2020. Wildfire management in Mediterranean-type regions: paradigm change needed. Environ. Res. Lett. 15 (1), 011001.

Moritz, M.A., Batllori, E., Bradstock, R.A., Gill, A.M., Handmer, J., Hessburg, P.F., Leonard, J., McCaffrey, S., Odion, D.C., Schoennagel, T., Syphard, A.D., 2014. Learning to coexist with wildfire. Nature 515, 58–66.

Myers, R.L., 2006. Living with fire—Sustaining ecosystem and livelihoods through integrated fire management. In: Global Fire Initiative. The Nature Conservancy, Tallahassee, Florida, USA.

Nepstad, D.C., Verssimo, A., Alencar, A., Nobre, C., Lima, E., Lefebvre, P., Schlesinger, P., Potter, C., Moutinho, P., Mendoza, E., Cochrane, M., Brooks, V., 1999. Large-scale

impoverishment of Amazonian Forests by logging and fire. Nature 398 (6727), 505–508.
Niekerk, D.V., 2014. From burning to learning: adaptive governance to wildfires in the North-West Province of South Africa. J. Hum. Ecol. 48 (2), 329–339. https://doi.org/10.1080/09709274.2014.11906802.
Page, S.E., Hooijer, A., 2016. In the line of fire: the peatlands of Southeast Asia. Philos. Trans. R. Soc. B: Biol. Sci. 371 (1696), 20150176.
Parisien, M.A., Moritz, M.A., 2009. Environmental controls on the distribution of wildfire at multiple spatial scales. Ecol. Monogr. 79 (1), 127–154. https://doi.org/10.1890/07-1289.1.
Radeloff, V.C., Helmers, D.P., Kramer, H.A., Mockrin, M.H., Alexandre, P.M., Bar-Massada, A., Butsic, V., Hawbaker, T.J., Martinuzzi, S., Syphard, A.D., Stewart, S.I., 2018. Rapid growth of the US wildland-urban interface raises wildfire risk. Proc. Natl. Acad. Sci. 115 (13), 3314–3319.
Rego, F., Rigolot, E., Fernandes, P.M., Montiel, C., Silva, J.S., 2010. Towards Integrated Fire Management. European Forest Institute, p. 16.
Rego, F., Moreno, J.M., Vallejo, V.R., Xanthopoulos, G., 2018. In: Faivre, N. (Ed.), Forest Fires: Sparking Firesmart Policies in the EU. DG Research and Innovation, Brussels, p. 48 doi: 102777/181450.
Reisen, F., Duran, S.M., Flannigan, M., Elliott, C., Rideout, K., 2015. Wildfire smoke and public health risk. Int. J. Wildland Fire 24, 1029–1044.
Rittel, H.W.J., Webber, M.M., 1973. Dilemmas in a general theory of planning. Policy. Sci. 4 (2), 155–169.
Rodríguez y Silva, F., O'Connor, C.D., Thompson, M.P., Molina Martínez, J.R., Calkin, D. E., 2020. Modelling suppression difficulty: current and future applications. Int. J. Wildland Fire. https://doi.org/10.1071/WF19042.
Salis, M., Arca, B., Alcasena-Urdiroz, F., Massaiu, A., Bacciu, V., Bosseur, F., Caramelle, P., Dettori, S., Fernandes de Oliveira, A.S., Molina-Terren, D., Pellizzaro, G., Santoni, P.A., Spano, D., Vega-Garcia, C., Duce, P., 2019. Analyzing the recent dynamics of wildland fires in Quercus suber L. woodlands in Sardinia (Italy), Corsica (France) and Catalonia (Spain). Eur. J. For. Res. 138 (3), 415–431.
San-Miguel-Ayanz, J., Moreno, J.M., Camia, A., 2013. Analysis of large fires in European Mediterranean landscapes: lessons learned and perspectives. For. Ecol. Manag. 294, 11–22.
Scott, J.H., Thompson, M.P., Calkin, D.E., 2013. A wildfire risk assessment framework for land and resource management. In: RMRS-GTR-315. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO, p. 83.
Smith, A.M.S., Kolden, C.A., Paveglio, T.B., Cochrane, M.A., Bowman, D.M.J.S., Moritz, M.A., Kliskey, A.D., Alessa, L., Hudak, A.T., Hoffman, C.M., Lutz, J.A., Queen, L.P., Goetz, S.J., Higuera, P.E., Boschetti, L., Flannigan, M., Yedinak, K.M., Watts, A.C., Strand, E.K., van Wagtendonk, J.W., Anderson, J.W., Stocks, B.J., Abatzoglou, J.T., 2016. The science of Firescapes: achieving fire-resilient communities. BioScience 66 (2), 130–146.
Steelman, T., 2016. U.S. wildfire governance as social-ecological problem. Ecol. Soc. 21 (4) https://doi.org/10.5751/ES-08681-210403.
Taleb, N.N., 2007. The Black Swan. Penguin Random House, New York.
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. Dis. Risk Reduct. 18, 138–153.
The Economist, 2020. Natural Disasters: Why California Is Experiencing its Worst Fires on Record (26 August 2020).
Thompson, M.P., Rodríguez y Silva, F., Calkin, D.E., Hand, M.S., 2016. A review of challenges to determining and demonstrating efficiency of large fire management. Int. J. Wildland Fire 26 (7), 562–573.
UNDRR, 2021. Disaster Risk. https://www.undrr.org/terminology/disaster-risk (Accessed on 21 February 2021).
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.
Verkerk, P.J., Martinez de Arano, I., Palahí, M., 2018. The bio-economy as an opportunity to tackle wildfires in Mediterranean forest ecosystems. Forest Policy Econ. 86, 1–3. https://doi.org/10.1016/j.forpol.2017.10.016.
Viedma, O., Moity, N., Moreno, J.M., 2015. Changes in landscape fire-hazard during the second half of the 20th century: Agriculture abandonment and the changing role of driving factors. Agriculture, Ecosystems and Environment 207, 126–140. https://doi.org/10.1016/j.agee.2015.04.011.
Water and Forestry, 2005. Resource Materials on the National Veld and Forest Fire Act No. 101 of 1998. Water Affairs and Forestry, Republic of South Africa. https://www.daff.gov.za/doaDev/sideMenu/ForestryWeb/webapp/Documents/ForestFire/192.168.10.11/nvffa.html.
Watts, J., Tacconi, L., Hapsari, N., Irawan, S., Sloan, S., Widiastomo, T., 2019. Incentivizing compliance: evaluating the effectiveness of targeted village incentives for reducing burning in Indonesia. Forest Policy Econ. 108, 101956. https://doi.org/10.1016/j.forpol.2019.101956.
Weber, D., Moskwa, E., Robinson, G.M., Bardsley, D.K., Arnold, J., Davenport, M.A., 2019. Are we ready for bushfire? Perceptions of residents, landowners and fire authorities on lower Eyre peninsula, South Australia. Geoforum 107, 99–112.
Weiss, C.H., 1997. How can theory-based evaluation make greater headway? Eval. Rev. 21 (4), 501–524.
Williams, J., Albright, D., Hoffman, A.A., Eritsov, A., Moore, P.F., Mendes de Morais, J., Leonard, M., San Miguel-Ayanz, J., Xanthopoulos, G., Lierop, P., 2011. Findings and Implications from a Coarse-Scale Global Assessment of Recent Selected Mega-Fires. Food and Agriculture Organisation of the United Nations.